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INCORPORATING ENVIRONMENTAL SUSTAINABILITY AT THE EARLY STAGES OF PRODUCT DEVELOPMENT

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Abstract- The awareness among people, companies and societies concerning environmental impacts has markedly increased in recent years. This has led many firms and practitioners to consider environmental aspects in various areas such as product development, service, and other areas. Product-based companies have realized that making environmentally sustainable products can be to their competitive advantage in the global market. To make sustainable products, companies need to integrate environmental issues into their product development processes. Accordingly, numerous eco-design tools have been developed. A majority of these tools can be applied only at later stages in the product development process to redesign products. However, the most effective way to consider environmental factors is to incorporate these issues at early stages in the process including planning and conceptual design phases. Therefore, this paper aims to identify applicable eco-design tools in the early stages of the product development process. In this paper, 77 eco-design tools were analyzed in-depth in accordance with their fundamental attributes and features, and then they were classified systematically. Based on this analysis, those applicable eco-design tools in the early stages of the product development process were identified and recommended accordingly. With regards to the findings of this research, only a limited number of eco-design tools can be used in the early integration of environmental impacts in the product development process. It is expected that this study will help eco-design practitioners choose proper eco-design tools for the early introduction of environmental issues and consequently, to design and develop environmentally sustainable products.

Keywords- Environmental Sustainability, Environmental Impacts, Eco-Design Tools, Early Integration, Product Development.

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Introduction

In the last decade, in light of the increasing awareness of the environmental impacts of products, companies have realized that the environmental performance of their products will afford a significant competitive advantage in the global market. Consequently, a major shift in product-based manufacturing firms has taken place recently from end-of-pipe solutions aimed at reducing the amount of harmful emissions to the environmental performance of products [1]. In conjunction with this shift, product development practices are deeply highlighted because products affect the environment at a number of points over their entire life cycle from raw material acquisition to the end of life stage. In this context, the environmental sustainability of products performs an essential role [2]. It is of major importance when addressing the environmental aspects at the early stages of the product development process, such as planning and conceptual design phases, where design concepts are flexible enough to eliminate environmental impacts. According to ISO/TR 14062 (ISO, 2002), the product design and development process into which environmental aspects must be integrated begins from the planning stage and continues through various stages of conceptual design followed by detailed design, testing/prototype, production market launch, and product review. However, early integration of environmental impacts is the core factor to developing environmentally sustainable products. The ISO/TR 14062 states that the introduction of environmental issues as early as possible in the product development process raises the opportunity for designers to consider and balance environmental requirements with other functions. The Design Council [3] argues that since over eighty percentages of costs related to products' economic and environmental are determined at the early phases of the process, the environmental impacts of products are mainly decided at those stages. Retzen [4] argues that one of the attributes of integrated product development is characterized by front-loaded development. In other words, during the early phases of the development process, such as the conceptual design phase, the resources are subsequently allocated at these stages in order to enhance the efficiency and avoid late changes in the process. She concluded that during the integration of the environmental aspects, the focus should be on the early development phases. Although a more recent survey revealed that the environmental aspects of products are primarily handled at the later design stages, most organizations recognize the need for the early integration of environmental aspects [5-7].

To enhance the environmental performance of a product, the concept of eco-design has been developed. Eco-design is the systematic consideration of design performance with respect to the environment, health, and safety over the entire product life cycle. Various eco-design tools have been developed for analyzing the environmental aspects of products [8, 9]. The application of eco-design tools generally include: (1) an analysis of environmental performance, (2) the selection and definition of priorities for product design improvement, and (3) the development of design guidelines and recommendations. Eco-design tools generally are classified into three categories: quantitative, semi-quantitative, and qualitative tools. The quantitative tools, such as life cycle assessment (LCA), are analytical and require a huge amount of data, time, and effort. Semi-quantitative tools, such as MET Matrix, need large amount of data while partially qualitative. Finally, qualitative tools, such as checklists, require less information. Eco-design practitioners are reluctant to apply the quantitative tools because of their time- and effort-demands and complexity. The same holds true for semi-quantitative tools as well. In contrast, very few feasible eco-design qualitative tools are available that can be applied at the early stages of the product development process.

