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# A multi-objective decision making approach for dealing with uncertainty in EOL product recovery

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ABSTRACT

Recently, product recovery is considered as a promising approach to increase the economic benefit and reduce the environmental impact of products at the end-of-life (EOL) phase. After disassembly, each component of an EOL product can have different EOL options such as reuse, remanufacturing, recycling and landfill. Depending on the selected EOL options of components, the recovery value of the EOL product will be different. Thus, it is necessary to develop a decision-making method for EOL product recovery in order to select the best EOL options of components for maximizing the recovery value. However, EOL product recovery is usually characterized by a high level of uncertainty due to disassembly operations, product quality conditions and external attributes such as consumer preference, market requirement and price. Limited research has examined uncertainty of EOL product recovery during the EOL phase. Moreover, there has been a lack of research on dealing with uncertainty of EOL product recovery in a quantitative manner.

To deal with this limitation, taxonomy of uncertainty metrics is developed through the whole EOL product recovery. The quantifications of uncertainty measures of EOL product recovery are formulated by different dimensions of quality condition, disassembly complexity and EOL recovery. A multi-objective decision making approach for dealing with uncertainty in EOL product recovery is proposed. Artificial bee colony (ABC) algorithm is employed to find the best EOL options of components with maximum feasibility and profit for EOL product recovery. A typical motor is used as a case study to illustrate the methodology. This paper addresses the uncertainty involved in determining the EOL options of components for EOL product recovery. The proposed approach closes a gap in the current EOL product recovery assessment criteria. By comparing to those selections of EOL options without considering uncertainty, the results show that considering uncertainty turns EOL product recovery more realistic and can give several good alternatives to decision makers.



## 1. Introduction

End-of-life (EOL) product recovery has been becoming more important over the past years, both from the environmental and emission reduction perspective as well as the economic and resource saving at the EOL phase. Product disassembly planning and EOL option selection are implemented in order to identify an appropriate EOL product recovery strategy. In general, product disassembly planning is defined as the organized process of taking apart a systematically assembled product. After disassembly, the EOL options of components are determined by EOL option selection. Each component of an EOL product can have different EOL options, for example, component can be reused without any treatment, recycled to recover its material elements, or landfill. Thus, the recovery value of the EOL product will be different with different selection of EOL options. For example, reuse of some components might be more cost-effective than disposal (Mangun and Thurston, 2002). Thus, at the beginning of the EOL phase, it is essential to determine the best EOL options of components of an EOL product in order to maximize the recovery value of an EOL product.

In general, there are several criteria to evaluate the recovery value of an EOL product such as cost and quality. However, EOL product recovery involves different sources of uncertainty such as product conditions, hazardous items, component damaging, recycling material purity requirements and disassembly time. The

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**Nomenclature**

| | |
|---|---|
| $C$ | The cost of selected EOL options |
| $C_{set}$ | The set of components |
| $c_{ru,i}$ | The cost of $c_i$ for reuse |
| $c_{re,i}$ | The recycling cost of $c_i$ |
| $c_{dp}$ | The disposal cost |
| $F$ | The feasibility of selected EOL options |
| $F_i$ | The corresponding uncertainty of the selected EOL option of $c_i$ |
| $G_p$ | The $p$-th assessment grade |
| $P$ | The profit of selected EOL options |
| $p_{c,i}$ | The given price of $c_i$ |
| $p_{m,i}$ | The given price from the recycling of the material per unit weight of $c_i$ |
| $R$ | The revenue of selected EOL options |
| $t$ | The engineer index |
| $p$ | The assessment grade index, $p = 1,2, \ldots,5$ |
| $r_1^{QC}$ | The physical condition attribute |
| $r_2^{QC}$ | The technical obsolescence condition attribute |
| $r_1^{DC}$ | The joint type of component attribute |
| $r_2^{DC}$ | The technical complexity attribute |
| $r_1^{ER}$ | The material environment impact attribute |
| $r_2^{ER}$ | The customer reference attribute |
| $x_{r,i}$ | Binary variable (1 if $c_i$ is destined for reuse; 0 otherwise) |
| $x_{d,i}$ | Binary variable (1 if $c_i$ is destined for disposal; 0 otherwise) |
| $\omega_j$ | the relative weight of the $j$-th uncertainty attribute of the criterion |
| $R_{ij}^t$ | The belief distribution of the $t$-th engineer assesses the $j$-th uncertainty attribute of a criterion |
| $m_{ij,p}^t$ | The basic probability mass of the assessment that the $t$-th engineer gives on $R_{ij}^t$ |
| $m_{ij,G}^t$ | The remaining probability mass of the assessment that the $t$-th engineer gives on $R_{ij}^t$ |
| $\overline{m}_{ij,G}^t$ | The remaining probability mass caused by the relative importance degree of the $j$-th attribute |
| $\tilde{m}_{ij,G}^t$ | The remaining probability mass caused by the incompleteness of the assessment on the $j$-th attribute |
| $\psi_{ij,p}^t$ | The $t$-th engineer's belief degree that assess $R_{ij}^t$ to assessment grade $G_p$. |
| $\psi_{i,p}$ | The belief degree engineer group assess to grade $G_p$. |
| $\psi_{i,G}$ | The belief degree engineer group. |
| $K$ | Coefficient, reflects differences and conflicts among assessments made by the members of engineer in numerical values |
| $u(G_p)$ | The assessment grade mapping function |
| $U(R_i)$ | The belief distribution of combined assessment of a criterion for $c_i$ |
| $\varpi$ | Coefficient, $\varpi > 1$ |

