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Disassembly and Classification for Recovery of EOL Products

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Abstract. Recovery of end-of-life (EOL) products is an environmentally and economically sound way to achieve many of the goals of sustainable development. Many product recovery systems are dependent upon destructive disassembly such as shredding, which undesirably causes a large volume of shredder dust and makes parts reuse impossible. Although non-destructive disassembly has been considered as an alternative for solving the problems, the classification of disassembled items has not been sufficiently investigated. In this paper, we propose a model that mathematically optimizes the disassembly and classification of EOL products. Based on the AND/OR graph that illustrates all possible disassembly sequences of a given product, we identify the physical properties that are considered as constraints in the model. As a result of the solution procedure, the recovery problem can be transformed into a mixed integer linear programming (MILP) model. We show an example that illustrates the concept of our model.

Keyword: end-of-life products, recovery, AND/OR graph, mathematical model

1. INTRODUCTION

Today, many manufacturing firms are seriously concerned with environmental problems such as the shortage of landfill space and material depletion. The rapid development and improvement of technical products have promoted additional demands and shortened lifetime of products, resulting in increasing disposal of used products. It is estimated that, in the US, approximately 11 million vehicles were scrapped in 1990 and the rate of disposal continues to increase. In Japan, every year five million automotive vehicles are disposed of as end-of-life (EOL) products. Most such EOL products are processed by hammer shredding for the purposes of size reduction and further recycling (Kimata 1999).

Recycling of scrap materials plays an important role in the conservation of energy because the remelting of scrap requires much less energy consumption than the production from raw materials. In many cases, however, shredding generates a large volume of shredder dust for which landfill costs are high. In addition, the contaminants included in the recyclable materials limit the usage of the materials and degrade their quality. Non-destructive disassembly can be an alternative to overcome the problems of shredder dust and the quality degradation of scrap materials.

Related to the issue on planning of disassembly and

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recycling, many studies have been carried out. Lee *et al.* (2001) provided a comprehensive review on the research field. Several studies suggested models or algorithms to search for the optimum disassembly plan (Johnson and Wang 1995/1998, Kaebernick *et al.* 2000, Krikke *et al.* 1998, Lambert 1999-(a) & (b), Meacham *et al.* 1999, Navin-Chandra 1994, Penev and de Ron 1996, Pnueli and Zussman 1997, Zhang and Kuo 1996). Navin-Chandra (1994) showed the recovery problem as a specific case of the "Traveling Salesman Problem". The study assumed that subassemblies and parts are like cities and that separating connected parts is similar to traveling between cities. Pnueli and Zussman (1997) suggested an algorithmic approach, the Optimal Disassembly (OD) algorithm, in order to quantitatively evaluate the EOL value of a product and to find its optimal recovery plan. They also tried to redesign the product based on expert knowledge with the aim of increasing its EOL value. Erdos *et al.* (2001) used a backward calculation method for algorithms that search the optimal disassembly plan within a product recovery graph. Lambert (1999-a) suggested a method for solving general optimal disassembly sequence generation problems by linear programming. However, most of the previous works have mainly focused on the disassembly sequencing problem only. The classification process of disassembled parts has not been sufficiently investigated in the studies.

To facilitate the reuse of disassembled materials, the scrap industries in several countries provide guidelines, including information of grades and classifications of scraps (Labson 1997). Since the scrap materials disassembled from EOL products are generally graded and priced based on the quality and the intended usage, their classification process must be explicitly considered at the initial stage of disassembly planning to maximize the recovery value of EOL products.

This paper proposes a mathematical model for optimizing the processes of disassembly and classification. We integrate all possible disassembly sequences of a given product in an AND/OR graph, and then identify physical properties related to the execution state of disassembly operations and the existence state of disassembled items. The physical properties are important factors that we need to focus on because these properties are considered as constraints in our model. As a result of the solution procedure, the recovery problem can be formulated as a mixed integer linear programming (MILP) model. Specifically, our model explicitly considers the classification process of disassembled items in terms of their quality and quantity. The market requirements for recyclable materials are met by combinatorial classifications of all items disassembled. By solving the MILP model, we could obtain the optimum recovery plan to achieve the maximum recovery value for an example case.

The remainder of this paper is organized as follows. Section 2 addresses the issue of disassembly sequence and suggests an algorithm to generate AND/OR graph. Section 3 describes the physical properties. Section 4 proposes a mathematical model and discusses the complexity of the model. Section 5 shows the concept of our proposal through an example together with sensitivity analysis for the optimal solution. Finally, Section 6 provides some concluding remarks.

