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Simultaneous Selective Disassembly and End-of-Life Decision Making for Multiple Products That Share Disassembly Operations

Environmental protection legislation, consumer interest in "green" products, a trend toward corporate responsibility and recognition of the potential profitability of salvaging operations, has resulted in increased interest in product take back. However, the cost effectiveness of product take-back operations is hampered by many factors, including the high cost of disassembly and a widely varying feedstock of dissimilar products. Two types of decisions must be made, how to carry out the disassembly process in the most efficient manner to "mine" the value-added that is still embedded in the product, and then how to best utilize that value-added once it is recovered. This paper presents a method for making those decisions. The concept of a transition matrix is integrated with mixed integer linear programming to determine the extent to which products should be disassembled and simultaneously determine the optimal end-of-life (EOL) strategy for each resultant component or subassembly. The main contribution of this paper is the simultaneous consideration of selective disassembly, multiple products, and the value added that remains in each component or subassembly. Shared disassembly operations and capacity limits are considered. An example using two cell phone products illustrates application of the model. The obtained results demonstrate the most economical level of disassembly for each cell phone and the best EOL options for each resultant module. In addition, the cell phone example shows that sharing disassembly operations between different products makes disassembly more cost effective compared with the case in which each product is disassembled separately. [DOI: 10.1115/1.4001207]

1 Introduction

Several factors motivate environmentally conscious product stewardship, including legislation and consumer interest in "green" products [1]. In addition, some products reach the end of their first lifecycle with components or subassemblies that still contain a significant portion of the value added by the original manufacturing process [2]. This can create an economic incentive for developing product take-back systems.

However, there are several impediments to cost-effective take back. According to Kara et al. [3], disassembly is one of the significant cost drivers in end-of-life (EOL) decision making. Another impediment is that, unlike the original manufacturing process, the feedstock to take-back operations varies significantly, as many different models, ages, and conditions are returned to the manufacturer.

There are many issues to consider. Is it necessary or desirable to disassemble the product down to individual components? How can the disassembly processes be made more efficient? Can the same disassembly operations be carried out for different products by sharing disassembly operations? What EOL decisions should be made for each component or subassembly?

The goal of this paper is to help answer these questions. It presents a new method for solving disassembly sequencing and EOL decision making simultaneously for multiple products. A mathematical model is used to determine the best subassembly level for multiple products and the best EOL decision for each subassembly.

The remainder of the paper is organized as follows: Sec. 2 provides a brief review of related research, and then the transition matrix concept and EOL decision making are introduced in Sec. 3. Section 4 presents a new methodology for simultaneously considering partial disassembly and EOL decision making for multiple products. In Sec. 5, our solution technique is illustrated with a cell phone example. Finally, Sec. 6 concludes the paper.

2 Background

Although there is significant literature on design for sustainability or design for disassembly, here we focus on the following:

- optimizing EOL decision making
- disassembly sequence planning
- disassembly sequence planning based on optimum EOL strategy

2.1 Optimizing EOL Decision Making. According to the U.S. Environmental Protection Agency (EPA), about 8×10^9 tons of industrial waste is generated annually in the United States. More than 214×10^6 tons of these wastes are regulated by the Resource Conservation and Recovery Act (RCRA) as hazardous wastes [4]. In addition, legislation such as European legislation on end-of life-vehicle (ELV), waste electrical and electronic equipment (WEEE), and the restriction of use of certain hazardous substances (RoHS) have forced manufacturers to evaluate their products to determine the recyclability of their products and identify the presence of regulated and restricted substances [5].

Contributed by the Design for Manufacturing Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received May 28, 2009; final manuscript received February 1, 2010; published online March 30, 2010. Assoc. Editor: Jeffrey Herrmann.

There are several alternatives for a product at its EOL, including disposal, recycling, re-use, repair, or remanufacturing [6]. One of the most important decisions for manufacturers is determining which of these alternatives (or combination of them) achieve the maximum recovery value of the product.

Several models for determining the optimal EOL strategy for the components of a product have been developed. Mangun and Thurston [7] developed product portfolio approach that helps in determining the time at which a product should be taken back, and identifies the components that should be re-used, recycled, or disposed. The objective of the model is to maximize total multiattribute utility for a portfolio compromised of three distinct market segments (technophiles, utilitarian, and green consumers).

Park et al. [8] conducted a comparative evaluation of four decision making methods for a washing machine at its EOL. The four methods were a two-dimensional diagram, eco-efficiency, a monetary method, and multiattribute decision making (MADM). Since all four methods have advantages and disadvantages, they recommended using all four simultaneously when considering both environmental and economic impacts. Xing and Belusko [9] considered "design for upgradability" as a method to reutilize a product and proposed an algorithm for determining an optimal design solution for product upgradability characteristics.

Bufardi et al. [10] proposed a multicriteria decision aid to help decision makers in selecting the best compromise EOL alternative based on their preferences and the performance of EOL alternatives with respect to the relevant environmental, social, and economic criteria.

Pandey and Thurston [11] considered a situation of a product comprising a mix of re-used/remanufactured components and introduced a method for assessing the resulting effective performance of a product with different component ages. In another research, Pandey and Thurston [12] used a heuristic nondominated sorting genetic algorithm (NSGA) to identify the optimal component level EOL decisions when there is more than one stakeholder.

