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Ecodesign methods focused on remanufacturing

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ABSTRACT

Understanding the product's 'end-of-life' is important to reduce the environmental impact of the products' final disposal. When the initial stages of product development consider end-of-life aspects, which can be established by ecodesign (a proactive approach of environmental management that aims to reduce the total environmental impact of products), it becomes easier to close the loop of materials. The 'end-of-life' ecodesign methods generally include more than one 'end-of-life' strategy. Since product complexity varies substantially, some components, systems or sub-systems are easier to be recycled, reused or remanufactured than others. Remanufacture is an effective way to maintain products in a closed-loop, reducing both environmental impacts and costs of the manufacturing processes. This paper presents some ecodesign methods focused on the integration of different 'end-of-life' strategies, with special attention to remanufacturing, given its increasing importance in the international scenario to reduce the life cycle impacts of products.

1. Introduction

Sustainability is a systemic concept related to the continuity of economic, social, institutional and environmental aspects. The consumption and production of products throughout their life cycles is at the origin of most of the pollution and resource depletion caused by our society. To successfully implement sustainable business models, it is necessary to promote a change in the economic values we endorse toward the life cycle thinking approach, due to the scarcity of raw materials, the environment's limitation to absorb residues and emissions, and the consumption needs of a growing population.

All products cause some types of impacts during their life cycles, from raw materials extraction to manufacturing, use and final disposal. These environmental effects are the result of linked decisions, conducted throughout the product's life cycle [1]. Life cycle economic systems come about from the integration of actions which are economically viable and environmentally efficient and may focus on different end-of-life alternatives and lifetime extension strategies.

The grounding of a strategy for integrating environmental issues into the product development process must consider the products' complexity and diversity and the fast evolution of knowledge and information on product designs and services [2]. It is important to notice, however, that no environmental improvement will be achieved unless new products are competitive and can fully replace lower environmental performance products. Thus, product's functionality, performance, aesthetics, quality and cost must be compatible with improved environmental performance requirements [3].

This paper is divided into 7 Sections. This first section deals with the Introduction. Section 2 describes the Theoretical Background of some fundamental concepts that must be understood in order to improve the environmental performance. It explains the concepts of Life cycle Thinking, ecodesign, End-of-Life Strategies and Remanufacturing. The research methodology applied to this paper is presented in Section 3 and Section 4 details the ecodesign methods focused on End-of-Life Strategies. The results and discussion are in Section 5, while Sections 6 and 7 present, respectively, the acknowledgements and references of this paper.

2. Theoretical background

When discussing sustainability and the ways to achieve it, there are some concepts that ought to be clarified. The scope of this paper is related to closing the loop of materials in a productive chain by means of providing feasible end-of-life alternatives to both organizations and customers. The proposal of such systems derives from understanding the entire life cycle of products, from raw material extraction to final disposition.

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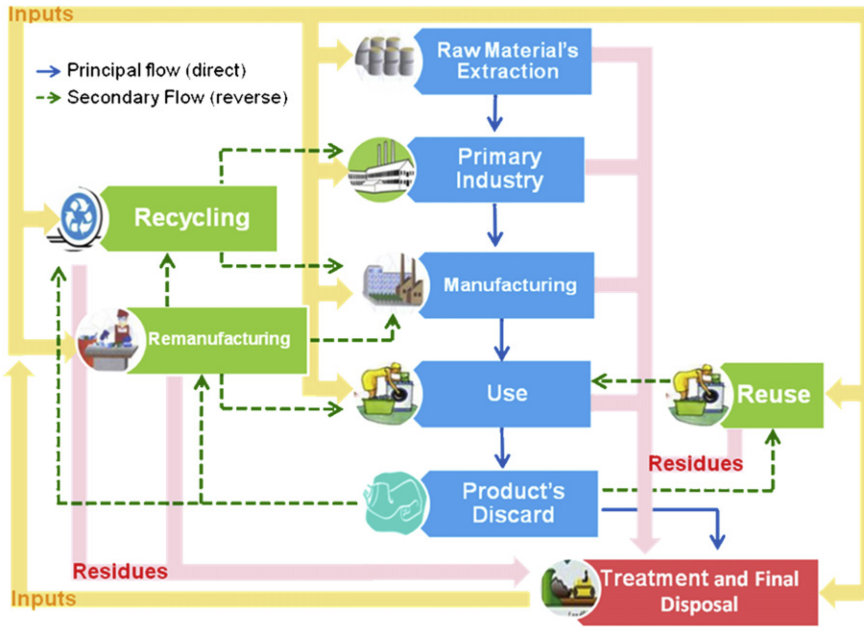

Fig. 1. Typical material product life cycle, with a focus on end-of-life alternatives as a way to help to maintain cyclic flow of materials contained in the products.

The introduction of the life cycle thinking is associated with efforts towards increasing efficiency throughout the product life cycle, which can lead to an extended responsibility of the involved parties. Thus, the main challenge is for organizations to consider the product life cycle fully, focusing on optimizing the interactions among product design, manufacturing processes and other life cycle activities, for instance usage and end-of-life treatment.

This section aims to describe some key concepts in understanding the importance of design, and therefore ecodesign, when choosing from end-of-life alternatives. There is a special focus on the remanufacturing process, which is increasingly and significantly important in Brazil and in the international scenario in face of internal and international regulations concerning the producer's extended responsibility.

2.1. Life cycle thinking

Life cycle thinking is the integration of life cycle perspectives into the overall strategy, planning and decision-making processes of an organization, taking into account economical, social and environmental considerations. This means a change in the profit oriented paradigm that has guided organizations throughout their activities. Heiskanen [4] defines the life cycle thinking as a new institutional logic, capable of gathering followers for different motives and engaging organizations into its practices. The author also emphasizes that the life cycle thinking implies that organizations are responsible for environmental damages caused throughout the entire product chain.

A life cycle perspective demands more from an enterprise's environmental initiatives, but also provides the possibility for significant advantages. These benefits may include improved competitive features and enhanced market image, closer cooperation with suppliers and customers as well as better relations with environmental authorities and with other joint partners [4].

