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Directions for instilling economic and environmental sustainability across product supply chains

Gül E. Kremer [a], Karl Haapala [b], Alper Murat [c], Ratna Babu Chinnam [c,*], Kyoung-yun Kim [c], Leslie Monplaisir [c], Ting Lei [d]

[a] School of Engineering Design and Department of Industrial & Manufacturing Engineering, Penn State University, 213T Hammond Building, University Park, PA 16802, USA
[b] School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, 204Rogers Hall, Corvallis, OR 97331, USA
[c] Industrial & Systems Engineering Department, Wayne State University, 4815 Fourth Street, Detroit, MI 48202, USA
[d] Department of Industrial & Manufacturing Engineering, Penn State University, 301C Engineering Units, University Park, PA 16802, USA

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ABSTRACT

Although sustainability is a frequent topic in product development literature, the often segmented and narrow scope of prior works limits the potential benefits of the industrial application of methods, models, and tools developed by the research community. The work herein has the goal of coalescing relevant, recent work supporting the economic and environmental aspects of sustainability for early stage product development by focusing on the interfaces between product design and supply chain operations. This discussion is intended to highlight past accomplishments and to be a call for action to the research community for the development of integrated methods, models, and tools to support sustainability initiatives across product supply chains. A literature review spanning product design, manufacturing, and supply operations management reveals several near-term research needs, which are organized into four highly promising foci addressing product architecture engineering, assembly/disassembly operation modeling, manufacturing process modeling, and joint optimization of life cycle activities. Finally, potential avenues for future collaborative research are presented and discussed.

1. Introduction

Consumers are demanding more environmentally sustainable products, motivated by increased awareness of environmental impacts. Simultaneously, environmental regulations, policies, and standards have been enacted globally that impact manufacturers (Gutowski et al., 2005). Yet, product manufacturers continue to struggle with how to set, assess, and achieve sustainability goals, which encompass economic, environmental, and social factors. To meet this challenge, the research community has developed many approaches, several of which are highlighted in the sections below and many others which have been reviewed by other authors at length (e.g., Baumann et al., 2002; Duflou et al., 2012; Gold et al., 2010; Haapala et al., 2013; Ilgin and Gupta, 2010; Ramani et al., 2010; Sarkis et al., 2011; Seuring and Müller, 2008; Subramanian et al., 2010; Umeda et al., 2012) in the areas of product design, product manufacturing and assembly, demanufacturing and remanufacturing, and supply chain management. Seuring and Müller (2008) synthesized an extensive literature review of 191 scholarly articles on sustainable supply chain management published during 1994–2007. They found that studies primarily focus on environmental issues and on empirical findings, and this fact has limited the development of a theoretical basis for supply chain management. Given this situation, in this paper, we review the sustainability literature with a specific focus on product design and supply chain operations, and then provide an action plan to improve the analysis and reduction of cost and environmental impacts in supply chains.

The goal of this paper is two-fold: first, to review and present recent research undertaken to advance environmentally and economically sustainable product development from the earliest stages of design through manufacturing and end-of-life (EOL) and, second, to define and discuss several near-term research foci that

* Corresponding author. Tel.: +1 313 577 4846; fax: +1 313 578 5902.
E-mail addresses: gkremer@psu.edu (G.E. Kremer), karl.haapala@oregonstate.edu (K. Haapala), amurat@wayne.edu (A. Murat), ratna.chinnam@wayne.edu (R.B. Chinnam), kykim@wayne.edu (K.-y. Kim), leslie.monplaisir@wayne.edu (L. Monplaisir), tingleipsu@gmail.com (T. Lei).

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can be addressed by the product design and manufacturing research community. Thus, the bulk of the discussion focuses on the fields of product design, manufacturing and assembly, and supply chain management activities. Accordingly, the novelty and contributions of this paper are two-fold. First, it provides a unified review of past work on sustainability across product supply chains and identifies gaps due to considering product design, manufacturing, and supply chain operations in isolation from each other. Secondly, and in an effort to close these gaps, it develops an integrated view of decision making in product design, manufacturing, and supply chain operations, under the lens of sustainability.

While definitions vary, it is generally agreed that sustainability requires "… the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment" (Mihelcic et al., 2003). A myriad of metrics have been proposed to measure progress and improvement, including those for economic, environmental, and social aspects of sustainable product development (Feng and Joung, 2011; Graedel and Allenby, 2002; Hutchins and Sutherland, 2008; Lu et al., 2010; OECD, 2008; Shuaib et al., 2011), e.g., capital, operational, and transportation cost; CO_2, SOx, and NOx emissions; and worker wages, benefits, and equality. The carbon footprint of a product is often used as a measure of its environmental sustainability. While carbon footprint has limitations, it is an important recent metric and used herein to focus the discussion around a concrete concept of environmental impact when needed. Ideas discussed in the context of carbon footprint can be extended to other environmental impacts as well. Similarly, economic impacts are only discussed in terms of direct, product-related costs. While integral to any sustainability evaluation, social aspects are outside of the scope of the present discussion.