While all these methods address EOL decision making, they are restricted to analysis of a single product, and do not explicitly consider alternative disassembly sequence planning.

2.2 Disassembly Sequence Planning. Several researchers have recognized that more efficient disassembly sequence planning is essential to making product take-back cost effective. According to Gerner et al. [13], generating a disassembly process consists of two main steps. The first is to determine the technically feasibility of alternative disassembly activities. The second is to evaluate those activities to establish the most efficient sequence of those activities.

Three main approaches are found in the literature for describing disassembly activities: AND/OR graphs, state diagrams, and disassembly precedence relationship graphs. Different approaches have likewise been adopted for modeling the product structure [6].

Johnson and Wang [14] presented a procedure of generating an optimal disassembly sequence based on maximizing the profits of material recovery. Three criteria were considered: material compatibility, clustering for disposal, and concurrent disassembly operations. Zhang and Kuo [15] proposed a graph-based heuristic approach for disassembly. Their model is embedded in an object-oriented modeling and graph representation, which is obtained by generating disassembly sequences. Others concentrate on related aspects of disassembly. For example, Srinivasan and Gadh [16] concentrated on the selective disassembly and proposed a new approach, disassembly wave propagation, for efficient selective disassembly of multiple components from a geometric model of an assembly.

2.3 Disassembly Sequence Planning Based on Optimum EOL strategy. Research in this area is concerned with how to disassemble a product and what to do with each of the resulting disassembled parts. Gonzalez and Adenso-Diaz [17] proposed a recurrent algorithm to determine the optimal EOL strategy based on the product bill of materials and its graphical CAD/CAM representation. Their model determines to what extent the product should be disassembled and what the EOL decision for each disassembled component should be (re-use, recycling, or disposal). Kara et al. [3] developed a "selective disassembly" concept, which requires the disassembly of selected components with re-use potential. According to their model a disassembly sequence for some selected components with minimal removal of other components is determined.

Kwak et al. [18] introduced a new concept of eco-architecture: "which represents a scheme by which the physical components are allocated to EOL modules." Mathematical programming is used to produce an optimum eco-architecture to find the best EOL strategy for each subassembly based on the estimation of the economic values and costs for possible EOL modules under given environmental regulations.

The method presented in this paper extends the work done by Kwak et al. [18] by taking into account multiple products and the capacity of the disassembly facilities.

3 Concepts of EOL Disassembly

Lambert [19] defined the disassembly process as a sequence of single operations for separating a component from a product or separation into two different subassemblies. There are many practical cases in which partial disassembly leads to better net revenue than the recovery of a complete set of single parts. This incomplete disassembly is called selective disassembly. As selective disassembly usually means incomplete disassembly, there are more degrees of freedom and, therefore, a greater number of feasible sequences than in the related assembly process.

In the case of disassembly of take-back products, the related subassemblies are called EOL modules. Kwak et al. [18] defined an EOL module as "a feasible subset of components that can be recovered or disposed without further disassembly according to a single EOL option."

In this paper, we assume that an EOL module can be processed through one of the following three options.

- Re-use: The EOL module can be used as a new one in the same (direct re-use) or another (indirect re-use) application after a simple cleaning, refurbishing, or repair process.
- Recycling: The EOL module is reprocessed to recover its raw materials. This typically involves shredding and component reforming processes.
- Disposal: The EOL module is land filled or incinerated.

EOL decision making has its own consequences from an economical, environmental, and social points of view [10]. It can be modeled as a multiattribute decision, which concerns different stakeholders including customers, manufacturers, recyclers, and other authorities. Each of them has its own criteria and objectives, which are sometimes in conflict. The decision whether to re-use, recycle, remanufacture, or dispose a product often requires inevitable trade-offs between cost, product performance, environmental effect, and energy consumption. In this paper, the EOL decision is considered only from the economical point of view of remanufacturers.

One of the key issues in determining the optimal disassembly sequence is to represent each disassembly operation and the related subassemblies in an appropriate way. Different methods have been developed to represent disassembly sequences, including undirected graph, digraph, AND/OR graph, and Petri net methods [20]. Lambert [19] showed the disassembly graph of a product in the form of a matrix: transition matrix T. This matrix represents the transitions caused by the possible disassembly operations. The cells of the matrix are presented by T_{ik}, in which index i refers to the different subassemblies and index k refers to the disassembly actions. $T_{ik}=-1$ indicates that action k destroys subassembly i,

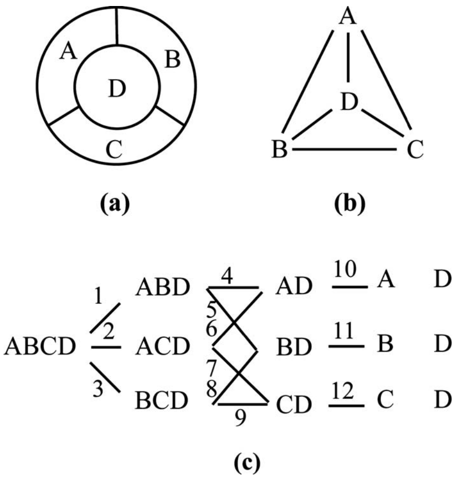

Fig. 1 Simple assembly (*a*), its connection diagram (*b*), and its disassembly graph (*c*) [23]

and $T_{ik}=1$ means that action k creates subassembly i. Other elements are 0.

