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Assessment of Sustainable Product Development Tools and Methods

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Abstract *Systematic consideration of environmental aspects within the early stages of product development (PD) can be considered highly significant in order for the overall environmental performance of the product to be improved. Many methods and tools have been developed aiming to enable this consideration and provide the properties that need to be considered and improved. This article provides an overview of some well-known and more applicable tools and methods that have been developed and are available today. The identified tools are generally classified in two groups: Guidelines and Analytical tools. The limitations and barriers of current tools are assessed and categorized and two areas for future work are proposed in order to address current limitations in the existing literature.*

Key worlds: Sustainability, Product development, Product life cycle, Triple bottom line (TBL), Sustainable product development, Environmental impacts.

1. Introduction

These days, people recognize that besides profits, there are other elements in the long-term success of companies and economies that are important to consider. Issues such as the future of generations to come and the future of the planet are gaining more significance. These concerns are measured as the triple bottom line (TBL), which stands for people, profit and the planet [1, 2, 3].

The growth of industrial products is dramatic and should be considered in the implementation of TBL. Product development (PD), as the first step of creating a product, has a great influence on its sustainability as by the end of the PD process, the sustainability attributes of the product are largely fixed. Early decisions in PD can have a significant or even dominant impact on the sustainability of product realization [4]. Therefore, adding sustainability to PD is increasingly becoming an important issue for companies [5]. Considering the environmental aspects of a product, PD becomes sustainable PD. Sustainable PD focuses on reducing or eliminating environmental impacts over a product life cycle by incorporating environmental considerations into product design. In many cases when environmental aspects are integrated into PD, it leads to synergies with other business interests, such as image improvement, new market opportunities and very often, cost reductions. Indeed, many organizations have faced economic benefits when environmental considerations were considered in the design process [6, 2]. Numbers of methods and tools have been developed to assist in integrating environmental aspects into the PD process.

This research assesses current tools and methods for sustainable product development in order to discover barriers and limitations of them. Sustainable PD is defined and the importance of life cycle thinking is highlighted. The ways to improve current tools and methods are considered and appropriate solutions are checked to be recommended as future works. Six major reasons for poor application of current tools are recognized and two ways for development are introduced. The literature review on which we report here is based on 160 articles in the field of sustainable design, sustainable product design, sustainable PD and sustainable tools and methods for PD. Publications were selected through searching various sources from the engineering, management, and policy studies disciplines. It should be mentioned that the number of publications that exist is large and consequently it was not possible to analyze all articles or books. Thus a screening process of the available material was needed in order to select the publications that should be considered for the study.

The article is organized as follows: the next section describes the product life cycle; Section 3 presents a discussion of sustainable PD, tools and methods for sustainable PD. Section 4 provides barriers and limitation of current tools and methods, and finally conclusions and future works are discussed in Section 5.

2. Product life cycle

A product life cycle is the successive and interconnected stages of a product system, from the extraction of raw materials or natural resources, to manufacturing, use and end of life. A product life cycle is the successive and interconnected stages of a product system, from the extraction of raw materials or natural resources, to manufacturing, use and end of life. Life cycle thinking means “widening views and expands the traditional focus on manufacturing processes to incorporate various aspects associated with a product over its entire life cycle” [7].

Essentially everything that is created goes through several key life cycle stages: extraction of raw materials, manufacturing, distribution and packaging, use and end of life (recycle, landfill or incinerate) [8]. Figure 1 is a general diagram which shows the circular nature of material flows through a product life cycle.

