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A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility

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ABSTRACT

This paper integrates two decision problems, namely, the design alternative selection and EOL option determination, for a family of products based on individual producer responsibility in the entire life cycle considering possible uncertainties. To address three pillars of sustainability (economic, environmental, and social), three objectives are considered: the maximization of the producer's profit, the minimization of the environmental impact, and the maximization of the social impact. Two constraints to control recovery and recycling rates are considered, which are usually imposed by legislative directives. A simulation-optimization model is developed to formulate and solve the model. An example based on a real-world case is provided to illustrate the application of the model. The proposed model is a useful tool for producers to evaluate the EOL performance of their products and to analyze the effect of EPR goals or regulations on their profitability, and for policy makers to predict the response of producers to a given package of circular-economy strategies.

1. Introduction

Responsible consumption and production is one of the 17 goals considered for Sustainable Development (SD) (UN, 2015). In order to reach this goal, traditional manufacturing disciplines should be changed. The current paradigm of production is mainly based on the linear economy, that is, "take, make, and dispose". However, the circular economy additionally considers the recovery phase to close the global energy and material loops. This can be achieved by designing products and services that reduce waste and minimize negative sustainability impacts.

In order to make European businesses and consumers shift towards a stronger level of the circular economy, the European Commission (EC) has adopted a new action plan named Circular Economy Package. This promotes closing the loops of product lifecycles and brings benefits for both economy and environment (by extracting the maximum value from raw materials, products, and waste; fostering energy savings; and reducing Green House Gas emissions). In 2015, the package was amended to include eco-design rules to make products more recyclable, and new targets were assigned for recycling and landfill rates. The EC presented an action plan, and introduced new targets for some directives by adding new legislative proposals; for more details see Bourguignon (2016). Such legislations make manufacturers responsible for the End-Of-Life (EOL) stage (Mascle, 2013).

Another driver for companies is to consider Extended Producer Responsibility (EPR), which integrates SD principles into their business. The EPR implicates that a producer is responsible for the environmental impacts of its products during their entire life cycles (Nnorom and Osibanjo, 2008). The EPR can be implemented as either *individually* or *collectively*, called the Individual Producer Responsibility (IPR) and the Collective Producer Responsibility (CPR). Under the IRP, each producer individually bears the cost of EOL treatment of its own brand products, while under the CPR, multiple producers cooperatively share the costs of managing all of their EOL products (Massarutto, 2014). Under the IPR, a producer may have sufficient interest to invest in designing more sustainable products, which are more easily and cheaply recyclable. However, under the CPR there is not enough incentive for such investment as the other producers benefit from this improvement at the EOL stage while they do not share the required investment (Lindhqvist and Lifset, 2003). In fact, under the CPR there is no incentive for producing products with more recyclability features if all producers pay the same recycling fee based on their market share (Nnorom and Osibanjo, 2008). The European Union (EU) converted the principle of the EPR to regulations in 2003 by introducing the Waste Electric and Electronic Equipment (WEEE) directive, which was recast in 2012 (Favot, 2014).

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As discussed above, integrating EOL-management issues with decisions made at the design stage is advantageous under the IPR. However, a remarkable issue in this integration at the design stage is the presence of uncertainty on what will occur at the EOL stage. Product units with identical design will have different statuses when reaching the EOL stage. Customers in various market segments may have different consumption behaviors. They may be careful or careless when using a product, which results in different quality levels at the EOL stage. In addition, they may be likely to return or not to return the used product units to EOL facilities or after-market sales. Hence, the relevant uncertainty should be considered to control the possible future risks in integrating design and EOL decisions.

The aim of this study is to develop a multi-objective stochastic optimization model that simultaneously integrates two problems of selecting design alternatives and planning EOL options for a family of products produced by a single producer under the IPR, where each product part can have finitely many design alternatives and EOL options. The objectives are maximizing the producer's total profit, minimizing the environmental impact, and maximizing the social impact while satisfying two constraints on the recovery and recycling rates. Fig. 1, schematically illustrates the components of the developed model.

Because of the complexity caused by the uncertain quality of EOL product units, the functions used in the objectives and constraints have no closed-form formulas and they are estimated by a simulation model. To find approximate Pareto optimal solutions of the model, the multi-objective Simulated Annealing (SA) is used (Rosen and Harmonosky, 2005; Ahmed and Alkhamis, 2009). To illustrate the applicability of the proposed model, it is applied to a hypothetical case study on a cell phone, and trade-offs among the three objectives are analyzed.