To define a transition matrix, all of the feasible subassemblies and feasible transitions (disassembly actions) should be enumerated, which is a difficult and time consuming process [18]. Nevertheless, some recent research has focused on this issue. For example, Zwingmann et al. [21] applied a constraint programming approach to efficiently solve the combinatorial problem of finding the feasible subassemblies. Kang et al. [22] developed an algorithm for automatic derivation of a transition matrix based on architecture of a product. Lambert [23] used a simple example to explain the transition matrix. Figure 1 illustrates the structure of this product and Table 1 shows the related transition matrix. Although in Table 1 each disassembly transition has been led to two subordinate disassemblies, the method presented in the current research is not restricted to two subassemblies. This is compatible with practical situations in which more than two subassemblies may have been resulted from each disassembly transition/action.

4 Method for Determining Optimal Subassembly Levels and EOL Decision for Multiple Products

In this section, a mathematical model for determining the optimal selective disassembly and EOL decisions for multiple products is presented. The main characteristics are as follows.

- The model does not restrict products to be disassembled up to their last bill of material levels. Selective or partial disassembly is considered in order to avoid unnecessary disassembly costs.
- The model includes consideration of the EOL value resulting from each of three possible EOL options (re-use, recycling, and disposal) for each feasible subassembly. In this paper, the EOL value is defined as the income or loss generated from a particular EOL decision for a specific EOL module. One method for estimating this value is to apply the costs associated with EOL operations used for each module times a coefficient based on market situations. This estimation of value does not contain the disassembly cost. Considering disassembly costs concurrently with resultant EOL value is expected to reveal the optimal sequence and degree of disassembly, which lead to the highest net income.
- The model considers multiple products that can share disassembly operations. Thus, disassembly costs can be reduced through economy of scale. Total disassembly cost includes both fixed and variable costs.

The model helps manufacturers maximize their income by determining the best disassembly plan for a set of different products based on capacity of disassembly facilities and the value of EOL decisions for each subassembly.

To clarify the concept of sharing and nonsharing disassembly transitions, an example of two simple products is shown in Fig. 2. Tables 2 and 3 show the related transition matrices of these two products.

The joining component between components A and B in product (a) is the same as the joining component between components E and F in product (b) so the required disassembly of these components in both products is identical. In this case, transition 4 shows this action, so transition 4 is a shared disassembly action between the two products. Another shared disassembly action is transition 1. Although the components engaged in disassembly action 1 in two transition matrices are not the same, the joint type

Table 1 Transition matrix of product ABCD

	0	1	2	3	4	5	6	7	8	9	10	11	12
ABCD	1	−1	−1	−1	0	0	0	0	0	0	0	0	0
ABD	0	1	0	0	−1	−1	0	0	0	0	0	0	0
ACD	0	0	1	0	0	0	−1	−1	0	0	0	0	0
BCD	0	0	0	1	0	0	0	0	−1	−1	0	0	0
AD	0	0	0	0	1	0	1	0	0	0	−1	0	0
BD	0	0	0	0	0	1	0	0	0	1	0	−1	0
CD	0	0	0	0	0	0	0	1	1	0	0	0	−1
A	0	0	0	1	0	1	0	1	0	0	1	0	0
B	0	0	1	0	1	0	0	0	1	0	0	1	0
C	0	1	0	0	0	0	1	0	0	1	0	0	1
D	0	0	0	0	0	0	0	0	0	0	1	1	1

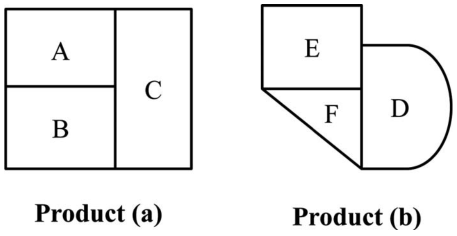

Fig. 2 Two products with some shared disassembly operations

Table 2 Transition matrix of product (a)

	0	1′	2	3	4′	5	6
ABC	1	−1	−1	−1	0	0	0
AB	0	1	0	0	−1	0	0
AC	0	0	1	0	0	−1	0
BC	0	0	0	1	0	0	−1
A	0	0	0	1	1	1	0
B	0	0	1	0	1	0	1
C	0	1	0	0	0	1	1

Table 3 Transition matrix of product (b)

	0	1′	2	3	4′	5	6
EFD	1	−1	−1	−1	0	0	0
EF	0	1	0	0	−1	0	0
ED	0	0	1	0	0	−1	0
FD	0	0	0	1	0	0	−1
E	0	0	0	1	1	1	0
F	0	0	1	0	1	0	1
D	0	1	0	0	0	1	1

between components AB and C in product (a) is the same as the joint type between EF and D components in product (b). So transition 1 also is a shared disassembly action.

