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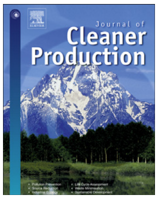

Review

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

Andrew N. Arnette [a,*], Barry L. Brewer [a], Tyler Choal [b]

[a] University of Wyoming, USA
[b] Nebraska Book Company Inc., USA

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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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* Corresponding author. Department of Management & Marketing, College of Business, University of Wyoming, Dept. 3275, 1000 E. University Ave., Laramie, WY 82071-2000, USA.

E-mail addresses: aarnette@uwyo.edu, andy.arnette@gmail.com (A.N. Arnette).

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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

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assess each DFX source, but some degree of judgment was required. For example, a paper with few citations, but a unique contribution could be selected for this review. However, the criteria facilitated the selection process by eliminating some less substantial papers right away. As the first round papers were read, each paper was examined for key references that would be essential to tracing the roots of that particular stream of DFX research. These references then formed the second round of literature that could be reviewed using the same criteria and reference selection method. This process was then repeated until useful new references were exhausted, enabling us to start with the most recent research and end at the seminal papers which provide the foundation for DFX research, as well as covering all points in-between. This structured approach ensured that the review was comprehensive, resulting in the analysis of over 250 sources, of which 122 were ultimately used for this paper. The earliest paper included was from 1983, with the final paper included being published in 2012. A distribution of the papers over this thirty year period is shown in Fig. 1.

In addition to analyzing the papers for content, we also classified the papers into one of four categories: Analytical, papers with quantitative focus and/or modeling techniques; Empirical, papers with case study or survey based results of practice; Review, papers that classified or provided an overview of previous research; and Theoretical, papers that developed the original concepts or hypotheses for the techniques. Fig. 2 shows that Theoretical work made up the largest portion of research utilized in this review, which makes sense as these efforts provide the definitions and details for these DFX techniques, which are often then utilized in the Analytical and Empirical research.

Finally, as we did not limit the potential journals, we analyzed from where the research was derived. Of the 122 sources used, 10 were books, handbooks, or reports, while another 10 were from conference proceedings. This left 102 journal articles, which were derived from 57 different journals. These journals were focused on areas of engineering, particularly manufacturing, technology, and design, and business, with an emphasis on operations research/management. There were journals from other areas, such as environmental studies and computer science, as well. Very few of the articles were derived from journals devoted solely to product design or development, showing the interdisciplinary nature of DFX research. Fig. 3 shows the top ten journal sources cited in this paper.

3. Literature review of DFX techniques

In the literature review that follows, we focus on formative, influential, unique, or well-cited papers that contributed most to the development of the particular DFX technique to provide the most informative, yet concise, overview possible. Beyond the more commonly researched design considerations discussed in the proceeding review, there have been a multitude of other DFX techniques developed. Some are focused on newer ideas that have yet to be integrated or are difficult to integrate into current designs, while others are applicable only to specific industries or products. Our discussion moving forward will center on widely accepted and broadly applicable techniques.

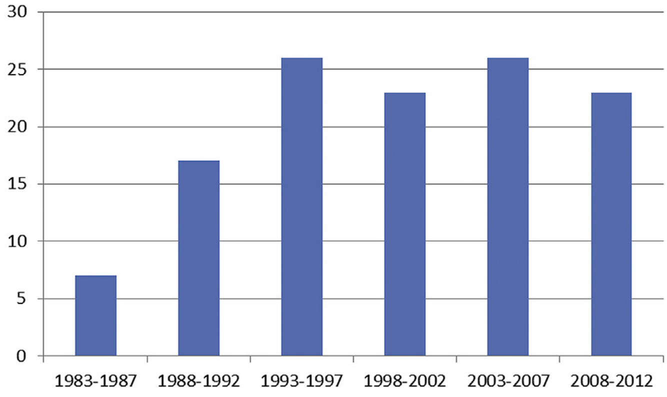

Fig. 1. Chronology of DFX citations.

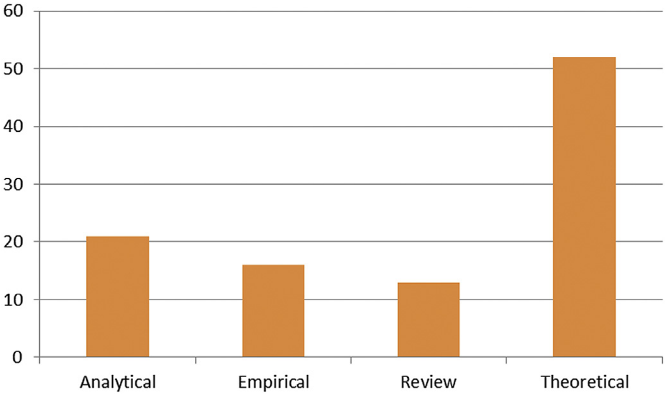

Fig. 2. Methodology classification of DFX citations.

The literature review is divided into three sections based on the dimensions of sustainability: economy, ecology, and equity. An additional section focuses on a review of integrated DFX approaches. Table 1 provides a reference for readers with descriptions of the DFX techniques included in the three sections and represents the final DFS taxonomy. Based on the literature review, Section 4 discusses the creation of the taxonomy in detail, including why techniques present in the literature review were not included in the taxonomy, the reclassification of DFX techniques in different dimensions of sustainability, how DFX techniques were simplified or combined, and what factors played a role in the process.

3.1. DFX in the economy dimension

The original "design for" approaches were created as a means of making the operations and production aspects of product creation more efficient and reducing time, cost, and errors. DFX techniques were developed to proactively manage these production issues. If designers anticipated potential problems and worked to eliminate

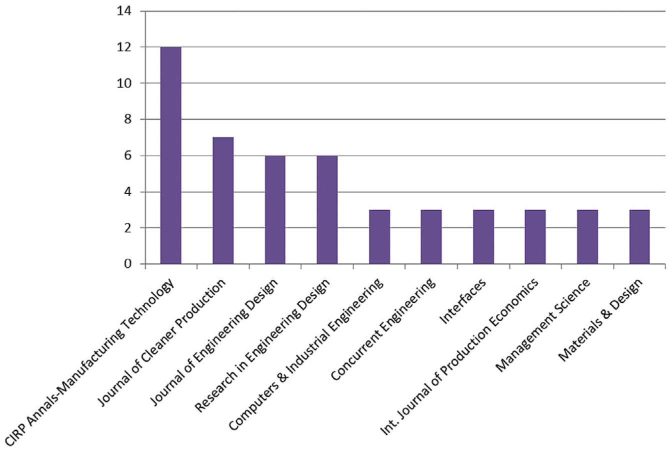

Fig. 3. Top 10 journal sources for DFX citations.

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Table 1
Taxonomy of DFS techniques.

Dimension	Abbreviation	Full name	Description
Economy	DFSC	Supply Chain	Design of products for efficiency within the supply chain
	DFL	Logistics	Focus on the distribution stage, designing products that can be shipped effectively
	DFMA	Manufacturing & Assembly	Design products that can be produced in an efficient manner
	DFM	Manufacturing	Focus on the manufacturing stage of production
	DFA	Assembly	Focus on the assembly stage of production
	DFF	Flexibility	Create products and product lines than can easily be modified to meet changing consumer needs
	DFMaCu	Mass Customization	Focus on customer segments through the use of mass customization
	DFMod	Modularity	Design of products with modular components
	DFQ	Quality	Creating products that have a high level of quality designed-in
	DFRb	Reliability	How long the product will operate before failure, at which point service is required
	DFP	Procurement	Finding the right suppliers for the right parts ensure smooth production, can coordinate with suppliers in design stage
	DFSp	Supportability	Consider the ways in which the product will be supported over the useful life, and how that support is delivered
	DFMt	Mainatainability	The ease with which a product can be maintained, and with proper maintenance, the life of the product can be extended
	DFSv	Serviceability	The ease with which a product can be serviced upon failure, whether by the consumer, company, or third-party
Economy & Ecology	DFSp & DF3R DFD	Disassembly	The disassembly and separation of parts, components, and materials
	DFSC & DFE DFRL	Reverse Logistics	Design for ability to receive returns for defective goods, as well as recovery of products at end-of-life
Ecology	DFE	Environment	Focus on environmentally friendly practices over the course of the product's life-cycle
	DFCRR	Chronic Risk Reduction	Minimize long-term ecological harm to the plant, community, and workforce
	DFEC	Energy Conservation	Minimize energy usage throughout supply chain and product's useful life
	DFMC	Material Conservation	Minimize materials used in supply chain and product's useful life
	DFWMR	Waste Minimization & Recovery	Minimize waste generated from the product, and if possible make waste recoverable (for recycling, energy creation, etc)
	DF3R	Remanufacture, Reuse & Recycling	Three potential environmentally-friendly outcomes for a product that has reached end-of-life
	DFRu	Reuse	Reuse of a product “as-is” or harvesting working parts and components for reuse, often in the form of repairs & replacements
	DFRem	Remanufacture	Remanufacturing a product to be like new and then reselling the product, often in a different market
	DFR	Recycling	Recycling of components, parts, or materials
Equity	DFSR	Social Responsibility	Design products that are produced in good conditions, don't impose harm on particular communities, support humanity

them through improved product design, they could more effectively achieve these goals. Over time, DFX techniques expanded beyond production to the entire supply chain and enabled consideration of the impact design has on the economic health of the company.