2. RECOVER STRATEGY

2.1 Disassembly sequence and AND/OR graph

A disassembly sequence can be defined as a set of disassembly operations that separate a product into its constituent subassemblies and terminal parts. There may be a number of possible sequences to disassemble assembled products completely because of the complex and hierarchical structure of products. Therefore, it is an important task to generate all possible disassembly sequences of a given product to search for its optimal recovery plan.

The issue of disassembly sequence generation has been addressed in many previous studies (Gungor and Gupta, 2001; Harisrinivasan, 1997; Ishii, 1995; Lambert, 1997; Mok, 1997; Subramani and Dewhurst, 1991; Zhang and Kuo,1997). Lambert (1997) used a liaison diagram to represent the disassembly sequences of a ballpoint pen. On the other hand, Homem de Mello and Sanderson (1990) introduced an AND/OR graph to represent assembly processes, which is founded to be applicable also to the disassembly sequencing problem. In this paper, we utilize the AND/OR graph to represent the possible disassembly sequences because the use of such a graph tool makes the solution procedure simple.

For example, the product shown in Figure 1 consists of four parts: *a*, *b*, *c* and *d*. Since part *c* is fixed on part *a*, we can first separate part *d* only, or *c* and *d* together. Due to the precedence relation between parts *b* and *c*, part *b* cannot be disassembled from part *a* without the removal of part *c*. Consequently, a total of two sequences are possible for disassembling the product completely as illustrated in Figure 2.

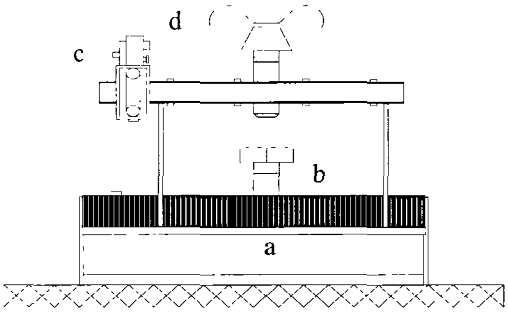

Figure 1. Simple product

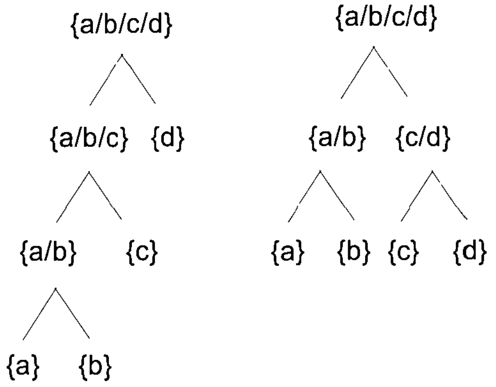

Figure 2. Two disassembly sequences

The two sequences of string-type and parallel-type were integrated in the AND/OR graph of Figure 3. In the figure, square nodes represent the root product, subassemblies and terminal parts, respectively. The numbered circular nodes represent technically possible disassembly operations. Here, we refer to the root product, subassemblies and terminal parts as "objects". The AND/OR graph requires fewer nodes than the two disassembly sequences; for example, the common objects in Figure 2, i.e. {*a*/*b*/*c*/*d*}, {*a*/*b*}, {*a*}, {*b*}, {*c*} and {*d*}, appear just one time in Figure 3.

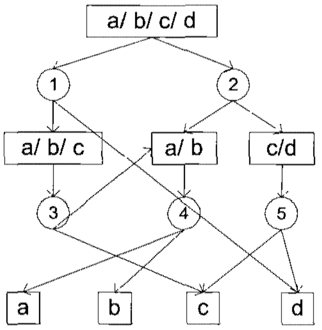

Figure 3. AND/OR graph

2.2 Generation of AND/OR graph

To generate the AND/OR graph may be a difficult and time-consuming task if the number of parts increases largely. We suggest an algorithm to carry out such a graph generation task effectively under the assumption that the precedence relations between parts are known in advance. In addition, it is assumed that one disassembly operation separates a parent object node into two child nodes. However, this can be easily extended to more realistic cases, in which one disassembly operation creates more than two child nodes from one parent node. The following definitions and notations are used in the algorithm.