The model presented here determines the optimal sequence and degree of disassembly, and EOL decisions for the resultant components and/or subassemblies. The index set, decision variables, and parameters of the model are summarized as follows:

(a) Index set:

  (1) i: feasible subassembly/EOL module
  (2) j: EOL option
  (3) k: feasible disassembly transition (action)
  (4) l: product type
  (5) N_l: the set of nonsharing disassembly operations for product l
  (6) S: the set of sharing disassembly operations

(b) Decision variables:

  (1) x_{kl}: number of modules of product type l that will be disassembled by transition k
  (2) y_{ijl}: the quantity of feasible subassembly i of product type l that are processed with EOL option j
  (3) z_k: the binary variable that shows whether disassembly transition k is done or not (this variable can be also defined as an integer variable that shows the number of facilities required for disassembly operation k; in the current research, it is a binary one)

(c) Parameters:

  (1) T_{ikl}: the value of cell (i,k) in transition matrix of product type l (it can be -1, 0, or 1)
  (2) C_{vk}: the variable cost of feasible disassembly transition k (U.S. \$)
  (3) C_{fk}: the fixed cost of facility using for disassembly transition k (U.S. \$)
  (4) V_{ijl}: the value of applying EOL option j for feasible subassembly i of product l (U.S. \$)
  (5) M_l: total quantity of product type l (units)
  (6) u_k: the whole capacity of disassembly operation k (units/h)

The problem can then be formulated as a linear program as follows:

Objective function:

$$\text{Max}\sum_l \sum_i \sum_j V_{ijl} y_{ijl} - \sum_l \sum_k C_{vk} x_{kl} - \sum_k C_{fk} z_k$$

The first term is the total value earned by executing EOL options for products subassemblies, the second term is the sum of variable cost of disassembly, and the third term is the disassembly fixed cost:

$$\text{subject to} \quad \sum_k T_{ikl} x_{kl} = \sum_j y_{ijl}, \quad \forall\, i,l \tag{1}$$

This constraint guarantees feasibility with respect to quantity. For example, consider module BCD in Table 1. Suppose that 40 units of this module are created by transition 3. These 40 units can be divided between transitions 8 and 9, and no more than 40 units can be disassembled by transitions 8 and 9. In addition, transactions 8 or 9 cannot be executed unless transaction 3 is executed.

The left term in the constraint ranges between 0 and the maximum number of feasible disassembly i in product l. Some components of subassembly i may be disassembled more by other disassembly transitions and some may be considered as an EOL module. Then the y_{ijk} will determine the related EOL option for those that are not considered for further disassembly.

$$x_{0l} = M_l, \quad \forall\, l \tag{2}$$

Constraint Eq. (2) shows that the initial disassembly action in the transition matrix must be executed.

$$x_{kl} \le u_k z_k, \quad \forall\, k \in N_l, \quad \forall\, l \tag{3}$$

Constraint Eq. (3) shows the capacity of nonsharing disassembly for each disassembly operation (facility).

$$\sum_l x_{kl} \le u_k z_k, \quad \forall\, k \in S \tag{4}$$

Constraint Eq. (4) shows the capacity of sharing disassembly operations. The summation is for those cases of products that can share operation k. The constraint forces that the summation of the numbers of modules of those products to be less or equal to the capacity of operation k. z_k is the number of facilities required for disassembly operation k, and u_k is the capacity of facility k.

The assumptions are as follows.

- Only one facility/resource is used for each disassembly operation.
- Disassembly time is fixed for all units of products.
- The resulting subassemblies of all units have the same quality condition.
- Information on sharing disassembly operations (i.e., which disassembly operations to share) is given.
- An EOL module can be processed through one of three options: re-use, recycling, or disposal.

The model has a low computational complexity. The proposed mixed integer linear programming problem can be solved using readily available optimization software. However, obtaining the disassembly structure of the products, which is basic information for developing the disassembly plan is a challenge, particularly for more complex products. Nevertheless, some recent research has concentrated on this issue [21,22,24]. For example, Kang et al. [24] proposed an algorithm to derive the disassembly structure of a product based on part-oriented precedence relationships and represented it as a transition matrix.

5 Example: Cell Phones

This section illustrates the model using cell phones, which presents take-back operators with a large number of different products with a relatively short lifecycle. More than 1800 models of cell phones are produced by more than 50 manufacturers and registered with the European Telecommunication Standards Institute [25]. Newer models offer improved features, and customers frequently replace their old phones with newer ones. Often the customer's current phones are still fully functional and not yet at the end of their useful lives. According to EPA estimates, approximately 140.3×10^6 cell phones were ready for EOL management in 2007 but only 14×10^6 phones were collected for recycling. Despite cell phone's small size and low material content, an active resale market makes cell phone take-back profitable [26].

The assumptions and structure of the proposed model do not restrict its application to a particular category of products. It can be applied to any set of products that can share disassembly transitions. Sharing disassembly operations between different products has the potential to make disassembly more cost effective. Personal computers are another example of this kind. While the collection rate of end-of-life PCs is increasing, only 20% are refurbishable without disassembly [27].

Since cell phones are the fastest growing segment of the United States waste stream [26] (due in part to their short life expectancy), the method proposed here is applied to two cell phone designs. These two cell phones can share some disassembly operations and are shown in Fig. 3. Tables 4 and 5 show the major components and their weights. Weights are estimated according to data collected by Gupta et al. [28] for a similar product.