The traditional manufacturing paradigm focuses on obtaining profits by selling as many manufactured products to the final customer as possible. The current paradigm change implies in considering life cycle aspects of products and optimizing their value and benefits through engineering, assembly, service, maintenance and disassembly. The new objectives include reducing the environmental losses and fulfilling restrictions over the life cycle [5].

One of the main objectives of life cycle economic systems is to increase resource productivity through a cycle built along the entire productive chain and actors, promoting cooperation among them and generating new business opportunities. According to Bourke [6], the market product life cycle includes all phases of a product's existence, from its conception, definition, production, delivery, maintenance up to its removal from the market at its end-of-life.

Improvements in all product life cycle phases can have positive impacts upon the greening of the supply chain. For example, in the introductory phases, the product is greatly influenced by design, and design for the environment will play a larger role at this stage. In mature and decline stages, the improvement of processes, in addition to having an efficient reverse logistics system will impact the environmental practices of the organization. For a multi-product analysis, environmental management decisions become increasingly complex. Nevertheless, within a company's product portfolio there should be differential environmental strategies and a focus on product life cycle development, which will depend on the products' life cycle maturity [8].

Fig. 1 illustrates a typical material product life cycle and shows some alternatives at its end-of-life phase.

The main flow is composed of the following phases: raw material extraction, primary industry, manufacturing, usage and product discarding at its end-of-life. The secondary flows are related to the different end-of-life strategies: reuse, remanufacturing and recycling.

Reuse is the process of collecting used materials, products, or components from the field, and distributing or selling them as used [9]. Remanufacturing consists of collecting a used product or component, assessing its condition, and replacing worn, broken or obsolete parts with new or refurbished parts. In this case, the original product's identity and functionality is retained [9].

Recycling is the process of collecting used products, components, and/or materials to disassemble, separate them into categories, and process them as recycled products, components, and/or materials [9].

It is important to notice that all these phases, including end-of-life alternatives, have inputs and outputs. Residues must be properly treated and disposed accordingly in order to decrease the environmental impact of the entire product life cycle.

The engineering activities addressing current industry's environmental impacts, from a product life cycle perspective, are connected to Life cycle Engineering, which can be defined as a set of processes to develop specifications in order to meet performance, cost and environmental requirements, as well as goals to increase the lifetime of a product, system, process or facility [7]. Life cycle Engineering aims to optimize the performance of a product throughout all life cycle stages. This process requires trade-offs so as to balance gains and losses, especially with regards to energy and material consumption during the production and usage phases, packaging, chemical content and end-of-life alternatives.

The comprehension of the whole life cycle enables the engineering team to identify and carry out additional benefits upstream in the supply chain and downstream in customer organizations or during end-of-life management. The activities under the scope of Life cycle Engineering are related to the application of technological and scientific principles to the design and manufacturing of products, aiming to protect the environment including resource conservation, while encouraging economic progress, optimizing the product life cycle and minimizing pollution and waste [7,10].

Life cycle Engineering proposes to improve the eco-efficiency of industrial activities, which can be defined as the ratio between the services provided by the activities and the environmental impacts associated with this service [7,11]. In order to obtain eco-efficiency, several Life cycle Engineering approaches can be applied, as for instance ecodesign, Life cycle Assessment, Cleaner Production, among others. This paper focuses on ecodesign methods related to products' end-of-life management and treatment alternatives.

2.2. Ecodesign

Ecodesign (term used in Europe) or Design for Environment (term used in the USA) defines a new way for developing products where the environmental aspects are given the same status as functionality, durability, costs, time-to-market, aesthetics, ergonomics and quality. Ecodesign aims at improving the product's environmental performance and may be seen as a way of developing products in line with the concept of sustainable development and life cycle thinking [12–16].

Ecodesign can be seen as a strategic design activity established to conceive and develop sustainable solutions. It generates sets of products, services and knowledge that enable consumers to sustainably achieve sustainable results. From another point of view, ecodesign is a proactive management approach that directs product development towards environmental impact reductions throughout its life cycle, without compromising other criteria such as performance, functionality, aesthetics, quality and cost [17,18].

The practice of ecodesign is essential to companies that have recognized that environmental responsibility is vital to long term success since it advantageously promotes reputation improvement, cost reduction, decrease in risks, lessening in residue generation, product innovation and attracting new consumers [19].

Different ecodesign methods have been developed to evaluate environmental impacts, putting in evidence potential problems and conflicts and facilitating choosing from among the possible product aspects by comparing the environmental design strategies. Baumann et al [1] identify more than 150 existing ecodesign methods and tools to implement what they call environmental product development (EPD). In the field of ecodesign research the terms "tool" and "methods" are often used interchangeably. This paper considers ecodesign methods as any systematic means to deal with environmental issues during the product development process [1,20].

Different ecodesign methods and tools have been developed since the early 1990s to evaluate the environmental impact of products and services and to improve the product development process as well as the product environmental performance.

There are methods and tools that enable the product developer to assess the product's environmental impacts over its life cycle and thereby, identify its environmental weak-points. Deciding which method and tool to use depends mainly on the stage of the product development process, i.e. how detailed the available information is. Time and cost can be reduced and the most "environmentally friendly" products can be produced if the Ecodesign tools are use early in the design process. Varying result accuracy, different methods and tools have been found to be useful.

The end-of-life ecodesign methods focused on closing the loop of materials generally include more than one end-of-life strategy. Since product complexity varies substantially, some components, systems or sub-systems can more effectively be recycled, reused or remanufactured than others. The proper end-of-life management system must be able to deal with these product parts characteristics and adjust the disassembling and parts separation processes to obtain higher profits and better environmental performance and results, optimizing the closure of material loops.

2.3. End-of-life strategies

Throughout this paper, the 'end-of-life' of a product is defined as the moment when a product no longer satisfies its user, whether it is a first-time purchase of a new product or not. This definition is adopted due to the fact that user preferences change faster than the product wears out. Some definitions may describe the 'end-of-life' as the point when the product cannot perform its functions any longer, due to failure or fatigue. This last definition will not be considered, however, since this description does not measure customer preferences during the life cycle and restricts the inclusion of 'end-of-life' alternatives to the cycle, such as reuse or remanufacturing.