3.1.1. Design for assembly (DFA)

Often noted as being the pioneering work in DFX, Boothroyd and Dewhurst (1983) developed techniques to design a product for the most economical and efficient assembly, known as design for assembly (DFA). Guidelines for optimizing the product assembly process took into account whether the process was manual or machine-based and the ease of assembling parts. However, assembly was not viewed independently of other design considerations and features, thus constraints based on these additional factors could limit the ability to achieve truly optimal assembly.

Over time, other approaches for incorporating DFA into the design process were developed. Laperriere and ElMaraghy (1992) developed a quantitative technique for planning the optimal assembly based on graph search algorithms. Sackett and Holbrook (1988) explored the role of DFA in decreasing design deficiencies. Warnecke and Baessler (1988) developed a rating system to evaluate the difficulty of assembling the parts and assessed the functional value each part added to the product. Thus parts with little functional value and high assembly difficulty receive low ratings, and a good product redesign would attempt to replace these parts with more functional or easy-to-assemble parts. Miyakawa and Ohashi (1986) detailed the Assembly Evaluation Method (AEM) developed by Hitatchi. AEM is based on the idea of “one motion for one part” and more complicated motions result in lost points. Overall acceptability of assembly plans are determined by assembly difficulty ratings and assembly-cost ratios.

The papers in this area share several features that define the idea of DFA. First, the number of parts, movements, and tasks are analyzed for possible reductions. Designers seek assembly efficiency by ensuring that each part is absolutely necessary and by combining parts if possible. Second, the assembly process should be designed to minimize the potential for assembly errors. Assembly simplification achieves these reductions by using parts requiring fewer tools and considering the interactions between steps. These ideas are the basis of many papers that develop quantitative or qualitative methods for objectively measuring the assembly difficulty or finding the optimal assembly sequence. The goal of DFA is to help designers explicitly consider the assembly process and ultimately design products that are assembled with the minimum required number of parts in the most efficient and economical way possible in order to reduce error and cost.

3.1.2. Design for manufacture (DFM)

The next DFX to rise to prominence was design for manufacture (DFM) which examines the production of the parts and components used in the assembly process. This was a natural step in the development of “design for” criteria, as the decisions made about manufacturing have a direct impact on assembly. Stoll (1986) provided one of the earliest overviews of DFM guidelines to ensure good design practices to help facilitate the manufacturing

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process and provide cost estimates early in the design phase. A number of the early DFM studies conducted were specific to the type of manufacturing processes employed (Dewhurst, 1987, 1988; Zenger and Dewhurst, 1988; Boothroyd and Radovanovic, 1989; Dewhurst and Blum, 1989; Knight, 1991), with many applications relying on CAD/CAM technology to facilitate the integration of design and manufacturing. However, most DFM techniques are limited, as interactions and relationships between decisions made during design and those decisions' impact on overall design are not explicitly considered. In recent years, DFM guidelines were combined with techniques such as axiomatic design (Gonçalves-Coelho and Mourao, 2007) or decision analysis (Holt and Barnes, 2011) to potentially remedy this deficiency. DFM is generally perceived as engineering-focused, but Mottonen et al. (2009) showed the role that management plays in facilitating DFM practices through a case study of an international communications technology firm. They found that one of the biggest challenges is converting design requirements into data adequate for managerial decision-making and other necessary product development steps. Overall, the focus of DFM is providing guidelines that designers should consider that impact product manufacturability. DFM guidelines are generally less explicit than DFA because the analysis is influenced by part type and manufacturing process.

In addition to considering DFM and DFA separately, these ideas are often combined into a single design for manufacture and assembly (DFMA) technique. Boothroyd (1994) synthesized the two concepts into one approach because manufacturing decisions have an impact on assembly. Therefore, one method could integrate the two design techniques in an effort to reduce cost, errors, and time to market.

3.1.3. Design for disassembly (DFD)

Many different DFX ideas followed in the wake of DFA and DFM. One of the most logical was design for disassembly (DFD), which is an outgrowth of DFA but is not the exact opposite or a reversal of the assembly process. Several researchers (Alting, 1991; Subramani and Dewhurst, 1991; Boothroyd and Alting, 1992; Jovane et al., 1993; Zussman et al., 1994; Alting, 1995) recognized the role of disassembly in a product's life-cycle. The reasons cited for the importance of disassembly were often environmentally-focused, such as recycling components at the end of a products useful life, based on take-back and end-of-life legislation in countries like Germany (Huisman et al., 2003), and increased environmental awareness among businesses. However, this idea was developed separately from the broader environmental design guidelines. The objective was to design a product that could be disassembled to facilitate the salvage of recyclable material and to safely dispose of unrecyclable material. Remanufacture was another environmentally-focused driver for disassembly, though economic reasons, such as service and maintenance, were heavily dependent on disassembly (Güngör, 2006). The growth of DFD research enabled DFX techniques relating to these specific topics. Discussion of these techniques follows in their respective sections.

Early DFD work examined how to make disassembly more effective. This approach often required assessment of assembly designs, as those decisions impact efficient disassembly. In addition, qualitative guidelines and quantitative models, such as graph search and utility functions, were developed to optimize disassembly sequences. Kroll's (Kroll et al., 1996; Kroll and Hanft, 1998) quantitative approach evaluated the efficiency of disassembly based on number of parts, types of tasks, tools required, and difficulty of tasks to estimate disassembly time and develop ratings of DFD effectiveness. Desai and Mital (2003) created a disassembly evaluation method that examines whether the disassembly process is destructive or not, whether it is total or selective, and the activities that follow disassembly (repair, refurbish, remanufacture, cannibalization, or recycling) to find effective disassembly designs. Cappelli et al. (2007) discussed the role of a virtual disassembly environment and used a pair of algorithms that evaluate disassembly methods to find the optimal sequence that minimizes the number of operations, thereby minimizing disassembly time and cost.

3.1.4. Design for serviceability (DFSv)

The concept of designing products so that they could be easily serviced upon failure is another important aspect of product design. The resulting literature, design for serviceability (DFSv), focuses on methods for improving serviceability during the product design stage for the benefit of the consumer and the company (Eubanks and Ishii, 1993; Ishii et al., 1993). Improvements in serviceability can decrease time and cost of service but the impact of other DFX on the serviceability of a product must also be considered. Previous work explored the need for effective DFA (Dewhurst and Abbatiello, 1996) and DFD (Sodhi et al., 2004) for DFSv to be realized.

Two issues that impact product serviceability are maintainability (the ease of maintaining a product at a reasonable cost during its useful life) and reliability (the probability of the product functioning as intended without failure for a given period of time). These topics were the subject of several works (Moss, 1985; Ireson et al., 1988; Dhillon, 1999) but have not held a prominent role in the DFX literature with few exceptions (Kuo et al., 2001). The basic objective of design for maintenance (DFMt) is to ensure the design facilitates product maintenance, which includes disassembly and serviceability. Design for reliability (DFRb) ensures that the product functions properly over time. Both DFMt and DFRb rely on design efforts ensuring correct product manufacturing and assembly and the quality of the design.

From a broader perspective, the role of after sales service and support has been recognized as a necessary component of successful business practices for many years (Armistead and Clark, 1991) and has been recognized as a competitive capability (Miller and Roth, 1994). However, support is often considered a business process that is developed and managed during post-production and is a matter of infrastructure, not product design. However, the recognition of several key factors regarding product support has changed this perspective (Goffin, 1990; Goffin, 2000; Goffin and New, 2001). First, design decisions have a direct impact on maintainability and reliability, thereby affecting the frequency of service and product support (Lele, 1986). Second, product design affects the amount of service required and the mode of delivery (Garvin, 1988). Thus, design for supportability (DFSp) covers all issues relating to service, maintenance, repair, and support (Goffin, 2000). Recognition of these aspects during the design process can be beneficial because support plays a major role in the post-production stages of a product's life-cycle and generates additional revenues. In the design phase, product features are often prioritized over other considerations and can result in designs that make support more difficult or expensive. In order to avoid this problem, DFSp recognizes the need to explicitly design the product with these factors in mind and to include support engineers or managers to facilitate more supportable designs (Goffin, 2000).

