A Graph-Based Approach to Disassembly Model for End-of-Life Product Recycling

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Abstract

Manufacturing industries are beginning to face one of the consequences resulting from the rapid development which has occurred during the last decade. The most evident effect is that landfill capacity is being used up. Therefore, a systematic approach to recycling is both urgent and imperative. It has been also recognized that appropriate disassembly of used products is necessary in order to make recycling economically and environmentally viable in the current state of the art reprocessing technology. This paper proposes a graph-based heuristic approach to the disassembly model. The model is embedded on a graph representation and object-oriented modeling, which is obtained by generating disassembly sequences. Information exchange within the disassembly model is done through three phases: (1) disassembly analysis, (2) database and data management, and (3) recycling cost minimization. With graph representation, the problem of identifying the optimal disassembly and recycling strategy is transformed into a graph search problem. By solving the graph search problem, one can determine the termination of disassembly, generate the disassembly sequence, calculate the disassembly cost, select recycling plans, monitor the material flow, and evaluate environmental compatibility of the product. In addition, this paper illustrates the prototype using personal computer disassembly as an example.

1. Introduction

A growing concern for the environment, especially about the waste and landfill, has motivated research into the design of more environmentally benign product. In Europe, 800,000 tons of old TV sets, computer equipment, radios, and measuring devices, and three million tons of automobile equipment are thrown into the national garbage center each year (Owen 1993). In the United States, the municipal solid waste (MSW) generated by households and industrial establishments is about 4 pounds per person each day (Gibbons 1992). Under pressure by European governments, global manufacturers are thinking about how to appropriately dispose of their worn-out products. Currently there is a trend towards increased product "take back" with special emphasis on disassembly and separation for product recycling and reuse.

The life-cycle approach is a useful way to examine the environmental impact of a product; however, environmental impact is only one of many issues for recycling. Other issues include material substitution and selection, disassembly sequence, and recycling cost. A more comprehensive approach is needed to integrate environmental and traditional design concerns. Generally, it is not possible to recover 100% of all materials used in the end-of-life (EOL) products. Components can rarely be re-used directly; therefore, most products must be disassembled or dismantled to be separate materials in order to recycle them as secondary materials. This paper proposes a graph-based heuristic approach for a disassembly model. The model is embedded on a graph representation and object-oriented modeling, which is obtained by generating disassembly sequences. Information exchange within the disassembly model is done through three phases:

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(1) disassembly analysis, (2) database and data management, and (3) recycling cost minimization. By solving the graph search problem, one can determine the termination of disassembly, generate the disassembly sequence, calculate the disassembly cost, select recycling plans, monitor the material flow, and evaluate environmental compatibility of the product.

2. Relative research

Most products are not designed within life cycle consideration today; therefore, the key is to design future products which can be easily disassembled and recycled (Mauro 1995). There has been significant research focused on design for recycling of automotive, electromechanical, electronic, and consumer products. Alting (1993) addressed recycling within a Life Cycle Design concept. Alting indicated that a product must be produced, distributed, used and disposed/recycled without harm to the environment in any of these phases. All of these phases must be considered from the perspective of the conceptual stage, where it is possible to accommodate the requirements of each successive stage while changing the outcomes in a cost-efficient manner. Amezquita *et al.* (1995) developed the reusability metrics based on life cycle factors of engineering systems. A validation strategy has been developed to determine the correctness and validity of these metrics.