According to Rose [21], 'end-of-life' strategies describe the approach or method employed when dealing with 'end-of-life' products. 'End-of-life' treatment concerns recovering value from products, including the activities associated with strategic planning and implementation of the collection and processing of used products along with the associated impacts to society and the environment.

Understanding the product's 'end-of-life' is important to reduce the environmental impact of the products' final disposal. Through ecodesign, a chosen 'end-of-life' strategy can be addressed, according to economical, environmental and local social needs. Rose [14] emphasizes that the adoption of corporate strategies regarding products' 'end-of-life' is mainly driven by market forces, especially in business-to-business activities. These forces have been encouraging companies to examine more closely their approach when dealing with a product at 'end-of-life', since numerous decisions are still made without a strategy, resulting in higher costs and lower success rates.

The main recovery strategies that can be identified are direct reuse, reuse after small repairs (also known as refurbishment), product service systems (PSS), recycling of materials, and remanufacturing (both of products or its components). When creating a hierarchy among the end-of-life alternatives, according to environmental impact, the direct reuse of a product comes highest in the rank, followed by PSS, refurbishment, remanufacturing, recycling and disposal [21].

The direct reuse implies that items are used by a second customer without prior repair operations, while refurbishment aims to restore products to working order, although with possible loss of quality. Moving towards reuse of products is an ideal solution for the product end-of-life approach in order to minimize environmental impact. However this approach, as a foremost strategy, would not be viable since it does not consider user needs or product quality.

The concept of Product Service System implies a shift in business thinking from selling products to providing service solutions to customer needs. Thus, the reuse, remanufacturing and recycling of products become more feasible and can be implemented more easily. The introduction of new ownership patterns, such as leasing focused on extended product lifetime, increases the manufacturers' interest in designing for durability, hence enabling the reuse of products and cores prior to recycling.

The challenge regarding PSS sustainability lies in developing system solutions, where products and services are integrated into a system in order to guarantee user satisfaction. The service provider typically takes responsibility for supplying, maintaining, taking back and recycling products, for example, their involvement in the system. Therefore, PSS should be defined as a system of products, services, supporting networks and infrastructure designed to be competitive, to satisfy customer needs and have lower environmental impact than traditional business models [22].

According to Mont [23], PSS is focused on addressing the use phase to reduce the total environmental burden of consumption. However, there is a need to consider carefully, the impact of other phases such as production and post-production activities, which can be performed through ecodesign. Mont et al. [24] state that, in order to contribute to environmental improvement, some criteria need to be fulfilled, such as: product leasing must be carried out directly between customer and manufacturer so that the manufacturer maintains a high interest in increasing product longevity through maintenance and upgrading; at the end of a products' life, they should be returned to the producer for remanufacturing and recycling; the decision-making process for product treatment must consider waste management hierarchy (reduce, reuse, and recycle).

Recycling is a process focused specifically on material recovery and should only be considered when all other alternatives are not economically feasible. It is characterized by the collection and reprocessing of materials both from residues of manufacturing processes and from those used in customer products. The processing of these materials often alters their basic characteristics, for instance material resistance, density and elasticity, implying in their use for less noble purposes after processed (secondary recycling). Recycling helps to reduce pollution, prolong the usefulness of landfills, and conserve natural resources, but cannot be the main end-of-life strategy of a company, a government or society.

The recycling process can be achieved with or without prior disassembly, which determines the quality of the resulting materials. Most of the recycled material quality does not meet specifications to be reused in the original products; nevertheless they still can be used in applications that require lower quality standards. When the recycling process is preceded by disassembly, the material recovered is likely to assume a broader range of applications.

Frequently, the cost of disassembly will outweigh the value of recovered products and materials so that such products end up being processed by shredding and mechanical material separation. Product shredding is a quick way to retrieve recyclable materials, although it usually results in low quality recycled materials. The disassembly of products previous to the 'end-of-life' alternative destinations can promote an increase of the purity of recovered materials, a safe disposal of hazardous parts and the recovering of subassemblies for reuse or remanufacturing. However it is very unlikely that the disassembly of many small products will ever be economically viable [25,26].

Recycling as a leading strategy goes against the economic feasibility of recovering the value added with each manufacturing step of a product, which could be achieved through the recovery of individual components. There are also environmental consequences associated to the recycling and other recovery processes, such as energy consumption, resource depletion, and waste generation, which must be considered during the decision-making process for the end-of-life pathways. Thus, it is of economic and environmental interest to recover and make use of the value remaining in used products [27,28].

Recycling denotes material recovery without conserving any production structure while remanufacturing conserves the product identity and seeks to bring the product back into an "as new" condition by carrying out the necessary disassembly, overhaul, and replacement operations [29].

The goal of value recovery is to retrieve components, assemblies, or whole modules from the product with the intent of reusing them in other products and process, by redirecting them to a second lifetime. It is, therefore, necessary to take into account aspects of life cycle design and engineering, i.e. the capability of systems for assembly, disassembly and diagnostics in all life cycle stages. Performed in a cluster process, remanufacturing can be an economically and environmentally better alternative to scrap-material recycling. The recovery of the products' value can then be achieved by means of demanufacturing and remanufacturing [5,27,30].

Demanufacturing can be defined as the breaking-down of a product into its individual parts with the goal of reusing parts, remanufacturing and recycling the balance of the components. It is a recovery strategy that focuses on retrieving product assets as a minimum disposal approach. The value recovery can only occur if the components can be easily extracted. In order to accomplish a profitable disassembly for demanufacturing, some aspects must be considered, including: development of product design that simplifies the disassembly of used products; planning the disassembly of products; identifying the degree to which a given product should be disassembled; establishing the logistics for collection and distribution of goods and analysis of uncertainty characteristics, including probabilistic returns, incoming part quality, varying recovery rates, and changing the demand for components [27,31,32].