3.1.5. Design for quality (DFQ)

For decades, quality has been an important topic for businesses that produce physical goods with W. Edwards Deming raising the visibility of this issue (Deming, 1982, 2000). However, the majority of this work focused on the production process and it was not until the development of quality function deployment (QFD) (Akao, 2004) in the 1960s that quality and product design began to

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intersect. QFD forced designers to consider how elements of product design relate to each other and how changes to one characteristic can impact other characteristics and thus overall product quality. Further exploration of product design's impact on quality was found in the work of Taguchi (1986) which emphasized the importance of parameter and tolerance design in yielding robust, high-quality products and is expressed visually through the quality loss function. Benchmarking, which has applications in a variety of contexts, can be used to ensure the quality of the product design by comparing it to the design of another product (Watson, 1993). These ideas have also extended to specific quality management approaches like design for six sigma (Koch et al., 2004). Quality has also been applied to DFM literature, focusing on reduction of defects in the production process (Das et al., 2000) or integrating design and manufacturing during the product development process to improve quality (Swink and Calantone, 2004). Although there has been recognition of the role quality plays in product success and the fact that quality needs to be designed into the product (Suh, 1995), the exploration of quality as an explicit DFX technique has been limited and quality mostly exists as a separate concept outside the narrower scope of product design.

3.1.6. *Design for mass customization (DFMaCu)*

As markets have become more fragmented and customers have increasingly valued more options or variations beyond basic product offerings, the ability of producers to meet this need through postponement of differentiation has enabled the concept of mass customization. A DFX approach was developed to address this additional product design consideration. Tseng et al. (1996) looked at design for mass customization (DFMaCu) as a vehicle for creating a product family architecture, supporting reuse and commonality among components and processes to facilitate transition between product variations.

Other research examined this same concept from slightly different viewpoints: modularity (Salhieh and Kamrani, 1999; Kim and Chhajed, 2000), configuration (Ostrosi and Bi, 2010), or localization (Lee et al., 1993). Two related ideas are design for flexibility (Palani Rajan et al., 2003) and design for variety (Martin and Ishii, 2002), both of which extend beyond mass customization to allow for the incorporation of future changes to product design with less disruption. Design for flexibility (DFF) is important to product development in today's competitive environment with the proliferation of specialized products for new customer markets and products with a short lifespan, requiring the ability to respond rapidly and with minimal disruptions or costs.

3.1.7. *Design for cost (DFC)*

Sheldon et al. (1991) discussed the role that cost plays in product development and how considerations of cost can help ensure affordability based on desired quality levels. Additional work on design for cost (DFC) dealt with the cost over the product life-cycle, showing that modifications in design can increase the manufacturing cost but reduce cost in other product life stages and lead to lower costs over the product's entire life (Xiao-Chuan et al., 2001). Research has also examined the opposite perspective, trying to ensure that the maximum amount of profit can be designed into a product (Mughal and Osborne, 1995).

3.1.8. *Design for supply chain (DFSC)*

As the importance of activities beyond internal operations increased, DFX techniques expanded to evaluate the impact of product design on other supply chain tasks. Although these new approaches can be largely placed under the umbrella of design for supply chain (DFSC), it is not prominent in the literature as a DFX topic. This is because DFSC is often viewed in broad terms such as being “concerned with designing the product while taking into account the impact on the performance and success of the supply chain” (Sharifi et al., 2006). Though this definition seems to account for the entire supply chain, the focus is mostly on the supply side. Discussions are centered on the suppliers' roles in product design and development, with case studies used to provide evidence that many problems could be avoided if suppliers were considered during, or integral to, the design process. Similar research has looked at the impact of design on lead time and ability to satisfy demand (Gokhan et al., 2010). Other research has shown analogous results (Handfield et al., 1997; Petersen et al., 2003), even if it was not framed as a DFX idea. This aspect of DFSC can therefore be described more accurately as design for procurement (DFP), with the upstream aspects of the supply chain being considered in the design process. Based on interviews and case studies, recent research (Pulkkinen et al., 2012) has developed a framework for DFP that looks beyond the design process, incorporating business processes, software support, and product management.

Although the design of a product can be improved through supplier involvement, the distribution of finished goods is important to product success as well. Though generally considered an area of product development that is a given as businesses rely on standard channels of distribution and transportation methods for many products, the concept of design for logistics (DFL) shows that product design impacts the packaging and transportation of a product and that incorporating these considerations into product design can make distribution more efficient and reduce costs (Dowlatshahi, 1996).

In general, DFSC, DFP, and DFL remain areas of the DFX literature which are underserved, with less attention devoted to these activities, even though product design is very influential on the success or failure of the supply chain. These business processes seem to be viewed as separate from the design process instead of recognizing that product design affects supply chain activities.

In addition to the traditional downstream flow of products in a supply chain, the role of reverse logistics (Dowlatshahi, 2000; Rogers and Tibben-Lembke, 2001; Tibben-Lembke, 2002) or closed-loop supply chains (Guide et al., 2003; Savaskan et al., 2004) is increasingly recognized as important for handling product service and support, returns, and product recovery at the end-of-life stage to support remanufacturing, recycling, and disposal. Reverse logistics not only facilitates achievement of environmental or sustainability goals, but also makes economic sense (Dowlatshahi, 2000). These strategic factors are more critical to the success of reverse logistics than the operational factors involved in recovering the product. While the earliest decisions to use closed-loop supply chains were driven by environmental concerns, often dictated by legislation, the strategic role of these concepts has become increasingly important (GuideDaniel et al., 2003). Rogers and Tibben-Lembke (2001) examined the overlap and differences between reverse logistics and green logistics, as well as breaking down the activities involved in reverse logistics and exploring where and why products are flowing through a reverse logistics system. The authors also found in a survey that barriers to reverse logistics include lacking importance and attention from management, and lacking policies, systems, and resources to properly implement reverse logistics. With respect to remanufacturing, Savaskan et al. (2004) examined different closed-loop supply chain structures and sought to determine the most effective and efficient way to facilitate product recovery. Although reverse logistics or closed-loop supply chains are generally not integrated into the product design process and have not been recognized as a DFX technique, their importance in enabling other DFX concerns cannot be overstated and should be a design process consideration.

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3.2. DFX in the ecology dimension

Beginning in the late 1980's, companies paid closer attention to their environmental impacts. Some concerns were driven by legislation, others by changing consumer attitudes, and others by negative attention given to companies with poor environmental records. Managers, engineers, and researchers recognized that many environmental impacts could be lessened through improved product design, leading to new DFX ideas to help minimize a product's environmental footprint.

3.2.1. Design for recyclability (DFR)

One of the first motivators for analyzing disassembly was the requirement or desire to increase a product's recycled parts. However, this early work often considered the recyclability of components a given, thus the focus was optimizing the removal of these components or materials for recycling. Soon to follow was design for recyclability (DFR) which takes a more proactive approach to increasing the recyclability of a product. Instead of simply recycling components after disassembly, DFR looks at the materials selected during the design phase and evaluates whether they can be recycled or not and, if not, seeks a recyclable material which can be used instead. By increasing the number of recyclable materials in a product design, the recycling yield after disassembly increases.

Kriwet et al. (1995) provided DFR criteria that not only addressed individual components, but considered assembly and disassembly operations of the product as a whole, as well as the roles of suppliers and customers. Huisman et al. (2003) took a holistic approach by developing a quantitative measure for recyclability that was weighted based on the environmental value of the recycled materials and the overall environmental burden of the recovery process, extending the view of recycling beyond the percentage of product that can be recycled. Gaustad et al. (2010) used a chance-constrained optimization model to develop recyclable alloys based not only on their initial product use, but also their uses and potential markets as recycled materials.

3.2.2. Design for remanufacture (DFRem)

Another DFX related to disassembly and environmental concerns, design for remanufacture (DFRem) is a prominent topic in the literature with its own set of guidelines and issues. Remanufacturing is the ability to take a product that has reached the end of useful life and recover it by “disassembling, cleaning, refurbishing, replacing parts (as necessary) and reassembling a product in such a manner that the part is at least as good as, or better than, new.” (Bras and Hammond, 1996) Although interest in remanufacture is often prompted by environmental initiatives or “take-back” legislation, there can be financial benefits from remanufacture as well (Giutini and Gaudette, 2003). DFD plays a large role in the ability to remanufacture a product as disassembly is the first stage of this process and DFRem is compromised if the product is unable to be disassembled effectively.

Ijomah et al. (2007) looked at DFRem as a means of supporting sustainable manufacturing goals within a firm and stated that remanufacturing is preferable to recycling from an environmental perspective as it returns a product to working condition rather than reducing it to raw materials. However, remanufacturing is only appropriate where there is a market for such products and remanufacturing may be restricted due to patents, obsolescence, and shifts within industry. In a review of DFRem literature, Hatcher et al. (2011) recognized several key problems with DFRem in practice. First, there is a lack of knowledge and understanding among designers. Second, even if the idea is understood, there are few products being remanufactured and even fewer designed for remanufacture. Finally, the tools for analyzing DFRem are severely lacking. In a follow-up paper (Hatcher et al., 2013), the authors studied three original equipment manufacturers from the UK mechanical industry sector to determine what external and internal factors affect the integration of DFRem into the design process. It was discovered that many factors are similar to those that influence design for environment decisions, but DFRem was not primarily identified as an environmental issue.

