Journal of Cleaner Production xxx (2014) 1–17

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Design for sustainability (DFS): the intersection of supply chain and environment

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ARTICLE INFO

Article history:
Received 9 May 2013
Received in revised form
6 March 2014
Accepted 9 July 2014
Available online xxx

Keywords:
Design for X
Sustainability
Environment
Supply chain
Strategy
Life-cycle

ABSTRACT

This new product development research reviews the "design for" or DFX literature to consolidate the current body of knowledge and to seek the future direction of the field. It finds that DFX techniques can be placed under the heading of sustainability in the dimensions of economics (dominated by supply chain design techniques), ecology (dominated by environmental design techniques) and social equity. A DFS (design for sustainability) taxonomy is presented to order and consolidate current techniques within these categories. A new DFX concept is developed that incorporates remanufacture, reuse, and recycling as one environmentally-friendly approach for end-of-life. A strategy and life-cycle phase framework is developed to enhance the application of DFX techniques by practitioners and to enable DFX strategy research. The current literature is deficient in addressing social equity and reverse logistics, and these areas should be further developed. Several other future research directions, including the need for aligning with theory and empirical testing, as well as exploring the relationships between the DFX techniques and dimensions of sustainability, are presented.

1. Introduction

The traditional view of design involves a scientist or engineer in a lab, inserting cutting edge technologies into products for which consumers are clamoring. However, the reality of new product development requires a much more pragmatic approach through the use of methodologies that will ensure design efforts address customer and societal needs from sourcing, through production, use, and on to the product's end-of-life. The development of product design methodologies for stages in a product's life-cycle or specific product characteristics were not prominent in the literature until the early 1980s. Boothroyd and Dewhurst (1983) studied the role that assembly considerations, constraints, and costs played in the design phase of a product and developed a series of guidelines to facilitate this process and make it more efficient, coining the term design for assembly (DFA). This work unknowingly started a movement in which product design would be related to all aspects of product development, production, distribution, use, and end-of-life. The numerous "design for" techniques developed have focused on such topics as manufacturing, supply chain, environment, and more, leading to the umbrella term Design for X (DFX) where X represents a specific activity, feature, or goal which should be considered during the product design phase. However, sustainability, which is a growing area of concern for many businesses, is still lacking a suitable "design for" approach. This paper will address this need through the creation of a design for sustainability (DFS) taxonomy based on previous work, new ideas, and future research directions.

Brundtland (1987) provides a common definition for sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Hart (1997) outlined the role that sustainability will play in the global economy, recognizing that stage two of this process focused on product stewardship. Hart outlines the role that design for environment (DFE) plays with respect to product stewardship, but recognizes that this is only one component of sustainable business development. Elkington (1998) coined the term "Triple Bottom Line" which refers to the three E's: ecology (environmental protection), equity (social equity), and economy (economic growth). Though one definition of sustainability has not

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http://dx.doi.org/10.1016/j.jclepro.2014.07.021
0959-6526/

been settled upon, the most common definition is based on the reconciliation of these "three pillars" or three E's (United Nations General Assembly, 2005). A common solecism in both popular nomenclature, as well as previous "design for" research (Vogtländer et al., 2001), has been the interchange of sustainability and environment. Focusing solely on environmental concerns while using the term sustainability is both misleading and improper as this concentration on one pillar of sustainability ignores the two other pillars, and can lead to designs that are not economical to produce or contain the potential for negative social impacts.

Several attempts have been made to create a broader DFS approach based in the DFX literature. Ljungberg (2007) applied the ideas of the "Triple Bottom Line" and evaluated the sustainability of six different types of materials in order to explore the role that material selection plays in sustainable product development. In addition, Ljungberg created a circular chain of product sustainability based on material, economy, design, market, equity, technology, and ecology. Jawahir et al. (2007) developed a model with six DFX elements: disassembly, environment, recycling, societal impact, functionality, and resource utilization and economy. These have been good first steps in creating a DFS model. However, both works focus on narrow aspects of product design considerations and fail to account for many other facets of product design, production, delivery, use, and end-of-life.