Disassembly planning is a key link between a product's end-of-life and the recovery alternatives in the products' life cycle. Financial aspects, including the costs of the disassembly process, the economic benefits of component reuse or material recycling and costs of final disposal, as well as the environmental impact of each end-of-life alternative should be considered during product design for easy disassembling [32,33].

The main objective of disassembly is the separation of specific fractions of products that will make the recovery and recycling processes faster and more efficient. Although there are many limitations that increase the difficulty of redesigning products for a more favorable disassembly strategy, ecodesign methods focused on 'end-of-life' strategies can help to overcome these limitations by designing the products for easier disassembly. Proper planning is essential to determine when to stop the disassembly process, known as the disassembly depth. Current economic analyses demonstrate that complete disassembly is rarely the optimal solution owing to disassembly costs [25].

2.4. Remanufacturing

From all the aforementioned 'end-of-life' alternatives, the remanufacturing process has been chosen as the main object of this study due to the current lack of legislation and normalization of this subject in Brazil and due to its increasing importance and recognition in the international scenario.

The interest in this theme has flourished in Brazil, mainly on account of international take back laws and trade issues. The current legislation treats remanufactured goods as used products, and there are no regulations concerning process and quality control other than the ones proposed by the industry itself. The market for remanufactured goods in Brazil has expanded (both inland and on an importing/exporting basis), and so has customer awareness, which are some of the reasons behind this and other studies currently being conducted in Brazil.

Remanufacturing is an 'end-of-life' strategy that reduces the use of raw materials and energy necessary to manufacture new products. Economically, remanufacture is an interesting strategy due to the fact it preserves the product's value added during the design and manufacturing processes. As for the environment, the importance of remanufacture lies on extending the product's lifetime by diverting them into a second life, given that if a product lasts longer through remanufacturing, less material is needed to meet customer needs [34].

There are different definitions for the term remanufacture. The US Automotive Parts Rebuilders Association [35] defines remanufacturing as the "process of restoring worn and discarded durable products to like-new condition". Sundin et al. [36] define remanufacturing in their study as "the process of rebuilding a product, during which the product is cleaned, inspected and disassembled; defective components are replaced; and the product is reassembled, tested and inspected again to ensure it meets or exceeds newly manufactured product standards".

The remanufacturing process can be described as a product recovery strategy focused on product restoration and reconditioning of its parts, in order to rebuild it according to its original design. Remanufacturing is an effective manner to maintain products in a closed-loop and to guarantee the proper management of products' 'end-of-life.' Remanufacturing helps to reduce environmental impacts and costs of the manufacturing processes, while reducing the final disposal costs of products and components [28,31].

Kerr et al. [28] consider remanufacturing the most efficient way to maintain products in a closed-loop. Through remanufacturing, products can be restored to a like-new condition, with the same quality and function as new products. Thus, remanufacturing of 'end-of-life' products and components reduces environmental and economical costs both in new product manufacturing as during its final disposal.

According to Kerr et al. [28], sustainable production and consumption will only be possible with closed systems. With remanufacturing, a much smaller fraction of the 'end-of-life' resources needs to be recovered through recycling. In addition, intelligent remanufacturing systems provide the opportunity for product upgrades, thereby extending product life and incorporating less environmentally harmful technology.

During the remanufacturing process, the product is treated in several steps, which are done in order to guarantee that the product meets new product standards. Overall, the remanufacturing process is divided in the following steps: disassembly, testing, repairs, cleaning, parts inspection, updating, parts replacement and reassembly. Each step must include specific quality control metrics. Occasionally, the original design may be improved in order to increase liability, make maintenance easier or add more sophisticated controls. The upgrading step is essential in order to ensure the continued viability of remanufacturing, and that it does not simply prolong the life of inefficient and obsolete products [28,34,37,38].

Williams et al. [30] describe remanufacturing as the recycling of durable products at a component part level. The used product, or core, is disassembled, cleaned, repaired or refurbished, reassembled and tested to produce a like-new product.

While repairing means to extend the life of a product, remanufacturing means to bring used products up to quality standards that are as rigorous as those for new products. Remanufacturing is a true industrial process with the advantages of mass production [25].

To successfully implement remanufacturable products, they should have been previously designed for this purpose. Some of the desirable characteristics for remanufacturable products include ease of disassembly, easy to clean, easy to control, easy to replace parts, easy handling, wear resistant and easy to reassemble, among others, which vary according to product characteristics [28,34,36].

Although these are important processes, demanufacturing and remanufacturing processes do not close the loop on their own. In addition to the technology to recover or reuse collected products, there are several problems in social systems, such as decision-making and institutional design, which can negatively impact the collection of goods and may restrict the aftermarket. Furthermore, decisions made exclusively by economic agents such as producers and consumers might affect the costs and benefits of the recovery process [39].

In face of these aspects involving the decision-making process for 'end-of-life' alternatives and all the implications these decisions have in the environment and society, it is important that these features are considered starting with the strategic planning of a corporation and made possible through ecodesign of new products and services.

3. Research methodology

The main methodology used in this study was the collection and interpretation of available data concerning Life cycle Management, ecodesign, 'End-of-Life' Strategies and Remanufacturing, by means of a systematic review. The systematic review made it possible for researcher to map existing knowledge and initiatives currently and previously developed. Besides a preview of discoveries, techniques, ideas and exploratory manners for the topic, the systematic review made it possible for the author to evaluate the significance of the information for the issue in question.

The systematic review is a specific research methodology, conducted in order to gather and evaluate the available studies on a matter, via a defined and strict sequence of methodological steps. Is consists of three basic steps: (1) the problem formulation, (2) the database definition and data collection, (3) and the data analysis and evaluation.

Through the systematic review it was possible to identify a large number of ecodesign methods, including those focused on 'end-of-life' strategies and alternatives.

4. Ecodesign methods focused on 'end-of-life' strategies

Among the ecodesign methods focused on end-of-life alternatives, such as remanufacturing, this study has chosen five methods to demonstrate the application of ecodesign in obtaining more sustainable products by means of a design that enables defining an optimum disassembly sequence and/or evaluating the design according to its critical 'end-of-life' aspects. These methods were selected due to their representativity, relevance and applicability to the issue, according to the literature.