3.2.3. Design for life-cycle (DFLC)

An underlying area of interest that drove DFD and DFR considerations was the concept of life-cycle analysis (LCA) or, in DFX terms, design for life-cycle (DFLC). DFLC forces designers to not only consider the impact of design on manufacturing and assembly, but on the other stages of a product's life as well, including use and what happens to the product at the end of useful life. The stages in the product life-cycle are often debated but Alting (1991) specified seven stages: need, design, production, distribution, usage, disposal, and recycling, and assigned costs to the company, user, or society at each stage. Most life-cycle research has focused on the post-usage stage wherein the product is disposed of or recycled, leading to the concepts of design for product retirement (Ishii et al., 1994) or design for end-of-life (DFEOL) (Rose et al., 2002).

3.2.4. Design for environment (DFE)

Design for environment (DFE) was introduced by Allenby and Fullerton (1991) and was expanded upon by Fiksel and Wapman (1994) wherein DFE is defined as the “systematic consideration during new product and process development of design issues associated with environmental safety and health over the full product life-cycle.” The motivation for engaging in DFE varies, whether to increase market share, reduce cost, or meet regulations or standards. DFE covers a breadth of topics and is therefore a larger category of considerations than most DFX techniques. Examples of areas covered by DFE include waste reduction, material selection, and energy use, as well as a number of “design for” techniques: DFD, DFR, DFRem, design for disposability, and design for reusability (DFRu). Fiksel (1996) further developed this work into a prominent tome on the subject, breaking DFE into distinct categories, most of which contain sub-categories of DFX criteria and guidelines, including new categories for chronic risk reduction, accident prevention, waste recovery and reuse, and contaminant avoidance. Application of DFE principles to manufacturing (Gungor and Gupta, 1999; Rounds and Cooper, 2002) and supply chain activities (Handfield et al., 1997; Bowen et al., 2001; Soylu and Dumville, 2011) has resulted in greatly reduced environmental impacts.

LCA also played a considerable role in prompting the analysis of a product's environmental impacts during its entire life-cycle, starting with raw material acquisition, through processing, manufacturing, and assembly, on to product use and service, and ending with product retirement and subsequent recycling, reuse, remanufacture, or disposal. Keoleian (1993) applied LCA to product design, emphasizing how DFE ideas could minimize environmental impact over the life-cycle. Later, Keoleian and Menerey (1994) stated that LCA and DFE “are difficult to distinguish from each other; they are usually considered different names for the same approach.” They defined environmental design requirements as the minimization of five categories: use of natural resources (particularly non-renewables), energy consumption, waste generation, ecological health threats, and human health and safety risks. The difficulty in implementing DFE is comparing environmental measures to cost, performance, and other traditional metrics. In addition to these environmental requirements, distribution, extending product life (durability, adaptability, reliability, serviceability,

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remanufacturing, and reuse), material selection, and recycling (of the product, scrap, packaging, and other sources of waste) affect environmental impact. By taking this holistic view of a product's life and the environmental impact over that life, DFE became a broad category under which many different ideas and techniques could reside, depending on the design process scope. Veroutis and Fava (1996) developed a matrix for use in DFE assessment based on the life-cycle phase and five environmental criteria. Ishii et al. (1994) argued that materials selected for the product heavily affected the end-of-life impact and should be a focal point of the design process. Gehin et al. (2008) developed a tool for incorporating sustainable end-of-life strategies in the development phase using DFE principles. Telenko et al. (2008) reviewed DFE and LCA research and concluded that effective DFE uses principles and guidelines to lower products' environmental footprint and takes into account the product life-cycle and the impacts occurring during that life-cycle, while LCA can only be performed as the design is near completion, and is often used retroactively, thus resulting in few design changes. Therefore, DFE guidelines are better drivers to minimize environmental impact.

Sarkis (1998) developed a quantitative method using the analytic network process to determine environmentally conscious business practices with DFE, and other DFX techniques, playing a role in these calculations. Santos-Reyes and Lawlor-Wright (2001) used the analytic hierarchy process and QFD to develop a structured DFE approach, leading to the creation of an environmental house of quality (EHOQ). The EHOQ uses environmentally-conscious product attributes and measurable parameters to evaluate the performance of these attributes. Similar to other QFD houses, the EHOQ can be used to define, evaluate, and examine trade-offs in order to quantify and improve a product's environmental performance. Francis (2009) also modified QFD to incorporate environmental metrics into the traditional customer and technical aspects considered with this method. The new QFD focused on reducing energy, water, and material use; increasing product recovery, reuse, and recycling; and minimizing general waste and environmental and health hazards.

To simplify and clarify DFE, Luttropp and Lagerstedt (2006) developed the “Ten Golden Rules.” These guidelines provide basic ideals to minimize environmental impact during pre-use, use, and after use product life phases. Hauschild et al. (2004) questioned the role that DFE plays in product development, arguing that current approaches limit the ability to achieve the most environmentally friendly products possible. Instead, they suggest starting with strategic considerations, then examining the product life-cycle and then, based on the results, applying DFE to product design. The ideas of DFE have been incorporated into new concepts like green design (Glantschnig, 1994), green product development (Chen, 2001), eco-products (Kobayashi, 2005), and eco-design. Eco-design in particular is a vast field of research that had roots in the DFX research, particularly DFE, at one time, but most contemporary eco-design research no longer looks at eco-design as part of a larger DFX tradition. Bovea and Pérez-Belis (2012) provide a good overview of current eco-design methodologies. As this paper is focused on DFX-based research, for the purposes of our analysis, these ideas are considered to be the same as DFE and our discussion is focused on environmental matters from a DFX-perspective.

3.3. DFX in the equity dimension

In recent years, DFX for the social equity component have begun to appear. Oosterlaken (2009) introduced design for development in which products are designed to provide opportunities for society, especially for the world's poorer residents. The concept of design for all (Marshall et al., 2010) is based on the idea that products should be designed to not discriminate amongst consumers based on age, size, abilities, or needs. Tromp et al. (2011) introduced the idea of design for socially-responsible behavior which includes ideals such as rejecting child labor and sweatshops and using design to tackle social problems. This paper aligns closely with the previously discussed work on influencing user-behavior, but this is one of the few design-related papers to discuss social responsibility in any detail and how design can be used to deal with these matters. However, these DFX are few in number and in need of more exploration to achieve proper sustainability.

3.4. Integrated DFX approaches

The need to account for, coordinate, and evaluate trade-offs when using multiple DFX techniques in product design has been the subject of previous studies. Several papers provided good literature reviews of various techniques (Kuo et al., 2001) but failed to address relationships between DFX's or work towards an integrated approach for managing DFX considerations in the design process. One of the earliest attempts at DFX integration (Tichem and Storm, 1997) discusses the role that a computer-based support tool for coordinating DFX could play alongside other design programs, like CAD, but only recognizes DFA, DFM, and DFD.

Other researchers have looked at the numerous DFX techniques available to determine which are the most pertinent to use and how to decide when to use these techniques. Chiu and Okudan (2010) developed a framework that consisted of fourteen DFX divided into two high-level categories, design for efficiency and green design, each with two subcategories. Design for efficiency was separated into product scope, consisting of seven DFX (such as DFM and DFA) and the system scope, consisting of three DFX (including DFSC and DFL). Green design was divided into eco-system scope, with three DFX (DFE, DFLC, and DFS), and the product scope which consists only of DFR. Based on these classifications, a matrix was developed with these fourteen DFX related to four phases of product design (needs assessment, conceptualization, preliminary design, and detail design) to specify the point in the design process that each DFX should be considered. However, the framework and matrix failed to consider relationships among DFX techniques, isolating them to the determined scope and only recognizing the stages in product design, not product life-cycle.

Holt and Barnes (2010) recognized the need for an integrated DFX approach to analyze tradeoffs in design decisions. The authors utilized ten DFX techniques and split them evenly between two categories: virtue and lifephase. Virtue techniques are used to assess how well a design meets requirements and includes DFE, DFQ, DFMt, DFRb, and DFC. Lifephase techniques ensure that the entire life-cycle is considered during the design phase and includes DFMA, DFEOL, DFD, DFR, and DFSC. However, some lifephase DFX cover multiple phases of the life-cycle and some DFX overlap (for example, DFR typically occurs when DFEOL is encountered). The authors discuss the necessity for an integrated approach based on decision analysis techniques (such as multi-criteria decision methods) that could better assess tradeoffs and evaluate the effectiveness of design as a future research goal.

