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DESIGN FOR SUSTAINABILITY: OVERVIEW AND TRENDS

Gaurav Ameta
Washington State University, Pullman, WA, 99164-2920, USA.

ABSTRACT

This paper presents recent trends in Design for Sustainability (DfS) with foresight and strategy as the point of view. We first provide a definition of design for sustainability based on the notion of sustainability. Then, we show the scope of various Design for X concepts in relation to the stages of product lifecycle and the triple bottom lines of sustainability; economy, environment and society. A survey of the recent studies for designing sustainable products is presented followed by the detail summary of various metrics that are used in relation to sustainability and designing environmentally friendly products.

Keywords: Design for Sustainability, Sustainability, DfX

1 INTRODUCTION

To understand the meaning of Design for Sustainability, we need to understand the meaning of the word sustainability or sustainable. The word "sustainable" was first used with respect to its current usage as sustainable development. Sustainable development is the development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." [1]. A definition of sustainability according to the US National Research Council is "the level of human consumption and activity, which can continue into the foreseeable future, so that the systems that provides goods and services to the humans, persists indefinitely" [2]. Other authors (e.g., Stavins *et al.* [3]) have argued that any definition of sustainability should include dynamic efficiency, should consist of total welfare (accounting for intergenerational equity) and should represent consumption of market and non-market goods and services. In this paper, Design for Sustainability will be defined as the design of products that are sustainable throughout their lifecycle. In other words, design of products that do not diminish or damage the available natural resources throughout the product's life cycle.

Due to the current climate change scenario, the notion of sustainability has recently gained wide interest. According to the United Nations Environment Program, climate change is affected by various human activities such as land use changes (through urbanization and deforestation) and fossil fuel burning (through transport, heating, agriculture, industry) [4]. Although Sustainability is a common objective of all entities over the world, its realization is difficult as it is engulfed in myriad of political, societal, regional, technological, economical, legal and geological issues. It is also quite evident that sustainable development is a dynamic process by nature [5, 6], as the biosphere and conditions around the world are ever changing and still quite unpredictable. Despite this unpredictability, scientist, governments, industry, consumers etc., have realized that increase in global temperatures is very likely due to the increase in anthropogenic (human) greenhouse gas concentrations. This increase in global temperatures, if not curbed, will have a debilitating effect on the viability of the biosphere to sustain life [7]. To impede and hopefully reverse the debilitating climate changes that have occurred, products should be designed for sustainability.

In this paper we present the current states and recent trends in design for sustainability. The next section presents the scope of design for sustainability with respect to a products lifecycle and other design for X notions. Section 3 summarizes the current state of standards for sustainability. Section 4 presents the current state of the art in measuring the notion of sustainability. Section 5 presents research efforts that relate to design for sustainability while section 6 will present future directions that should be pursued to achieve sustainability of products.

2 SCOPE

Sustainability has been attributed with three bottom lines; environment, economy and society. Design for sustainability is an umbrella notion which includes various design for X concepts. Figure 1 depicts the three bottom lines of sustainability as part of the design for sustainability. While considering design for sustainability, past research has mainly focused on Design for Environment and Economic aspects. In reality, research in design for sustainability should cover, design for environment, economic aspect and social aspect in conjunction.

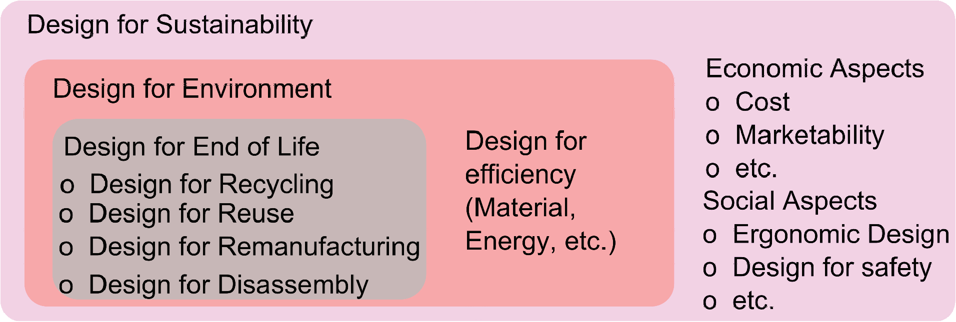

Figure 1 Scope of Design for Sustainability

Table 1 shows different design for X concepts with their coverage/influence on different stages of a product life cycle. Design for environment focuses on optimizing/reducing the impact of the product on the environment at the use and end of life phases of the product life cycle. It is the design for sustainability that includes all the issues of the product in all the stages of the product life cycle.