Product development covers the stages of concept development, product design, supply chain design, and production ramp-up and launch (Krishnan and Ulrich, 2001). Design stage is iterative and complex, and includes defining, conceptualizing, refining the design to ultimately commercialize a product in the market (Ogot and Kremer, 2004). The shape, dimensions, functions, components, and materials are all decided during the design process; as a consequence of this, up to about 70% of product cost (Appelqvist et al., 2004) and 80% of product quality (Dowlatshahi, 1992) are decided during the design stage. One can posit that product life cycle environmental impacts are similarly designed-in. Merging early eco-design tools with life cycle data and developing a better understanding of product and environmental interactions are key to achieving sustainable product development (Ramani et al., 2010). Baumann and colleagues (Baumann et al., 2002) reviewed the green product development literature from engineering, management/business studies, and policy studies. One of the primary conclusions of this extensive review is that there is need for a systemic perspective where environmental optimization and emissions reduction should be considered across the entire supply chain.

It is estimated that about 72% of GHG emissions are related to household consumption (Hertwich and Peters, 2009), implying that consumer products and services, and their supply chains are the major contributor. Matthews et al. (2008) asserted that only 26% of total supply chain emissions are identified and mitigated. Moreover, the increasing trend towards outsourcing is leading to the substantial growth of the global carbon footprint, even without accounting for associated transportation, due to less efficient energy generation and manufacturing processes in developing nations (Herrmann and Hauschild, 2009). In fact, much of the success in CO_2 emissions reductions in developed countries are due to exported industrial production to Asia. In 2005, about 30% of the emissions in China were attributable to the production of exports (Weber and Matthews, 2008). Thus, analytical methods are needed to aid in the development of products and related supply chains and will be further reviewed in this paper.

The rest of the paper is organized as follows: Section 2 reviews prior work; Section 3 discusses four promising foci for instilling sustainability across product supply chains; Section 4 presents results from preliminary work to instill sustainability across product supply chains; finally, Section 5 suggests directions for future research and concludes.

2. Prior work

A recent review by Chiu and Kremer (2011b) identified 12 different tools (guideline sets, metrics, mathematical models, and methods) for Design for Environment (DfE) and DfS. It was readily evident, however, that these methods focus on environmental sustainability and are deficient in incorporating economic sustainability. Several of these works are listed in Table 1 below.

Considerable research has been undertaken to integrate life cycle concerns into the design stage through design for X (D) concepts (e.g., design for manufacturing (DfM), design for assembly (DfA), and design for environment (DfE)). However, there is no research-based evidence on how various DfX tools complement or compromise one another across the supply chain (Chiu and Kremer, 2011a, 2011b). In addition, while other DfX principles have been studied for decades, the design for environment (DfE) and design for sustainability (DfS) methods have been developed more recently. Given that gaps exist at the interface of DFA, DFM, and design for supply chain (DfSC), the integration of these methods with DfE and DfS is absent from the prevailing literature. Filling this gap by identifying important research questions and their answers is timely and will address the needs of industrial decision makers. Since they inherently take a holistic view, DfE and DfS methods interface with all other DfX approaches, which differentiates them from other DfX considerations (e.g., DfM is fXonly concerned with the manufacturing stage). We assert that manufacturers must remain cost competitive, and design for sustainability is not complete without simultaneous consideration of environmental and economic aspects (e.g., carbon footprint and costs) of manufacturing and assembly activities across the supply chain. Several studies have been done to integrate economic sustainability into design and into manufacturing processing; these are summarized in the following Table 2.

Accordingly, design for manufacturing, design for remanufacturing, product sustainability, and supply chain optimization are used to classify prior work and they are briefly discussed below.

2.1. Design for manufacturing

A recent review by Chiu and Kremer (2011a) identified 17 different tools (guideline sets, metrics, and methods) for DfM and DfA implementation; these two concepts are found to be most mature among all DfX concepts. For example, Stoll (1988) described strategy-based and practice oriented 13 DfM guidelines focusing on: (1) modular design, (2) multi-use parts with standardization, and (3) ease of assembly to increase the manufacturability. Fabricius (1994) proposed a set of guidelines, defining a "seven step procedure for design for manufacture," to enhance the linkage between design and manufacturing using a metrics-based model. Other methods include, but not limited to, the assembly-oriented design process (AODP) method (Warnecke and Bäßler, 1988), the assembly evaluation method (AEM) by Boothroyd and Alting