Hepperle et al. (2011) developed a quantitative method for determining the most important relationships between DFX techniques (product characteristics and life-cycle phases) using a multiple-domain matrix approach. The results are based on defining these relationships in general terms and then computing measures of degree centrality, distance centrality, and betweenness centrality, rather than being based on one specific example. Some interesting results are found such as the importance of DFA and DFD with respect to other DFX, but the choice of DFX techniques in the analysis is too narrowly focused. The authors included many

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techniques discussed previously but left DFE in very broad terms and did not include many prominent techniques like DFSC, DFL, DFP, and DFQ, amongst others. The work is heavily-focused on manufacturing-related topics, and 25 of the 27 techniques are derived from the same four sources, and many of the techniques derived from these sources did not appear in any of the other literature reviewed for this paper. In addition, the authors analyzed DFX with respect to sixteen different life-cycle phases but these are not enumerated in the work, with the exception of five which are discussed in the results (manufacturing, assembly, packaging and warehousing, transportation, and maintenance).

A quantitative approach was developed using DFA, DFD, DFMt/DFRb, DFR, and DFE to determine overall design performance (Sy and Mascle, 2011). An equation was developed for each of the five DFX techniques which can be combined and weighted based on preference to define a life-cycle feature rating. The authors also created matrices wherein 37 design strategies and twelve life-cycle attributes were related to the five DFX techniques to better assess impacts from design decisions.

4. Design for sustainability (DFS)

Looking through the original literature, there were over 75 different DFX techniques found which can be overwhelming and difficult to navigate. As discussed in the previous section, there have been some attempts at developing integrated DFX approaches previously but they contained flaws with respect to types of techniques selected or the lack of relationships between techniques, as well as the application of the classifications. Therefore, a need remains to combine and condense the disparate DFX approaches into a single taxonomy, centered on the idea of DFS, which can help designers and managers through the design process and provide a contribution for future research.

4.1. Taxonomy creation

The creation of this taxonomy was based on several criteria: 1) which DFX techniques are most prominent in the literature and broadly applicable to product design, eliminating those with little impact or that were too specific; 2) where do DFX techniques overlap to enable consolidation into fewer, more standardized DFX; 3) where are the relationships between DFX techniques, recognizing interrelationships and that decisions made with respect to one DFX can impact another DFX; and 4) where are the potential holes in the literature, creating new DFX techniques to cover areas where more development or research is needed. The resulting DFS taxonomy is presented in Table 2 along with examples of prominent design considerations, performance outcomes, and the tools available for each technique. The tools are classified as follows: quantitative (those that develop equations, often to optimize or to calculate values that can be improved through design changes), analytic (those that use other methods of systematic examination), or guidelines (including rules of thumb or principles to which the design should adhere). If there were no tools of this ilk available for a DFX technique, but the ideas and benefits of these techniques have been explored through development of theory, case study, or other means, then this has been labeled as a conceptual framework. Table 2 provides a general understanding of how the technique is applied and the desired impact. The boundaries in this taxonomy are not always clearly defined, because of the relationships between techniques. A change based on one DFX technique can impact the design considerations related to other DFX techniques employed in the design process, even across different dimensions of sustainability. However, with the exception of two key DFX techniques, we have classified the techniques to which dimension they are most significantly related while acknowledging the influences that exist among these techniques across dimensions.

Many of the traditional business and engineering-based DFX techniques are related to the economy dimension of sustainability, which we have focused around DFSC (supply chain). The category of DFMA (manufacturing & assembly), with the subcategories of DFM (manufacturing) and DFA (assembly), was created to cover the production phase. Other subcategories of DFMA include flexibility (DFF), which includes two subcategories, DFMaCu (mass customization) and DFMod (modularity), and DFQ (quality), with the subcategory of DFRb (reliability). DFF was selected as the higher-level category because flexibility incorporates ideas encompassing both subcategories but extends beyond those factors to anticipate future needs, while mass customization and modularity are two ways to enhance the flexibility of the production process. Though DFRb was found in the literature to be a component of serviceability, in reality DFRb is often dictated by product quality and is listed as a subcategory of DFQ.

However, production is just one stage in the supply chain. Therefore, DFSC includes four additional subcategories: DFP (procurement), DFL (logistics), DFRL (reverse logistics), and DFSp (supportability). DFP and DFL are featured in previous literature, while DFRL is a new contribution. The development of this category and subcategory was based in part on the Supply Chain Operations Reference (SCOR) model developed by the Supply Chain Council (1999). SCOR consists of five main phases: plan, source, make, deliver, return. The planning stage covers the entire model, while source, make, and deliver flow sequentially towards the customer and return represents the backwards flow to the producer. With respect to DFX, the planning stage is the design phase itself wherein decisions have an impact on the other phases. DFP enhances sourcing, DFMA improves making, and DFL makes delivery more efficient. However, return has not been considered as an explicit DFX technique, though the concept of reverse logistics or closed-loop supply chains are not new. Therefore, the creation of DFRL would fill this DFSC gap, enabling complete consideration of SCOR model activities. Reverse logistics is becoming increasingly important for implementing returns and moving products that will be remanufactured or recycled at the end-of-life. From a design perspective, DFRL generates questions about how product design relates to reverse logistics, looking beyond the choice of channels and methods for accepting returns and recovery. If a defective product is returned, can that product be remanufactured or recycled? When a product reaches the end-of-life, how does product design influence the reverse logistics process? Is the product kept whole or are only certain components returned? How does packaging influence the return process? For example, Preserve brand toothbrushes are packaged in a sleeve designed for returning the old toothbrush by mail. This reverse logistics design is essential because toothbrushes are made from Number 5 plastic which cannot be easily recycled in many areas. These types of considerations should be part of the design process for products with closed-loop supply chains. As DFRL is important for both supply chain and environmental reasons, it was classified as belonging to two dimensions of sustainability.

DFSp was placed under DFSC as the DFSp occurs during the product's useful life and represents a point after delivery in the product life-cycle. Although not part of the SCOR model, DFSp completes the range of supply chain activities in the product life-cycle. DFSp, was selected as the higher-level category under which DFMt (maintainability) and DFSv (serviceability) are grouped based on previous research (Goffin, 2000).

The second component of sustainability relates to ecological factors, with DFE (environment) as the highest-level category here with several subcategories: DFCRR (chronic risk reduction), DFEC

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Table 2
DFS primary design considerations and potential performance outcomes.

Dimension	Abbreviation	Design considerations	Proposed performance outcomes	Tools available
Economy	DFSC	Very broad category for which no explicit considerations have been developed; the use of the subcategory considerations can be used to improve supply chain performance		Conceptual Framework (Sharifi et al., 2006)
	DFL	Design to decrease packaging, while protecting the product; to withstand transportation environmental factors; to reduce product size for storage and transportation; to ensure compatibility with material handling equipment (Dowlatshahi, 1996)	Decreased packaging and shipping costs; decreased in transit and storage damage; decreased logistics lead-times (Dowlatshahi, 1996)	Guidelines (Dowlatshahi, 1996)
	DFMA	Though often combined in discussions, these are two very separate techniques for the construction of a product; the considerations should be based on the process used		Guidelines (Boothroyd, 1994)
	DFM	Design to eliminate expensive manufacturing processes and materials; design to ensure process feasibility (Stoll, 1986; Holt and Barnes, 2011)	Increased production efficiency, quality, flexibility, reliability, and innovation; lower production costs (Lehto et al., 2011; Boothroyd, 1994; Stoll, 1986)	Quantitative (Dewhurst and Blum, 1989), Guidelines (Gonçalves-Coelho and Mourao, 2007), Analytic (Holt and Barnes, 2011)
	DFA	Design to reduce the number of parts, tasks, and motions; design to consolidate functionality of parts; design to reduce difficulty of processes (Boothroyd and Dewhurst, 1983; Warnecke and Baessler, 1988)	Increased production efficiency; decreased production costs; decreased time to market (Boothroyd and Dewhurst, 1983; Warnecke and Baessler, 1988)	Guidelines (Boothroyd and Dewhurst, 1983), Quantitative (Laperriere and ElMaraghy, 1992; Warnecke and Baessler, 1988)
	DFF	Design considering the probability of changes in customer need/want; to enable product reconfiguration (Palani Rajan et al., 2003)	Increased ability to respond to changes; increased ability to add variety efficiently; increased customer satisfaction (Palani Rajan et al., 2003)	Guidelines (Palani Rajan et al., 2003)
	DFMaCu	Design to enable commonality and reusability between product parts and processes; to enable design variations for customer selection centered on a product platform; to enable short response lead-times (Tseng et al., 1996; Tseng and Jiao, 1998; Salhieh and Kamrani, 1999; Kim and Chhajed, 2000)	Increased customer satisfaction; increased profit margins; Increased product variety and flexibility; decreased response time (Tseng et al., 1996; Tseng and Jiao, 1998; Salhieh and Kamrani, 1999; Kim and Chhajed, 2000)	Guidelines (Tseng et al., 1996)
	DFMod	Design components around functional elements; design modules to have loosely coupled interfaces enabling module variation in products; design to enable component replacement within modules; design modules to allow combination of a variety of modules (Gershenson et al., 2010; Jose and Tollenaere, 2005; Salhieh and Kamrani, 1999)	Increased product flexibility and variety; improved maintainability; decreased assembly time and cost; decreased design time; extended product life; decreased inventory costs (Gershenson et al., 2010; Jose and Tollenaere, 2005; Salhieh and Kamrani, 1999)	Guidelines (Salhieh and Kamrani, 1999)
	DFQ	Design to ensure elements of product design relate; to eliminate defects in production processes; to meet customer requirements; to ensure a robust product for manufacturing and use (Akao, 2004; Das et al., 2000; Kuo et al., 2001)	Decreased defects in production; increased product life; decreased costs, increased customer satisfaction (Akao, 2004; Das et al., 2000; Kuo et al., 2001)	Guidelines (Demings 1982), Analytic (Akao, 2004)
	DFRb	Design to use proven components; to identify and eliminate critical failure modes, for simplicity and redundancy (Ireson et al., 1988)	Increased mean time between failure, increased revenue because of product differentiation (Ireson et al., 1988)	Guidelines (Ireson et al., 1988)
	DFP	Design to enable parts communality with other products, to leverage existing supplier relationships; to enable an agile supplier network; to enable integration of suppliers with strategic core competence (Handfield et al., 1999; Fixson, 2005; Pulkkinen et al., 2012; Sharifi et al., 2006; Soylu and Dumville, 2011)	Decreased sourcing and production costs; increased input and product quality; standardization of materials; improved time-based performance (Handfield et al., 1999; Fixson, 2005; Pulkkinen et al., 2012; Sharifi et al., 2006; Soylu and Dumville, 2011)	Conceptual Framework (Pulkkinen et al., 2012)
	DFSp	Design to improve installation, user training, maintenance, customer support, and product upgrades, to increase standardization of components (Goffin, 2000; Goffin and New, 2001; Soylu and Dumville, 2011)	Decreased product support costs; increased in support efficiency; competitive advantage through support that differentiates product, increased revenue (Goffin, 2000; Goffin and New, 2001)	Conceptual Framework (Goffin, 2000; Goffin and King, 2001)
	DFMt	Design to increase standardization of parts; to increase accessibility of high failure components; to simplify repair process; to reduce repair times; to improve fault isolation (Moss, 1985; Goffin and New, 2001; Kuo et al., 2001)	Decreased mean time to repair, decreased downtime; decreased costs (Moss, 1985; Goffin and New, 2001)	Guidelines (Moss, 1985)
	DFSv	Design for compatibility with service infrastructures; for accessibility; for increased standardization; for streamlined service process; for	Increased profit; decreased mean time to service; decreased total cost of product ownership; increased	Quantitative (Ishii et al., 1993)

