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Product Redesign for Improved Value Recovery via Disassembly Bottleneck Identification and Removal

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Abstract

Making progress towards a circular economy requires the reuse of material/components to realize their maximum utility. Integrating end-of-life (EOL) considerations into the design of products will greatly facilitate the recovery of material/components at EOL, and enable their reintroduction into new product life cycles. Past research has largely employed qualitative or single objective oriented approaches for environmental product design. This paper presents a quantitative method for value recovery, in which disassembly bottlenecks are identified and removed by improving upon an existing design. The approach determines the value that can be recovered from EOL products through different EOL options. For a given EOL scenario, major bottlenecks are generally associated with joints, material incompatibility, and product architecture. Once the bottlenecks to rapid, cost effective dismantling of EOL products are identified, different design changes are considered to reduce the time/cost required to recover components/materials. To demonstrate the effectiveness of the method, a hard disk drive is used as a case study.

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Keywords: Design for Environment; Circular Economy; Recycling

1. Introduction

The circular economy principle requires the reuse of product end-of-life (EOL) materials/components to obtain maximum utility [1]. At present, product designers rarely give much consideration to how products will be managed at their EOL. Integrating EOL considerations into product design will greatly facilitate the value recovery of products at the end of their working lifespan.

There is a history of design philosophies, principles, and practices that seek to address environmental considerations during product design, e.g., “design for environment,” “eco-design,” “design for recycling,” and “design for disassembly” [2-10]. Often, these methods focus on the use stage of the product, and give little attention to the product EOL. When the product EOL stage is considered, emphasis is frequently limited to recycling, as opposed to recovering the maximum value from the used product. Moreover, many of these design methodologies take the form of guidelines and semi-quantitative methods.

Guidelines are generally qualitative principles and are widely utilized in industry. In the present context, guidelines are often suggestions that can be used to promote the recyclability of the components within a product. For instance, Dowie and Simon developed guidelines that covered three categories: materials, fasteners & connections, and product structure [11]. Rose et al. proposed a design advisor that guides designers to specify the end-of-life strategies [12]. Thorn developed a tool to assist designers to select product retirement strategy based on environment implication [13]. Sample guidelines include “Use materials which can be recycled,” and “Fasteners should be easy to remove.” A challenge associated with using guidelines to promote value recovery is the lack of clear operational definition. Words like “easy” and “good” have no communicable meaning, i.e., they lack the specificity needed for industrial implementation.

A common feature of semi-quantitative methods is that they seek to transform experiential or subjective observations

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into engineering characteristics that are represented quantitatively. Quality function deployment (QFD) is an example of a semi-quantitative method that may be used to support eco-design. Devanathan et al. developed a semi-quantitative eco-design methodology that can be used in the early design stages, using a combination of QFD and life cycle analysis [14]. QFD requires that designers determine which parts are most environmentally important and improve associated design features [15]. One drawback is that correlations established between environmental performance and engineering characteristics are based on experience or engineering judgment as opposed to rigorous analysis. Another drawback is the lack of solid links between design changes and environmental performance.

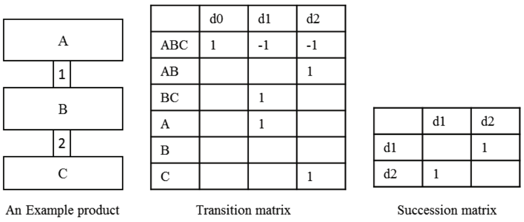
When EOL value recovery is considered, material, joint, and part configuration are often the targeted design features to be improved [16-19]. In the EOL stage, products will be dismantled into several modules in a certain sequence to obtain maximum profit. Recycling rate of products will be increased, if eliminating the incompatibility of material composition of each module that will be recycled for material can be done in design stage. Choosing easily detachable joints reduces dismantling time. Last but not least, ease of access to reusable components will minimize the chance that the components will be damaged during disassembly.

Unlike the impact of guidelines and semi-quantitative methods, the impact of designing features on EOL value recovery can be quantified. By quantifying, the ease with which a given design may be recovered, reused, remanufactured, or recycled, the environmental performance of a product may be evaluated, and the best candidate among alternative designs may be selected. For instance, a model was developed to calculate the recyclable mass of consumer electronic products and the economic value of any recovered materials [20]. For another instance, a product configuration optimization method was developed for application to EOL disassembly [21]. These methods are single design feature oriented, and other important design features are neglected.

As noted, it is necessary to improve multiple design features and quantify the effect of the change on value recovery. To fill the gap, this paper proposes a quantitative approach that considers design features: joints, materials, and product configuration. The approach begins by modeling the EOL product value recovery process using mathematical programming, then continues with removing disassembly bottlenecks based on EOL scenario analysis, and evaluates the value recoverability of a new design. A case study for a hard disk drive (HDD) is conducted to demonstrate the approach.

2. A Model for EOL Value Recovery

As stated in the authors' previous work, knowledge of key product, process and market information is essential to construct a model for EOL value recovery [22, 23]. Product information provides spatial constraints among components and material composition. The value of recycled or disposed components is reflected through the market demand and price. Process information shows existing technology and what tools are available to disassemble a product of interest. An example product is shown in Figure 1. The product consists of three parts A, B, C with joints 1 and 2. To proceed, information should be collected about material composition of each part, and what tools can be used to easily detach joints 1 and 2. In addition, check out possible EOL options of part A, part B, part C, component AB, and Component BC. The reason of investigation of components AB and BC is that each component may be the final EOL module for recycling or reuse. The definition of transition matrix describes all the possible dismantling operations when an EOL product is disassembled. To illustrate how to generate the transition matrix, take the example of removing A away from ABC (operation d1). In the column of d1, -1 indicates that ABC is disassembled and 1 means that BC and A are generated. The rest of entries are filled with zeros. "d0" is always to be conducted, which means that the entire product is given and will be shredded or disposed as a whole or disassembled to smaller modules. The definition of succession matrix describes flows of operations. In the case of the example product, the flows might be from d1 to d2 or from d2 to d1. The cost of dismantling is composed of base operation and transition cost coming from detaching joints, and changing tools and direction during the flow of operations.



	d0	d1	d2
ABC	1	-1	-1
AB			1
BC		1	
A		1	
B			
C			1

Transition matrix

	d1	d2
d1		1
d2	1	

Succession matrix

Fig. 1 An example product, transition matrix and succession matrix

A mathematical model for the dismantling may be constructed. The formation of problem is as follows.

Variables and Parameters:

1) I is the set of feasible subassemblies. The index i is used to refer to a specific subassembly.
2) J is the set of feasible disassembly operations. The index j is used to refer to a specific operation.
3) C is the cost matrix whose elements C_{jk} representing the transition cost from operation j to operation k.
4) E is the end-of-life option revenue matrix with elements E_{il} representing the revenue when subassembly i is processed to produce end-of-life option l.
5) S is the succession matrix with elements S_{jk}. $S_{jk} = 1$ means that operation k can follow operation j. Otherwise, operation k cannot be conducted after operation j.
6) T is the transition matrix with elements T_{ij}. The possible values for T_{ij} are -1, 1, and 0. When $T_{ij} = -1$, the jth operation will disassemble the ith subassembly. When $T_{ij} = 1$, it indicates that the ith subassembly will be released by the jth disassembly operation. The initial operation is to assume that a