Disassembly sequence analysis: A possible disassembly sequence is to remove one parts without interference from other parts. Arai and Iwata (1993) proposed an evaluation method for the ease of assembly/disassembly based on the kinematic simulation system. In the kinematic simulation system, the part is decided to be removed by comparing the evaluation standard values of candidate parts when several parts can be removed at the same time. By using the product model of 3-D solid geometry, possible movements of each part in the product are calculated, and the removal possibility from the product can be searched. Ko and Lee (1987) determined the direction of disassembly by taking the direction of the normal to the largest mating face of each part in the subassembly. Khosla and Mattikali (1989) improved the method of Ko and Lee by considering the mating conditions of all the faces of the subassembly. Each subassembly face which mates with a non-subassembly face restricts the degree of freedom in the direction of the outward normal to the face. Homem de Mello and Sanderson (1991) have developed a system which permits parts to have both planar and cylindrical faces. All of the disassembly motions must be straight-line translations or screw motions. Li *et al.* (1995) used a simulated annealing algorithm to find economically optimal sequences that give the maximum return value and provide a suggestion about where the disassembly operation should stop. A precedence relationship among the components is analyzed; however, Li *et al.* did not consider the modularity among the components. Modularity is integrating different component and/or subassemblies that share a physical relationship and some similar function. In disassembly and recycling analysis, modularity design is focused on the physical relationship and similar retirement method (e.g., re-use, remanufacture, high grade recycling, low grade recycling, chemical decomposition recycling, incineration recycling, and disposal) (Simon 1991). Chen *et al.* (1994) used Suh's (1990) independent design axiom to derive the measurement of product modularity. Ishii *et al.* (1995) proposed clumping by the technology life cycle, which can aggregate the component's material compatibility. In the clumping method, materials and fastening methods should be compatible with existing reprocessing technologies. Gu and Yan (1995) used the liaison graph, decomposed the liaison graph into sub-groups, generated the disassembly sequence for each sub-group, merged disassembly sequences for sub-groups, and reversed it into assembly sequences.

Product recycling cost: It is important to find the economically optimal disassembly sequences that give the maximum return value and determine whether the disassembly operation should stop. Usually, product recycling includes disassembly, material reprocessing, disposal cost, and salvage profit (Zhang and Kuo 1996). Disassembly cost is defined as the cost to separate the components of end-of-life (EOL) products to be recycled. Most components are joined together with methods that prevent them from being separated (e.g., ultrasonic, welding or adhesives and fasteners). The more components are disassembled, the higher the disassembly costs will be. Material recycling cost is defined as the total cost to reprocess the material for reuse by different recycling methods. As different recycling methods are used, the different material reprocessing cost are calculated. Usually, the more components are disassembled, the higher the material reprocessing cost will be. Disposal cost is defined as the cost of landfill dispose of the components which can not be reused or reprocessed. Usually, the disposal cost is simply the landfill fee. Salvage benefit is defined as the value of components for resale in marketing. When the components are recycled, they can be reused in the production line as raw materials or parts.

3. Disassembly Model

The key to recycling EOL products depends on the planning of disassembly processes and recycling strategies. To build a theoretically sound disassembly model, three phases are involved: disassembly analysis, database and database management, and recycling cost minimization.

<u>Phase I - disassembly analysis</u>. In this phase, product structure and disassembly sequence are analyzed. The structure of the product refers to the geometric components and assembly relationship among the components. During this phases, the disassembly strategies are evaluated and the disassembly sequences are determined. To obtain the disassembly sequence, the graph theory is used to split the products into several sub-assembly. Also, the disassembly precedence is used to obtain a disassembly tree. Most of the time, there exists many feasible disassembly sequences. Groups of these disassembly sequences are represented by a disassembly tree.

<u>Phase II - database and database management</u>. After the product structure is analyzed, the material properties are investigated. There is a need for a material database containing information on the component's physical properties (e.g., material characteristics, weight, volume, toxicity), recycling methods, (e.g., reuse, remanufacture, high/low grade recycling). Some materials cannot be recycled because of their physical properties. For instance, the printed circuit board (PCB) is commonly used by FR-4 (FR = "fire resistant") - glass reinforced polyester resin with additives to reduce flammability. The resin is thermoset PE with many additives. Therefore, PCB can not be recycled because of its physical properties.

<u>Phase III - recycling cost minimization.</u> The third step is to determine the disassembly strategy and recycling cost. When the product's structure has been clarified, it will be found that not every disassembly operation is suitable. Some operations are not possible because there are no physical