Despite the importance of applying eco-design tools in the early stages [10, 11, 12, 13], no unified study exists on the eco-design tools used to identify applicable tools for early integration. This is aggravated by the fact that the literature of eco-design tools is widely dispersed and is, therefore, difficult to track. According to Lindhal [14, 15], eco-design tools' selection is unstructured and occasionally depends on the specific tool's popularity rather than a real analysis of the need.

Hence, the eco-design practitioners require a systematic guide to help them select proper eco-design tools for fulfilling their specific needs and expectations. In fact, they need to learn about the limitations of the majority of eco-design tools that might be confronted when applied in the early stages. Additionally, since designers face the lack of data availability during the early stages of the product development process, a systematic review of eco-design tools can help the designers choose the proper tools and gain the utmost benefits of them. The purpose of this paper, therefore, is to unify and gather together extensive eco-design tools, then analyze and classify them in a systematic way. In this research, the main emphasis for the early integration of environmental aspects is on "planning" and "conceptual design" phases where product-design concepts are flexible enough to eliminate the environmental factors. As a result, product designers must take effective actions during these early stages of the process. This research, therefore, analyzes eco-design tools based on their fundamental features and finally identify and recommend proper tools for the early integration of environmental issues into the product development process.

Why Eco-design?

The scope of this research is to investigate eco-design tools. In light of increasing population and the demand for products, designers began to consider not only diminishing costs and enhancing quality but also integrating environmental factors into the product development process, which became known as eco-design or design for environment (DfE). Eco-design has received considerable attention from companies in various sectors because of the increased demand for environmentally friendly products [16]. According to Wenzel [17] the reasons organizations are taking interest in the development of eco-products are: reduced costs by optimizing the use of resources and processes, improved public and brand image of the company and decreased violations by eliminating environmental impacts.

Eco-design has been described in a variety of ways in the literature. According to Bakker [18], eco-design can be defined as "*the development of products through the application of environmental criteria aimed at reducing environmental impacts throughout all stages of the life cycle of the product*." The concept of eco-design has also been described as "*designing products considering environmental issues, minimizing its environmental impacts at every opportunity possible*" [19]. Other authors [20] mention that eco-design refers to "*actions taken in developing products aimed at minimizing the environmental impacts of products throughout their whole life cycle, without compromising other essential characteristics such as performance and cost*." Based on these statements, eco-design can briefly be defined as "*an approach to product development concerned with the reduction of environmental impacts through all stages of the product life cycle.*"

Life cycle thinking is at the core of the eco-design approach. Life cycle thinking introduces a key paradigm shift in the way environmental challenges are addressed and analyzed because it inherently analyzes the impacts of products over the whole life cycle, i.e., from raw material and resource extraction to the end-of-life of a product. Life cycle thinking is a broad concept that helps conceptualize environmental problems as a systems-level issue that considers all environmental factors from cradle to grave and finds all possibilities for the environmental improvement of products along their entire life cycles [21, 22].

Recently, many studies have been published in the area of "eco-innovation", including the eco-design approach. Carrillo-Hermosilla [23] defines eco-innovation as "an innovation" that improves environmental performance. Even though eco-innovation is linked to various related concepts such as eco-design, it is mostly concerned with the technological aspects of environmental innovation. In other words, eco-innovation primarily emphasizes on "innovation." Thus, methods such as TRIZ can be used to devise eco-innovative solution strategies [24, 25]. For instance, after evaluating a product in terms of various environmental factors, innovative solutions can be explored by using methods, such as TRIZ, in order to increase the efficiency and improve the product's environmental aspects. However, integrating environmental aspects into product development is itself a process that needs proper eco-design tools. These tools are applied to the product development process during the entire life cycle of the product to eliminate environmental aspects. This process at the end can be integrated with the eco-innovation methods, which may result in innovative environmental solutions. Therefore, this research differentiates the definition of eco-design approach with eco-innovation based on "*when*" and "*how*" these methods can be utilized and implemented.