Definitions and notations

□	object node
○	disassembly operation node
↘	arc to link object and disassembly operation nodes
α	generation step of child object nodes
β	creation order of individual child object node
$a_{\alpha\beta}$	object node created in β^{th} order at generation step α
m	order of disassembly operations (m=1, 2,..., M)
$d^m_{\alpha\beta}$	possible disassembly operations of $a_{\alpha\beta}$
$S_{\alpha\beta}$	set of possible operations of object node $a_{\alpha\beta}$
A_α	set of the product node or subassembly nodes at generation step α
$T_{\alpha\beta}$	number of elements of set $S_{\alpha\beta}$
T_α	number of elements of set A_α

The suggested algorithm consists of four steps. In the first step, the root product object to be disassembled is identified and its related sets A_α and $S_{\alpha\beta}$ are generated. In the second step, we create nodes of disassembly operations up to $T_{\alpha\beta}$. We then identify child objects to be disassembled by each disassembly operation node, and generate nodes of the child objects iteratively. Next, the created nodes are linked by arcs. When generating the child object nodes, it is important to generate only new object nodes that have not been previously generated. This is because we can reduce the number of variables used in our mathematical model by eliminating the redundant object nodes. The third step implies that the above steps should be repeated until newly generated object nodes are all the nodes of terminal part objects. By numbering the node orders of objects and operations, we obtain the AND/OR graph in the final step. The algorithm can be represented as follows.