Table 1: Scope of different DfX concepts in relation to the product lifecycle

	DfSustainability	DfEnvironment	DfManufacturing	DfCost	DfSafety
Design	X				
Manufacturing	X		X	X	
Supply Chain	X				
Use	X	X			X
End of Life	X	X			

Figure 2 depicts various design for X concepts in relation to the triple bottom lines of sustainability; economy, environment and society. Most of the time when a product is designed, cost is one criteria that is always considered. Therefore, Design for Environment and Design for Safety would always include decision making based on economics of the product. Design for sustainability should therefore optimize the design based on environmental, economic and societal factors.

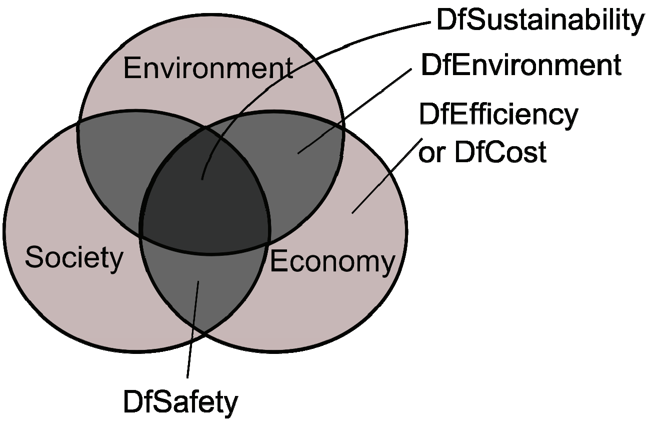

Figure 2 Various Design for X concepts in relation to the triple bottom lines of sustainability.

3 STANDARDS

To create products that are sustainable, standards are required to guide the sustainable development of a product. Although, various standards have been developed in the last two decades to guide sustainable development, they have been either too narrow or too broad in scope. In this section, we present a summary of some of these standard that influence product sustainability. The list is not meant to be comprehensive and there is no intent of giving preference to the included standards. These are just a sample of the available standards.

ISO 14000 standards create a systematic approach for reducing the impact on the environment due to the activities of an organization [8]. ISO 14000 standards include the ISO 14020 series for environmental labeling, ISO 14040 for Life Cycle Assessment, ISO 14064 for Green House Gases, to name a few. ISO 19011 provides guidelines for auditing quality and environmental management systems [9].

WEEE is an acronym for the “Waste Electric and Electronic Equipment” directive [10]. Basically the WEEE directive makes the manufacturers of equipment responsible for the waste. Therefore, the manufacturer should have the infrastructure available to recycle/reuse/process the waste equipment at the end of product’s life.

RoHS stands for the “Restriction of Hazardous Substances” directive [11]. It lays down the limit (0.1% by weight) on the use of Lead, Mercury, Cadmium, Hexavalent Chromium, Polybrominated biphenyls and Polybrominated diphenyl ethers, separately, in electronic equipment.

REACH is an acronym for the “Registration, Evaluation, Authorization and Restriction of Chemicals” regulation [12]. It imposes health and safety *evaluation* of all chemicals of one ton or more by *registering* with European Chemicals Agency for *authorization*.

ELV stands for “End of Life of Vehicles” directive [13]. It is similar to WEEE, but is imposed on automotive manufacturers instead on electronics/electrical manufacturers. All electronic equipment in an automobile should follow the ELV directive. IMDS [14], IPC-1752 [15] and JIG-101 [16] are acronyms for “International Material Database System,” “Institute of Printed Circuits” and “Joint Industry Guide,” respectively. IMDS manages materials for automotive manufacturers, while JIG-101 and IPC-1752 manage material for electronic equipments.

4 RELATED LITERATURE

As discussed in section 2, Design for Environment concept is to design a product that has minimal environmental impacts. Life cycle assessment (LCA), have been developed by International Organization for Standardization (ISO) [8], for assessing the environmental impacts of products. By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process. LCA has been widely popular for identifying environmental impact of a product or process. LCA methodology has been incorporated into several commercial (SimaPro [17] and GaBi [18]) and academic environmental assessment tools (EioLCA [19], TRACI [20], BEES [21] and EcologiCAD [22])

Despite the large application of LCA, it has been attributed with some drawbacks related to (a) System Boundaries (b) Data Issues and (c) Methodology Issues such as (Weighing methods, Aggregation methods and Comparison across indices)[5, 23-28]. The methodology issues are related to the selection of appropriate metric for comparing products. Moreover, LCA only provides methodology for assessing the environmental impacts and does not provide any guidelines for reducing the impacts.