Plenty of eco-design tools have been developed to date, and in the literature, a huge amount of research has addressed the application of these tools in different contexts. One of the most important research areas of eco-design is how to apply and incorporate eco-design tools into the product development process. In the context of the product development process, it is possible to address environmental aspects either at the early or later stages of the process. Despite the fact that integrating environmental issues at the later stages of the process is straightforward and easily accomplished, the most effective way is to incorporate these aspects at the early stages where the design concepts are still flexible and decisions have not been finalized. Numerous studies discuss the implementation of eco-design at the post-specification stages of the product development process [26-28]. According to Bhamra [6] if eco-design is only used at the later stages of the product development process, only minor environmental changes can be made and therefore firms may have difficulty applying the principles successfully.

Two major implications can be drawn from the literature. The most efficient way to apply eco-design tools is to 1) select proper eco-design tools that follow the fundamental core of the eco-design approach, including life cycle thinking; and 2) address the environmental impacts of products at the early stages of the product development process. Despite the importance of applying eco-design tools at the early phase based on life cycle thinking, the widely dispersed literature on eco-design tools lacks a unified and systemic study. Throughout the next section of this paper, therefore, various eco-design tools will be systematically classified and then analyzed to recognize proper eco-design tools for their early integration in the product development process and alignment with life cycle thinking.

Research Methodology

The following major steps were taken to identify applicable tools for the early stage of the product development process:

I. *Review*: The existing literature of eco-design tools was reviewed in-depth, and then the tools were classified into three categories. Each category featured attributes of the tools, provided a brief description, and the application domain of the tools was explained;

II. *Analysis*: The exiting eco-design tools were investigated and analyzed in detail based on four criteria: life cycle perspective, input and output data type, applicability to the product development context and the phases of the product development process where they can be applied.

Review

First, a considerable number of eco-design tools in the literature were reviewed. Research on the incorporation of environmental aspects into the product development process is now into its third decade. During these years, many tools have been developed for facilitating the eco-design principles into the product development process. In order to conduct an extensive review on these existing eco-design tools, more than a hundred publications were gathered with a focus on academically authoritative texts such as academic books, journals, research reports, government reports, and companies' publications. According to this comprehensive literature review, the eco-design tools were classified based on their fundamental features, into three general categories, namely quantitative tools, semi-quantitative tools, and qualitative tools. The quantitative tools such as the life cycle assessment (LCA) are analytical tools and require a large amount of data, time, and effort. Quantitative tools usually require quantitative data and the results of applying these tools can be either quantitative or qualitative. The semi-quantitative tools such as MET Matrix, need a somewhat large amount of data and at the same time are partially qualitative. Either quantitative or qualitative data are used as the input for these tools, and the output can be either quantitative or qualitative. Finally, qualitative tools such as checklists, guidelines, strategies, and network diagrams are rudimentary tools that require less information and depth. Indeed, the qualitative tools are used for quick evaluations and an integration of environmental issues. The majority of these tools requires qualitative data as input and generates qualitative results.

In addition to this general categorization used in the research, there might be alternative ways to classify the eco-design tools. For instance, Navarro [29] classified the eco-design tools based on "functional" and "form" criteria. The "functional" criterion includes design stage, life cycle stage, and problem level while the "form" criterion consists of required resources to use the tool, e.g., software or data, the level of difficulty of employing the tool, techniques of the information process, and the typologies of industries or services for which the tool can be utilized. Additionally, more criteria, such as knowledge and skills, can be added to the classification of eco-design tools.

It is worth noting that only those eco-design tools have been considered in this research that can be applied in the product development process and classified into the three categories developed in this article with regards to their fundamental features. In other words, other tools and methods, such as standards or software, are not within the scope of this research and are, therefore, excluded.