(a) (b)

Fig. 3 Product 1 (*a*) and product 2 (*b*)

5.1 Model Inputs. The transition matrices for each product are shown in Tables 6 and 7. For simplification in this example, the joining parts (e.g., screws, clips, and bolts) have not been included in the transition matrices. The sets of sharing transitions (those that require the same resources, facilities, and disassembly operations) and nonsharing transitions are defined as follows:

$$S=\{1,2,3,4,5,7,8\}, \quad N_1=\{0,6,9,10\}, \quad N_2=\{0',6',9'\}$$

Another input for the model is the EOL option value matrices for these two cell phones, which indicate the estimated income from making each feasible EOL decision for each feasible subassembly. So, re-use for EOL modules results in positive value while disposal results in negative value. Table 8 shows the result of the research performed by Bhuie et al. [26] regarding the cost for collection and processing of cell phones. It is assumed that the resulting subassemblies of all units have the same quality condition. Different value matrices may be required in the case of different quality conditions. Theories of probability and reliability engineering can be used for mathematical modeling and analysis of EOL value. Uncertainty of the product quality and its impact on the EOL value can be regarded in the future research.

Table 4 Main components of product 1

Part label	Component name	Weight (g m)
A	Battery cover	6.23
B	Battery	30.80
C	SIM card holder	0.83
D	Aerial cover	3.21
E	Front cover	9.81
F	Key board	2.26
G	Housing	2.34
I	Printed circuit board	16.56
J	Screen	2.49

Table 5 Main components of Product 2

Part label	Component name	Weight (g m)
A	Battery cover	6.11
B	Battery	33.34
C	SIM card holder	0.97
H	Top dark gray cover	4.1
E	Front cover	10.62
F	Key board	2.45
I	Printed circuit board	17.93
J	Screen	2.70

Table 6 Transition matrix of product 1

	0	1	2	3	4	5	6	7	8	9	10
ABCDEFGIJ	1	−1	0	0	0	0	0	0	0	0	0
BCDEFGIJ	0	1	−1	0	0	0	0	0	0	0	0
CDEFGIJ	0	0	1	−1	0	0	0	0	0	0	0
DEFGIJ	0	0	0	1	−1	0	0	0	0	0	0
EFGIJ	0	0	0	0	1	−1	0	0	0	0	0
GIJ	0	0	0	0	0	1	−1	0	0	−1	0
EF	0	0	0	0	0	1	0	0	−1	0	0
IJ	0	0	0	0	0	0	1	−1	0	0	0
GI	0	0	0	0	0	0	0	0	0	1	−1
A	0	1	0	0	0	0	0	0	0	0	0
B	0	0	1	0	0	0	0	0	0	0	0
C	0	0	0	1	0	0	0	0	0	0	0
D	0	0	0	0	1	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	1	0	0
F	0	0	0	0	0	0	0	0	1	0	0
G	0	0	0	0	0	0	1	0	0	0	1
I	0	0	0	0	0	0	0	1	0	0	1
J	0	0	0	0	0	0	0	1	0	1	0

For estimating the cost associated with each of EOL decision, the operations associated with each EOL decision have been indicated in Table 9.

For providing an appropriate baseline for the example, estimates were derived using the cost data in Table 8, operations associated with each EOL option shown in Table 9, and the proportional weight of each module. The operational cost of each EOL option for each unit is multiplied by the proportional weight (g m) of each module in order to estimate the cost of EOL option. Then the estimated cost is multiplied by 1.2, 1, and −1 coefficients for re-use, recycling, and disposal options, respectively, to reflect the relative EOL value (income or lack thereof) of each EOL option. These coefficients can be estimated based on the

Table 7 Transition matrix of product 2

	0′	1	2	3	4	5	6′	7	8	9′
ABCHEFIJ	1	−1	0	0	0	0	0	0	0	0
BCHEFIJ	0	1	−1	0	0	0	0	0	0	0
CHEFIJ	0	0	1	−1	0	0	0	0	0	0
HEFIJ	0	0	0	1	−1	0	0	0	0	0
EFIJ	0	0	0	0	1	−1	−1	0	0	0
FIJ	0	0	0	0	0	0	1	0	0	−1
EF	0	0	0	0	0	1	0	0	−1	0
IJ	0	0	0	0	0	1	0	−1	0	1
A	0	1	0	0	0	0	0	0	0	0
B	0	0	1	0	0	0	0	0	0	0
C	0	0	0	1	0	0	0	0	0	0
E	0	0	0	0	0	0	1	0	1	0
F	0	0	0	0	0	0	0	0	1	1
H	0	0	0	0	1	0	0	0	0	0
I	0	0	0	0	0	0	0	1	0	0
J	0	0	0	0	0	0	0	1	0	0

Table 8 Costs for collecting and processing cell phones (per unit) [25]

Process	Cost (U.S. $)
Collection	6.00
Transportation	0.35
Dismantling	0.03
Refining	0.32
Dispose of nonhazardous waste	0.01
Dispose of hazardous waste	0.03

Table 9 Operation associated with three post recovery decision

Operation	Decision Disposal	 Re-use	 Recycle
Collection	X	X	X
Transportation to disposal centers	X		
Dismantling	X		X
Refining			X
Dispose of nonhazardous waste	X		
Dispose of hazardous waste	X		

selling price of EOL modules and may change according to market situation.