The five selected ecodesign methods intended for the 'end-of-life' of products are presented in section 4.1.

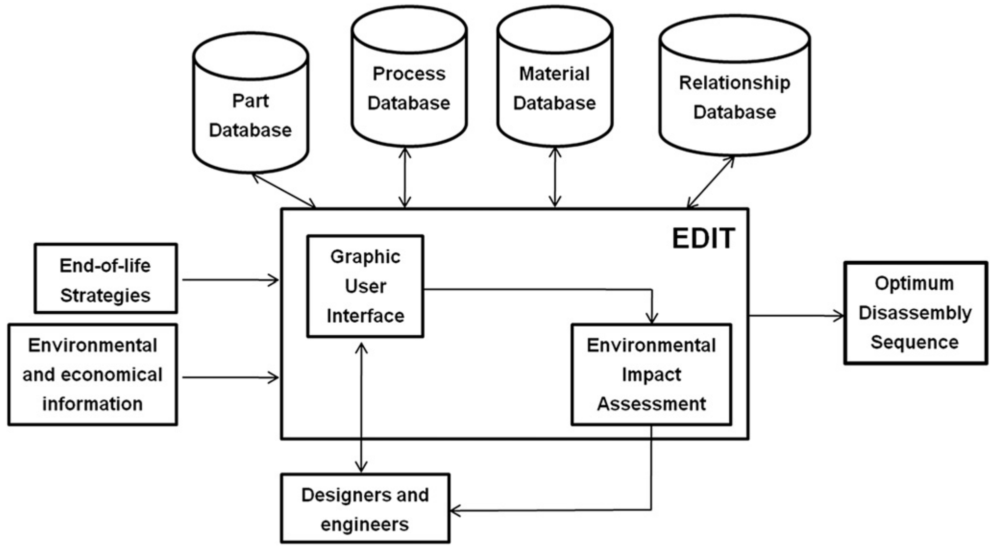

Fig. 2. Major inputs and outputs for EDIT, with especial regard to the relations between the designers and the software.

4.1. Environmental design industrial template (EDIT)

Environmental Design Industrial Template is a computer tool explained by Spicer et al. [40], from the University of Windsor, Canada; it was developed to evaluate the design of products in terms of their 'end-of-life' effects and to help in developing suggestions for improvement. This software is built upon the understanding of the key relevance of economics and product design have upon 'end-of-life' product management decisions.

The definition of the product in the software is based on three objects: materials, parts and processes, which allow the user to analyze the effects of a product's design at its 'end-of-life.' The assembly sequence is determined by the product designer/producer in the planning phase by creating different connections among materials, parts and processes. Given the product design, the tool will generate a product disassembly sequence that optimizes profit generation in a way that' end-of-life' treatments can be evaluated.

The product designers can then make modifications to the design of the product and evaluate the effect caused by each change. Therefore, the user is able to define how and with what material the product will be made off, to choose parts and processes considering some environmental and economic information, to access and modify the available database, and to simulate 'end-of-life' results.

Given the information provided by the product design team, for instance information on materials (weight, toxicity, disposal costs) and on recycling – material recycling cost and energy used in the process, the software tells the designer the amount of product that can be reused, remanufactured, recycled, or that requires disposal. It also considers specific toxic or recyclable parts of the product. Finally, it indicates the time and energy consumed during disassembly.

Fig. 2, presented by Spicer et al. [40], illustrates the inputs and outputs in the method. It also shows the relationships between the product designing team and the program.

'End-of-life' strategies and environmental and economic information are provided by the designer. Due to local variations, the user must supply information on costs as well as retail prices for parts that can be reused or remanufactured. Thus, given the product's design, EDIT is able to simulate an optimum disassembly sequence with the larger economic value. As a result, the product designer will be guided with regard to the extent to which the product can be reused, remanufactured, recycled and what quantity will require management at its 'end-of-life,' plus the time and energy that will be required for the disassembly process.

4.2. D4N

D4N is a design tool described by Murtagh et al. [41] not only to analyze the products' life cycle, but also to provide guidelines for product redesign. The product analysis includes all 'end-of-life 'issues; the design is evaluated according to previously established ecological and economic metrics. The resulting guidelines are incorporated into the method in a way to make the redesign process simpler for product designers and to make the process easily evaluated.

One of the main aspects of this tool is with regards to the minimal data input requirements for the product designer to provide into the software. The D4N system can take advantage of the existing data from 3D-CAD models of the product's design. The data from CAD systems are automatically extracted and located in a connection graphic, hence allowing for the generation of a disassembly sequence so that important components can be removed quickly, avoiding unnecessary disassemblies.

The program interacts with the CAD files to determine part relationships and generates a relationship graph. An interpreting program generates a disassembly sequence, indicating the order in which parts can be removed. Disassembly rules imposed by the designer determine the order in which parts must be removed, ensuring that important (ecologically and economically) parts are removed as early as possible, thus avoiding unnecessary disassembly.

Fig. 3, developed by Murtagh et al. [41], illustrates the general idea of the D4N concept. The program outputs are mainly graphics and guidelines to redesign, which provide support for the design activities during the early design stages, so that changes in design are low cost and highly effective.

The designer's data are necessary to establish the connections among parts and part's materials. The user's data are complemented by databases containing information on materials, environmental impacts, 'end-of-life' treatments and costs. Databases must contain, for each material, its disposal method, its environmental impact and the costs of recycling or material reprocessing.