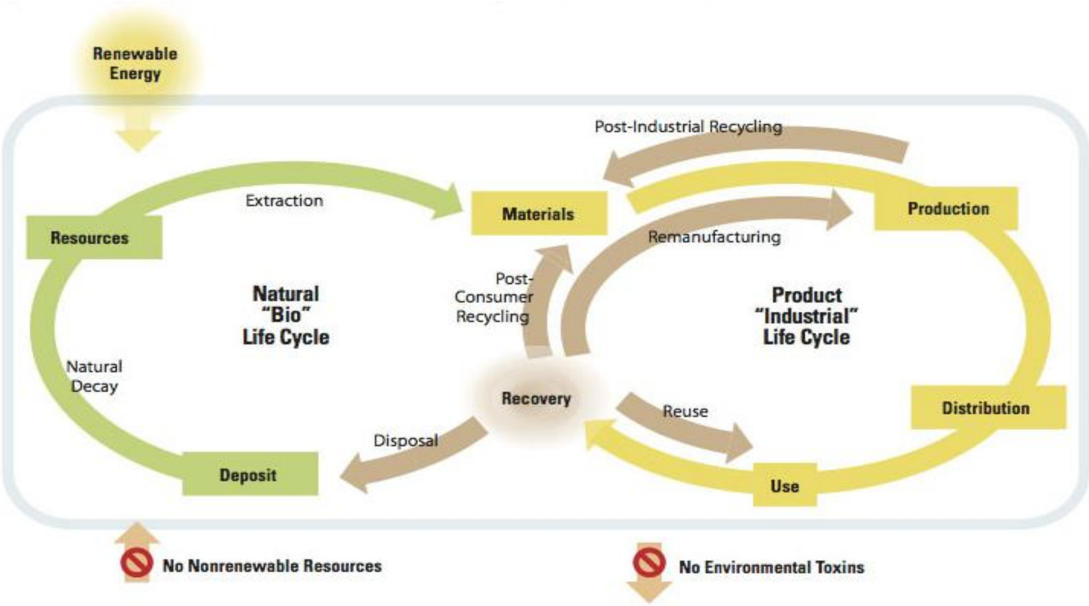

Figure 1.Life cycle of product [9].

Each of the life cycle stages has a variety of inputs such as material, energy and water and outputs such as solid waste, emissions, products and by-products. These can be identified and assessed for their environmental impacts at each of the life cycle stages that products and materials go through.

Any environmental, economic or social assessment method for products has to take into account the full life cycle from the raw material selection, to the end of life of the product. In other words, a systems approach has to be taken. Only in this way can trade-offs be recognized. Life cycle thinking is the prerequisite of any sound sustainability assessment. It does not make sense to improve (environmentally, economically, or socially) one part of the system in one step of the life cycle, or in one environmental compartment, if this improvement has negative consequences for other parts of the system which may be greater than the advantages achieved [10].

In the life cycle of a product, PD takes place before production and it occurs once for each new product. It is well known however that only 5–7% of the entire product cost is attributable to early design, the decisions made during this stage lock in 70–80% of the total product cost. Correspondingly, we can hypothesize the same to be the case for environmental impacts [4, 5]. “Based on the estimation from the EU report, 80-90% of all product-related environmental impacts are determined during the design phase of a product.” [11]. This means that product sustainability is largely specified during the early design stage. Therefore, PD is one of the most important stages influencing global sustainability. In particular, early design decisions can have a major impact on sustainability. These decisions not only relate to material and manufacturing choices but have far-reaching effects on the product’s entire life cycle. Therefore, considering downstream life cycle data in the PD process is essential to achieving true sustainable PD [4].

3. Sustainable PD (tools and methods)

Taking the life cycle approach to PD requires conducting functionality analyses at the early concept development phase to know how the decisions that are made in PD can ultimately affect the efficiencies of the product across its life. Sustainable PD considers life cycle environmental features of the product during development.

Much research has been done on how companies can integrate environmental criteria into the product design and development stages. A significant number of methods and tools have been developed in order to provide relevant information for engineer designers and product developers about the environmental performance of the product. Although new methods and tools are constantly introduced, it can be presumed that they first arose during the 1990s with the expansion of the design for environment and eco- design concepts [12]. The use of tools is frequently mentioned in literature as an important part of the sustainable PD approach and to provide significant support for the integration of environmental aspects into PD [13, 14, 15, 16, 17]. The term “tool” and “method” in this context are defined in a broad sense as any type of systematic aid to integrate TBL aspects into the product design and development. The tools and methods have been proposed in the literature can range from general frameworks and recommendations to more detailed and complicated environmental assessment tools [12]. They can be categorized in two main categories: guidelines and analytical tools. Focus is given to the tools and methods that are developed and can be employed already during the product development and design process in order to consider the sustainability aspects during those stages. Therefore a compilation of well-known and more applicable tools, that are available today for integrating environmental aspects into PD, is selected and will be described in the next sections, although for barriers and limitations we attempted to consider all of the tools and methods in the literature.

3.1. Guidelines

This category includes all type of methods and tools that provide guidance and generic recommendations on what aspects to consider during product design and development in order to minimize the environmental burdens that can appear during the life cycle of the product. In this category there are several methods and tools, as described in what follows.