		component storage and transportation (Eubanks and Ishii, 1993; Cavalieri et al., 2007)	customer satisfaction and loyalty (Eubanks and Ishii, 1993; Cavalieri et al., 2007)	
Economy & Ecology	DFSp & DF3R DFD	Design to ensure easy access to fasteners and joints, to minimize parts, tasks, and tools required for disassembly; to lower destructiveness and selectiveness of disassembly process (Telenko et al., 2008; Kroll et al., 1996; Kroll and Hanft, 1998; Cappelli et al., 2007)	Lower disassembly costs and times, reduce component destruction, increase disassembly yields (Telenko et al., 2008; Kroll et al., 1996; Kroll and Hanft, 1998; Cappelli et al., 2007)	Analytic (Subramani and Dewhurst, 1991), Quantitative (Zussman et al., 1994; Huisman et al., 2003)
	DFSC & DFE DFRL	Design to enable customer support preventing returns; to package and ship the product or components; to enable profitable or low cost outcomes for returned or end-of-life products (Rogers and Tibben-Lembke, 2001; Dowlatshahi, 2000; Tibben-Lembke, 2002)	Increased product recovery rates; decreased costs; increased revenue; reduced returns (Rogers and Tibben-Lembke, 2001; Dowlatshahi, 2000)	Conceptual Framework (Dowlatshahi, 2000; Rogers and Tibben-Lembke, 2001; Tibben-Lembke, 2002)
Ecology	DFE	Systematic consideration of environmental safety and health (Fiksel and Wapman, 1994)	Reduced environmental impact (Fiksel and Wapman, 1994; Houe and Bernard, 2007)	Guidelines (Fiksel, 1996; Luttropp and Lagerstedt, 2006), Analytic (Gehin et al., 2008; Santos-Reyes and Lawlor-Wright, 2001), Quantitative (Sarkis, 1998)
	DFCRR	Design to reduce hazardous materials used in production and products and hazardous waste generated during production. Design to reduce hazardous emissions or waste during use (Fiksel, 1996; Francis, 1997).	Reduced hazardous material exposure to humans, flora, and fauna; reduced hazardous emissions and other hazardous material pollution (Fiksel, 1996; Francis, 1997)	
	DFEC	Design to reduce energy consumption during production and use by using more efficient components (light weight for vehicles) and processes, to ensure rapid warm up and power down (Fiksel, 1996; Francis, 1997, Mayyas et al., 2012; Telenko et al., 2008).	Reduced cost, reduced energy usage; increased profits through differentiated energy efficient products (Fiksel, 1996; Francis, 1997, Mayyas et al., 2012)	
	DFMC	Design to reduce product dimensions; to utilize components made of renewable, abundant, and recyclable resources (Fiksel, 1996; Francis 1997; Ljungberg, 2007; Mayyas et al., 2012; Telenko et al., 2008)	Reduced cost; reduced packaging requirements; reduced raw materials consumption; increased throughput (Fiksel, 1996; Francis 1997; Ljungberg, 2007; Mayyas et al., 2012)	
	DFWMR	Design to reduce waste; to increase use of biodegradable materials (Fiksel, 1996; Francis, 1997; Hart, 1997)	Reduced cost; reduced raw materials consumption, reduced waste from production and nonrecyclable components (Fiksel, 1996; Francis, 1997; Hart, 1997)	
	DF3R	Newly created category in this research; can be just one, or some combination, of the three techniques below based on the product		
	DFRu	Design to standardize components across the age of product models; to enhance durability of reuse targeted components; improved recovery of products and parts (Keoleian and Menerey, 1994)	Increased salvage of components; reduced cost; reduced energy and raw materials consumption (Keoleian and Menerey, 1994)	Guidelines (Keoleian and Menerey, 1994)
	DFRem	Design to enable disassembly, assembly, cleaning, testing, repair and replacement; to select durable components, to enter markets accepting remanufactured goods (Bras and Hammond, 1996; Ijomah et al., 2007; Hatcher et al., 2011)	Products sold at greater profits; reduced costs, raw materials and energy consumption (Bras and Hammond, 1996; Ijomah et al., 2007; Hatcher et al., 2011)	Quantitative (Bras and Hammond, 1996), Guidelines (Ijomah et al., 2007)
	DFR	Design to increase recyclable material inputs and outputs, to minimize material variety (Huisman et al., 2003; Francis, 1997; Kriwet et al., 1995).	Increased percentage of recyclability; more recycled and recyclable inputs, increased recycling efficiency; reduced raw materials consumption (Huisman et al., 2003; Francis, 1997; Kriwet et al., 1995).	Guidelines (Kriwet et al., 1995), Quantitative (Huisman et al., 2003; Gaustad et al., 2010)
Equity	DFSR	Design to enable linkages with society; to consider non-traditional markets; to eliminate social problems (Porter and Kramer, 2006; Tromp et al., 2011).	Increased worker retention rates; increased value for society; change in societal/user behavior (Porter and Kramer, 2006; Tromp et al., 2011).	Conceptual Framework (Porter and Kramer, 2006; Tromp et al., 2011)

(energy conservation), DFMC (material conservation), DFWMR (waste minimization & recovery), and DF3R (remanufacture, reuse, and recycle). The first four subcategories represent ideas that enforce DFE principles, while the last category is a creation of this research effort. DF3R combines three potential end-of-life outcomes for products: reuse (DFRu), remanufacture (DFRem), and recycling (DFR). These outcomes are related, though with differing degrees of environmental value. Reuse can be done either in part or as a whole, the later representing the most environmentally-friendly option, wherein a product is deemed “good enough” to be resold as is or can be donated if there is no viable resale market available. Remanufacture represents an intermediate level as it keeps the majority of the product intact, cleaning and repairing it to like-new condition. Sometimes a product may not be reused in whole or remanufactured, but contains good parts and components that can be salvaged for use in future repairs or products, representing the second form of reuse. Recycling is the lowest level in this hierarchy wherein products are disassembled and separated for recycling. A product could be designed for one of these Rs specifically or could be designed with all three in mind and based on product condition at the time of return or recovery; it could then be disassembled and meet one or more of these categories. For example, a product in poor condition might not be worth remanufacturing but good components could be harvested for reuse, and the rest of the materials recycled. A good condition product could then be remanufactured with the reused components from the poor condition product. Another topic in the literature related to these techniques is design for disposal wherein a product is disposed of at the end of the life-cycle. This idea can be thought of in two different ways: first, the materials disposed of at the end-of-life are those that cannot be reused or recycled and represent the “remainders” from this process. The design of a product in which the emphasis falls on increasing reuse and recycling, while limiting the amount of material that must be disposed of, corresponds to DFWMR. The second view of disposal that appears in the literature is that a product must be disposed of safely, such as refrigerator components, CFL bulbs, or batteries, which corresponds with DFCRR ideals. Therefore, disposal as a separate technique would be redundant with the other principles of DFE and DF3R.