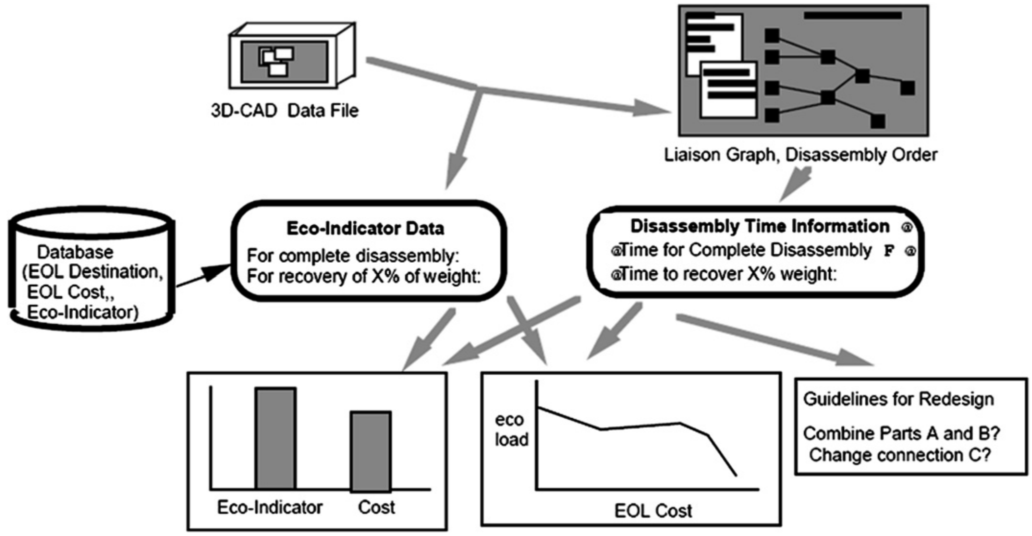

Fig. 3. Model of the D4N concept and its redesign oriented outputs.

Environmental impact evaluation is based on an eco-indicator value (PRé Consultants). The main environmental effects considered in this system include the greenhouse effect, ozone layer depletion, smog, acidification, air and water toxins, and waste disposal, among other. The cost parameter gives the overall costs involved in the recycling or disposing of all the product parts. The disassembly cost is also considered; its calculation is based on the required labor, parts processing time and the market price for materials.

The user can choose the best design and disassembly sequences by changing the program requirements, such as the percentage of material that must recycled, type of parts to be removed primarily, and the degree of disassembly, which will directly affect the disassembly sequence and costs. The designer can experiment with different combinations to determine an optimum design, according to graphics and guidelines provided by the D4N itself.

4.3. Environmental design support tool (EDST)

The Environmental Design Support Tool (EDST) was developed at Texas Tech University by Yu et al. [42]. EDST was developed to support the early design phases of products. It is a tool based on a disassembly model, and decision-making and database management system. According to the authors, disassembly is the first step in evaluating a product's environmental performance by this tool, and it provides the time needed for disassembly, number of distinct components and other information. EDST consists of extracting the disassembly model, analyzing the disassembly capacity of the design in concern, material assessment and suggestions, and finally recyclability evaluation.

The tool evaluates a product's design on terms of its environmental sustainability, i.e. material selection, recyclability and disassembly analysis. The disassembly analysis includes disassembly time calculation, number of distinct components, and the percentage of disassembly fasteners. It generates an index number to help evaluate the disassembly process, in which the larger the number, the more difficult the disassembly will be. The tool enables the user to change the disassembly relationship of the components in order to improve disassembly performance.

Material evaluation is made through an index composed by material weight, total amount of different materials used and total amount of dangerous and recyclable materials used. This index is obtained through a questionnaire and guidelines, by means of checklists, list boxes and multi-choices about material selections, which are connected to the EMI database.

Recyclability evaluation is focused on residue management and pollution control. Material 'end-of-life' alternatives are reuse, remanufacture, recycling to high grade material, recycling to low grade material, incineration with energy recovery and final disposal, according to the kind of material used.

Fig. 4 was presented by Yu et al. [42], and demonstrates the relationships among the disassembly model of the product designed and information from the database in order to generate the index number, thus enabling the designer to assess the consistency of its disassembly process.

EDST can help designers consider the environmental impacts of their newly designed products and it is, therefore, an important decision support tool for environmentally conscious design.

4.4. Method to assess the adaptability of products (MAAP)

This method was described by Willems et al. [43]. The main purpose of this method is to evaluate the product's conformity at assembly, maintenance, repair, upgrade and remanufacture processes. The conformity of a product is represented by a metric, μAdaptation, which is calculated by the program. The more this value tends to one (1), the better the design suits adaptation, while the more it tends to zero (0), the worse it is. A secondary objective of the method is to locate potential improvement areas in the product's design.

Method clearness is guaranteed by specific sub-metrics, related to remanufacturing, maintenance, repair and upgrading, which enables the designer to track down the causes of the non-conformity. The sub-metrics were selected based on their importance according to the literature review, and narrowed down to design driven issues. Therefore, environmental policy issues are not taken into account.

All sub-metrics add together to develop the adaptation metric, along with parts, connectors and space. The sub-metrics are then divided in sub-criteria: parts (components and removal direction), connectors (number of different components in each group, number of different components, number of connectors and tools), space (visibility, reach, identification and direction to disassembly), remanufacture (disassembly maintenance, assembly and

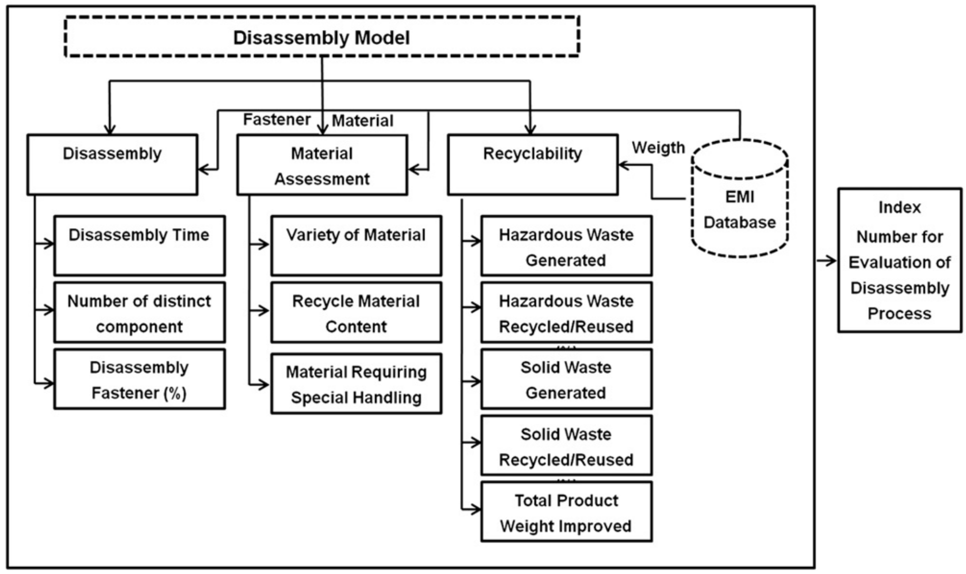

Fig. 4. EDST: Relationships among the disassembly model of the designed product and the database information.

architecture structure), repair (disassembly, assembly and architecture structure repair) and upgrade (functional and interface decoupling).