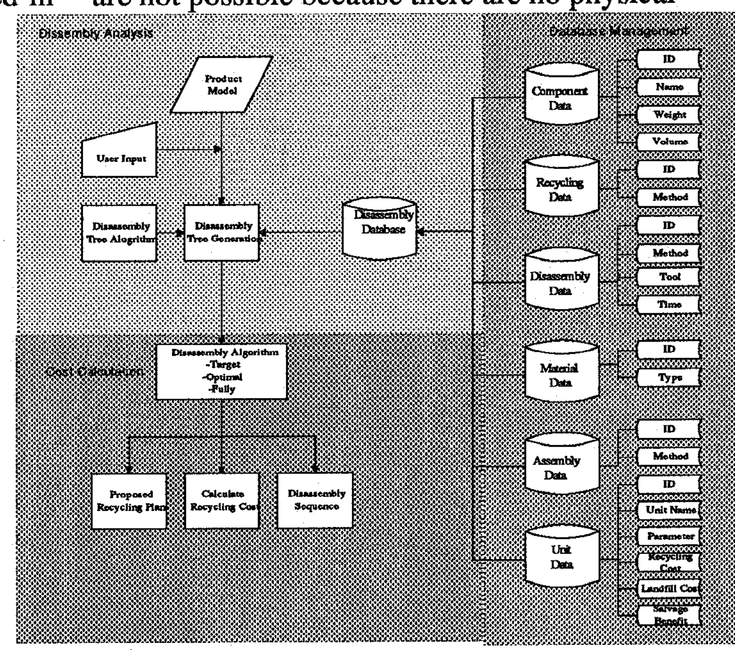

Figure 1: A disassembly model

relations between the components, while others cannot be carried out because the joints are fixed and no physical separation is possible (welding, soldering, etc.) In addition, disassembly is not the reverse of assembly, and many operations can be omitted if they are not profitable. Therefore, the recycling costs are studied in this step. The above phases are formulated as a disassembly model for EOL product recycling and is shows in figure 1.

3.1 Disassembly Analysis

In order to generate the disassembly sequence, it is important to represent the geometric and non-geometric information about the assembly. A prerequisite to developing an appropriate model for EOL product disassembly is the use of a product assembly model. Many product assembly models reported in the literature has been developed based on the language of the graph (Gu 1995). In this study, the assembly relationships among components of a product are represented as a graph with the vertices representing components (fasteners are treated as components) and edges representing assembly relationships. After carefully studying various assembly models, a graph-based disassembly model for the purpose of recycling was developed. Two distinct features of the model are: (1) fasteners are treated differently from components, (2) a product model is represented using graphs and matrices, namely, component-fastener graph and disassembly precedence matrices, and (3) groups of disassembly sequences are represented as a disassembly tree.

Component-fastener graph. This graph represents the component-fastener relationships among the components. A component is a constituent part of a product, without which the product will not function properly. A fastener is used to attach one component to another for the purpose of assembly. Examples of fasteners include screws, rivets, inserts, etc. In a component-fastener relationship graph $G_C = (V, E)$ the components are represented as the vertices $V = \{v_1, v_2, \ldots, v_n\}$, where n is the number of components. Their relationships are represented as the edges $E = \{e_1, e_2, \ldots, e_m\}$, where m is the number of edges. If two components v_i and v_j $(i \neq j)$ are joined by fasteners, then $(v_i, v_j) \in E$; otherwise $(v_i, v_j) \notin E$. The graph G_C is an undirected graph. The vertices and edges in graph G_C are modeled using object-oriented techniques. While the object vertex consists of component information including its name, weight, material type, etc., the object edge consists of fastener information including the number of fasteners, fastener type, etc., and the object fastener refers to the disassembly method between components. Figure 2 shows all the information contained in the vertex, edge and fastener.

Class Vertex {	Class Edge {	Class Fastener {
ID;	ID;	ID;
Name;	Name;	Name;
Material_Type;	Number_of_Fastener;	Disassembly_Method;
Weight;	Fastener_ID;	Disassembly_Tool;
Recycling_Method;	}	Dissasebly_Time;
Recycling_Cost;		}
Number_of_Child;		
Child_ID;		
}		

Figure 2: Data information in disassembly model

Figure 3 shows a partially disassembled personal computer (PC) and it's corresponding component-fastener graph is shown in Figure 2.

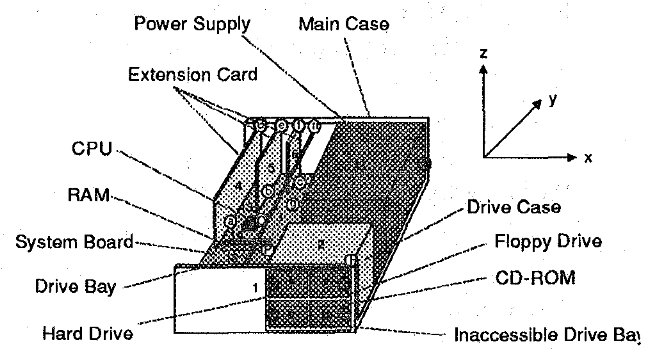

Figure 3. A partially disassembled personal computer (PC).