Applications of various conceptual design methodologies can also be seen in the literature with focus on environmentally conscious design. For early design decision, environmentally conscious design factors have been integrated into QFD by several researchers [29]. They propose a four phase QFDE methodology to identify and improve environmentally critical components in a product. They incorporate environmental requirements from two viewpoints: customer and engineering. Analytical Hierarchical Process has been combined with LCA for identification of environmental impacts of a product at early design phase [30, 31].

Study on integrating functional requirements and environmental performance into design decision, on manufacturing steel roller bearing and rotation shaft, has been attempted by [32]. Application of intelligent learning systems towards conceptual stage LCA has been attempted by [33]. They have also reported development of product classification system based on an approximate LCA for conceptual design stage in [34]. Development of collaborative internet based design of environmentally conscious products has been attempted by [35]. Similar decision support system for life-cycle management has been reported by [36]. Applications of a simplified matrix based LCA for early design can be seen in the literature [37]. A fuzzy linear programming extension was implemented by [38].

5 METRICS

In this section we will look at various issues related to sustainability metrics and some examples of metrics studied in the literature.

5.1 Issues

Scoping sustainability and defining clear system boundaries are critical for properly defining metrics for design of products for sustainability [39]. Various metrics developed so far to measure the progress towards sustainability have been classified by Mayer [5] and Jain [40] into: a) indicators, b) indices and c) frameworks:

5.1.1Indicators

Indicators basically measure a single parameter of a system, e.g., CO2 emission or energy use. A detailed survey of indicators has been conducted by Patlitzianas *et al.* [41]. They have classified indicators into various types such as descriptive, normalized, comparative, structural, intensity, decomposition, causal, consequential, and physical. Keffer *et al.* propose a framework for developing a classification of indicators [42]. In the framework, indicators are classified based on aspects and categories. Categories are broad areas of influence related to environment, economy and society, referred to as the triple bottom line of sustainability. Aspects are defined as general type of data that is related to a specific category. Indicators then become the specific measurement of an individual aspect that can be used to demonstrate the status and performance of a system relative to a particular aspect and category. Keffer *et al.* classified indicators into core indicators, that are applicable to all businesses, and supplemental indicators, that are selected based on the needs of a particular business and its stakeholders [42].

5.1.2 Indices

Indices are basically aggregates of several indicators, e.g., Ecological Footprint (a ratio of the amount of land and water required to sustain a population to the available land and water for the population) or Environmental Vulnerability Index (consists of indicators of hazards, resistance and damage). Indices represent a single score by combining various indicators of different aspects of a system.

Key requirements for sustainability indices, as proposed in Bohringer and Jochem [43], are: a) rigorous connection to the definitions of sustainability, b) selection of meaningful indicators representing the holistic fields, c) reliability and availability of data for quantification over longer time horizons, d) process oriented indicators selection, e) possibility of deriving political objectives and f) adequate normalization, aggregation and weighing of the underlying variables

The strengths and weakness of several sustainability indices are compared by Mayer [5]. The authors identify several issues across sustainability indices: system boundaries, data inclusion, standardization and weighing methods, aggregation methods, comparisons across indices. Rigorous mathematical requirements for indices are presented by Ebert and Welsch [44].

5.1.3Frameworks

Frameworks present large numbers of indicators in qualitative ways, e.g., the vulnerability framework [45] or the CRITINC Framework [46]. Frameworks do not aggregate data in any manner. An advantage of frameworks is that the values of all indicators can be easily observed and are not hidden behind an aggregated index. The disadvantage of using frameworks is that they are hard to compare over time although this is possible by using Hasse diagrams [47]. A brief review of sustainability frameworks is provided by Mayer [5].

In a recent article by Sikdar, indicators were identified as 1-D metric as they would quantify changes in only one of the bottom lines of sustainability [48]. Indices could be a 2-D metric or 3-D metric, in a sense that they could quantify changes in either two or three of the bottom lines of sustainability.

5.2 EXAMPLES

In this section we will survey metrics and their categories that have been used to evaluate products from manufacturing enterprises.

5.2.1 Sustainability Metrics

Datschefski proposed that the sustainability of a product should be measured using recyclability, safety, efficiency, use of renewable energy and social effects [49]. *Recyclability* implies that the materials used for producing, distributing and using a product can later be useful for some other enterprise in a closed loop. *Safety* indicates not just safe for humans but includes the safety in all of releases from the product to air, water, land or space from the production, distribution and use of a product. This would again indicate that all byproducts should be safely consumable in other enterprises/environmental systems. High *efficiency* implies less (than the current) use of energy, material and water during production, distribution and use of a product. *Use of renewable energy* indicates that the product be produced, distributed and used by consuming as much renewable energy as possible in a cyclic and safe manner. *Social effects* refer to the support of basic human rights and natural justice in production, distribution and use of a product.

