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SUSTAINABILITY ASSESSMENT METHODOLOGY IN PRODUCT DESIGN: A REVIEW AND DIRECTIONS FOR FUTURE RESEARCH

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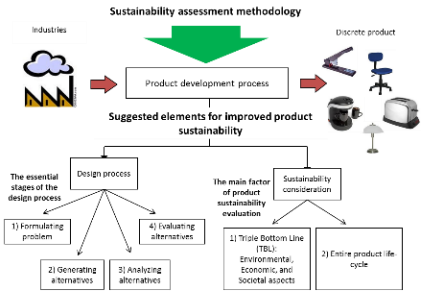

Abstract

To achieve sustainable product design, it is crucial to use sustainability assessment during the product design process. In this paper, numerous sustainability assessment methodologies in product design are reviewed. A comprehensive assessment of sustainability has been reported to present better performance for improving product sustainability. This review focused on the consideration of sustainability elements by previous researchers that have proposed integrated design tools, commercial software tools and combination both methods in supporting the methodologies. Based on this review, it can be concluded that the inclusion of sustainability performance among the assessment criteria in the design process activities is suggested as a critical point of concern which presents a challenge and is a great opportunity to develop useful guidelines or directions for industries or any product-based project so that the proposed approach will be accepted for implementation in the working environment.

Keywords: Sustainable product design, product sustainability, product design

Abstrak

Untuk mencapai reka bentuk produk yang lestari, ianya penting untuk menggunakan penilaian kelestarian semasa proses reka bentuk produk. Dalam kertas kerja ini, pelbagai kaedah penilaian kelestarian dalam reka bentuk produk dikaji semula. Satu penilaian menyeluruh kelestarian dilaporkan membentangkan prestasi yang lebih baik untuk kelestarian produk. Kajian ini memberi tumpuan kepada pertimbangan elemen kelestarian oleh penyelidik sebelumnya yang telah mencadangkan alat bersepadu reka bentuk, alat perisian komersil dan gabungan kedua-duanya bagi menyokong metodologi. Berdasarkan kajian ini, ianya boleh disimpulkan bahawa penerapan prestasi kelestarian dikalangan kriteria penilaian dalam aktiviti proses reka bentuk dicadangkan sebagai titik kritikal dimana satu cabaran dan peluang baik bagi membina panduan berguna kepada industri atau

projek supaya pendekatan yang dicadangkan akan diterimapakai untuk pelaksanaan dalam persekitaran kerja.

Kata kunci: Reka bentuk produk lestari, kelestarian produk, reka bentuk produk

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1.0 INTRODUCTION

New products are designed and developed based on design paradigms timely, depending on market forces where sustainable design has been the latest paradigm shift in design focus [1]. Methods that can be applied during the product design process have a greater effect on a future product attributes since a great variety of decisions need to be made [2, 3]. Achieving sustainable product design has been giving significant awareness to worldwide industries as one of the important practice during decision-making in creating a new product and improving product sustainability [4, 5].

According to Badiru [6], sustainability implies the ability to sustain (and maintain) a process or object at a desirable level of utility. Sustainability for a product in general definition is the ability of the product to be sustained over it life-cycle. In the final design stage, to select which of the designed products are sustainable requires the ability to measure sustainability in a quantitative, or qualitative approach. However, to achieve sustainable yield, sustainability assessment is critical [1]. In relation to that, sustainability requires methodological, scientific, and analytical approach to make it effective for managing the product design activities [7, 8].

2.0 CONSIDERED ELEMENTS FOR IMPROVING PRODUCT SUSTAINABILITY

Sustainable development is frequently used as a business driver all over the world [9, 10]. Organisations that are successful in the world competition market have put strengthen on sustainable development in their product [10, 11]. Even no standard approach has been practiced nowadays, but integrating the sustainability requirements into the product development is a widely accepted strategy in principle [12]. Sustainable development began in the 1980s as a reaction to the negative environmental and societal impacts of the major approach to economic growth [11, 13]. The World Commission on Environment and Development (1989) defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." From a business point of view, the concept of sustainability is based on the aggregation of the three indicators – environmental, economic, and societal aspects [12, 14, 15, 16].