Algorithm

```
STEP 1 Identify the node of product object ($a_{\alpha=0,\beta=1}$).
       Generate sets $A_{\alpha=0}$ and $S_{\alpha=0,\beta=1}$.

STEP 2 If $\beta \leq T_\alpha$, then continue the following steps.
       Otherwise, go to STEP 3.

    step 2.1 Generate set $S_{\alpha\beta}$ associated with $a_{\alpha\beta}$.
             Draw the disassembly operation nodes up to $T_{\alpha\beta}$.

    step 2.2 Link object node $a_{\alpha\beta}$ and the element
             operation nodes of $S_{\alpha\beta}$ with arcs.

    step 2.3 While $m \leq T_{\alpha\beta}$, repeat this step.
             Identify the child object nodes that were
             created by operation node $d^m_{\alpha\beta}$.
             Check if the same object nodes already
             exist in the AND/OR graph.
             Draw only the object nodes that were newly
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        created.
        Link operation node $d^{m}_{\alpha\beta}$ and its relevant
        object nodes with arcs.
        Set $m = m+1$.

    step 2.4 Set $\beta=\beta+1$, then go to STEP 2.

STEP 3  Set $\alpha=\alpha+1$, then generate set $A_\alpha$.
        If $A_\alpha \neq \{\emptyset\}$, go to STEP 2.
        Otherwise, go to STEP 4.

STEP 4  Number the nodes generated. AND/OR graph is
        completed.
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3. SOLUTION APPROACH

3.1 Physical properties

In this section we will focus on understanding the physical properties considered as constraints in the mathematical model to be developed in the next section. The analysis will be performed based on Figure 4 which represents the process of disassembly and classification of the simple product addressed in Section 2. In the figure, a total of five containers are available for the classification process of disassembled items from the example product. Recyclable materials, for instance, can be classified into containers 1, 2 or 3. On the other hand, reusable parts are classified into container 4, and finally contaminants or valueless items are thrown into container 5 for disposal.

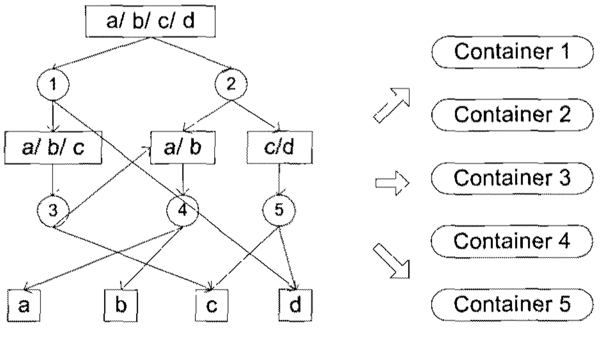


Figure 4. Disassembly and classification

To develop the mathematical model, we identify the physical properties, i.e. object existence, precedence relations and object existence and classification, based on the disassembly and classification process of Figure 4.

3.1.1 Object existence

This property covers the existence state of an object. If, for instance, the product object {*a/b/c/d*} is separated by either operation 1 or operation 2, the object does not exist any more. New child objects can be created by carrying out its lower level operations: objects {*a/b/c*} and {*d*} by operation 1, {*a/b*} and {*c/d*} by operation 2. Similarly, operations 3, 4 and 5 generate new terminal parts {a}, {*b*}, {*c*} and {*d*} or subassembly {*a/b*}, respectively. If we assume that only operations 1 and 3 are done, then the three objects, i.e. {*a/b*}, {*c*} and {*d*}, are the final result of the disassembly.

3.1.2 Precedence relations

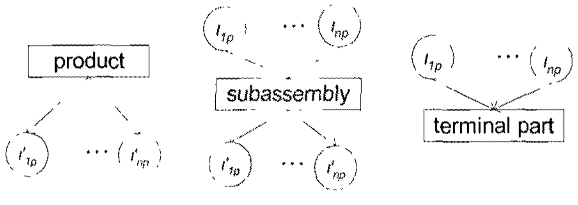
A precedence relation which resulted from the complex and hierarchical structure of products exists in two successive disassembly operations. In Figure 4, operation 3 cannot be executed if operation 1 is not done, while operation 3 can be executed if once its precedent operation has been done.

3.1.3 Object existence and classification

This property considers the classification process of existing objects. That is, only existent objects can be classified into containers for further process. This is because the original object does not exist any more if it has been disassembled. Since objects {*a/b*}, {*c*} and {*d*} are the final objects when we do operations 1 and 3 only, any other objects cannot be classified into containers.

3.2 Object sets