5.2.2 Design for Environment Metrics

Various quantitative and qualitative metrics for eco-friendly product design were compared by [50]. As quantitative methods, Material Intensity per Service Unit (MIPS), Cumulative Energy Demand (CED), and EcoIndicator 95 (EI95) were analyzed. As qualitative methods, Kodak-Guidelines (KGL), Integrated Product and Process Development (IPPD), and Ecodesign Checklist Method (ECM) were chosen. Several products were compared after the completion of detail design. Therefore, the method selected is not suitable for early design decision making. A similar analysis for comparing the environmental impacts of product after the detail design has been accomplished in [51]. A review of eco-indicators used in product development is provided by [52].

5.2.3 Others

In this section we will survey studies for three metrics, viz., energy, exergy and carbon weights.

(a) Energy: During a products life cycle, energy is consumed at most of the stages; design, production, use and disposal. Energy use varies throughout a products life cycle and is different for different products. Energy accounting and reduction during product use (use phase) is governed by standards such as Energy Star [53], which supports a number of industries. Energy Star does not include the energy consumption during the manufacturing phase of a product life cycle. Various studies [54, 55] at the Department of Energy (DoE) focused on accounting the energy usage and emissions in different manufacturing industries.

(b) Exergy: Environmental impacts of different manufacturing processes have been extensively studied by Gutowski's research group [57-60]. They identify environmental impacts by accounting for the exergy of the manufacturing process. Exergy is defined as the potential of a system to cause a change as it achieves equilibrium with its environment (heat reservoir) [61]. When the environment is used as heat reservoir, exergy is the energy that is available to be used.

(c) Carbon Weights: Further details of energy-related carbon dioxide emissions in U.S. manufacturing were studied by Schipper [62]. Product related CO_2 emission accounting has been reported by Jeswiet [63]. However, the author generalized the computation of CO_2 factors from electricity requirements and did not consider the variability of different manufacturing processes.

6 TRENDS AND FUTURE DIRECTIONS

Design for sustainability has mostly been considered as the design for environment, eco-design and environmentally benign design. Societal aspects of design have been studied very superficially.

6.1 Practical Applications

Applications of Life cycle assessment (LCA) are increasingly becoming a part of product development process. Various tools that are used for performing LCA are Sima-Pro, Gabi, TRACI and BEES. Usually the result of LCA from these tools is a graph of environmental impact criteria (such as, Ozone depletion, Carcinogen, Emission, etc.) that can be used to compare two products in order to judge or choose a more sustainable product. In order to conduct LCA, inventory databases are needed. The inventory databases are created by mostly European enterprises. Some inventory studies are being conducted by US government [64] and private enterprises [65] too. Several data format are used for inventory databases, such as excel or XML based formats. One of the XML based data format for inventory database is called Eco-Spold [66].

6.2 Theoretical understanding

Although Life-cycle assessment guidelines have been developed by International Standards Organization, different system boundaries, metrics and units generate contrasting results. Despite the fact that a lot of metrics are being studied and created for different kinds of industries and applications, due to the dynamic nature of sustainability it has been difficult to create theoretical understanding of the uses and impacts of different metrics. The current research in theoretical understanding of LCA is being focused on the interaction of multiple-lifecycles of products.

6.3 Future Research Issues

New studies need to be conducted towards understanding the interaction of design theory and the interface of the triple bottom lines of sustainability; society, economy and environment. Metrics for measuring sustainable design are currently inconsistently defined. Strategic research into identifying core design for sustainability metrics, i.e., metrics that are uniformly defined and globally harmonized, needs to be conducted.

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Contact: Gaurav Ameta
School of Mechanical and Materials Engineering – 2920
Washington State University, Pullman, WA 99164-2920
USA
Tel: +1-509-335-8218
Email: gameta@wsu.edu
URL: http://www.mme.wsu.edu/people/faculty/faculty.html?ameta

Gaurav is Assistant Professor in the School of Mechanical and Materials Engineering at the Washington State University, since August 2008. He received his Ph.D. in Mechanical Engineering from Arizona State University in 2006. His research interest include (a) Sustainable and energy efficient product life cycle and (b) Geometric problems in design, manufacturing and inspection.