Fig. 5, which was published by Willems et al. [43], contains all sub-metrics and the related criteria used in the MAAP method in order to obtain the μAdaptation value. It is possible to see that this method considers a large number of variables when determining the relation between the product design and the environment, mainly by addressing the disassembly process.

Combining the different level metrics into a single adaptation metric is done by inverse weighted addition. This procedure ensures that the magnitude, idealization, obliteration and

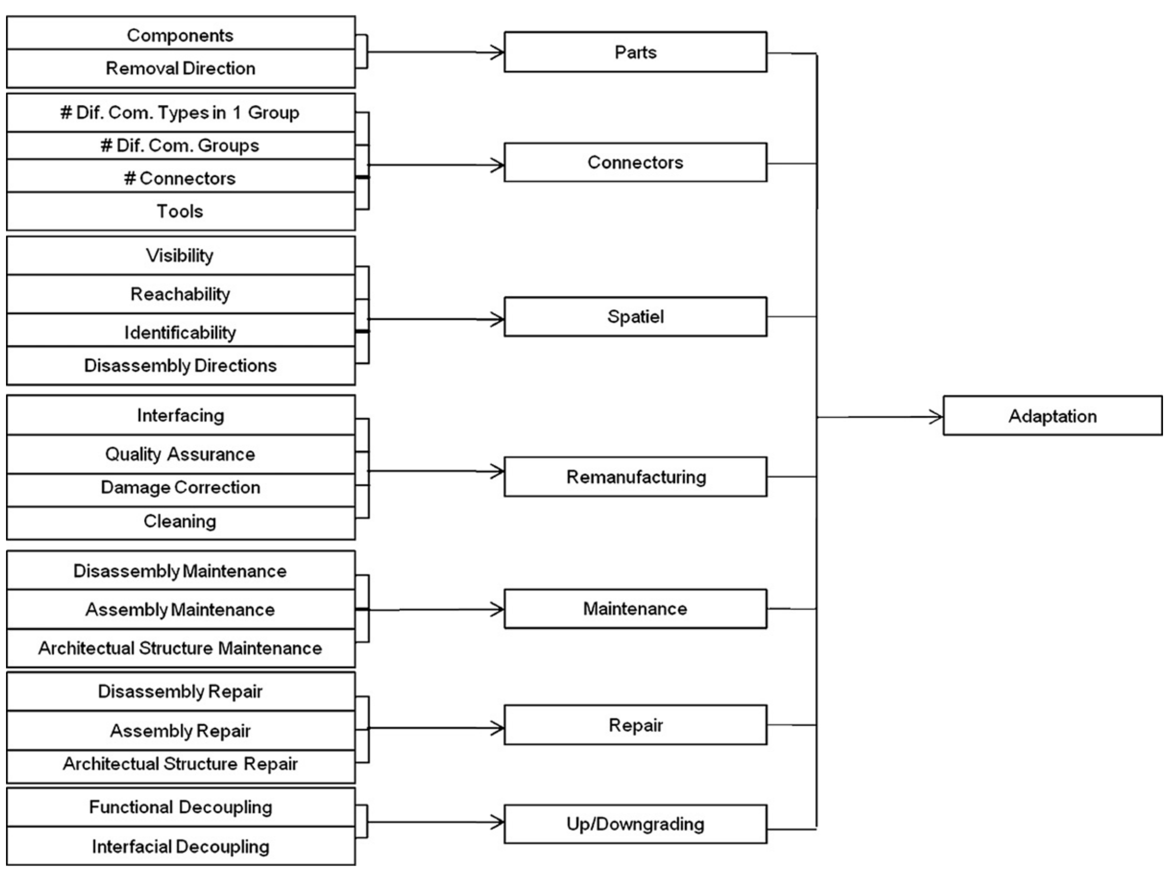

Fig. 5. Sub-metrics and associated criteria considered in obtaining the conformity metric (μAdaptation).