The physical properties can be represented as generalized forms by categorizing all objects into three sets. Figure 5 shows the three object sets, i.e. set of the product object, set of subassembly objects, set of terminal part objects.



(a) product (b) subassemblies (c) terminal parts

Figure 5. Three object sets

In the figure $i_{1p} \ldots i_{np}$ are the higher level operations of object *p*, while $i'_{1p} \ldots i'_{np}$ are the lower level operations. In Fig 4, for example, product {*a/b/c/d*} belongs to the set of the product object, while subassemblies {*a/b/c*}, {*a/b*} and {*a/b*} belong to the set of subassembly objects, and terminal parts {*a*}, {*b*}, {*c*} and {*d*} belong to the set of terminal part objects.

4. MATHEMATICAL MODEL

4.1 Formulation method

Related to problems of product recovery, there may be several objective criteria such as cost/ benefit, energy use and environmental load. For the development of a model, we use an objective function in terms of cost and benefit. In the model, the physical properties and market requirements are considered as constraints. The market requirements for recyclable materials restrict the qualitative and quantitative boundaries for each container. The quality level of a recyclable material, which is sold at market values (US $) per kg, is calculated by the mass ratio of the material and its contaminant. Moreover, we assume that several specified objects considered to be reusable are sold at their individual prices, but disposal costs must be paid for contaminant materials. The following notions are used for general expressions of the model.

Notations

p	index for object $(p=1, 2,\dots, P)$
q	index for container $(q=1, 2,\dots, Q)$
n	Index for disassembly operation $(n=1, 2,\dots, N)$
i_{np}	integer variable representing execution state of higher level operations of object p $\begin{cases} =1 & \text{if operation is executed,} \\ =0 & \text{otherwise.} \end{cases}$
i'_{np}	integer variable representing execution state of lower level operations of object p $\begin{cases} =1 & \text{if operation is executed,} \\ =0 & \text{otherwise.} \end{cases}$
i_n	integer variable representing execution state of disassembly operations $\begin{cases} =1 & \text{if operation is executed,} \\ =0 & \text{otherwise.} \end{cases}$
j_p	integer variable representing existence state of object p $\begin{cases} =1 & \text{if object } p \text{ exists,} \\ =0 & \text{otherwise.} \end{cases}$
k_{pq}	integer variable representing classification state of object p $\begin{cases} =1 & \text{if object } p \text{ is classified into } q, \\ =0 & \text{otherwise.} \end{cases}$
S_{hp}	set of higher level operations of object p
S_{lp}	set of lower level operations of object p
S_{pd}	set of the product object
S_{sb}	set of subassembly objects
S_{tp}	set of terminal part objects
DC_n	disassembly cost of operation n
MV_q	market value of recyclable materials classified into container q
m^+_p	mass of recyclable materials in object p
m^-_p	mass of contaminants in object p
x_{pq}	mass of recyclable materials of object p classified into container q
y_{pq}	mass of contaminants of object p classified into container q
z_q	mass of objects classified into container q
QN_q	quantity boundary of container q
QL_q	quality boundary of container q

Here, $i_n, j_p, k_{pq}, x_{pq}, y_{pq}$ and z_q are decision variables of the problem. The recovery problem is formulated as the following mixed integer linear programming model. The objective function (1) is to be maximized. The first term sums up the returns of recyclable and reusable objects, while the second term is the cost summation of executed disassembly operations.

$$\max \left\{ \sum_{q=1}^{Q} MV_q \times z_q - \sum_{n=1}^{N} DC_n \times i_n \right\} \tag{1}$$

subject to

$$\sum i'_{np} + j_p = 1 \qquad p \square S_{pd}, i'_{np} \square S_{lp} \tag{2}$$

$$\sum i_{np} - \sum i'_{np} - j_p = 0 \qquad p \square S_{sb}, i_{np} \square S_{hp}, i'_{np} \square S_{lp} \tag{3}$$

$$\sum i_{np} - \sum i'_{np} \geq 0 \qquad p \square S_{sb}, i_{np} \square S_{hp}, i'_{np} \square S_{lp} \tag{4}$$