Quantitative Eco-design Tools

Quantitative tools generally require large amounts of data and time for their use. The main eco-design quantitative tool is the Life Cycle Assessment (LCA). According to ISO 14040 [30, 31], "*LCA is a method to assess environmental impacts of a product or a service and is standardized by ISO*" [31]. Although LCA reveals a quantitative environmental profile objectively based on the results of detailed product design, it cannot be applied at the early stages of product design, and in the case of redesign, designers need a reference product. In addition to LCA, there are other types of quantitative tools that are primarily based on monetary approaches such as Cost-Benefit Analysis (CBA), and other types of quantitative tools that are fundamentally based on the flow of input and output, for instance, material flow such as Input-Output Analysis (IOA).

Semi-quantitative Eco-design Tools

Semi-quantitative tools usually require a large amount of data; they are partially qualitative. These tools are used where quantifying is preferred but not an absolute requirement. One of the most famous semi-quantitative tools is MET Matrix, which is a tool used to analyze a product's impact on the environment throughout its life cycle [10]. The principle behind a MET Matrix is that it establishes an environmental profile of a product by analyzing the product throughout its entire life, using the product life cycle as a basis. Additionally, a couple of companies have developed their own semi-quantitative tools that are customized based on their systems and product development processes such as AT&T's Matrix and Target Plot and Boeing's Process Environmental Matrix.

Qualitative Eco-design Tools

Unlike quantitative and semi-quantitative tools, qualitative tools are simple to utilize and require less data and time. Generally, the time required to complete the quantitative tools depends on the product's complexity, the data availability and the users' knowledge of the product [32, 33]. The major advantage of qualitative tools is that they have a high potential to be used at the early stage of the product development process because they do not require detailed and analytical data. The qualitative tools can be categorized into different groups based on their features and functions such as matrices, network diagrams, guidelines/strategies, and checklists.

Analysis

The main purpose of this step was to analyze the applicability of eco-design tools into the product development process. To gain a better understanding of the applicability of the tools, four criteria were utilized as follows:

1. *Life cycle thinking*: Life cycle thinking is the fundamental principle behind the eco-design approach. It involves consideration and analysis of a product's entire life stages, which is considered to be a crucial factor in the integration of environmental aspects into the product development process. Thus, this is the most basic and important criterion to analyze the applicability of eco-design tools into the product development process. In this research, this criterion means that whether the tool has a life cycle perspective that can encompass the entire life cycle of a product.
2. *Input and output data type*: Each specific eco-design tool needs input data that can be processed to produce the output data. These input and output data can be either quantitative or qualitative based on the features of the tool. For instance, some of the tools require quantitative input data, whereas others need qualitative data. In addition, there are tools that require a combination of both the quantitative and qualitative input and output data.
3. *Applicable to product development*: Despite the fact that plenty of eco-design tools have been developed, only a certain number of tools can be applied to the product development process. For example, some of the existing tools can only be utilized for evaluating environmental policies of a company. Therefore, this criterion identifies whether the tool is feasible in the product development or not, which is primarily based on the main objective of a tool.
4. *Product development phases where they can be applied*: According to the ISO/TR 14062 [12], for this research, the generic model of product design and product development process has been adopted that begins with planning to conceptual design, followed by detailed design to testing/prototype, production market launch, and product review. Thus, this criterion displays the stage of the product development process from which the eco-design tool can be used to incorporate environmental issues.

According to the analysis, some of the tools are not applicable to the product development process because of their main objective. For instance, the Environmental Weather Map and Environmental Policy Checklist are used for corporate policy. Therefore, they cannot be applied in this process.

Results

Implications can be gained from the analysis of the eco-design tools. One major implication is that life cycle thinking is applied by thirty-nine applicable eco-design tools, which is equal to 60% of all referenced tools. In the analysis of the tools, full coverage of the product life cycle from material extraction to the end-of-life was considered to be the fundamental attribute. For instance, LCA and most of the eco-design qualitative checklists have a life cycle perspective. However, there are many eco-design tools that do not cover the entire product life cycle such as Philips Fast Five Awareness and Eco-Estimator among others. Having a life cycle perspective is regarded as a vital factor that firms should consider when choosing appropriate eco-design tools for achieving the most effective and practical outputs.