In the past few years, several streams of research have developed that address the concept of "design for sustainability" that are based in literature unrelated to DFX. Howarth and Hadfield (2006) based their approach on the three E's and provided a way to analyze both raw materials usage and product design for sustainability, based on topics such as disassembly, recycling, waste generated, and energy usage. Other works approach this idea from different angles, such as economics, efficiency equations, and the intersection of production and consumption (Spangenberg et al., 2010) or through a focus on innovation and cleaner production (Clark et al., 2009), rather than through the lens of DFX research. Another burgeoning field is design for sustainable behavior (DFSB) (Wever et al., 2008; Lilley, 2009), which explores how design can be used to influence consumer behavior to improve sustainability. This approach focuses on consumers through the lens of social psychology and associated methodologies, rather than focusing purely on the design aspects that play a role in the sustainability of a product. This consumer-centered view of sustainability is part of a larger stream of research focused on user intent (Lockton et al., 2010). Though these papers and the work found in this paper discuss the role of sustainability and product design, it should be noted that these works are not identical in focus, scope, background, or purpose. For instance, the DFX work that provides the foundation for this research is heavily focused on aspects that producers control, while DFSB is focused on the actions of consumers. In addition, none of the works discussed in this paragraph are a continuation of the DFX literature, as a comparison of the citations in those works and the previous research examined in this work shows little-to-no commonality.

As the role of sustainability in business has grown, the recognition that product design plays a key part in helping to achieve sustainability is undisputable. As shown above, attempts have been made to look at sustainability and product design from different perspectives. Though these streams of research have been quite fruitful, the fact remains that the DFX literature is still lacking a comprehensive approach to evaluate the sustainability of a product design using the three E's of sustainability. The goal of this paper is to provide a comprehensive overview of the prominent DFX techniques. Based on this literature review, a DFS taxonomy is created which simplifies and relates the DFX techniques. This taxonomy is then applied to a matrix based on strategy and the life-cycle phase of the product. The result is a useful tool to help identify which DFX techniques are most applicable to a given product during the design phase for a company to achieve sustainability goals, as well as providing a way to examine the relationships and trade-offs between design decisions across the three pillars of sustainability. The paper concludes with future research directions.

2. Methodology

The DFX literature is extensive with hundreds of papers covering many topics across several disciplines. This complexity makes it difficult for researchers and practitioners to keep up with developments in DFX. In addition, some of the research covered similar ideas but with different names, and even techniques with the same name often take on different meanings, approaches, and guidelines. Therefore, before creating the DFS taxonomy an extensive literature review was required. The goal of this review was not to provide an exhaustive classification of all previous research, but instead to deliver a useful overview of techniques. To perform this literature review we adapted the methodology developed in Newbert (2007). The search was conducted through the use of Google Scholar for two reasons: 1) it includes nearly all peer-reviewed journals from numerous publishers and databases in one search engine; and 2) it features a "Cited By" feature, allowing users to see the impact the article had on the field, and which articles cited this work.

The first round of the search was conducted on articles, conference proceedings, and books published between 2002 and 2012. The search was conducted based on combinations of the following keywords: "design for", "product", "DFX", and specific types of techniques (such as "environment", "sustainability", and "disassembly"). This search was conducted with no constraint placed on journals or disciplines. This search yielded hundreds of potentially useful results, but only 40 papers were selected based on the abstracts. The following criteria were used to determine their selection:

1) Relevance – was the work appropriate and more specifically, is this part of the DFX literature body? There are many other product design literature streams, and we wanted to remain focused on those built from the tradition of DFX. Wandering too far from the DFX literature has the potential to explode the body of knowledge beyond the scope of this paper.
2) Substance/Contribution – was the published work significant, did it provide greater insight than other work in the same area? The DFX literature is extensive, and some papers only provide marginal contributions to existing body of knowledge. This literature review is not intended to be exhaustive; rather it should be representative of the work that has been done previously.
3) Applicability – could the paper provide insight that could be useful to a broad variety of products and industries? Many DFX papers were hyper-specific for certain industries in ways that would not provide benefit to other industries. We wanted to avoid these papers and focus on work that could helpful in a range of contexts. However, this did not mean that certain methods or case studies on select industries were automatically removed from consideration, as many of these works provided a unique contribution that could be applicable in other fields.
4) Citations – using Google Scholar's "Cited By" function we were able to see how many times a work had been cited, and by whom. This was beneficial is assessing the degree of impact this work had on the field.

Although the selection process for any literature review is subjective, these criteria enabled the research team to more objectively

Please cite this article in press as: Arnette, A.N., et al., Design for sustainability (DFS): the intersection of supply chain and environment, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.07.021