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Sustainable product design and development: A review of tools, applications and research prospects

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ABSTRACT

Due to increasing pressure for achieving sustainability objectives, the concept of sustainable product design and development is gaining more attention in recent research. In the past, a plethora of eco-design tools that address only the environmental aspect have been developed. Hence, previous review articles focused mainly on eco-design tools, such as life cycle assessment (LCA) and others. Unlike previous studies, the main contribution of this article was to review and analyze the recent and emerging product design tools (published from 2007 to 2017) which considered other dimensions of sustainability along with the environment. Based on the criteria of sustainability dimensions, this paper proposed a generic and broader classification scheme to enhance the understanding of these recent tools. Those which included two aspects of sustainability were categorized as partial sustainable product design (P-SPD) tools, and those which covered three aspects of sustainability were classified as sustainable product design (SPD) tools. The analysis revealed that SPD tools were less mature and standard as compared to P-SPD tools. The majority of both P-SPD and SPD tools were based on a life cycle perspective. However, P-SPD tools were found to be more useful at early design stages. In addition, this paper presented the case studies of the tools to decipher their practical utility. It also discussed the hurdles and problems associated with the methodological development and practical utility of the tools. Founded on these difficulties, future research directions were presented. In essence, a coordinated and responsible effort among practitioners, governments, societies and researchers is needed to ensure the successful implementation of the tools.

1. Introduction

Sustainability or sustainable development has become a significant and major research area these days (Zhen et al., 2015). The challenge of realigning the present path of development on a sustainable trajectory concerns all sectors of society, including engineering and manufacturing (Rosen and Kishawy, 2012). Manufactured products impact all three facets of sustainability; economy, environment and society throughout their entire life cycle; material extraction, manufacturing, transportation, use and disposal (Tarne et al., 2017). It was found that about 80% of sustainability impacts are decided at the product design stage (Keoleian and Menerey, 1993; Kulatunga et al., 2015; Lewis and Gertsakis, 2001). To address this issue in the manufacturing sector, designing and production of sustainable products was found to be an important strategy to achieve sustainability (Moreno et al., 2011; Ameli et al., 2016) and cleaner production objectives. Thus, considering the triple-bottom line concept (Hacking and Guthrie, 2008; Hall, 2011) in product design, sustainability can be defined as the ability of a product to work continuously while ensuring lowest environmental impacts and providing economic and social benefits to the stakeholders.

A sustainable product design solution deals effectively with a product's functional attributes and also balances the three dimensions of sustainability appropriately (Bereketli and Genevois, 2013; Hosseinpour et al., 2015). All three sustainability aspects must be considered as an integral part of sustainable design (Gennari, 2000; Jia et al., 2017). However, initially, environment was the only concern for product design. So, developing an environmentally friendly or ecological (eco)-design was practiced during the first wave of sustainability (Lofthouse and Bhamra, 2012). Since then, an abundance of tools called eco-design or Design for Environment (DfE) tools were developed to provide support during the product design phase (Navarro et al., 2005; Shi et al., 2017).

Because of the fact that previously, many studies focused on developing eco-designs, most of the review articles were also based on

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eco-design tools (Bovea and Pérez-Belis, 2012; Poulikidou, 2012; Germani et al., 2013; Chang et al., 2014). Even a recent review by Rossi et al. (2016) in this field was also focused only on eco-design tools while investigating the hurdles in implementing these tools in the industry. However, nowadays, sustainable product design and development which is a comprehensive concept is getting more attention. As a result, new tools are emerging along with the improvements in the existing eco-design tools to account for other dimensions of sustainability. This phenomenon is happening at a fast pace, notwithstanding there is no recent review, which could establish their methodological development separately and show the weaknesses and strengths of these emerging tools. A relevant review article by Hassan et al. (2017) was found which covered eco-design and sustainable product design tools in one article. However, the main focus remained again on eco-design tools. Along with this, their approach was very brief, only limited tools were discussed shortly and they did not describe the methodology of the tools. That paper also ignored the relevant case studies. Thus, there is a need to review the recent tools according to the triple-bottom line concept, while analyzing their methodologies and case studies. Bridging this gap, this article is aimed to provide a comprehensive and broader review of the most recent tools and case studies.

It was also noted that before the introduction of economic and social aspects of sustainability in product design, eco-design was generally considered as sustainable design. Flores-Calderón et al. (2010) found that the contradictory and sometimes misleading use of the concept of sustainable product has become a challenge. It was also advocated to consider eco-design tools differently from sustainable product design tools because they lack the strategic principles of sustainability (Byggeth and Elisabeth, 2005). However, this confusion and ambiguity is still visible in many recent research articles. For example, Ramani et al. (2010) used the term “sustainable” but the mentioned tools were eco-design tools rather than meeting all three requirements of sustainability. Chang et al. (2014) performed a review of life cycle assessment (LCA) for sustainable product development, although LCA is related to environmental aspects only. Likewise, Buchert et al. (2017) reviewed 11 methods for designing sustainable products, however only 3 methods were based on all three aspects of sustainability.