Another implication is that a vast majority of the eco-design tools (sixty-four, or 83% of the total number of tools) can be applied to the product development process. The main purpose of these tools is to evaluate the environmental performance of either general or specific products and develop solutions to enhance product performance in terms of environmental sustainability. In addition to these applicable tools, there remain tools that cannot be utilized in this process that are generally used for evaluating the environmental policy or strategy of a company, for example, the Environmental Statement and/or Environmental Report Checklist.

Furthermore, a considerable number of the eco-design tools can be applied from the "detailed design" stage of the product development process. The compelling reason is that these tools require analytical and quantitative data, which are unavailable during the planning and conceptual design stages. Fifty-two eco-design tools, including quantitative and semi-quantitative tools, are classified in this group, which is equal to 81% of the applicable tools. However, among the eco-design tools, four eco-design qualitative tools, or 6% of the applicable tools, can be utilized from the "conceptual design" stage, and eight eco-design qualitative tools, or 13% of the applicable tools, can be applied from the beginning of the product development process, or the "planning" phase. Moreover, all of these findings underscore the fact that the availability of eco-design tools from the early stages of the product development process is too limited for a small number of tools.

Systematic analysis of the eco-design tools reveals an important finding; whereas companies have a much greater degree of flexibility in choosing and using the eco-design tools applicable to the "detailed design" stage, product design concepts are inflexible at eliminating the environmental impacts in the later stages of the product development process. However, practitioners are imposed with limitations on choosing the applicable tools at the early stages of the process where decisions about design concepts can still be adjusted to remove environmental factors. Therefore, this reality poses a paradox between the availability of eco-design tools in different stages of the product development process and the needs of organizations to integrate environmental aspects early in the process.

Discussion

The early integration of environmental impacts into the product development process helps companies and practitioners gain substantial benefits from the environmental sustainability of their products. In this context, eco-design tools play a vital role. Despite the fact that there are many existing eco-design tools, a very limited number of the tools can be utilized for the purpose of early integration. As shown in [Table-1], out of the 77 tools studied in this research, only twelve eco-design tools can be applied in the early stages of the product development process. Quantitative tools are not among these applicable tools because of their fundamental attributes, requiring analytical data that are unattainable at the early stages of the process. All eco-design quantitative tools have a life cycle perspective and are applicable in the product development process, except for Cost-Benefit Analysis (CBA) and Total Cost Accounting (TCA), which are accounting (monetary)-based quantitative tools. However, the quantitative tools can be incorporated at later stages in the process, from the "detailed design" phase. However, this late integration will not enable companies to develop environmentally sustainable products.

The eco-design semi-quantitative tools also follow a similar pattern. Out of fifteen semi-quantitative tools, only five tools encompass the entire product life cycle including MET Matrix, AT&T Matrix and Target Plot, Environmental Product Life Cycle Matrix (EPLC), The Environmentally Responsible Product Assessment Matrix, and MECO. All semi-quantitative tools are feasible in the product development process, except for Strategic Environmental Assessment (SEA), Environmental Risk Assessment (ERA), and Environmental Effect Analysis (EEA), all of which are assessment-based tools. Likewise, as quantitative tools, none of the semi-quantitative tools can be utilized at the early stages of the product development process.

Eco-design qualitative tools, however, show different behaviors. Twenty-three of the forty-eight tools cover the complete life cycle of a product, and forty tools are applicable to the product development process. The tools that are not applicable usually are used for the evaluation of the environmental performance of a company or the evaluation of policies. The most interesting finding is that twelve eco-design qualitative tools can be applied to the early stages of the product development process. These tools encompass the life cycle perspective, in which they cover the whole life cycle of a product. Additionally, these are the most qualitative-based tools that can be applied in the early integration of environmental aspects since detailed, quantitative data are not available and are not required in the early stages of the process. As a result, these tools meet the fundamental criteria of applicability of eco-design tools in the early stages of the process. Therefore, these qualitative eco-design tools with a life cycle perspective are the most appropriate tools.