In addition to producers, policy makers can also use our proposed model for evaluating the effectiveness of alternative policies. They can simulate and predict a producer's behavior when facing their new regulations or policy strategies such as introducing new or amending in mandatory targets, taxes/subsides, penalties, and collection schemes. In our numerical study, it is shown how the model can be a useful instrument for studying the effect of new circular-economy regulations on producers.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the problem definition and mathematical formulation. Section 4 explains our solution method based on simulation-based optimization. Section 5 provides a hypothetical case study, and Section 6 concludes the research results.

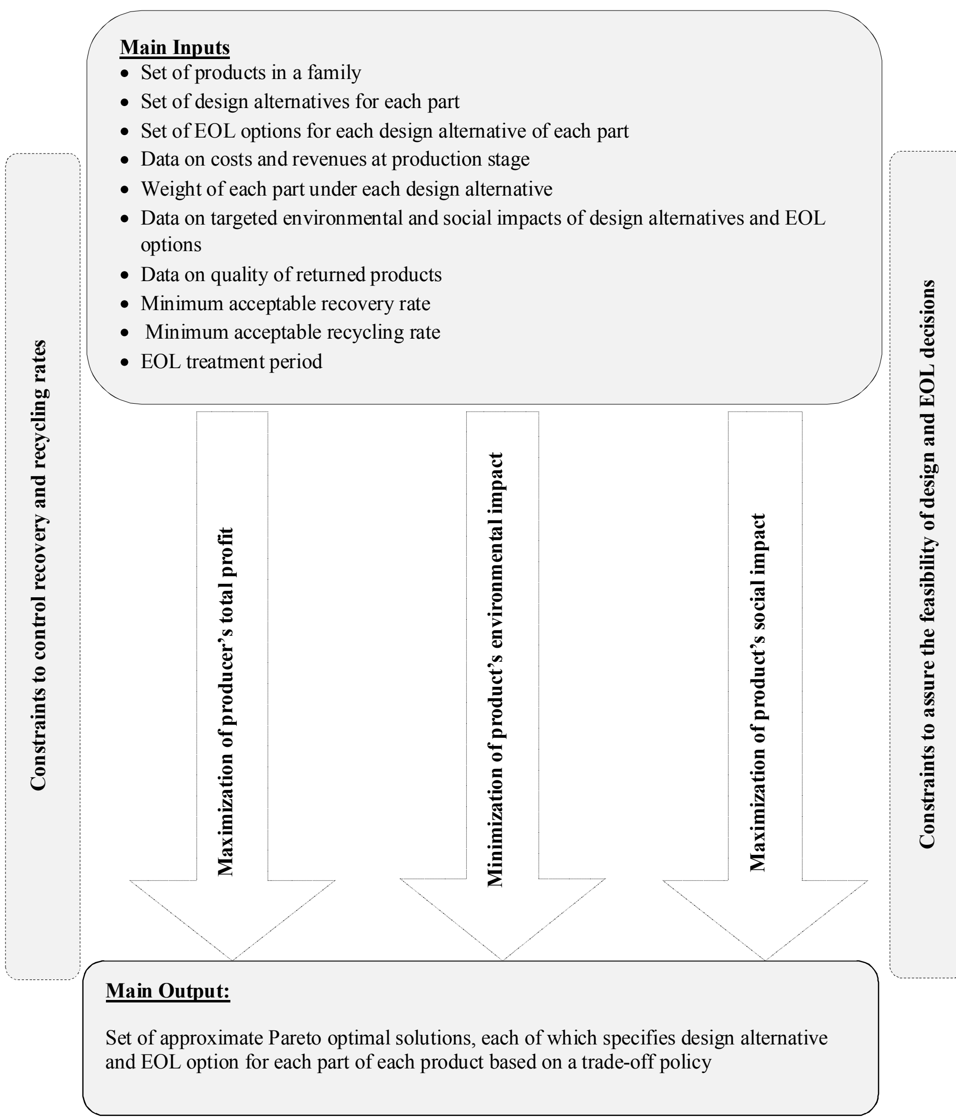

Fig. 1. The proposed model for integrating design and EOL considerations.