$$\sum i_{np} \leq 1 \qquad p \square S_{sb}, i_{np} \square S_{hp} \tag{5}$$

$$\sum i'_{np} \leq 1 \qquad p \square S_{sb}, i'_{np} \square S_{lp} \tag{6}$$

$$\sum i_{np} - j_p = 0 \qquad p \square S_{tp}, i_{np} \square S_{hp} \tag{7}$$

$$\sum_{q=1}^{Q} k_{pq} - j_p = 0 \qquad \square p \tag{8}$$

$$x_{pq} - m^+_p \times k_{pq} = 0 \qquad \square p, q \tag{9}$$

$$y_{pq} - m^-_p \times k_{pq} = 0 \qquad \square p, q \tag{10}$$

$$z_q - \sum_{p=1}^{P} (x_{pq} + y_{pq}) = 0 \qquad \square q \tag{11}$$

$$\sum_{p=1}^{P} (x_{pq} + y_{pq}) - QN_q \geq 0 \qquad \square q \tag{12}$$

$$\sum_{p=1}^{P} y_{pq} - \left(\sum_{p=1}^{P} x_{pq}\right) \times QL_q \leq 0 \qquad \square q \tag{13}$$

$$i_n, j_n, k_{pq} \in \{0,1\} \qquad \square n,p,q \qquad (14)$$

$$x_{pq}, y_{pq}, z_q \geq 0 \qquad \square n,p,q \qquad (15)$$

Constraints (2) restrict the properties of the product object. For an illustration, let us refer to Figure 5. In Figure 5-(a), the product object has n lower level operations: $i'_{1p} \ldots i'_{np}$. Table 1 shows relations between the existence state of the object and its lower level operations. If an operation is executed ($\sum i'_{np} = 1$), the product object does not exist any more ($j_p = 0$). Thus, the object can be existent only when $\sum i'_{np} = 0$.

Table 1. Set of the product object

case	$\sum i'_{np}$	j_p
(1)	1	0
(2)	0	1

Constraint (3) specifies the properties of subassembly objects. The existence state of a subassembly object is dependent upon both its higher level operations $i_{1p} \ldots i_{np}$ and lower level operations $i'_{1p} \ldots i'_{np}$. Based on Figure 5-(b) and Table 2, we can observe that a subassembly object is existent only when $\sum i_{np} = 1$ and $\sum i'_{np} = 0$. Constraint (4) restricts the precedence relations between two succeeding operations. Constraints (5) and (6) are necessary because only one disassembly sequence among alternatives can be selected as the optimal sequence.

Table 2. Set of subassembly objects

case	$\sum i_{np}$	$\sum i'_{np}$	j_p
(1)	1	1	0
(2)	1	0	1
(3)	0	0	0

Constraint (7) restricts properties of terminal part objects based on Figure 5-(c). Table 3 indicates that a terminal part object can be existent only when $\sum i_{np} = 1$.

Table 3. Set of terminal part objects

case	$\sum i_{np}$	j_p
(1)	1	1
(2)	0	0

Constraint (8) specifies the relations of object existence and classification for each object. Constraints (9) and (10) calculate the mass of recyclable materials and contaminants, respectively. The mass ratio of the two materials can be estimated by constraint (11). Finally, constraints (12) and (13) restrict the qualitative and quantitative boundaries of containers for the recyclable materials.

4.2 Complexity analysis

The complexity of a recovery model depends upon the possible disassembly sequences of a product. It is not easy to explicitly calculate the number of the sequences since it is limited by the hierarchical structure of products and the precedence relations of their constituent parts. By relaxing the limitation, however, we attempt to calculate the maximum sequence number of a given product.

For an illustration, refer to Figure 6. Let us assume that a product consists of r parts. In the figure, N_r implies the number of disassembly sequences of the product. We assume that $N_1 = 1$ if $r = 1$. Then $N_2 = 1$ if $r = 2$ because only one operation is possible to disassemble two parts. In this way, we calculate further N_r recursively by equation (16) although r becomes larger.

$$Nr = \sum_{s=1}^{s<\frac{r}{2}} [{}_rC_s \times N_s \times N_{(r-s)}] + \sum_{s=\frac{r}{2}} [\frac{{}_rC_s \times N_s \times N_{(r-s)}}{2}] (r \geq 3) \qquad (16)$$

In equation (16), s is the number of parts included in the child nodes, which are disassembled from the parent node (s = 1, 2, 3,..., r/2). Thus, s must be equal to (r/2 - 0.5) if r is an odd number. Since no precedence relation of parts exists, we have rCs combinatorial disassembly operations that separate a parent node into two child nodes having s and (r-s) parts, respectively.

