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Innovative Applications of O.R.

A case study of an integrated fuzzy methodology for green product development ☆

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ABSTRACT

Green product development has become a key strategic consideration for many companies due to regulatory requirements and the public awareness of environmental protection. Life cycle assessment (LCA) is a popular tool to measure the environmental impact of new product development. Nevertheless, it is often difficult to conduct a traditional LCA at the design phase due to uncertain and/or unknown data. This research adopts the concept of LCA and introduces a comprehensive method that integrates Fuzzy Extent Analysis and Fuzzy TOPSIS for the assessment of environmental performance with respect to different product designs. Methodologically, it exhibits the superiority of the hierarchical structure and the easiness of TOPSIS implementation whilst capturing the vagueness of uncertainty. A case study concerning a consumer electronic product was presented, and data collected through a questionnaire survey were used for the design evaluation. The approach presented in this research is expected to help companies decrease development lead time by screening out poor design options.

1. Introduction

Due to increasing awareness of environmental issues, green product design (e.g., carbon reduction) has been a challenging new area of inquiry. There are many tools for green product design, some as simple as a checklist or the Materials, Energy, and Toxicity (MET) matrix. Among them, Life-Cycle Assessment (LCA) has gained noteworthy attention. LCA is a scientific model used to analyse the environmental impacts of a product by taking its whole product life cycle, including material selection and production, manufacturing, usage, delivery, end-of-life treatment, and so on, into consideration (Hawkins, Hendrickson, Higgins, Matthews, & Suh, 2007; Yung et al., 2012). Conducting an LCA can help designers understand the environmental impacts of a design by quantifying the secondary (i.e., undesired) outputs of the whole life cycle and then converting them into measureable impact items for analysis (Cerdan, Gazulla, Raugei, Martinez, & Fullana-i-Palmer, 2009). LCA has been employed in various applications such as the electricity market (Stoppato, 2008), packaging materials (González-García et al., 2011), building projects (Tsai, Yang, Chang, & Lee, 2014), and so on.

Despite the popularity of LCA, a recent survey indicated that it is ranked as only the ninth most popular tool for eco-design (Knight & Jenkins, 2009). In contrast, some qualitative tools, such as the aforementioned checklist, guidelines, and simple analytical tools, such as MET, are voted as more popular than LCA. This may be partly attributed to the shortcomings of LCA. A survey indicated that 68% and 63% of respondents considered LCA time-consuming and costly, respectively (Cooper & Fava, 2008). In addition, accuracy of the data collection is also a barrier to successful LCA, and thus some studies are conducted taking this into account (e.g., Chan, Wang, White, & Yip, 2013). Handling data uncertainty and inaccuracy are important in the design stage because the final options are often not well-defined at that point. Furthermore, modelling or coding of the LCA required sophisticated, and usually proprietary, software (Favi, Germani, Marconi, & Mengoni, 2012; Vallet et al., 2013). In summary, conducting an LCA is not an easy task.

Therefore, there is a need to develop innovative approaches for, or to supplement, LCA. In this paper, a screening approach that can alleviate the shortcomings of LCA is proposed. To be precise, a hierarchical structure is employed to represent the life cycle of a

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product design in order to break down the complex problem into such a hierarchy. Then, fuzzy logic is used to take uncertainty into consideration as a screening tool. A hybrid, two-step approach is adopted (details to be discussed in Section 3). The proposed approach can be used as a screening tool to reduce the number of eco-design options and to identify key improvement areas. It is particularly useful in the early stages of design when different options can be evaluated and screened out. The rest of the paper is organised as follows. Section 2 briefly reviews the two methods employed in this study, followed by the descriptions of the model in Section 3. Then, Section 4 presents how the method can be applied in a real-life case study in selecting eco-design options. Numerical examples are provided in this section. The findings are then discussed in Section 5, and Section 6 concludes this paper.

2. Literature review

In recent years, there has been an increasing awareness of environmentally conscious practices (Carter & Carter, 1998; Rao & Holt, 2005; Sarkis, 1998; Yung et al., 2011). These practices include environmentally friendly design (sometimes referred to as eco-design), green procurement, sustainable operations, and a number of end-of-life practices such as recycling and remanufacturing. Environmental awareness may be a consequence of regulatory pressures to protect the environment. For example, the European Council's directive (2009) on energy related products (ErPs) requires manufacturers to comply with eco-design principles in order to sell their products to the European Union. Preventive rather than corrective actions should be taken as early as possible during the design phase of ErPs in order to identify and reduce environmental impact of the product's whole life cycle. This practice is becoming an important element in new product development. Decisions regarding raw materials selection, electricity consumption during use phase, packaging design, end-of-life treatment, etc. can potentially have a profound environmental impact. Adding eco-design principles to the design process may further burden organisations. On the other hand, however, it also helps to boost the progression of organisations to reduce adverse effects on the environment (Zhu & Sarkis, 2003).