Tables 10 and 11 show the EOL value matrices for products 1 and 2, respectively. A value of $-\infty$ in a matrix cell refers to an infeasible EOL option. In this particular case, the values for all EOL decisions of the intact, undisassembled product are considered as $-\infty$. So the product cannot be re-used, recycled, or disposed directly.

Table 12 shows other data required:

- variable cost of each disassembly transition
- capacity of each disassembly operation
- fixed cost of the facility that has been used for each disassembly transition

Table 10 Matrix of EOL decision value for product 1

	Re-use	Recycling	Disposal
ABCDEFGIJ	$-\infty$	$-\infty$	$-\infty$
BCDEFGIJ	$-\infty$	$-\infty$	$-\infty$
CDEFGIJ	$-\infty$	$-\infty$	$-\infty$
DEFGIJ	$-\infty$	$-\infty$	$-\infty$
EFGIJ	2.36	$-\infty$	$-\infty$
GIJ	2.01	$-\infty$	$-\infty$
EF	$-\infty$	1.2	−0.95
IJ	0.48	$-\infty$	$-\infty$
GI	1.60	$-\infty$	$-\infty$
A	$-\infty$	0.46	−0.49
B	$-\infty$	2.30	$-\infty$
C	$-\infty$	$-\infty$	−0.06
D	$-\infty$	0.23	−0.24
E	$-\infty$	0.73	−0.74
F	$-\infty$	0.19	−0.17
G	0.19	0.17	−0.17
I	1.39	1.23	$-\infty$
J	0.204	0.18	−0.18

Table 11 Matrix of EOL decision value for product 2

	Re-use	Recycling	Disposal
ABCHEFIJ	$-\infty$	$-\infty$	$-\infty$
BCHEFIJ	$-\infty$	$-\infty$	$-\infty$
CHEFIJ	$-\infty$	$-\infty$	$-\infty$
HEFIJ	2.38	$-\infty$	$-\infty$
EFIJ	2.21	$-\infty$	$-\infty$
FIJ	1.74	$-\infty$	$-\infty$
EF	$-\infty$	1.87	−0.52
IJ	1.56	$-\infty$	$-\infty$
A	$-\infty$	0.40	−0.43
B	$-\infty$	2.22	$-\infty$
C	$-\infty$	$-\infty$	−0.06
E	$-\infty$	0.70	−0.75
F	$-\infty$	0.16	−0.17
H	0.30	0.27	−0.29
I	1.35	1.19	$-\infty$
J	0.204	0.18	−0.19

It is assumed that only one facility/resource is used for each disassembly operation.

5.2 Results. This mixed integer linear problem was solved for 560 units of product 1 and 350 units of product 2 using commercially available optimization software (Excel Solver 2007). The results are shown in Tables 13 and 14 for products 1 and 2, respectively.

The optimal value of the objective function is $1279 and the optimal solution indicates that the values of variables z_1, z_2, z_3, and z_4 are 1, so transitions 1–4 should be executed. It should be added that all of these operations are shared operations.

Table 13 shows that product 1 should be disassembled up to the EFGIJ module. Among the disassembled modules, modules A, B, and D should be recycled, and module C should be land filled. 490 units of module EFGIJ should be disassembled by applying transition 5 to reach to EF and GIJ modules (see Table 6). GIJ modules should be re-used and EF modules should be recycled.

These results are summarized in Fig. 4. In this figure, the product is presented according to its EOL modules and their interactions. Kwak et al. [18] called this architecture of the product as eco-architecture.

In this figure, the interactions between EOL modules mean the transitions (operations) needed for disassembly. These interactions are those transitions that have been defined in the product's transition matrix.

The results for product 2 are shown in Table 14 and Fig. 5. Product 2 should be disassembled up to HEFIJ module. 260 out of 350 units of HEFIJ should be re-used and the remaining 90 units will be disassembled further by applying transitions 4 and 5. The resulting modules H, EF, and IJ will be re-used, recycled, and re-used, respectively. Components A and B are recycled, and component C is disposed of. It seems that the disassembly of more units of module HEFIJ is restricted by the capacity of transition 4. Here z_4 is a binary variable that shows whether disassembly transition 4 is performed or not. This variable can also be defined as an integer variable, which determines the number of facilities required for disassembly operation 4. There should be a trade-off between the fixed cost of adding a new facility and the value earned by further disassembly considering economy of scale.

The result of this model cannot only help the manufacturer plan the disassembly process but also help the designer modify the product according to the disassembly levels and EOL decision for each disassembled module. For example, the result for product 1 indicates that the subassemblies GIJ and EF do not require further disassembly, so the designer should not expend efforts on "design for disassembly" for this module. In addition, since recycling is recommended for module EF, the designer should consider utilizing the same material for both components if possible to facilitate recycling. Standardization of disassembly operations and designing disassembly transitions as sharing ones between different products can be regarded as another modification.

What if sharing disassembly operations were not considered between products? In order to show the effect of sharing disassembly operations, the model was also solved for 560 units of product 1 and 350 units of product 2 separately. Figures 6 and 7 illustrate the disassembly level of these products when the model was solved separately for them.