Tools and methods for sustainability measurement and assessment are urgently needed by the world society [17]. Developing methodologies or strategies in product design for sustainable product design that will provide many benefits in product lifecycle stages have been investigated by many researchers over the past many years [18]. Basically, the lifecycle stages of a product starts from raw material extraction and move through to the finished product. It is necessary to consider the entire product life cycle while assessing the performance of a product's sustainability since this approach is one of the important aspects of concern in a sustainable product [15, 18, 19, 20].

Hemdi *et al.* [21] developed sustainability evaluation method using fuzzy inference approach for designers and decision makers to assess products and processes by considering the three major aspects of sustainability over the entire product lifecycle. Afterwards, Ghadimi *et al.* [22] stated that this method is sufficient in terms of the sustainability elements but weighting for their each selected element was lacking where continuous improvement is necessary. In relation to that, a new product sustainability assessment by applying Fuzzy Analytical Hierarchy Process (FAHP) to weight selected elements and fuzzy logic to assess the product sustainability level based on acquired weights. However, even the tools used have been continuously improved to be more precise assessment, these approaches were focused only on manufactured products which the assessment were not implemented during the design platform. Sustainability assessment required wider area from design phase until product end of life hence this method is not suitable since it does not cover at the early design phase.

According to Yan and Feng [23], methods of sustainable product design can be the core principles in all the traditional design methodologies in which the desired outcome is a sustainable product. Sustainable products are generally defined as those products designed with a consideration for environmental, societal, and economic aspects to protect public health, welfare, and the environment over their full commercial cycle, and thus provide for the needs of future generations [14]. Since the important criteria that need to be considered in product design include a wide variety of environmental, economic, and societal aspects, the desire to assess the selected sustainability criteria for a product has pushed product designers to find new appropriate methods and tools. Therefore, to achieve the objective of sustainable design in developing products, an approach needs to be systematically developed for improved product

sustainability. All these requirements play an important role in the early design stage, in which more benefits can be obtained in the consequent process of a product lifecycle, and further investigation of this area is important.

A systematic approach to improve product sustainability involves the integration of the concept of sustainability and appropriate design tools and this approach acts as support tools in the process of design. Many methodologies that based on this approach have been in development for almost three decades [24]. To evaluate a product sustainability throughout its entire lifecycle during the early stage of the design process requires support tools, and the factors that contribute to the triple bottom line (TBL) aspects in each stage of a product lifecycle should be aggregated into a single score or at least lead to a single decision [25, 26].

Generally, most of the proposed tools developed for improving product sustainability are implemented in the conceptual design stage, and this phase has become one of the top priorities of ongoing researches in the literature to help designers develop product concepts [27, 28]. In addition, the concept of sustainability can be integrated into preliminary design during all phases of the design process [29]. Sheldrick and Rahimifard [24] clearly highlighted that the preliminary stage has the greatest influence over the environmental impact of a product due to the fact that approximately 80% of the total impact is decided after only 20% of the design activity has been completed. It is believed that by measuring the sustainability by taking configuration design is one of the design activities in the preliminary stage is more meaningful since the result is taking consideration of design configuration. It is because this phase also has potential for implementing the concept of sustainability, as well as a systematic approach for improved product sustainability. A summary of the suggested elements to be considered in the sustainability assessment methodology during the product design process is illustrated in Figure 1.

