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An ARIZ-based life cycle engineering model for eco-design

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ABSTRACT

Cleaner production issues require not only effective management and prevention but also a new design and engineering paradigm. This study presents an ARIZ-based life cycle engineering (LCE) model for implementing eco-designs of products. The aims of the proposed model are (1) to restructure a set of new product models through modular analysis of alternative attributes associated with the morphological approach; (2) to develop an effective assessment method that integrates the three dimensions of LCE analysis into a single decision support tool using the aggregation operator of weighted generalized means; and, (3) to search for improvement opportunities and refine preferred engineering options by means of the algorithm for inventive problem solving (ARIZ) methodology. The applicability of the ARIZ-based LCE model is demonstrated through a case study of an in-flight meal service.

1. Introduction

With a growing awareness of environmental implications of industrialization, population growth, climate change, and resource scarcity, industries are facing various pressures from their stakeholders, customers, and governments to reduce their environmental footprints and develop new solutions that are environmentally friendly. During the last two decades, product design and development (PDD) processes have increasingly accounted for environmental issues, and many industries have adopted new strategies and practices in their PDD tasks. Previous research has found that most product-related environmental impacts are determined during the product design stage, which provides an intervention point to implement environmental goals (Baumann et al., 2002; Pongrácz, 2009). However, conventional end-of-pipe approaches to environmental issues mainly focus on pollution prevention and waste management through avoiding or minimizing potential environmental impacts without considering the design of products. Eco-design is a concept that aims at reducing environmental impacts throughout entire product life cycles via improved product design. It emerged in the 1990s with the realization of changing product concepts from mass production and consumption to sustainable consumption and production patterns. Although there are numerous definitions of eco-design in the literature (e.g., Charter and Tischner, 2001; Graedel and Allenby, 2002; ISO/TR 14062, 2002; Lee and Park, 2005), most definitions emphasize that eco-design is a systematic process that identifies the environmental aspects of a product and integrates them into the product design in the early phase of PDD.

Eco-design strategies can be broadly categorized into the following eight goals: (1) reduction of the number of different materials and selection of the most appropriate ones; (2) reduction of environmental impact in the production phase; (3) optimization of the distribution phase; (4) reduction of environmental impact in the use phase; (5) extension of the product's useful life span; (6) simplification of product disassembly; (7) design for reuse; and, (8) design for recycling (UNEP, 1997). In practice, eco-design integrates multifaceted aspects of design and environmental considerations and involves human sustainability priorities together with business interrelations (Karlsson and Luttropp, 2006). Various eco-design techniques have been developed (e.g., Wimmer and Züst, 2003; Pochat et al., 2007), which can be classified broadly as guidelines/standards (e.g., BS 8887-1, ISO 14006, and UNE 150301), checklists (e.g., Smart ecoDesign™ checklists), comparative tools (e.g., Life cycle development strategy (LiDS) wheel and Eco-compass), and analytic methods (e.g., eco-indicators, Ecodesign Pilot, environmental effect analysis, environmental impact assessment, life cycle assessment (LCA), and material, energy and toxicity (MET) matrix). These techniques are employed to evaluate the environmental impact of products and improve the PDD process as well as the environmental performance of products (Luttrop and Lagersted, 2006; Casamayor and Su, 2013). However, from a practitioner's perspective, Knight and Jenkins (2009) found that eco-design techniques may not have been widely adopted by industries because such techniques are not necessarily generic and

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immediately applicable, but instead require some form of process-specific customization prior to use, which can, in turn, act as a barrier to adoption.

Although LCA is recognized as an effective method for evaluating the environmental burdens associated with a product, process, or activity, it is marginal as a design tool since there are certain limitations that make it impossible to carry out a detailed assessment in the early phases of the PDD process (Poudelet et al., 2012). LCA is a means of choosing pre-determined design options rather than generating environmentally compliant options (Deutz et al., 2013). The practice of product design is considered a critical determinant for a successful eco-design of products. However, previous research has shown that many existing eco-design techniques fail because they are aimed at strategic management or retrospective analysis of existing products but do not focus on design practices (Walker, 1998; Lofthouse, 2006). Deutz et al. (2013) argued that eco-design needs to extend beyond niche markets to achieve significant environmental goals. They also indicated that the existing eco-design literature is largely silent on design theory which is potentially a critical oversight since sustainability needs to be incorporated at the very outset of the design process as a functional requirement of the product. Eco-design should focus on the early design phase of products to identify functional, economic, and environmental problems, and any other associated risks (Jeswiet and Hauschild, 2005). Life cycle engineering (LCE) was first proposed in the mid-1990s (Ishii, 1995; Betz et al., 1998) and emerged in response to the need to develop life cycles that cause the lowest possible environmental impacts while still offering economic viability under the consideration of technical boundary conditions. It provides a means to reconcile the relationship between environmental implications and engineering requirements, and can be applied to developing eco-designs of products.