Modularity analysis. Modularity analysis is used to simplify the complexity of a product. All of the components which share the same characteristics are grouped into a sub-assembly. The analysis starts with searching for cut-vertices in the component-fastener graph. A cut-vertex is defined as a vertex whose removal disconnects the graph. If a cut-vertex is found, the graph is split into two or more sub-graphs. Each sub-graph represents a module. These modules are the child vertices of the parent vertex. The fasteners that must be removed in order to obtain a child vertex (a module) are embedded in the edge connecting the child vertex with its parent. For each of these modules, the same procedure is applied until no cut-vertices can be found. In figure 5, component 1 and component 2 are cut-vertices; therefore, the graph was split into 9 sub-graph. The corresponding modules are $\{V_1\}$, $\{V_2\}$, $\{V_3, V_4, V_5, V_6\}$, $\{V_7\}$, $\{V_8\}$, $\{V_9\}$, $\{V_{10}\}$, $\{V_{11}\}$, $\{V_{12}\}$.

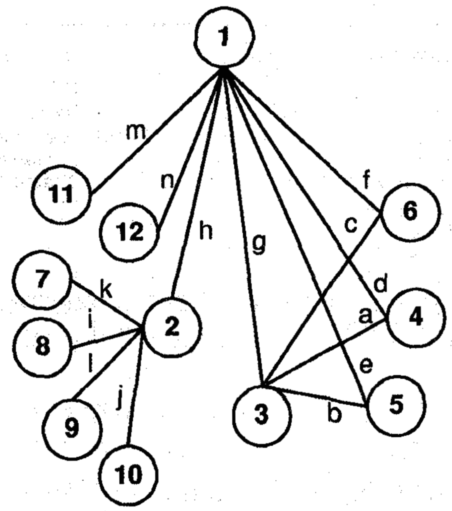

Figure 4: Component-fastener relationship graph for the assembly shown in Figure 1.

Disassembly precedence metrics. After the components are simplified by modularity analysis, the disassembly precedence metrics is analyzed. Precedence is defined between contacting parts; if the absence of a part gives more freedom of movement to another part, then the former has precedence over the latter. The precedence relation is local to the parts concerned, and signifies the partial order of disassembly (Yokota K, and Brough D. R., 1992). Disassembly precedence means a component cannot be disassembled before certain other components. Table 1 shows the disassembly precedence metrics of the 9 sub-graph in figure 5. For example, sub-graph {3,4,5,6} can not be removed until sub-graph {1} (±y, and -z direction) and {11} (±x, and +z direction) are removed.

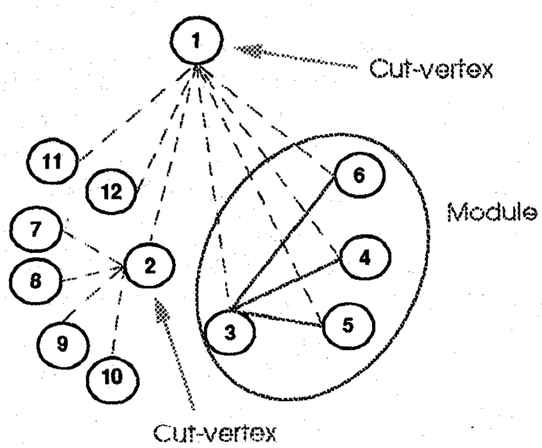

Figure 5: Modularity analysis

		+x	-x	+y	-y	+z	-z
Cut-Vertex	**1**	-	-	2-12	2-12	2-12	-
Cut-Vertex	**2**	7-10	7-10	1	1, 11	7-10	7-10
	3-6	11	11	1	1	11	1
	7	2	2	√	2	2	2
	8	2	2	√	2	2	2
	9	2	2	√	2	2	2
	10	2	2	√	2	2	2
	11	-	4, 5, 6	1, 2	1	√	1
	12	-	-	-	-	√	1