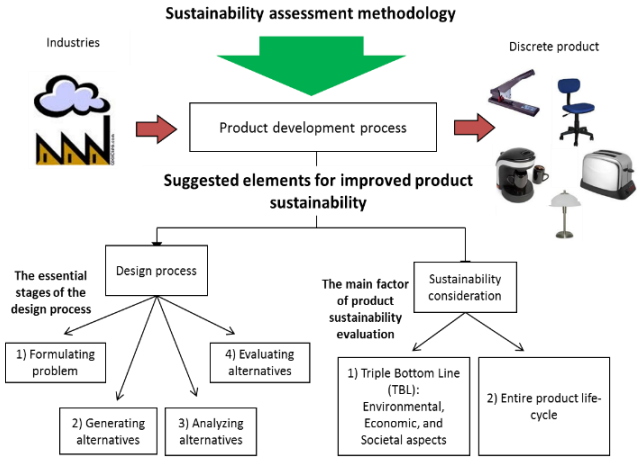

Figure 1 Summary of the suggested elements for improved product sustainability

3.0 SUSTAINABILITY ASSESSMENT IN PRODUCT DESIGN

3.1 A Review on the Previous Sustainability Assessment in Product Design

In recent years, many sustainability assessment methodologies have been introduced in product design for improved product sustainability. These methodologies aid inexperienced product designers during early design stages in bridging the gap between sustainability criteria and product design [27].

Several researchers have integrated design tools associated with the concept of sustainability in order to meet the desired objectives focused on individual goal as shown by Baki [12], Yan *et al.* [28], Kengpol and Boonkanit [30], Vinodh and Rathod [31], Vinodh *et al*. [32], Wang *et al*. [33], Tseng *et al*. [34], Hassan *et al*. [18], Hassan *et al*. [35], Hassan *et al*. [36].

For the purpose of designers to incorporate sustainable development issues related to product design, Baki [12] introduced a framework to promote innovation solution by incorporating Theory of Inventive Problem Solving (TRIZ) into the idea of generation process. Before proceed to the details of design stage, a product idea was comparatively evaluated in terms of sustainability criteria for each TBL aspects. Similarly with Vinodh *et al*. [32], this study proposed a framework for decision support in order to develop Ecodesign product at the conceptual design phase by integrate the TRIZ, Analytical Hierarchy Process (AHP) and environmentally conscious quality function deployment (ECQFD). As for Wang *et al*. [33], TRIZ was applied to handle the contradiction for problem solving process during the product design phase in the developed framework. What is interesting in this framework, 39 parameters with 40 inventive principles were used. All tools developed by previous researcher [12] [32] and [33] were able to solve the problem in unique way.

In other scenario, there was a methods developed using scoring system methods by Hassan *et al*. [18], Hassan *et al*. [35], and Hassan *et al*. [36]. As shown by Hassan *et al*. [18], a systematic approach for evaluating sustainability of configuration design was proposed. The method was designed based on weighted decision matrix and artificial neural network (ANN). In this study weighted sustainability score was introduced by utilization of ANN, which is able to estimate the final performance in a single value. Previously, Hassan *et al*. [35] introduced an integration of morphological analysis theory and ANN for selecting the most sustainable alternative product assembly. Meanwhile, Hassan *et al*. [36] was integrated conceptual design activities with a method named product sustainability index (ProdSI), during selecting the best possible configuration for product design. All proposed approach considering TBL aspects needed.

In the case of investigation of sustainable product conceptualization, Yan *et al*. [28] provided a method named sustainability product conceptualization system (SPCS). The developed system used acquisition

technique; design knowledge hierarchy and knowledge represent structure. In this system, initial design options can be obtained using morphological configuration such combining different part options. Subsequently, in this study, Hopfield network was applied to narrow down initial design space based on it is criteria. However, the results on the sustainability assessment in not precise since the analysis does not considered the weightage option. It is believed by considering the weight, the result of sustainability assessment is more reassure.