Another DFX technique proved difficult to classify as exclusively or mostly in the economic or ecological dimension. DFD (disassembly) plays a major role in both DFSp and DF3R, with neither category taking precedence. A product may be designed with economic focus but no consideration for environment or vice versa. Therefore, DFD cannot exist solely under either category. DFD enables both supply chain and environmental matters.

The final component of sustainability, equity, defined here as design for social responsibility (DFSR), is the one most often overlooked in business and in the design process. As outlined in the literature review, the need for recognizing social equity has been growing in recent years but still lags behind the economic and environmental design issues. This need will be addressed further in Section 5.

Two prominent DFX techniques were not included in the taxonomy: DFC (cost) and DFLC (life-cycle). DFC was not included as most, if not all other DFX, take cost into account. DFLC was excluded as many of the other techniques are unequivocally related to life-cycle phases, making DFLC redundant. However, the role of life-cycle phases is crucial to design decisions and is further explored in next section.

A graphical depiction of the relationships between the DFX categories and subcategories is shown in Fig. 4. The figure distinguishes between hierarchical relationships (shown as solid lines) and influences (shown as dotted lines). To better distinguish the relationships, the broader categories are shown as squares while subcategories are represented as circles. The three dimensions of sustainability, DFSC (economic), DFE (environment), DFSR (equity) influence each other. To simplify the chart, if an influence exists between two categories, then that influences extends through the rest of the hierarchical relationships. For example, DFSC and DFE influence each other, therefore DFP and DFL are influenced by and influential on DFE goals. However, there are numerous implicit influences in the chart. These influences can exist solely within one dimension of the taxonomy or they can cross from one dimension

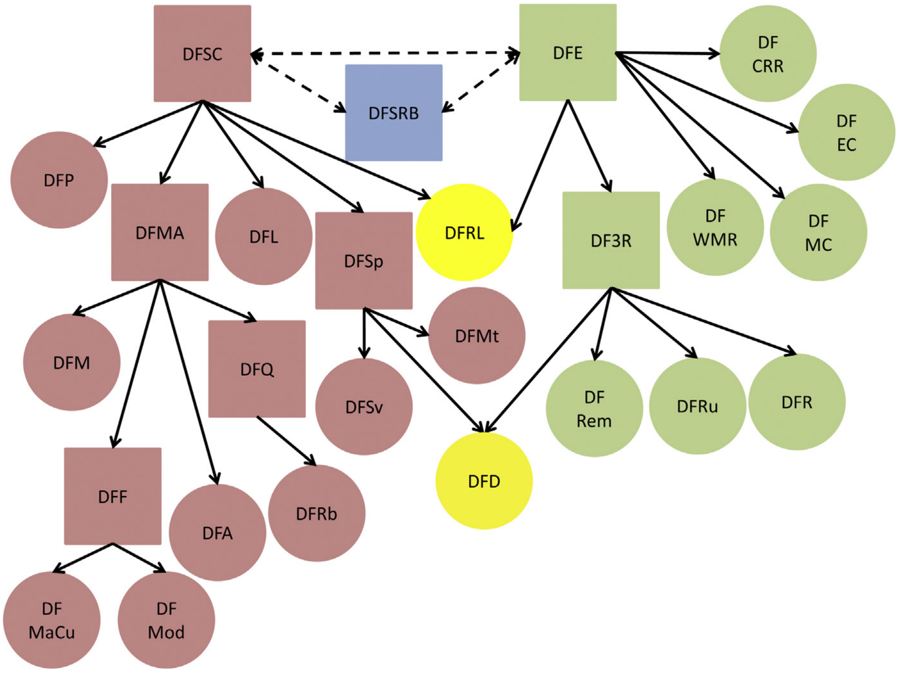

Fig. 4. DFS hierarchy and relationships.

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to the other. Here are several examples of the first category: if a product is reliable, it requires less support, service, and maintenance over the life of the product; if quality is an issue, then that impacts the procurement and manufacturing designs. In terms of cross-dimensional influences, there are many examples: if a product is high-quality, it often has a longer useful life than other products, reducing the environmental impact; modularity can impact assembly which in turn impacts disassembly, influencing the supportability and DF3R capabilities of the product. Enumeration of all influences among the techniques on this chart would be extremely difficult without sacrificing the usability of this figure. It is important to note that this taxonomy is to be used in a way consistent with ideas of concurrent engineering, with each DFX technique being considered simultaneously with the other techniques, thus forcing previously ignored relationships and impacts to be considered in the design process. In addition, further exploration of these relationships is one of the future research directions outlined in Section 5.

4.2. Relationship with life-cycle phases

The decisions regarding which DFX criteria to apply are directly influenced by the life-cycle phases of the product's existence emphasized in the design process. If a company designs a product for which no support is provided and the end-of-life simply involves the consumer throwing the product away, then certain DFX techniques, like DFD or DF3R, do not apply to that product. Therefore, another need in the DFX literature is to create a method to better define the application of DFX based on product life-cycles. Previous attempts to do this focused solely on design phases, not life-cycle phases (Chiu and Okudan, 2010); used DFX to represent life-cycle phases and then related design criteria to the life-cycle focused DFX (Sy and Mascle, 2011); or chose DFX techniques that were insufficient and did not present all life-cycle phases (Hepperle et al., 2011).

In addition to the need to relate DFX techniques to life-cycle phases, there is a need to link product development to the appropriate strategy. Previously missing from the research was the ability to tie selection of strategy to the applicable DFX techniques. Strategy is the business-level decision mechanism that should guide competitive decisions with respect to a product or product family. When the firm decides the strategy it will pursue, decisions made by firm functions and for each product life-cycle phase should jointly support the chosen strategy. Porter (1985, 1994, 1998) indicated that there are two main strategies: cost leadership and differentiation. Firms that apply a cost leadership strategy attempt to reduce cost in their value chain to be cost competitive, while those firms pursuing differentiation attempt to meet customer value requirements based on service or features (Porter, 1996). DFX techniques enable the pursuit of both strategies at different phases in the product life-cycle. Table 3 presents a matrix that prescribes which DFX techniques could be used for product design at different life-cycle phases based on strategy. Product characteristics will drive the use of some DFX and the elimination of others within the selected strategy.

As seen in the table, many of the DFX techniques, specifically those relating to DFE, DFD, DFSR, DFF, and DFQ, are not relevant when pursuing a low-cost strategy. Though these techniques can be profitable, they often require additional infrastructure and foresight which may be unachievable by companies solely interested in keeping down costs. Issues of ecology and equity represent differentiation opportunities for pursuing customer segments with interest in these areas, giving rise to products created from recycled materials, fair trade, and other "green" products. In addition, DFF is heavily related to product differentiation as the capabilities provided through flexible design are perceived as valuable by consumers.

The matrix has the dual purpose of providing structure for DFX research and application. In the case of research, it enables researchers to examine DFX techniques in contexts that enable strategy hypothesis testing. For practitioners, the matrix provides a framework for selecting appropriate DFX techniques to achieve improved performance based on strategy at appropriate product life-cycle stages. It provides a snapshot that designers can use to ensure they adequately design the cost and differentiation elements in to the product for its lifecycle.

5. Future research

Although we saw that the body of knowledge is evolving and improving, there are a number of future research activities that would enable substantial steps forward. The first major effort needed is the application of theory and building theoretical frameworks for DFX research. Currently DFX research makes the assumption that the application of DFX design considerations will result in the desired product or process performance. Theoretical frameworks that describe conceptual definitions of variables, domain limitations, theoretical relationships, and theory predictions (Wacker, 1998) are essential to advance the DFX body of knowledge. Theory should incorporate the nature of the product, intended use, design goals, product strategy, market conditions, the environment, social conditions, and relevant business processes. These frameworks should enable application "in many instances by explaining the who, what, when, where, how and why certain phenomena will occur" (Wacker, 1998). Researchers should examine existing theories for applicability to the DFX constructs and extend applicable theories into this domain. Building theory in the DFX arena will enable researchers and practitioners to validate the importance and use of these techniques within the broader business and new product development environments.

The second area of future research is empirical and analytical testing. As researchers work to build testable theoretical frameworks, they should gather data to test the ability of DFX techniques to deliver desired performance results. This study categorizes DFX techniques by life-cycle phase and by strategy (Table 3) to identify the DFX techniques design teams could select. This strategy life-

Table 3
DFS, strategy and life-cycle matrix.