Table 1: Disassembly precedence matrices

Disassembly tree generation. The final disassembly tree is constructed based on the disassembly modules and the disassembly precedence metrics of the EOL product. Referring to the disassembly precedence metrics shown in Figure 3, {1} and {2} are the cut-vertices which are considered to be disassembled lastly. Only sub-assembly {11}, {12}, {7}, (8}, {9) and {10) can be disassembled from the +z, and +y direction. Therefore, in the first step of disassembly, only {11}, {12}, {7}, {8}, {9}, and {10} are disassembled. The other sub-graphs are merged together because after some components are disassembled, the cut-vertices will change. Perhaps new cut-vertices will be generated, or old cut-vertices will change to become non cut-vertices. Example is sub-graph {2}, after {7} through {10} are removed, {2} is no longer a cut-vertex. Figure 6, shows the first step of the disassembly tree. The process should be repeated to find the cut-vertex and evaluate all the disassembly precedence metrics until a complete disassembly tree is generated. Figure 7 shows the final disassembly tree.

3.2 Material database management

In the activities of disassembling and recycling, material information related to EOL products is especially needed, including information on material properties (e.g., material compatibility, and toxicity, substitution possibilities, environmental persistence, energy usage, material costs, and recycling costs and procedures). Although some material data and information exist, it is not easily accessible to the design and manufacturing community. Manufacturers cannot directly control all materials used to manufacture products because many product and process materials are supplied by outside companies. This lack of knowledge about materials and their impacts is greatly detrimental to the incorporating environmental concerns into the design and manufacture of products. Hence, when a disassembly model is developed, the material information should be taken into consideration for design trade off and manufacturing alternatives.

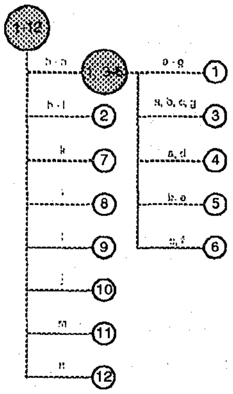

Figure 6: The first step of disassembly tree

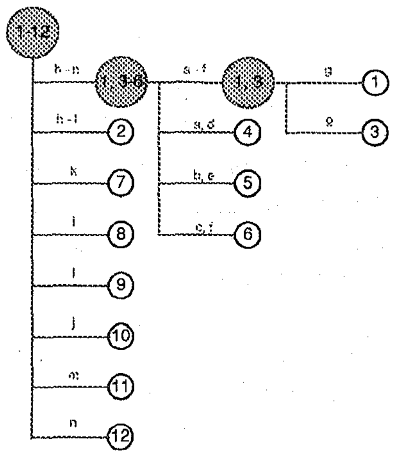

Figure 7: The final disassembly tree

3.3 Recycling cost minimization

Termination of disassembly. The termination of disassembly is determined based on the issue of cost and profit. Three types of cost and one type of profit are addressed: (1) disassembly cost, (2) material reprocessing cost, (3) disposal cost, and (4) salvage profit. The total cost is calculated as the sum of the disassembly cost, material reprocessing cost, and disposal cost minus salvage profit. For each component, the disposal cost, the disassembly cost, and the recycling cost and salvage benefit are compared. Only one alternatives will be selected, which means only one method of retiring will be applied to the component: 1) the component will be disassembled, 2) the component will be disposed into landfill, or 3) the component will be recycled and sold in the market. The recycling cost is formulated as follows (figure 8):

$$(C_{TR})_{V^0} = \min \sum_{i=1}^{u} \sum_{i=1}^{v} \left(E^q_{(\sigma_q)_i} + \min \left\{ \begin{array}{l} (C_P)_{V^q_{(\sigma_q)_i}} X_{(V^q_{\sigma_q})_i} \\ (C_M - C_S)_{V^q_{(\sigma_q)_i}} Y_{(V^q_{\sigma_q})_i} \\ (C_D)_{(V^q_{\sigma_q})_i} Z_{(V^q_{\sigma_q})_i} \end{array} \right\} \right)_j$$

$$X_{(V^q_{\sigma_q})_i} + Y_{(V^q_{\sigma_q})_i} + Z_{(V^q_{\sigma_q})_i} = 1$$

$$X_{(V^q_{\sigma_q})_i}, Y_{(V^q_{\sigma_q})_i}, Z_{(V^q_{\sigma_q})_i} \in [1,0]$$