Meanwhile, Bevilacqua *et al*. [3], Maruschke and Rosemann [37], Schneider *et al.* [38], Gehin *et al.* [39], Vinodh [40], and Russo [41] used a commercial software tool. Most of the software tools are based on a Life Cycle Assessment (LCA) approach to evaluate the environmental aspects and potential impacts associated with a product and related services over its entire life [42]. Another methodology is a combination of both methods. The models that combine both methods involve the use of an LCA approach in design methodologies to improve the deficiencies and satisfy the needs of sustainable product development. Examples of the methodologies such as Fargnoli *et al*. [5], Devanathan *et al.* [43], Trappey *et al.* [44], Kuo *et al.* [45], Bernstein *et al.* [46], Vinodh and Rathod [47], Lindow *et al.* [26], Abdalla and Ebeid [27], Romli *et al*. [48], Wang *et al*. [49], Lu *et al*. [50], Yang [51], Mahmood *et al.* [52] and Russo *et al.* [55]. It is acknowledge that LCA only covered the environmental analysis without concerning about social aspect and economy aspect. That is why previous researchers combined the other methodology with LCA such Social Life Cycle Assessment (SCLA) and Life Cycle Cost (LCC). However, the result of the analysis might not very accurate since the analysis had been done separately for each aspect. In addition, one analysis of LCA take quite a long time since it plays with varies data.

In order to help designers in facing eco-design problem, Fargnoli *et al*. [3] had proposed a specific design method for sustainability procedure named Design Management for Sustainability (DMS). DMS contains of two phases; 1. Design planning 2. Design and development. This method was outlined and tested though it is application to the re-design of an engine driven grass timer as a case study. By using this method, it is claimed that proposed method allowing user to perform design activities compliance with own sustainability goal. However, DMS more focus on management at the early design phase without concerning from cradle to grave as mentioned earlier.

There was a framework proposed by Trappey *et al*. [44] that adopted LCA, quality function deployment for environment (QFDE), TRIZ and the projections of green conceptual design improvement based on ANN approaches. The aim of the developed framework is to support environmental conscious and energy using product development. LCA and QFDE were applied for assessing and comparing the environmental impact of human activities during production and provision of products. Next, TRIZ was applied to support R&D for creating an innovative product design ideas effectively and efficiently during design stage. Finally, ANN model was developed to support of environmental conscious product design.

Different scenario shown by Kuo *et al.* [45], an Eco-quality function deployment (Eco-QFD) model was proposed to aid a product design concerning environmental aspects. In this research, a fuzzy group method was applied to Eco-QFD during product planning uncertainty for decision making process. This model considers overall customers satisfaction and encourages enterprises for producing environmental-friendly product. What is interesting about this model is environmental acceptability and overall customer satisfaction can be obtained. However, eco-QFD only take environmental consideration which is not enough for sustainability assessment since it do not cover social aspect and economy aspect.

On the other hand, Romli *et al.* [48] presented an integrated eco-design decision making (IEDM) method, which is all the product sustainability consideration was conducted within a special eco-design house of quality. IEDM consists of three phases; 1. LCA, 2. Eco-design process (Eco-Process) model, and 3. Enhanced eco-design QFD process. This method utilises of a set of the Eco-Process parameters and their relationship. This approach more focusing on quality aspect of the product during the decision making process. As a sustainability assessment, all sustainability aspect should be considered from early design phase until end of product life.

There was a specific methodology developed by Mahmood *et al*. [52], considering LCA and fuzzy logic for assessing the sustainability only for membrane system. This methodology applied LCA in order to obtain sustainability parameters, which were used as an input for the fuzzy formulation. It was claimed that results from the methodology is understandable and easy for interpretation since the final result can be obtained in a single value index. Even this methodology concerning from early design phase until product end of life, this method only applicable for membrane system only. The parameters develop in this methodology specifically for membrane system hence not suitable for other general items.

3.2 Summary of the Previous Sustainability Assessment in Product Design

A review on the previous sustainability assessment methodologies as an approach to improve product sustainability in product design has been summarized as presented in Table 1. This summary is based on the concept of sustainability that takes into consideration TBL (environmental, economic, and societal aspects) and the entire product life cycle, and the preliminary design stage.

