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A multi-objective model for selecting design alternatives and end-of-life options under uncertainty: A sustainable approach

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ABSTRACT

Sustainable product design, which focuses on evaluating the future impacts of products at the design stage, is an important task for the achievement of sustainability goals. A product's designer has significant freedom at the design stage, so end-of-life (EOL) considerations can be taken into account at this stage. This paper presents a bicriteria stochastic optimization model based on individual extended producer responsibility to improve product EOL management by considering life cycle issues at the product design stage. The objectives are the maximization of the total profit and the minimization of the product's environmental impact with respect to regulatory restrictions, such as the waste electrical and electronic equipment directive. Uncertainties are considered, to mitigate risks of unknown information that may come to light in the future. Various risk measures are used in the model. A simulation-based method is presented to determine the model's Pareto optimal solutions. A hypothetical case study is provided, and several sensitivity analyses are carried out. Results show that the regulatory restriction strongly affects the number of Pareto optimal solutions. Moreover, taking environmental considerations into account results in a significant profit reduction. It is also observed that using different risk measures yields considerably different sets of Pareto optimal solutions.

1. Introduction

The subject of sustainable development (SD) is to pay attention to the future impacts of our activities in order to sustain finite resources. An important task in moving toward SD is to change production and consumption behaviors. Hence, the number of environmental policies and legislations has increased in recent decades to focus on reducing products' environmental impacts throughout their life cycle stages: raw material extraction, design, manufacturing, consumption and end-of-life (EOL) management. The latter has attracted more attention in the last few decades because of environmental concerns and legislative constraints. Waste management has been developed to resolve these challenges. Formerly, producers were mostly focused on the quality and cost of their products, and environmental issues were considered only in 'end-of-pipe' actions to meet environmental regulations. However, ignoring the future consequences of product design during its life cycle made most EOL management programs inefficient. For example, in most computers, the main board is made of incompatible materials. Metals and plastics are put together in such a way that separating and recycling them are impossible, or at least very costly (Shokohyar et al., 2013). Hence, environmental concerns progressively turned into focusing on other drivers, namely, extended producer responsibility (EPR) and environmental labeling. EPR is a method for integrating SD principles into business. It implies that the producer is responsible for the environmental impact of its product during the entire life cycle, from resource extraction to EOL (Nnorom and Osibanjo, 2008). Nowadays, many producers in a number of countries are organizationally and financially responsible for the take-back of their products at the end of their life cycle (Dehghanian and Mansour, 2009). Also, a number of companies, especially in Europe, have made significant innovations in their products' life cycle management. These innovations seem to have much wider effects than just satisfying regulations. As a result, better products and processes are being designed that are more competitive in the universal market (Nnorom and Osibanjo, 2008). Van Rossem et al. (2006) found that the emergence of EPR resulted in various environmental policy-making trends. These trends highlight preventive measures over curative approaches, enhance life cycle thinking and change the "command-and-control" approach to a non-prescriptive, goal-oriented one. Its incentive mechanisms make industries to continuously improve their products and processes'.

A fundamental issue in designing and implementing EPR is whether the producers' responsibility should be individual or

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collective. In the former case, producers pay specifically for the EOL processing of their own brand products. In the latter situation, all producers cooperatively share the costs of all their product waste management (Nnorom and Osibanjo, 2008). It has been argued for many years that, in order to effectively enhance design, an individual responsibility system is needed, as opposed to a collective responsibility system in which producers achieve their goals jointly. In collective systems, the advantages of investing in product improvements do not go only to the company itself, but are shared and diluted among all producers in the group (Lindhqvist and Lifset, 2003). As an example, when a producer pays the recycling costs for its own products, it benefits from designing products that are more easily and cheaply recyclable. However, there is no incentive for producing products with more recyclability features if all producers pay the same recycling fees on the basis of their market share (Nnorom and Osibanjo, 2008).

As EPR emphasizes the responsibility of producers to reduce the EOL environmental impact, producers should move toward enhancing the efficiency of their product recovery processes by integrating EOL management considerations at the product design stage, in order to achieve a more efficient and manageable EOL phase. The importance of this integration becomes clearer in the real world, where not only design decisions affect the EOL outcome, but EOL decisions also influence the design decisions. For example, if a designer knows that a part will have to be disposed of at its EOL, s/he can select less durable materials with a similar performance in order to avoid over design, compared to cases where the part will be remanufactured. As another example, two adjacent parts that are going to be recycled should be made of compatible materials to be managed efficiently at EOL. Hence, many researchers have focused on design for disassembly. Kuo et al. (2001) provided a review paper on product disassembly and EOL. Tsai and Zhang (2000) presented a graph-based heuristic approach to perform a disassembly analysis for electromechanical products. The results of the analysis can be used by designers to evaluate the 'disassemblability' and 'recyclability' of products, and the desirable changes can then be made at the design stage. González and Adenso-Díaz (2005) proposed a model in which the EOL strategy and the depth of disassembly inside the structure leading to the highest profit are determined, given the product's structure (obtained from its bill of materials). Behdad et al. (2010) developed a new method for solving disassembly sequencing and EOL decision making simultaneously, for multiple products, by using a mathematical model to determine the best subassembly level and the best EOL decision for each subassembly. Behdad and Thurston (2012) addressed a problem involving disassembly, component repair or replacement, and reassembly. Their method considers tradeoffs between cost and probability of damage during the process.