Similar confusion and deceptive usage was found in many other papers as well, such as Buchert et al. (2014), Kara et al. (2014), Wisthoff et al. (2016) and Huang et al. (2017). These confusions and contradictions generally hampered the utility of product design tools (Byggeth et al., 2007). So, keeping all these in view, there is a need for a recent review while bearing in mind the definitions and understanding of different concepts. A generic classification scheme is required to differentiate between the emerging tools and reduce the confusing usage of terminologies. Grounded on this, one way is to differentiate such tools based on the sustainability dimensions that they included.

Moreover, normally, previous review articles reported tools and case studies in separate papers. For example, Rossi et al. (2016) and Hassan et al. (2017) discussed product design tools only and case studies were not included in the same articles. However, presenting case studies in a same paper can improve the understanding and usefulness of the tools. Thus, unlike previous reviews, an article that reviews both tools and case studies is more beneficial. In short, this article presents a literature review of the most recent tools and case studies for sustainable product design which were published from 2007 to 2017, while analyzing them based on the triple-bottom line along with other criteria.

The reason for considering this time frame (2007–2017) is that a common methodology for life cycle costing (economic dimension) was first introduced in 2007 (Gundes, 2016), after which many studies started to use it in product design (Hunkeler et al., 2008; Utne, 2009). Although the methodological guidelines to evaluate the social dimension were prepared by the United Nations Environment Programme in 2009, this review starts from 2007 by taking the adoption of life cycle costing as a reference point. Additionally, a decade review is normally considered sufficient to investigate the recent trends and developments.

In this paper, eco-design tools are discussed very briefly because many reviews are already available in this subject. Other tools are classified as partial sustainable product design (P-SPD) and sustainable product design (SPD) tools which are discussed and analyzed in detail along with their case studies. The presentation of the article and classification scheme is aimed to reduce the confusions related to the use of concepts and terminologies in this field. Basically, the article is organized as follows. Section 1 briefly introduces the article, whereas some general concepts are presented in Section 2 and the methodology is described in Section 3. The detailed review of tools for product design is presented in Sections 4 and 5. Section 6 presents the practical applications of different tools. Analysis of tools and potential future research directions are reported in Sections 7 and 8 respectively. The implications of this study are provided in Section 9 and finally, important conclusions are made in Section 10.

2. Background and general concepts

2.1. Sustainable and eco-product design

The concept of sustainable product design could easily be understood by considering the term “design” which is a creative activity to choose between different possibilities (Manzini, 2006). Sometimes, design is assumed as just a good idea, sketch or an object. However, it is a very broad concept encompassing the efficient and effective generation and development of ideas through a process that leads to the development of a product (Morris, 2016). Conventionally, there are four stages of a typical design process (Gagnon et al., 2012). The first stage is planning and problem definition which is followed by conceptual design. At the conceptual design stage, identification of the product’s function is done, alternative concepts are generated and design specifications are determined. The third stage is the preliminary design which includes elaboration and evaluation of alternative concepts and selection of the best concept. The final stage is the detailed design at which the chosen alternative is elaborated in detail, further evaluation and optimization is done, requirements for manufacturing and maintenance are identified, and documentation and communication is done.

Boyko (2009) improved the conventional design process by incorporating ‘sustainability tasks’ along all design stages. The main sustainability tasks are: (1) determining and prioritizing sustainability issues that form a “sustainability agenda”; (2) generating sustainability advice on preliminary designs using relevant tools and underlining tradeoffs between sustainability issues; (3) evaluating the performance of the design against the sustainability agenda; (4) generating a strategy for sustainability tracking. Furthermore, Gagnon et al. (2012) described the detailed tasks at all four stages of a sustainable design process. In short, traditional product design focuses on product functionalities, quality and costs for meeting customer requirements, whereas sustainable product design (SPD) systematically views the entire product life cycle for functional, environmental, and economic performances (Lu et al., 2011).

For the sake of definition and differentiation, all three aspects of sustainability must be considered as an integral part of a sustainable design (Gennari, 2000). Sustainable product design plans and stresses the importance of the entire life cycle of a product from its raw material selection, conceptual and structural formation, manufacturing, and usage to its end-of-life, reuse, and recycle (Peng et al., 2013; Gagnon et al., 2012). The main objectives of sustainable product design are to reduce a product’s resource use and emission to the environment, as well as improve its socio-economic performance throughout its life cycle, from cradle to grave (Gagnon et al., 2012). However, eco-design has been researched to consider mainly environmental impacts for a product design (Yu et al., 2015). Within the literature, there are multiple terms, all of which somehow point towards the “integration of environmental aspects into product design and development” (ISO,