In Design for Environment, a guide to sustainable PD, Fiksel [18] defines seven basic principles for companies that want to make PD sustainable as follows: Embed life-cycle thinking into the PD process, Evaluate the resource efficiency and effectiveness of the overall system, Select appropriate metrics to represent product life-cycle performance, Maintain and apply a portfolio of systematic design strategies, Use analysis methods to evaluate design performance and trade-offs, Provide software capabilities to facilitate the application of DFE practices, Seek inspiration from nature for the design of products and systems.

Simon et al [19] introduce ARPI (Analyse, Report, Prioritize, Improve), as a four stage framework for implementing eco design. Firstly an environmental assessment from a life cycle viewpoint is performed. Then the result of analyses is communicated to the company and the feedback is collected. Thirdly the feedback and environmental issues are prioritized and in the last stage improvements are suggested and implemented. ARPI is just a guideline and does not provide methods for analyse, report, prioritize and improve tasks. The method for each step should be selected by the company.

Maxwell and Vorst [2] present sustainable products and/or services development (SPSD). SPSD is a framework for implementing sustainable product and/or service development throughout the entire lifecycle of a product and/or service. One of the important goals of this method is to reduce environmental effects by using services instead of product in terms of reducing the volume of products manufactured while maintaining or increasing profits for the company through service provision. This method could be improved when is combined with an analytical method such as life cycle costing to do more analyses of using services.

Luttropp and Lagerstedt [20] describe “Ten golden rules”, which encompass ten general guidelines based on best practice rules which pick up on the key issues necessary when attempting and teaching eco-design. Ten guidelines are: hazardous, housekeeping, weight, energy, upgrade, lifetime, protect, information, mix, structure. The guidelines are intended to be applied early during the goal and specifications stage of the PD process.

Byggeth et al [5] developed a method for sustainable PD (MSPD) by defining sustainable product analyses (SPA) modules which include strategic guiding questions to identify potentially critical activities during the life cycle. SPA modules are used at the end of each phases of PD and contain: Product function, Product design, Material type, Production processes and Purchase.

Ljungberg [21] presented a guideline for sustainable PD with special regard to material, design and ecology. The guideline includes a description of materials selection and models for design based on a sustainable society. The selection of material is to optimize a product mainly with regards to: Production methods, Function and structural demands, Market or user demands, Design, Price, Environmental impact and Lifetime.

Ulrich and Eppinger [9] define seven steps in terms of considering environmental aspects of product in PD phases as follows: set DFE agenda, identify potential environmental impact, select DFE guidelines, apply DFE guidelines to initial design, assess environmental impact, refine design, reflect on DFE process and results.

Such tools provide general guidance to the designers of the product, acting in some cases as rules, monitoring or exclusion lists or recipes for environmentally friendly design. They summarize key environmental aspects which should be considered during decision making processes. They often act as a checklist to ensure that the user is aware of the main issues during the design.

3.2. Analytical tools

Analytical tools provide detailed and/or systematic analysis at specific stages of either the product development process or lifecycle in order to have an overview of the environmental performance of the product as well as an indication of the properties that need to be improved [18]. They help the designer to identify specific areas and activities related to the product that need to be optimized. These methods are for different purposes such as: screening to narrow design choices among a set of alternatives, performance assessment to estimate the expected performance of designs, Trade-off analysis to compare the expected cost and performance of several alternative design [19]. Some well-known tools of this category are discussed as follows.

The most common technique for evaluating environmental impacts of a product probably is the life cycle assessment (LCA) methodology [20] that has been practiced by industry worldwide for over three decades [21]. The methodology involves four major steps: Determine the goals and scope of the LCA; Compile an inventory of energy and material inputs and environmental outputs across all relevant life cycle stages; Evaluate relevant environmental impacts associated with the life-cycle inputs and releases; Interpret the results to lead to a more informed decision. These steps should be regarded for all PLC stages. Its accuracy and wide scope requires an enormous amount of data for completion. This makes LCA very complex and time consuming. Because of this reason, researchers developed simplified life cycle assessments to reduce the amount of data required [22, 23]. In the Simplified life cycle assessment (SLCA) the methodology is the same as LCA, but some parameters such as inventory data or certain impacts are not investigate during the implementation and evaluation process [24]. The SLCA and LCA methods can only indicate the specific life cycle stage where the majority of the impact is occurring. The engineers must then come back to their usual resources and design process, in order to generate alternate solutions.