Comparing Figs. 6 and 7 to Figs. 4 and 5 shows that when two products are disassembled together, the remaining capacities of transitions 4 and 5 from product 1 can be applied to further disassembly of product 2. On the other hand, when products are disassembled separately, executing transition 4 for product 2 is not economical due to the trade-off between the fixed cost of facility 4 and the value added that is still embedded in further disassembly of module HEFIJ. In terms of the objective function, solving the model considering sharing disassembly operations resulted in a

Table 12 Fixed and variable costs of disassembly

Transition	Transition type	Disassembly time (s)	Variable cost (U.S. \$)	Capacity (units/h)	Fixed cost (U.S. \$)
0	Nonsharing	0	0	1500	0
1	Sharing	3	0.029	1200	1000
2	Sharing	2	0.019	1800	1000
3	Sharing	3	0.029	1200	1000
4	Sharing	10	0.09	650	400
5	Sharing	4	0.038	580	400
6	Nonsharing	30	0.29	1200	1000
7	Sharing	20	0.19	1800	1000
8	Sharing	3	0.029	1200	2000
9	Nonsharing	40	0.38	900	500
10	Nonsharing	20	0.19	1200	1000
0′	Nonsharing	0	0	2000	0
6′	Nonsharing	50	0.48	800	1000
9′	Nonsharing	20	0.19	1800	2000

profit of \$1278.79, whereas solving the model separately for products 1 and 2 resulted in losses of (\$476.4) and (\$1297.95), respectively. So, sharing disassembly operations has made EOL decision making and disassembly planning profitable and has increased net profit by \$3053.14.

The model allows the capacity of facilities to be shared between those products that can share disassembly operations. In the worst case that the set of sharing disassembly operations is empty, particularly when take-back products are more complex, the model can be solved for each of them separately.

Table 13 The optimal number of subassembly modules and related EOL decision for product 1

	Re-use	Recycling	Disposal
EFGIJ	70		
GIJ	490		
EF		490	
A		560	
B		560	
C			560
D		560	

Table 14 The optimal number of subassembly modules and related EOL decision for product 2

	Re-use	Recycling	Disposal
HEFIJ	260		
EF		90	
IJ	90		
A		350	
B		350	
C			350
H	90		

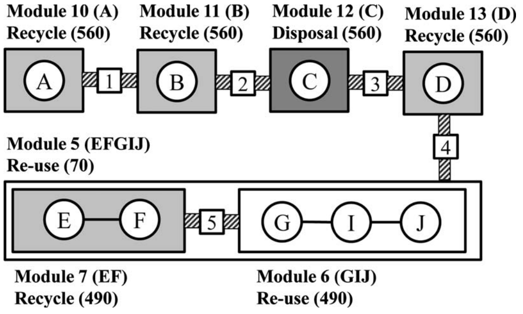

Fig. 4 EOL Modules and disassembly transitions of Product 1

To sum up, researches focused on effective design of joints parts [29] along with the results of the current research can help remanufactures reduce the disassembly cost as one of the significant cost drivers in EOL decision making.

5.3 Sensitivity Analysis. Model results are influenced by facility capacity. The limited capacity of transitions 4 and 5 restricted further disassembly of module HEFIJ in product 2 and EFGIJ in product 1. Seventy units of module EFGIJ of product 1 may need further disassembly. So transition 5 capacity can be increased 70 units. Further capacity may be needed to disassemble the module EFIJ in product 2, but as transition 4 is a precedence transition for 5, increasing the capacity of transition 5 without increasing the capacity of transition 4 is useless.

Say, that the manufacturer wants to increase the capacities of transitions 4 and 5, but due to budget limitations the capacity of only one of those facilities can be increased by 50 units. Tables 15 and 16 show the results of increasing the capacity of transition 4 by 50 units, and Tables 17 and 18 illustrate the results of this increase for transition 5.

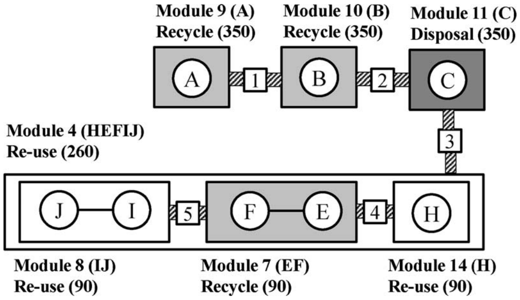

Fig. 5 EOL Modules and disassembly transitions of product 2

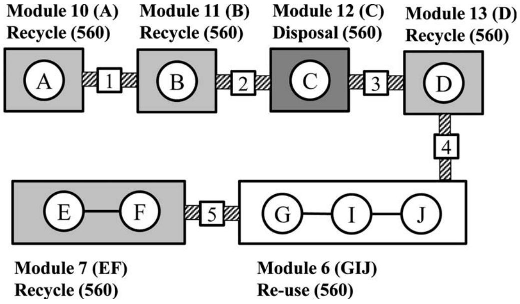

Fig. 6 EOL Modules and disassembly transitions of product 1 when model was solved just for product 1

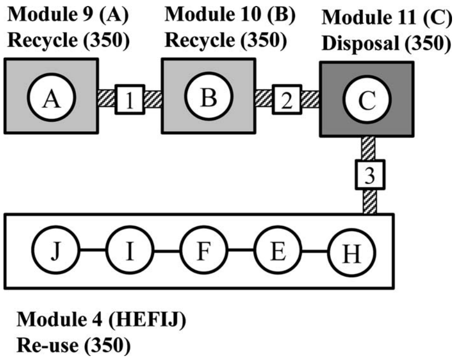

Fig. 7 EOL Modules and disassembly transitions of product 2 when model was solved just for product 2

Increasing capacity of transitions 4 and 5 by 50 units increases profit by 20.5 and 40.6 units, respectively. Comparing Tables 14 and 16 shows that increasing capacity of transition 4 resulted in further disassembly of module HEFIJ. Then, more EFIJ modules were assigned to transition 5.