		Product life-cycle stage				
		Sourcing	Production	Distribution	Use	End-of-Life
Strategy	Low Cost Leadership	DFP	DFMA, DFM, DFA	DFL	DFSp, DFSv, DFMt	
	Product Differentiation	DFP, DFQ, DFRb, DFF, DFE, DF3R, DFR, DFRem, DFRu, DFCRR, DFEC, DFMC, DFWMR, DFSR	DFMA, DFM, DFA, DFF, DFMaCu, DFMod, DFQ, DFRb, DFE, DFCRR, DFEC, DFMC, DFWMR, DFSR	DFL, DFE, DFCRR, DFEC, DFMC, DFWMR	DFD, DFSp, DFSv, DFMt, DFE, DFCRR, DFEC, DFMC, DFWMR, DFSR	DF3R, DFR, DFRem, DFRu, DFD, DFRL, DFE, DF3R, DFR, DFRem, DFRu, DFSR

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cycle framework in concert with applicable theory can be a starting point for hypothesis development. Real theory testing begins when hypotheses can be deduced from theory and empirical and analytical models can be tested to validate theory predictions and relationships (Handfield and Melnyk, 1998). Empirical and Analytical testing will enable researchers to move DFX from a position of conceptual discussions to one that has tested concepts, principles, and frameworks. Researchers need to determine the domain of these techniques across industries, markets, and product types. The ultimate goal should be to have valid, tested theory that informs the new product development body of knowledge and practitioners.

Another area that requires future research is to expand the strategy and product life-cycle matrix (Table 3) to include hybrid strategies, in which companies engage in both low-cost and differentiation strategies. There is not one hybrid strategy available, as these exist on a spectrum based on the degree to which one strategy is favored over the other with pure low-cost or pure differentiation representing extreme points. Assigning DFX techniques to the appropriate strategy and life-cycle phase is a logical, straight forward process. However, the potential for a design team to face the scenario of designing a product that requires differentiation and low cost leadership is a very real possibility. A valuable contribution can be made through the use of case study research that documents specific hybrid scenarios and that elaborate the desired configuration for the unique context. Development along all phases of the life-cycle would provide much needed insight. It is important to note that the matrix may need to be expanded to document a number of hybrid strategies for identifiable contexts. The result may be a handful of common hybrids that demand a unique arrangement of DFX strategies.

A fourth area for additional exploration is enumerating the influences and relationships among the techniques in the DFS taxonomy. Given the large number of influences that exist, Fig. 4 only recognized the influences among the three dimensions of sustainability. While several examples of additional influences were given in taxonomy discussion, there is a need to further develop and recognize the role that these influences play with respect to product design and trade-offs between decisions in the design process. Previous research (Hepperle et al., 2011) tried to accomplish this task through matrix analysis, but failed to account for many prominent DFX techniques. A similar approach could be utilized, with increased recognition for these additional techniques. Complete enumeration of these influences would probably require numerous papers to effectively capture the complexity. One recommendation would be to select a key technique and fully develop the relationships that exist between this technique and all other techniques. Through an iterative process, a full understanding of the relationships and influences will begin to coalesce. The product design process advocated for in this paper requires the simultaneous recognition of the impacts that changes with respect to one DFX technique might have on the other design considerations based on other DFX techniques. Greater recognition of these relationships also has the potential to reconcile long-standing sources of conflict between economic, environmental, and equity dimensions, showing that improvements in one dimension do not have to mean sacrifices in others. Analysis of these relationships can help further the development of useful tools for designers and the achievement of true sustainability, that of explicit consideration and improvement in all three E's, through product design.

Fifth, although many of the DFX techniques have been extensively developed, there are several that need to be developed further. Two DFXs recognized in the taxonomy standout at this time for immediate development. First is the area of DFSR, where firms design for social responsibility or social equity. This area is expansive and underexplored. The difficulty with DFSR is that it spans many disciplines. It is not just a business or engineering decision, but rather a social decision. Although businesses make these types of decisions every day, this type of design emphasis often requires governmental intervention. Developing this area may require the creation of additional DFX techniques with their unique design considerations. These techniques could include efforts to increase the capability of the handicapped, or to eliminate child labor and prevent other forms of abuse, among many other concerns. Their development goes beyond the scope of a more traditional DFX that will be used by a design team for a product to a societal design team with the objective to change opportunities and responsibilities, and to eliminate restrictions or negative societal aspects. This challenging endeavor could overshadow all previous DFX research. Porter and Kramer (2006) discussed the role that corporate social responsibility plays in aligning strategy and society, acknowledging that sustainability is one of four key principles driving this behavior. The authors provide an approach for examining the linkages and impacts that the value chain has with society, how to prioritize these issues and develop a strategic approach for addressing these issues that ultimately create shared value for companies and society. Many of this work's concepts can be applied to the future development of DFSR. The second area for DFX development is DFRL. As previously stated, reverse logistics has not been developed as a DFX technique. As we examined the SCOR Model and the concept of DFSC, we realized that reverse logistics was an area that had been neglected. Although design for logistics can affect the reverse logistics process, there are plenty of scenarios where used components, recyclable materials, or remanufactured end items must make their way back through the supply chain. This movement to comply with regulation, to capture remaining value, or to remove hazards from the community is essential to the operation of the closed-loop supply chain. Making DFRL a design technique has the potential to cut costs by planning and developing the infrastructure and activities that the supply chain must execute. It could make proactive returns more efficient and less eventful.

Finally, there is a need to explore the relationship between producer-focused research and consumer behavior-oriented concepts to improve the sustainability of products. Given the potential for the environmental impact from some products to be far greater during the use phase of the life-cycle compared to the sourcing, production, and distribution stages, the ultimate measure of sustainability for a product can be heavily dependent on the user. The economic and social equity dimensions of sustainability can also be impacted based on user behavior. The work presented in this paper focused on DFX techniques that most often correspond with producer-controlled elements of product design. That is not to say that these elements of product design have no impact on user behavior. For example, a vehicle may be designed to only run on ethanol or other biofuels, thereby limiting the ability for drivers to produce excess emissions. However, the driver may still operate the vehicle in a less-than-efficient manner, thus the need for a feedback mechanism to improve the driver's behavior. Implementation of such devices, as well as other techniques, corresponds with the research being conducted on design for sustainable behavior (DFSB). As the sustainability of a product is measured, and the design altered for improvements, it is important to remember the role of the user. Therefore, an important avenue for future research would be trying to better understand the relationship between DFX-based approaches to product design and those focused on user behavior. Integration of these two distinct concepts will provide an even stronger view of product sustainability throughout the entire life-cycle. In addition, the 3P's (product, process, and people) will be fully accounted for with increased recognition of people in the sustainability of a product.

There are a number of rich areas for future DFX research, and the areas discussed in this section are not mutually exclusive and in fact should be explored simultaneously for an improved understanding of sustainability and product design. For example, better attempts at understanding the relationship between DFS and DFSB or greater enumeration of the relationships between techniques could be based on empirical testing. As researchers take on the challenges of DFX research, they need to consider how they can enhance the design process to give the results firms and consumers desire.

6. Conclusions

This research of the current state of the DFX literature revealed a number of trends and deficiencies. Perhaps the most glaring finding of the research is that DFX is very practitioner focused. Most research is fashioned in the attempt to provide the design team with the necessary tools or design considerations to successfully address a problem that traditionally exceeded the responsibilities of new product design. This is important as teams are being asked to consider the life-cycle of the product from sourcing to end-of-life. This research makes a contribution by giving practitioners a framework to decide which DFX techniques are applicable to a given product design based on strategy and life-cycle phase.

Another major step forward with this research is to place DFX under the DFS or design for sustainability heading, categorizing based on economic, ecologic, or equity considerations. The idea of designing with the triple bottom line in mind is essential as we move new product development forward. Even if our focus is entirely economic, the design firm needs to move beyond the motivation of the sale to other essential supply chain design considerations to capture the value that a short-sighted product design leaves on the table. In doing so, the relationship between environmental and social design considerations will be impacted positively.

This paper takes a major step forward as it begins to integrate DFX techniques in the area of supply chain with those in the area of environment. Previous studies treated the two as mutually exclusive. The understanding that decisions in one area positively or negatively impact the other area should raise a level of awareness between supply chain and environment design considerations that did not previously exist. More effort to understand these relationships further enhance the supply chain - environment nexus. Harmonious integration between the dimensions of sustainability and the related DFX techniques is required to fully realize sustainability goals.

As a research team we see the potential value of DFX for design teams that can selectively apply techniques for their unique requirements. New product development should be able to achieve new levels of performance that bring products to customers that add value in ways that were not previously conceived or expected. As academic researchers, we need to apply the rigor of our discipline to ensure that we assist in this journey to deliver design processes that have this capability.

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