Table-1 *Summary of the Analysis of Eco-design Tools*

Category of Tools	Number of Tools	Number of Tools		
		With Life Cycle Thinking	Applicable to Product Development	for Early Integration into Product Development
Quantitative	14	12	12	0
Semi-quantitative	15	5	12	0
Qualitative	48	23	40	12
Total	**77**	**40**	**64**	**12**

Table-2 *Integrating Environmental Aspects at the Early Stages of the Product Development Process*

Stage	Goal	Recommended Eco-design Tools	Action List	Output
Planning	Develop feasible design ideas Prepare environmental requirements	- Eco-Portfolio Matrix - Quality Function Deployment for Environment (QFDE) - Environmental Objectives Deployment (EOD) - Environmental Benchmarking - Eco-design Web	- Determine internal and external factors - Analyze national and international environmental policy and regulations - Determine the main environmental aspects related to the product's function - Prepare a brief list of the main environmental impacts expected over the entire life cycle of the product - Select a proper environmental design approach - Evaluate environmental performance of a reference product	- Practicable design ideas Environmental requirements list
Conceptual Design	Develop one or more design concepts that meet environmental requirements	- Dominance Matrix - The Eco-Design Checklist	- Develop environmental measurement units, scales and targets - Analyze significant environmental aspects over the product life cycle (life cycle thinking) - Apply environmental requirements and ensure they are met in the development process	One or more environmentally sustainable design concepts

Early integration of environmental impacts is the fundamental factor to developing environmentally sustainable products. According to the ISO/TR 14062 [12], the introduction of environmental aspects as early as possible in the product development process raises the opportunity for designers and practitioners to consider and balance environmental requirements with other functions. For this purpose, product designers must take effective actions during the early stages of the process. As shown in [Table-2], the main objective of the "planning" phase is to develop feasible design ideas, and prepare environmental requirements. Designers need to take appropriate actions on these goals such as analyzing internal and external factors and environmental policies, determining the main environmental aspects expected over the whole life cycle of the product, choosing appropriate environmental design approaches, and evaluating the environmental performance of a reference product. The output of this stage is feasible design ideas as well as an environmental requirements list. The most effective and applicable tools for this stage that apply life cycle thinking are the eco-portfolio matrix, quality function deployment for environment (QFDE), environmental objectives deployment (EOD), environmental benchmarking, and eco-design web.

In the "conceptual design" phase, the primary objective is to develop design concepts that are consistent with environmental requirements. The actions that designers need to perform include developing environmental measurement units, scales and targets, analyzing significant environmental aspects over the product life cycle, and applying environmental requirements that result from the planning phase. These actions yield "one or more environmentally sustainable design concepts" as the outcome of this stage. The dominance matrix and eco-design checklist, which have life cycle perspectives, are recommended for application at this stage to obtain the desirable results.

Conclusion

The primary objective of this paper is to collect and analyze more than 70 eco-design tools to identify which tools may be integrated early in the product development process. In this paper, the eco-design tools were scrutinized based on their characteristics and then categorized in a systematic way. This research presents as its key finding that only a limited number of eco-design tools are applicable for the early integration of environmental impacts in the product development process. Accordingly, based on the analysis of the eco-design tools, action lists and the appropriate tools were recommended for their use in the early stages of the process, either in the planning or conceptual design stages. In spite of the importance of early integration, the crux of the process of integrating environmental factors into product development lies in the fact that this process is continual and alterable, and should incorporate the policies and strategies of companies. Organizations need to maximize the impact of innovation and provide plenty of opportunities to enhance the environmental performance of products. In summary, this article can be used as a basis for early integration and the creation of opportunities for environmental improvements.

There are some areas of future research that can benefit from this research. The first is to focus only on the applicable tools at the early stages of the product development process and analyze them in-depth to gain a better understanding of the tools as well as the integration process. Next, this research can be applied in a real product development case study to show the results of applying eco-design tools. Other important future research might be the development of a new eco-design tool that is completely feasible from the early stages of product development and does not require analytical data, which are not available at the early stages of product development.

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