Since the reduction of the environmental impacts of a product lifecycle must be the priority compared to economic and societal aspects in order to achieve sustainable development, most of the previous sustainability assessment tools have been developed

with a focus on environmental protection and so-called eco-design (environmentally conscious design). These can be found especially in commercial software tools where the tools lack the integration of the TBL aspects, and focus instead on the environmental aspect [27]. In addition, most of them neglect the third aspect of the TBL aspects and do not consider the entire product lifecycle. These deficiencies may lead to an imperfect sustainability assessment process. It is believed by taking consideration of all TBL aspects, the result of sustainability assessment may more meaningful towards sustainability aspects.

Most of the tools have been integrated during the conceptual design phase which overlooks the other phases in the preliminary design stage. The conceptual design became the top priority of research to redesign the product concept to be more sustainable. To achieve the process of design comprehensively, most of the tools provide an assessment at the end of their methodologies, but they are lacking in terms of selecting the most sustainable product of the different design alternatives they generated in the early stage. Lindow *et al.* [26] came to the same conclusion, claiming that analysing the sustainability of different product alternatives is the toughest task since such comprehensive tools are not yet available. Therefore, it should be highlighted that a tool capable of evaluating a product with regard to sustainability considerations and selecting the most sustainability-oriented performance of a particular design alternative among the possible design alternatives of a product is still lacking and further investigation is required to fill these gaps.

Table 1 A summary of the previous sustainability assessment in product design

Authors	Year	Concept of sustainability			Entire product lifecycle	Preliminary design stage	
		Environment	Economic	Social		Conceptual design	Others
Bevilacqua *et al*. [3]	2007	X	X		X	X	
Fargnoli *et al*. [5]	2014	X	X	X	X	X	
Baki [12]	2007	X	X	X		X	
Hassan *et al*. [18]	2016	X	X	X	X		X
Lindow *et al*. [26]	2013	X	X	X	X	X	
Abdalla and Ebeid [27]	2011	X	X	X	X	X	
Yan *et al*. [28]	2009	X	X			X	
Kengpol and Boonkanit [30]	2011	X		X		X	
Vinodh and Rathod [31]	2011	X		X		X	
Vinodh *et al*. [32]	2014	X		X		X	
Wang *et al*. [33]	2010	X		X		X	
Tseng *et al*. [34]	2012	X		X		X	
Hassan *et al*. [35]	2012	X	X	X		X	
Hassan *et al*. [36]	2013	X	X	X	X		X
Maruschke and Rosemann [37]	2005	X			X		
Schneider *et al*. [38]	2008	X			X	X	
Gehin *et al*. [39]	2009	X			X	X	
Vinodh [40]	2010	X			X	X	
Russo [41]	2011	X			X	X	
Devanathan *et al*. [43]	2009	X		X	X	X	
Trappey *et al*. [44]	2009	X		X	X	X	
Kuo *et al*. [45]	2009	X		X	X	X	
Bernstein *et al*. [46]	2010	X			X	X	
Vinodh and Rathod [47]	2010	X		X	X	X	
Romli *et al*. [48]	2015	X	X	X	X		X
Wang *et al*. [49]	2010	X		X	X	X	
Lu *et al*. [50]	2011	X	X	X	X	X	
Yang [51]	2007	X	X		X	X	

Authors	Year	Concept of sustainability			Entire product lifecycle	Preliminary design stage	
		Environment	Economic	Social		Conceptual design	Others
Mahmood *et al.* [52]	2015	X	X	X	X		X
Russo *et al.* [55]	2016	X			X	X	

The methods that combine an LCA approach and design tools have considered the concept of sustainability and the essential stages of the design process more than the integrated design tools and the commercial software tools. This is because they attempt to overcome some of the limitations by integrating the TRIZ method for generating ideas of design concepts, QFD for achieving total customer satisfaction, or LCA for assessing environmental impacts over the entire product life cycle. However, these methods are not appropriate for overcoming such limitations since they have more disadvantages than advantages. One of the disadvantages are the result of sustainability assessment might be bias depending on the separated analysis.