In fact, the ErP directive is not the only regulation that can be found in the electronics industry. In recent years, other regulations have included the Waste Electrical and Electronic Equipment (WEEE) Directive, the Restriction of Hazardous Substances (RoHS) Directive and also the aforementioned ErP Directive (Trappey, Ou, Lin, & Chen, 2011). Given its short life cycle, the electronic industry is considered one of the fastest growing streams of waste generation (Gurauskienė & Varžinskas, 2006). If an electronic product cannot comply with any one of these directives, it is prohibited from being traded in the member states of the European Union. There is, however, no universally applicable tool to show compliance with these regulations; thus, the ErP Directive was created partly to address this issue (Yung et al., 2011). This is the motivation for this study's proposal of an LCA-based fuzzy methodology for green product development.

LCA is a systematic and scientific tool that can help designers analyse the environmental impact of a product and has been applied in various applications over the last three decades (Guinée et al., 2011). In an LCA, a product's whole life cycle is taken into consideration (Junnila, 2008). This means that LCA can provide the designers a complete view of the environmental output and, hence, the impacts of the product. Because of this unique feature, LCA has attracted increasing attention from both researchers and practitioners, and numerous studies can be found in the literature (e.g., Bovea & Gallardo, 2006; Kobayashi, 2005; Thoming & Erol, 2005). LCA may also be employed to address legislative mandates, especially in light of the requirements introduced in the European Union (e.g., the ErP directive) (Trappey et al., 2011; Yung et al., 2012).

In essence, LCA involves multiple life cycle phases and requires the assessment of different environmental aspects (European Council, 2009). It is not uncommon that decision-making problems involve multiple criteria. The problems are even more difficult to address if some of the criteria are qualitative in nature. Saaty (1978) developed a well-known Analytic Hierarchy Process (AHP), which can handle such Multi-Criteria Decision-Making (MCDM) problems. The basic idea is to represent such problems by a hierarchical structure with different criteria and sub-criteria. Then, pairwise comparisons among those criteria are performed so that the weightings of the criteria (or priority in some applications) with respect to the problem can then be estimated. AHP is one of the widely used approaches to prioritise multiple factors that can affect decisions involving multiple judging criteria, and tradeoffs can always be found between different factors (Tan, 2005). Applications of AHP are numerous (Ho, 2008).

Although the discrete scale of AHP has the advantage of simplicity and ease of use for pair-wise comparison of alternatives, it has often been criticised from several perspectives in the literature (Bana e Costa & Vansnick, 2008; Belton & Stewart, 2002; Smith & von Winterfeldt, 2004). One of main criticisms is that AHP cannot handle the uncertainty and ambiguity present in deciding the ratings of different attributes (Chan & Kumar, 2007). Uncertainty, which comes from inaccurate measurement, lack of data, model assumptions, etc., often complicates the interpretation of outcomes of LCAs (Huijbregts, 1998). On the one hand, not addressing the uncertainties of LCAs will call into question the outcomes of LCAs. On the other hand, incorporating uncertainty into the LCA will improve the value of its outcome but make it more complicated to perform. It is acknowledged in the literature that quantifying uncertainties in LCA will support informed decision making and prevent erroneous decision making that might result from neglecting uncertainties (Cowell, Fairman, & Lofstedt, 2002; Lenzen, 2006). Another stream of research uses fuzzy logic, which can handle uncertain information, to mitigate this weakness (Zadeh, 1965). In this paper, the two approaches employed are Fuzzy Extent Analysis and Fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS). The former was developed by Chang (1996) and the non-fuzzy version of the latter was introduced by Hwang and Yoon (1981). This section briefly summarises the two approaches and provides reasons for why an integrated approach is needed.

The first application (or evolution) of fuzzy AHP is to replace deterministic values in the pairwise comparisons process with linguistic parameters (e.g., more important, very important, and so on), which are characterised by fuzzy membership functions (Van Laarhoven & Pedrycz, 1983). Later, Chang (1996) developed the Fuzzy Extent Analysis to help formulate the multi-tier fuzzy decision-making process. Like the basic fuzzy AHP, the fuzzy judgement matrix is first constructed with the help of linguistic parameters. Then, the synthetic degree value is calculated (instead of defuzzifying the matrix). These values are also fuzzy numbers, and because of this analysis, the method is called extent analysis. The main advantage of this method is that the computational effort is reduced. Since its inception, the method has been used in many applications. For example, Kahraman, Cebeci, and Ulukan (2003) applied this method for the supplier selection problem using three main criteria: supplier criteria, product performance criteria and service performance criteria in the hierarchical model. Lee, Kang, Hsu, and Hung (2009) employed a similar approach to analyse the green supplier selection problem in the hi-tech industry. Environmental factors, such as green product development, environmental management, and so on, are added to the hierarchical