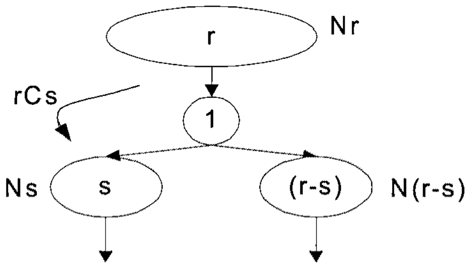


Figure 6. Combinatorial disassembly

The first term of the equation sums up the combinatorial numbers of disassembly sequences while $s < r/2$. Only when r is an even number and $s = r/2$, the numerator of the second term should be divided by two because N_s and $N_{(r-s)}$ generate entirely identical disassembly sequences. For example, if $r = 3$, then $s = 1$ because $r/2 = 1.5$. Thus, $N_3 = {}_3C_1 \times N_1 \times N_2 = 3$.

Furthermore, if $r = 4$, then $s = 1$ and 2 because $r/2 = 2$. Since we already knew $N_3 = 3$, $N_4 = {}_4C_1 \times N_1 \times N_3 + ({}_4C_2 \times N_2 \times N_2)/2 = 15$. Similarly, further N_r can be calculated recursively for a larger r. However, the actual numbers of disassembly sequences of a product are usually less than N_r due to the precedence relations between parts.

The disassembly sequence generated by the suggested equation contains (r-1) nodes of operations and (2r-1) nodes of objects. Accordingly, we may need a total of $N_r(3r\text{-}2)$ variables to solve a problem where any precedence relation is not permitted. Even though we consider a recovery problem with precedence relations between parts, the algorithm suggested in Section 2 is useful in developing a recovery model for the problem by eliminating the redundant variables.

5. NUMERICAL EXAMPLE

5.1 Problem background

Generally, a vehicle consists of approximately 15,000 parts that include many types of materials, e.g. steel, iron, glass, plastic, and non-ferrous metal. There is a common trend in the material composition of a car towards increased usage of light-weight materials such as plastics and light metal alloys. However, ferrous metals still hold a high percentage of mass in vehicles (Mildenberger and Khare, 2000). Many vehicle products still contain recoverable parts and materials after their useful lives, thus we show the concept of our model by using a simple vehicle case. For the simplicity's sake, we consider a vehicle that consists of 21 modularized parts of ferrous metal, non-ferrous metal and plastic as shown in Table 4.

In Appendix, we present the AND/OR graph generated based on three sequence alternatives of the vehicle. In the AND/OR graph, all nodes of disassembly operations and objects are numbered 1 to 46 and 1 to 64, respectively. Ferrous metals are considered as recyclable material, while non-ferrous metal and plastic are considered as contaminant materials. Each of existent objects has to be classified into its appropriate container among five containers. For example, objects of ferrous material only or ferrous and non-ferrous together are to be classified into container 1, 2 or 3. Some reusable objects will be classified into container 4 if they are existent. Finally, objects of non-ferrous or plastic are to be classified into container 5 as contaminants. Table 5 shows the qualitative and quantitative boundaries of containers related to recyclable materials. To solve the problem, an MILP model was developed based on the formulation method proposed in the previous section.

Table 4. Material information

modularized part name		material type (kg)		
		steel	bronze	plastic
a	Door mirror			
b	Front window motor		4.0	
c	Front harness		4.0	
d	Front door	70	3.0	
e	Front seat			2.0
f	Rear window motor			
g	Rear harness		3.0	
h	Rear door	60	3.0	
i	Rear seat			3.0
j	Bonnet	50		
k	Rear lamp			
l	Trunk cover	40	5.0	
m	Floor carpet			3.0
n	Engine	170		
o	Bumper			5.0
p	Front lamp			
q	Inside harness		3.0	
r	Chassis	130	5.0	
s	Tire			6.0
t	Glass			3.0
u	Body	210		

Table 5. Qualitative and quantitative boundary

quality boundary	quantity boundary
$QL_1 \leq 0.001$ $QL_2 \leq 0.01$ $QL_3 \leq 0.1$	$QN_1 \geq 100$ $QN_1+QN_2 \geq 300$ $QN_1+QN_2+QN_3 \geq 500$

5.2 Results