QFD is one of the great tools in the conceptual design phase and it also identifies the voice of the customer for market-driven product and service designs but this tool is limited to embodiment and detail design. In addition, QFD-based tools involve qualitative measurement and the development of correlations between needs and technical attributes are completely reliant on designers' perspectives. The TRIZ is selected by many researchers, as this tool is capable of handling functionality and creating innovative product design ideas effectively but at the end of the process, designers need to work hard to select the best concept from the variety of solutions. Furthermore, the use of the TRIZ requires an expert on this application or courses to explain how it works.

LCA is a tool capable of evaluating and enabling the estimation of the cumulative environmental impact resulting from all stages in the product life cycle. LCA has been used to provide more direction but the weakest aspect of LCA is the time and effort needed to collect information that sufficiently describes the life cycle. According to Russo [41], the LCA approach is too complex and not a user-friendly tool, and it is not useful in the design process. Although the LCA can be applied for sustainable assessment, the deficiencies in terms of only considering environmental impact factors and difficulties in decision-making in the selection of the most environmentally friendly products from alternatives may limit its useful application [18]. Furthermore, the application of LCA is not compatible to be used during design stage because the amount and specificity of information generated by an LCA cannot be used by the designers for their daily decisions.

As mentioned earlier, there is hardly found in the literature that reports sustainability assessment in product design that covers all the required TBL aspects. Earlier assessment tools, methodologies and approach do not indicate clearly the sustainability assessment methodology in product configuration design. Hence, it is timely a comprehensive methodology for assessing the sustainability of product configuration design required.

4.0 DIRECTIONS FOR FUTURE RESEARCH

Development of sustainable products should follow some set of rules, procedures, or a general process that may affect the product's quality and performance; for example, the structure of a design methodology affects the sustainability performance of a product to be designed. Besides, selection of the most sustainable design among the best product assembly alternatives is crucial in decision-making when completing the design methodology due to handle trade-off situation among sustainability criteria [18]. Accordingly, some essential aspects from the summary of the previous sustainability assessment tools need to be investigated for further improvements in order to improve product sustainability comprehensively while the product is being designed.

Moreover, the proposed tools and methods should be capable of supporting the process of design and practical enough to be adopted in the working environment of product designers. The essential aspects of a sustainability assessment methodology include the consideration of a TBL approach which covers the entire product lifecycle and the incorporation of the concept of sustainability at the early design stage. Another suggestion is using metrics or indicators to measure sustainability of different product alternatives that are attributable to product design improvements, where better values mean better sustainability based on a single scale or score [53, 54]. This system will be more meaningful and easy to understand by the general public.

In addition, the inclusion of a sustainability performance evaluation among the criteria in the configuration design phase, the generation of several possible design alternatives of a product, the evaluation of the generated design alternatives with regard to sustainability criteria, and the selection of the most sustainable design among the generated design alternatives is suggested as a critical point of concern in the sustainability assessment strategy. This presents a challenge and is a great opportunity to develop useful guidelines or directions for industries or

any product-based project so that the proposed approach will be accepted for implementation in the working environment [18].

5.0 CONCLUSION

A sustainable product can be defined as a product that has little impact on the environment, and at the same time, has been designed with consideration of the economic and societal aspects to ensure future benefits. To meet the challenge of developing a successful sustainable product, a sustainability assessment methodology should plays an important role.

This paper has clearly presented a review on some of the previous sustainability assessment methodologies in product design. The basis of this process is acknowledged by many researchers in the literature with the key point of consideration being the integration of the concept of sustainability and appropriate design tools into the preliminary stage of the design process. Those approaches have been practically implemented into the product development process for sustainable product design.

Furthermore, several lacks and directions have been discussed for future research opportunity.

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