uncertainty may decrease the profitability and feasibility of disassembly and product recovery operations. Therefore, uncertainty should be considered when EOL options of components are determined.

Although some stochastic modeling approaches can be used to handle these issues based on sufficient historical data for uncertain parameters, it is difficult to formulate actual and exact random distribution functions due to the lack of reliable historical data. Therefore, the aim of this paper is to develop a method to deal with uncertainty in EOL product recovery in a quantitative manner, which can make EOL product recovery as feasible and profitable as possible. In comparison with the existing research, there are three contributions of this paper. 1) In order to deal with uncertainty in EOL product recovery, this paper develops taxonomy of uncertainty metrics, which encompassing the entire EOL product. The quantifications of uncertainty measures of EOL product recovery are formulated by different dimensions of quality condition, disassembly complexity and EOL recovery. 2) To solve the EOL option selection problem under uncertainty, this paper establishes a general model of EOL options selection with maximum feasibility and maximum profit for EOL product recovery. A decision-making method based on artificial bee colony (ABC) algorithm is proposed to find the best EOL options of components. 3) By comparing to those selections of EOL options without considering uncertainty, this paper shows that considering uncertainty turns EOL product recovery more realistic and can give several good alternatives to decision makers. It leads to the flexibility of decision making in EOL product recovery under uncertainty.

This paper is organized as follows: In Section 2, related literature is provided and the contribution of the study is clearly identified. In Section 3, taxonomy of uncertainty metrics of EOL product recovery is established. A general model for EOL option selection problem under uncertainty is elaborated and a multi-objective decision-making method based on ABC is presented in Section 4. Section 5 presents the solutions to a case study of EOL product recovery under uncertainty for a typical motor. Section 6 concludes this paper and describes future research.

## 2. Literature review

Recently, there has been growing interest in determining and selecting EOL options to address and meet practical requirements of EOL product recovery. Decision making methods are widely applied in EOL selection. Bufardi et al. (2004) proposed an assessment model of performances of EOL recovery options, where three criteria are considered: environmental criterion, social criterion and economic criterion. Ziout et al. (2014) collected influencing factors of EOL recovery and group influencing factors of EOL recovery into four major categories: engineering factors, business factors, environmental factors and societal factors. Ilgin and Gupta (2010) investigated the influences of environmental impact, quality, legislative factors and cost for EOL product recovery and divided them into qualitative and quantitative factors. Jun et al. (2007) presented an estimation model of the recovery value based on the degree of quality of component. Bakar and Rahimifard (2008) proposed an economic framework and modeled the total cost for different EOL options in EOL product recovery. Ravipudi et al. modeled the attributes that influenced the EOL options selection for a given product and developed a digraph to calculate the performance of the alternative product EOL options. Ghazalli and Murata (2011) presented an evaluation model of product recovery by integrating an economical cost model and an environmental cost model. Cheung et al. (2015a, b) presented an EOL product recovery cost estimation model based on a semi-automatic data searching method for products with low volume, high complexity and long life. Later, they proposed prediction model of product EOL costs at early design concept. On the other hand, a number of methods applies mathematical algorithms to select optimal EOL