The developed MILP model was solved by using a commercial software Xpress-MP. The optimum solution of the example case was obtained in 12 seconds on a personal computer with a Pentium □processor. Among the alternative sequences given in Appendix, sequence (c) was selected as the optimal one (see Table 6). The other sequences of non-optimal are omitted in the graphical representation of the optimal solution of Figure 7. The lined and dotted squares represent the existent and non-existent objects, respectively. The optimal depth is achieved when a total of ten operations were executed in the optimum sequence. As a result of the disassembly process, a total of eleven existent objects were classified into their respective containers from 1 to 5. This solution returns the maximized objective value of 1260 (US $).

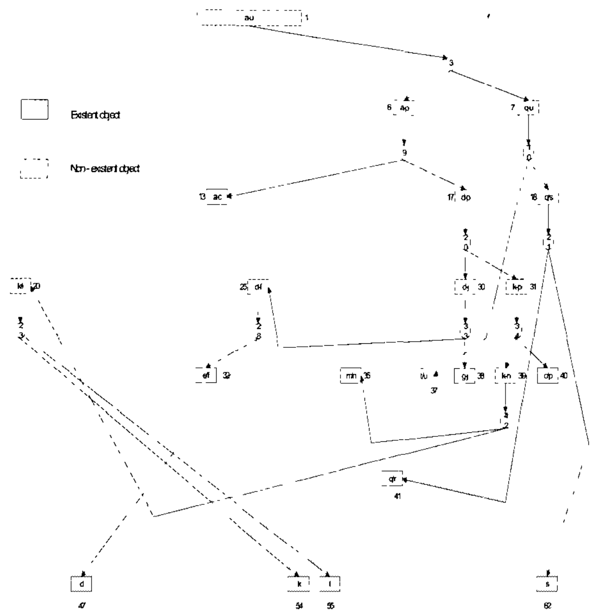


Figure 7. Graphical representation of the optimal solution

Table 6. Numerical results

objective value	1260
optimal sequence	(c)
executed operations	3, 9, 10, 20, 21, 23, 28, 33, 34, 42
classification of existent objects	Container 1:32, 40, 62 Container 2:13, 55 Container 3:38 Container 4:35, 41, 47, 54 Container 5:37

5.3 Sensitivity analysis

Since there are levels of uncertainty for the forecasted data for a strategic planning model, to determine the sensitivity of the solution to changes in parameters such as costs and limits is important. However, the generic IP model does not provide a straightforward sensitivity analysis. The sensitivity analysis for the IP model is often performed by fixing all integer decision variables at their optimal values and running the corresponding LP model (Williams 1985). In the recovery problem considered in this study, the integer variables are the major decisions that determine the executions of disassembly operation (i_n), the existence of objects (j_p) and their classifications (k_{pq}). Thus, the procedure of fixing those integer variables at their optimal values of zero or one provides meaningful economic information, considering the effects of marginal charges on the continuous variables. For the continuous variables z_q that represent the mass of total objects classified into container q, we studied to find their marginal ranges maintaining the optimality of the problem as shown in Table 7. The table indicates that the current solution maintains its optimality if the market price of z_1 is in range of 2.2858 ~ 3.0000. For z_2 and z_3, the marginal ranges of the current prices are 2.0000 ~ 3.1818 and 0.0000 ~ 1.2500, respectively.

Table 7. Sensitivity analysis of z_q

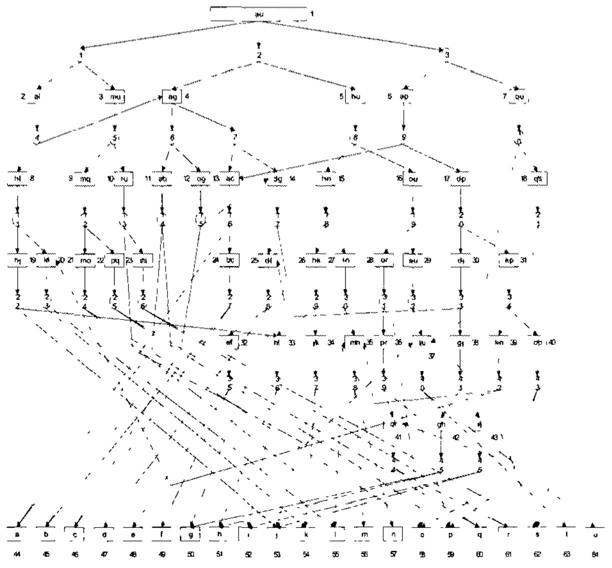
variables	current value	allowable decrease	allowable increase
z_1	3	0.7142	0.0000
z_2	2	0.0000	1.1818
z_3	1	2.0909	0.2500

6. CONCLUSIONS

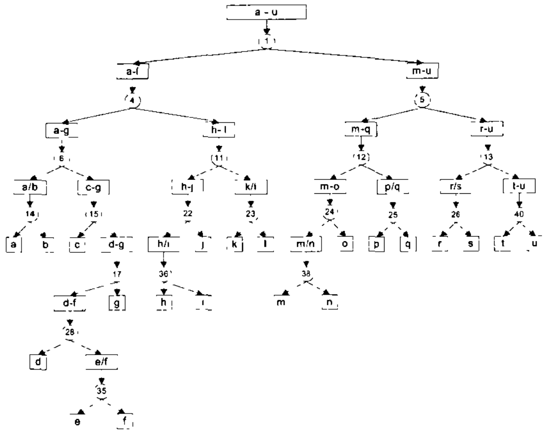
In this paper we proposed a mathematical model that simultaneously optimizes the disassembly and classification. To search for the optimum recovery plan of a given product, we integrated all possible disassembly sequences of the product in an AND/OR graph. We also categorized all objects of the product, subassemblies and terminal parts into three object sets to simplify the analysis of the physical properties. As a result, the recovery problem could be formulated as an MILP model. Our model explicitly considers the combinatorial classifications of all disassembled items to meet the market requirements. By solving the MILP model, we could obtain the optimum recovery plan to achieve the maximum recovery value for an example case. Problems related to disassembly planning and scheduling of multi-products becomes more important in execution stage of product recovery. Further research will be focused on the issues.

APPENDIX

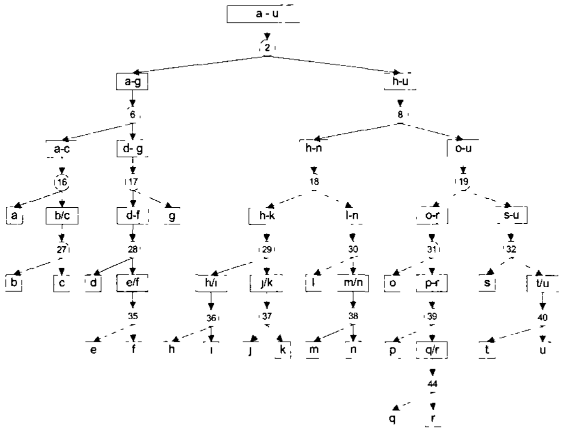
1) AND/OR graph of the three alternative sequences



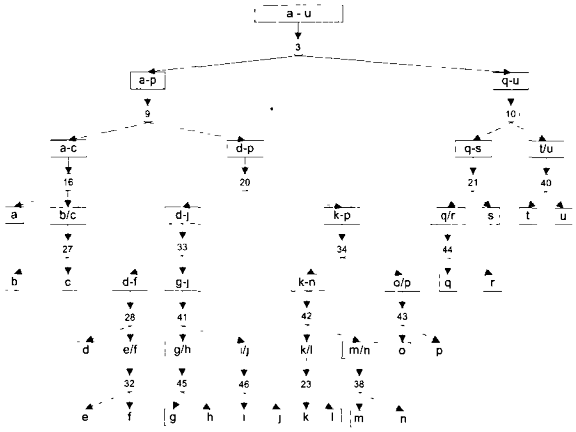
2) Alternative sequence- (a)



3) Alternative sequence- (b)



4) Alternative sequence- (c)



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