Design for EOL is another approach presented by Li et al. (2008) to design products for ease of disassembly, reuse, remanufacture and material recovery. Mascle (2013) developed the methodology of "design for rebirth" in order to design a product according to objectives defined by its EOL and generic engineering requirements. Krystofik et al. (2015) suggested a method for encouraging product remanufacturing and waste generation reduction by combining the economics of green design with intellectual property rights as an instrument for sustainable waste management. Ardente et al. (2015) studied the relations between EOL treatments, product design and relevant policies. They concluded that it is necessary to develop product and waste policies interactively to guarantee that regulatory requirements will be satisfied and to maximize environmental and economic performances for both producers and recyclers.

Some of the most challenging items in the waste stream are electrical and electronic equipment (EEE); because of their growing quantity and diversity, and their burden on the waste stream. Thus, issues related to their management need special attention (Shokohyar and Mansour, 2013). The introduction of the waste electrical and electronic equipment (WEEE) directive in the EU, whose primary aim was to reduce the impact of disposing of EEE, led to more responsible behavior by producers and consumers (Nnorom and Osibanjo, 2008). This directive is based on individual responsibility (Lindhqvist and Lifset, 2003) and was a major move toward sustainable resource and waste management practices. Umeda et al. (2013) proposed a design support method for improving the recyclability of electronic and electrical products with a change of material compositions and EOL options. The method estimates the recycling rate of a product based on its EOL option and supports the designer in generating design alternatives, which in turn, increase the recycling rate. Kwak and Kim (2010) studied the potential role of product design (design for upgrade, repurpose and commonality) in the prevailing obstacles to e-waste recovery. They proposed a framework to analyze the effects of product design differences on a product's recovery, as well as the desirable architectural characteristics from the EOL perspective. Ongondo and Williams (2011) assessed the voluntary mobile phone take-back network in the UK and concluded that further exploration of alternative approaches to managing EOL mobile phones is needed.

A remarkable problem in EOL management is the existence of returned products with identical design but with a different status at EOL facilities. This makes implementing the previously determined EOL options impossible, as parts with similar design may require different EOL processing. Many researchers considered uncertainty in their EOL management research without including product design. For example, Li and Azarm (2000) considered uncertainties in the market size, production cost, selling price, and discount rate of a product. Inderfurth et al. (2001) investigated the uncertainty of returns and of demands for the different serviceable options. Jin et al. (2011) considered optimal reassembly decisions for modular products, with both supply and demand uncertainties in terms of timing and quality. Researchers have implemented simulation models at an early design stage to overcome the problem of verifying the outcome of a decision before taking it to the real world considering its emergent uncertainties as well as product design complexity. Some reasons for the complexity of design problems are as follows: it is concerned with multidisciplinary knowledge (Tang and Wenhui Fan, 2010), product life cycle phases are composed of interrelated information and process elements (Xiao et al., 2010), and unexpected changes affect the models (Pierreval and Durieux-Paris, 2007). For example, a method was developed by Wang and Zhang (2012) to simulate design problem which covers many traditional disciplinary areas. Many issues are addressed in their work, such as system modeling, the use of computing technologies and the runtime interaction between subsystem models. As another example, Moon and Mavris (2011) pursued a modeling and simulation method to perform a rigorous damage or failure analysis in a design process, especially in the early design phase.

In the above-mentioned research literature, there is a gap as regards the need for a decision-making tool for designing complex products composed of multiple parts, and assigning EOL options to each of the parts, taking into consideration environmental regulations as well as business goals. The reason for this is that when considering EOL activities, only simple products can be processed by human insight without accessing detailed life cycle information (Um et al., 2008). Nevertheless, to the best of the authors' knowledge, such an analytical model, based on individual EPR, which integrates uncertain EOL management issues in a product's design process by simultaneously considering profit, environmental impact and legislation, has not been developed by the researchers in this area. Thus, this paper presents a novel