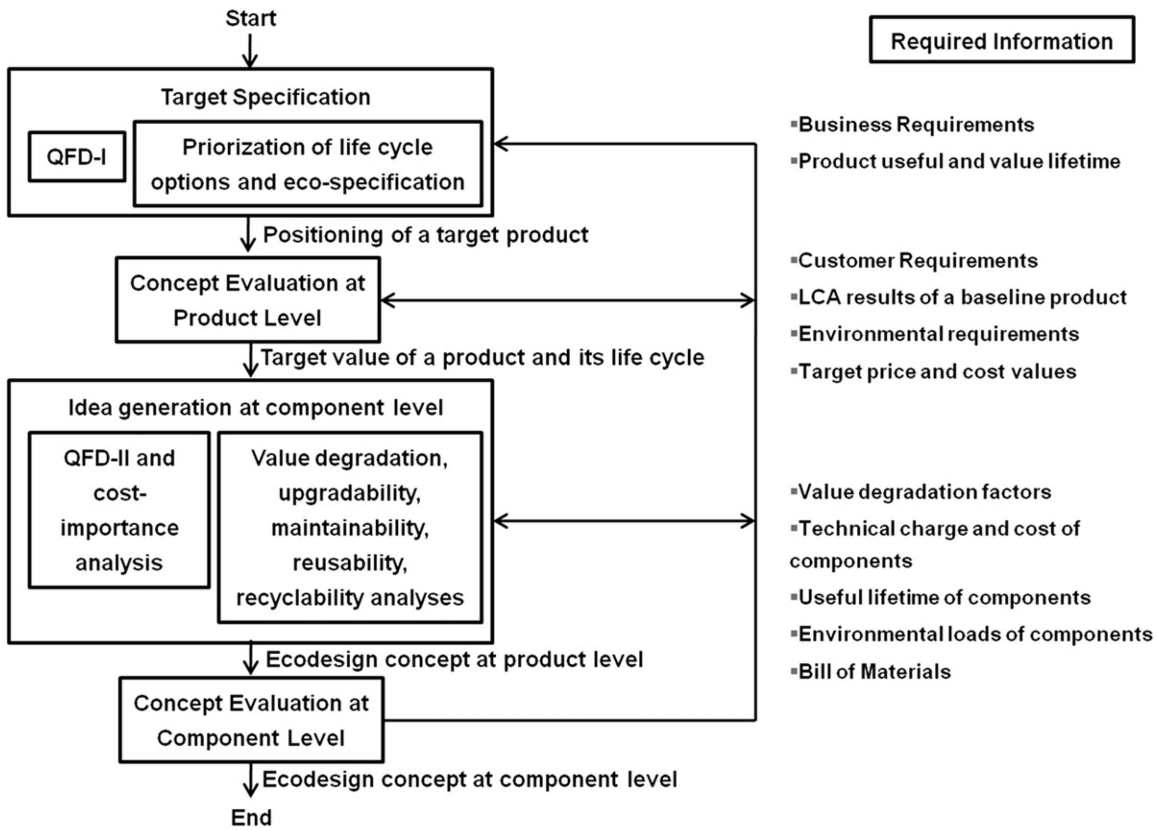

Fig. 6. LCP methodology – information flow and needed incoming data.

weighting criteria are finalized. The evaluation is made through the ratio between the ideal and the real values of a specific parameter. Based on the metrics result, the method provides guidelines for product improvement in terms of its adaptation.

4.5. Product life cycle planning (LCP)

The Product Life cycle Planning was described by Kobayashi [44] as a methodology to help the designer establish an ecodesign concept of a product and its life cycle by assigning appropriate life cycle options to the product components. The product life cycle planning (LCP) is a systematic methodology that allows the user to include detailed environmental requirements through a life cycle perspective. The environmental aspect is integrated to quality and cost aspects at early design phases, while respecting customer demands such as cost and performance.

The method focuses on product upgrades, product maintenance, lifetime extension, product or component reuse, and material recycling. At the first stage, a medium or long term production plan and a product plan are established according to business requirements and product lifetime. At the next stage, product specifications and its life cycle are established.

The need to reconcile the needs of the customer with environmental requirements led the authors to make an adjustment of values for quality and environmental characteristics, by means of a semi-quantitative concept evaluation method. The design evaluation is based on the requirements imposed by the company's market strategy, and can easily be applied to real projects.

Fig. 6 (Kobayashi [44]), represents the flow of information in the LCP methodology and the needed incoming data for each step. It is possible to notice the feedback process in every step, so as to optimize the design of the product.

To support LCP based on the proposed methodology, a software tool, the LCPlanner was developed as a macro program in Microsoft Excel. LCPlanner efficiently supports the processes in LCP, because it can use imported cost aspects in the early design phases. The LCPlanner makes various matrices and analysis charts automatically using the data input from the designer and the imported data from other environmentally oriented tools.

5. Results and discussion

The review of this collection of studies reveals that environmental awareness has increased worldwide. The inclusion of the remanufacturing process as an 'end-of-life' alternative for products, in Brazil and around the world, can become increasingly important in the same way that ecodesign methods are made available to designers.

There are several methods of ecodesign that can be successfully applied to the earlier phases of the product development process in order to improve the feasibility of the 'end-of-life 'strategies. It can be observed that these methods usually include more than one 'end-of-life' strategy, since all 'end-of-life' strategies are related and not all product components can be remanufactured. It was found that these tools tend to integrate considerations of customer needs and with other requirements such as environmental requirements, economic considerations, this makes the product design process more interesting to organizations and more economically sensible.

All five methods emphasize the importance of disassembly when addressing 'end-of-life' management. Some of them (EDIT, D4N and EDST) use the disassembly planning as an economical strategy, while others simply consider it as one of the means to improve the environmental quality of products.

EDIT is a tool that seeks to establish a product disassembly sequence that optimizes profit generation. This approach is important since products will not have a proper end-of-life strategy application if they are not economically feasible or if there are regulatory aspects over these activities. D4N has the important attribute of considering and determining the environmental impact of a product according to its parts and materials (by using the Eco-Indicator). Nevertheless, this method has a highly subjective level, which requires better prepared designers on environmental issues, so that designers must choose the best design and disassembly sequence considering environmental and consumer variables.

The EDST tool evaluates product designs regarding their environmental sustainability, i.e. material selection, recyclability and disassembly analysis. The advantage of this tool is that it generates a single index number, which provides valuable information to the decision makers, which in turn allows them to establish and fulfill their priorities. In the same way, MAAP provides a metric, μAdaptation for use by decision makers, which interprets the adaptation of the design according to assembly, maintenance, repair, upgrade and remanufacture processes. It is clear that this method considers further life cycle phases than the previous ones, and can be considered more complete and more closely related to life cycle thinking.

Finally, LCP follows the line of considering upgrade, maintenance, lifetime extension, product or component reuse and material recycling. Based upon this perspective, this method can be considered complete, given that it considers all possible 'end-of-life' facets by addressing product parts and components. It also considers the integration of product quality and environmental requirements, which is essential to help to contribute to more sustainable societal patterns.

The decision to use one method or another must be made by the project design team according to the product's characteristics and the organization's strategy. The criteria for method selection, therefore, can vary immensely among organizations.

In Brazil, there are many variables to be considered in order to implement a remanufacturing system, such as governmental laws and directives which regulate such activities, the establishment of a reverse logistics system and proper product return to the remanufacturers so the products can be remanufactured. Use of ecodesign and organizational initiatives are important for Brazil to make more progress toward societal sustainability. This also requires consumer support and pressure to bring about the necessary changes in the system.

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