Comparing Tables 17 and 13 shows that increasing transition 5 capacity resulted in further disassembly of module EFGIJ in product 1. Since transition 4 is a precedence transition for 5, increasing transition 5 capacity by itself does not affect the related results of product 2.

Table 15 The optimal number of subassembly modules and related EOL decisions for product 1 when transition 4 capacity was increased by 50 units

	Re-use	Recycling	Disposal
EFGIJ	120		
GIJ	440		
EF		440	
A		560	
B		560	
C			560
D		560	

Table 16 The optimal number of subassembly modules and related EOL decisions for product 2 when transition 4 capacity was increased by 50 units

	Re-use	Recycling	Disposal
HEFIJ	210		
EF		140	
IJ	140		
A		350	
B		350	
C			350
H	140		

Table 17 The optimal number of subassembly modules and related EOL decisions for product 1 when transition 5 capacity was increased by 50 units

	Re-use	Recycling	Disposal
EFGIJ	20		
GIJ	540		
EF		540	
A		560	
B		560	
C			560
D		560	

Table 18 The optimal number of subassembly modules and related EOL decisions for product 2 when transition 5 capacity was increased by 50 units

	Re-use	Recycling	Disposal
HEFIJ	260		
EF		90	
IJ	90		
A		350	
B		350	
C			350
H	90		

Disassembly time is another input that influences the results of the model. The disassembly time of connection is different depending on the length of product life and chemical and physical degradation during the usage stage. In the current case, disassembly time is assumed to be fixed for all units of products, but in practice it may not be the case. Suppose that the disassembly times for transition 4 based on previous data are estimated to be 7 s, 8 s, 9 s, 10 s, and 11 s with probabilities of 0.15, 0.20, 0.35, 0.20, and 0.10, respectively. So after solving the model for 560 units of product 1 and 350 units of product 2, the estimated income based on different disassembly times and in consequence different disassembly variable costs is shown in Table 19. The expected income based on this distribution function is $1285.22. The manufacturer can determine the confidence interval of its income according to any statistical distribution for disassembly time. Further analysis of results will be considered in future research.

6 Conclusion

This paper addressed two problems that detract from the cost effectiveness of product take-back operations. The first is the costs that are incurred when a product is fully disassembled unnecessarily, and the second is the mixed feedstock presented by dissimilar products. To solve these problems, a method for evaluating simultaneous partial disassembly and EOL decision making for multiple products was presented. Considering sharing disassembly operations between products with similar architectures is one of the key features of this method. A mixed integer linear model optimization was introduced for solving the problem, and an illustrative example using cell phones was presented. The model was solved for two cell phones with similar disassembly architecture under the assumption that sharing information of disassembly operations is given. Then, it was compared with the case when each product is disassembled separately. The results show the economic benefits of sharing disassembly operations compared with considering products separately. The results also show the optimal disassembly level for each product and the best EOL option for each resulting module. The designer can apply the obtained results to modify the product design based on disassembly levels and EOL decisions for each disassembled module. A sensitivity analysis was conducted to show how the results of the model are influenced by the capacity of the facilities.

Table 19 The resulting incomes of different disassembly time for transition 4

Disassembly time (s)	Probability	Income (U.S. $)
7	0.15	1296.34
8	0.20	1290.49
9	0.35	1284.64
10	0.20	1278.79
11	0.10	1272.94

The result of this research can be extended in several ways: First, sharing EOL operations as well as disassembly operations between products may bring additional cost savings. In the current research, only the sharing of similar operations at the disassembly stage have been integrated in the model, but considering sharing operations at the recovery stage of the products could also help reduce the cost of multiple product recovery. Second, considering cases of multiple products with both shared operations and shared common components may reduce the cost of satisfying customer demands via economy of scale. Third, the objective function can be extended to maximize the multiattribute utility, which directly includes environmental impacts and product quality. Fourth, uncertainties such as disassembly time and quality of the take-back products can be added to the model. A more precise estimation on disassembly time and also EOL value based on quality of return products will lead to more cost saving especially in the case of mass recycling. In addition, simulation tools and statistical methods can be applied to deal with the uncertainties embedded both in the model structure and in the model parameters. Fifth, more precise methods are needed for estimating EOL value. Finally, anticipating EOL decisions can result in significant design modifications, so determining the specific redesign guidelines according the results of the model can be a focus point for future research.

Acknowledgment

This material is based on work supported by the National Science Foundation under Grant No. DMI-07-26934.

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