The implementation of eco-design requires a complex problem-solving process to provide products with descriptions of physical structures that perform specified functions with the considerations of economical reasonability, social compatibility, and ecological necessity. Within this context, the present paper offers a life cycle engineering (LCE) model for implementing eco-design, the purpose of which is to develop an effective eco-design technique that integrates the algorithm for inventive problem solving (ARIZ) and LCE into a holistic methodology. This model can be used to assist industries in developing eco-designs of products based on informed procedures. The remainder of this paper is organized as follows. Section 2 introduces the materials and methods including LCE, ARIZ, and the proposed ARIZ-based LCE model, respectively. Section 3 presents the results of applying the proposed model to implementing eco-designs of products through a case study of an in-flight meal service. A discussion is given in Section 4 and conclusions and recommendations for further research are offered in Section 5.

2. Materials and methods

2.1. Life cycle engineering (LCE)

Life cycle engineering (LCE) is a practical tool for analyzing product life cycles through choices about product concepts, structures, materials, and processes. It refers to engineering activities that include the application of technological and scientific principles to the design and manufacture of products with the goal of protecting the environment and conserving resources, while encouraging economic progress (Jeswiet, 2003). LCE has been widely used in related research areas since the mid-1990s (Gu and Sosale, 1999; Saur et al., 2000; Ribeiro et al., 2008; Peças et al., 2009). In the literature, there are three main research branches under the scope of LCE: (1) definition of guidelines and frameworks fostering the application of LCE philosophy in the early design phase of products; (2) development of design strategies and approaches aimed at the implementation of LCE principles into a product to improve reliability; and, (3) development of tools and models that apply the LCE principles to compare alternatives during the product or process design phase (Peças et al., 2009).

LCE can be defined as a decision-making methodology that considers technical performance, economic viability, and environmental sustainability throughout the duration of a product life cycle (Betz et al., 1998; Wanyama et al., 2003). It provides informed decisions for product developers to analyze and assess products with an end-to-end perspective (Zhu and Deshmukh, 2003). According to the LCE guidelines proposed by Cooper and Vigon (2001), the LCE framework includes the following four steps: (1) targeting the assessment; (2) preliminary assessment; (3) detailed assessment; and, (4) developing specifications. The first two steps are classified as the option definition, which refers to technology selection and changes, and involves the development of technical order. The key point of the option definition is to make decisions concerning the use of materials, techniques, and equipment. The latter two steps relate to specification development, which supports the development of process order. Detailed information about the life cycle is used to refine preferred engineering options, and requirements for improvement are addressed to the greatest extent possible.

Previous research has indicated that decisions made at the design stage influence 70–85% of the total cost of a product (Daetz, 1987; Sheldon et al., 1990; Boothroyd et al., 2001; Hauschild et al., 2005) as well as its technical performance and environmental impact (Graedel and Allenby, 2002; Wanyama et al., 2003; Jeswiet and Hauschild, 2005). Traditional engineering analysis focuses primarily on a product's technical performance. LCE incorporates the three dimensions of analysis by which the examination of the technical, economic, and environmental dimensions provides an in-depth insight and a solid foundation for decision making to scrutinize the tradeoffs and implications of product design alternatives (Fava et al., 2000; Wanyama et al., 2003). The application of LCE involves the conceptual combination of life cycle assessment (LCA), life cycle cost (LCC) analysis, and technical evaluations, ensuring that all critical factors are assessed within the framework of decision-making with a view toward sustainability (Ribeiro et al., 2008; Pecas et al., 2009). It provides a comprehensive methodology to assess earlier engineering decisions, which in turn guide the expansion or contraction of the coverage to ensure that the broadest set of improvement opportunities and substantial environmental implications are considered. However, there are many practical barriers to a product's life cycle design, and some conflicting problems can even influence the implementation of eco-design (Van Hemel and Cramer, 2002). Consequently, the development of an effective method to resolve conflicting problems and provide practicable strategies for finding solutions continues to be a critical issue for both academics and practitioners in fields related to environmental design and management.

2.2. Algorithm for inventive problem solving (ARIZ)

TRIZ, a Russian acronym, translated into English as "Theory of Inventive Problem Solving (TIPS)", was introduced by Altshuller and his colleagues in the mid-1940s (Altshuller, 1988). It is a scientific methodology for creative problem solving, which seeks to eliminate conflicting problems and provides a range of strategies for finding solutions in the PDD process (Allshuller, 1996). The philosophy of TRIZ is based on five key elements, namely ideality, functionality, resources, contradiction, and evolution, which