Brezet [28] propose MET matrix, a simple to use environmental analysis method, is applied to map the different environmental impacts of a product during its life cycle and then identify the most significant ones. It can be used early in the product planning and development stage. It provides a general view of the inputs and outputs of each phase of the product life cycle focuses on three aspects of a product: materials, energy and toxicity. MET identifies the main environmental aspects and possible environmental improvement options. The data and results of the tool can be both qualitative and quantitative (when weighting factors are applied to the impact categories).

Yarwood and Eagan [29] propose the Design for environment matrix (DfE Matrix) as a semi- quantitative assessment tool to evaluate different aspects of the product design in relation to their environmental performance. The tool has two modules: a matrix and a list of 100 questions. The matrix is filled with the individual scores. The scores are obtained by answering the questions for each of the life cycle stage (every answer can obtain 0-5 points). The scores can be used to identify areas and aspects that need to be considered and optimized by the designers of the product. The DFE matrix could be used by the designers to provide them rough information about aspects and parameters of the product that might need improvements.

Masui et al [3] introduce the quality function deployment for environment (QFDE) as one of the few methods that link the stakeholder requirements to the environmental performance of product. They define four phases as: deployment of VOC to Engineering Metrics (EM), deployment of EM items to Components of Product, estimate the effect of design changes on the engineering metrics, and the last phase is translating the effect of design changes on EM into environmental quality requirements. QFDE identifies the relationships between different requirements and can help design engineers select the most effective design changes' plan. The various requirements are weighted based on their importance and an evaluation process is then performed in order to rate the relationship between the requirement and the environmental parameter [25].

Hastings [31] defines Life Cycle Costing (LCC) as the analysis of the cost of acquiring, introducing, operating, maintaining and disposing of equipment which include all internal costs plus external costs incurred throughout the entire life cycle of a product, process or activity. It is "cradle to grave" cost analysis. In LCC the costs related to acquisition, operation and through life support are brought together in a spreadsheet or in a similar purpose built system, and the total costs across the life cycle are calculated in the form of the Net Present Value (NPV) and the Equivalent Annual Cost (EAC).

The Product Sustainability Index (ProdSI) is a common qualitative assessment product sustainability evaluation method that comes from Fliksel [32]. The ProdSI evaluates sustainability base on TBL (economic, environment and society) in five levels with specific clusters and sub clusters in each sub-index of economic, environment and society. Zhang et al [33] present a new methodology to evaluate five-level Product Sustainability Index (ProdSI) based on a set of product sustainability metrics. They define different metrics for each of the sub clusters. Weights are assigned to all sub-indexes, clusters and sub clusters base on the importance of each.

Some of the tools presented above contain only an evaluation process in order for the impacts to be defined and in some cases quantified, while others provide prioritization and weighting of the identified impacts in order for the user to screen the most important issues that need to be considered. There have been efforts to combine different tools in this category such as LCC with LCA [26] or multi criteria decision making with LCA [27]. Comparisons of different product concepts, alternatives and improvement options are also offered by some of the tools listed in this category.

May et al [11] have criticized environmental tools and methods for having a rather vague connection to the PD process. Also relevant tools are not available for product design phase and existent tools are not adapted to designers' needs, therefore sustainability could not be integrated during early design in most of the cases [11]. In the next section limitation and barriers of current tools and methods are assessed.

4. Limitation of current tools and methods

Although a vast number of tools have been developed, there still appear to be barriers to their adoption in use. We can summarize list of reasons for poor industrial use of tools as follows:

Weak support of trade offs: In the PD, there are many elements to consider and mostly, trade-offs are necessary when choices have to be made between different alternatives. In order to support different trade-off situations, the tool should include criteria in a sustainability perspective and other important aspects e.g. cost, quality [28]. Byggeth et al [36] have analyzed fifteen different eco-design tools and highlighted the significance of a new eco-design tool having an evaluation method which provides support in trade-off situations.

Difficult to learn, understand and use: Environmental impacts are one of the many other constraints designers must meet when developing a product. They have very little time to dedicate to them [29, 18]. Some of the tools such as LCA require high training and data gathering to implement. Although the objective with such tools is to assist product designers and increase the consideration of environmental aspects during the product design process, increased data and time requirements can be considered as significant obstacles for those objectives to be fulfilled, and for the tools to be actually used [30, 31, 2]. Also the information attained is often too vague and general, or too complex and abstract to immediately highlight possible solutions. On the other hand tools such as, The Ten Golden Rules showed guidance consisting mainly of general statements broad enough to cover a range of issues, such as “Use the lowest energy-consuming components available”, without any additional information to back it up. Therefore it is of little direct use to the designer [28, 18].

Weak connection with PD process: the linkage between eco-design tools and PD process is weak or completely missing [32, 2]. Most of the eco design tools and methods activities act as a separate stream [5]; this can marginalize efforts resulting in them and reduce efficiency of the methods. A method or tool should work and promote within PD process; it cannot stand as separate activity [33, 34]. It has been highlighted that researchers in this field need to investigate PD processes to know how environmental concerns can be translated into product specifications [35, 30]. Sometimes the problem is in company with unstructured PD process.

Lack of life cycle thinking: some tools and methods consider one or two stages of life cycle. As mentioned before it has a great risk. The best example is design for X tools for each specific phase of the product life cycle, like design for manufacture, design for assembly, design for disassembly, design for reuse, design for recycle etc. These tools are developed in isolation, and there is very little or no integration of these tools into the design process. During PD there is a need to consider the whole lifecycle rather than a single phase of a product in order to ensure that detrimental environmental effects are reduced and not just relocated to other areas of the products life [36].

Lack of holistic method: To have a sustainable new product we need guidelines and checklists to consider different drivers of sustainability in each of the phases of a PD process. In addition, we need to analyze sustainability of the proposals in different phases of PD. Also we should have trade off tools to select between different alternatives. Although there have been some efforts to provide a more holistic approach [4], qualitative tools like guidelines are used in the initial phases, and quantitative tools like LCA, which require great amount of data, time and effort, are used in the later stages of design. There is no communication between these tools or results of them. Lofthouse [44] highlighted the importance of developing holistic tool for industrial designers, recognizing that a combination of guidance, checklist, education and information, along with well-considered content, appropriate presentation and easy access, are critical to success.

Lack of communication: Tools and methods should promote multifunctional teamwork. In current tools there is no clear indication, on who would be the most suitable user of tool. Environmental experts have all necessary knowledge to do the assessments and translate the results, while engineers are more aware of the product specifications [16]. Although in the literature emphasize the importance of multifunctional teamwork and the exchange of information [37, 38, 30], the nature of the implementation process of some tools and methods sometimes makes it impossible for both sides to be able to use the tools. In addition, the outcome of such tools can be difficult for everyone to understand and correctly communicate to the rest of designers or company in general.

5. Future work

Based on the presented barriers and limitations, in this section we propose two solutions to address current shortcomings. They can be explained as new methods for sustainable PD that can cover the requirements of designers in the PD process and that integrate sustainability. The insights presented are important for future work which will focus on the following.

1) Developing a model to support trade-offs in sustainable PD

In sustainable PD, besides the need of making trade-offs between different environmental issues, sometimes we need to trade off between environmental issues and other features of new products such as cost, quality etc. Developing a new method that could model different features and make this trade-off could be investigated. Life cycle design could be treated as an optimization problem to maximize value-added activities while minimizing resource consumption and waste disposal activities. The new model is not just making an evaluation and comparing different proposals but it models different specifications of a new proposal to find out the optimum point of each one. An optimization model could be used to model sustainability, quality and cost in the PD process in order to find the optimum level of their combination. Therefore designers need not select between different solutions since they can find the optimal solution.

2) Defining a systemic holistic method that considers different features of sustainability and product life cycle in appropriate and related phases of PD.

There are various works on tools and methods, but little is said on how to combine and integrate these within the design process. Also there is no comprehensive method that could be useful for the whole lifecycle of a product in various stages of its PD for both synthesis and analysis [40].

The required method consists of different kinds of guidelines and analytical methods that are integrated. The question on how to combine the results of different tools, or even to integrate different tools, is open for study [31]. In the new method, specific guidelines and checklists would be defined for different phases of the PD process that begin from the first phase and continue until the end of the process. A prioritization matrix would be applied to evaluate and prioritize different solutions, and also tools for making trade offs would be considered. One of the goals is to integrate different applicable tools with each other in such a way that the output of one could be used as an input of the other. Guidelines should be defined based on the standard PD process and the method would support the information regarding when and how the different environmental features should be considered in the PD process in order to increase the connection between the new method and the PD process. Finally the holistic method should be easy to use and understand.

6. Conclusion

In this article we highlighted the importance of sustainable PD and categorized different well-known existing tools and methods for sustainable PD into two major groups. The lack of current tools and methods is assessed and categorized into six groups. Finally, future work in this area is discussed.

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