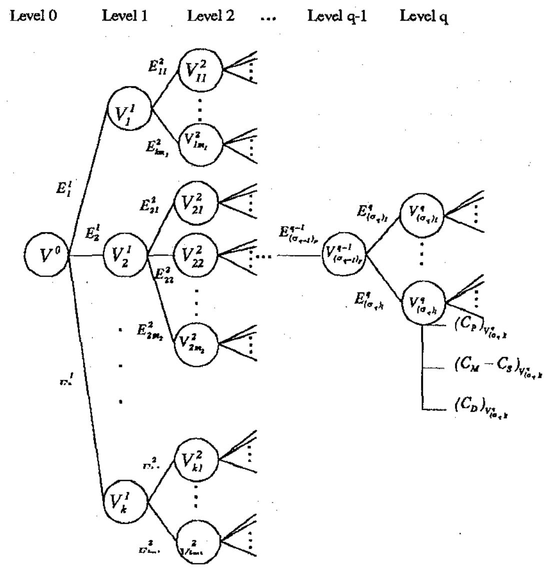

Figure 8: recycling cost in the disassembly tree

$(C_P)_{V^q_{(\sigma_q)_i}}$	:disposal Cost in vertex $V^q_{(\sigma_q)_i}$
$(C_D)_{V^q_{(\sigma_q)_i}}$	:disassembly Cost in vertex $V^q_{(\sigma_q)_i}$
$(C_M)_{V^q_{(\sigma_q)_i}}$	:material Recycling Cost $V^q_{(\sigma_q)_i}$
$(C_S)_{V^q_{(\sigma_q)_i}}$	:salvage Benefit $V^q_{(\sigma_q)_i}$
$(C_{TR})_{V^0}$	:total Recycling Cost in vertex V^0

$V^q_{(\sigma_q)_i}$: vertex of q level in the disassembly tree, where $\sigma_q = k_1 k_2 ... k_q$, in which $i = 1, 2, ..., u$

Disassembly cost $(C_D)_{V^q_{(\sigma_q)_i}}$: In the disassembly tree, the disassembly cost is associated with each link. Disassembly cost is a function of labor cost and disassembly time. The disassembly cost is associated with each link, DC_i, is calculated as:

$$(C_D)_{V^q_{(\sigma_q)_i}} = C_L \times (\sum_{k=1}^{n} T_k)$$

i: index of link i and component i,
C_L : labor cost per hour,
$(C_D)_{V^q_{(\sigma_q)_i}}$: the cost to disassemble the component i,
T_k : time to remove the fastener k.
k : $1...n$, number of fasteners in link i

Material recycling cost $(C_M)_{V^q_{(\sigma_q)_i}}$: After the components are disassembled, some components can be directly reused, while the others should be reprocessed (e.g., remanufacturing or high/low grade recycling) before they can be directly reused. As different recycling methods are used, the different material reprocessing costs are calculated.

$$(C_M)_{V^q_{(\sigma_q)_i}} = (R_1 C_{rue})_i + (R_1 C_{rem})_i + (R_1 C_{high})_i + (R_1 C_{low})_i + ... + (R_1 C_x)_i$$

i: index of component i
$(C_M)_{V^q_{(\sigma_q)_i}}$: recycling cost for component i
R_j: decision variable, where $j = 1,...,n$

$$\sum_{i=1}^{n} R_i = 1, \quad R_i \in [0,1]$$

C_{rue}: reuse cost of component i
C_{rem}: remanufacturing cost of component i
C_{high}: high grade recycling cost of component i
C_{low}: low grade recycling cost of component i
C_X: other recycling cost of component i

Disposal cost $(C_P)_{V^q_{(\sigma_q)_i}}$: It is a function of either weight, volume, or other property, like toxicity, *etc.*

$$(C_P)_{V^q_{(\sigma_q)_i}} = D_1 \times W_i + D_2 \times V_i + ... + D_j \times X_i$$

i: index of component i
DSC_i: disposal cost for component i
D_j: weighted value of disposal cost where $j = 1,...,n$
W_i: weight of component i
V_i: volume of component i
X_i: other physical property of component i

Salvage profit $(C_S)_{V^q_{(\sigma_q)_i}}$: When the components are recycled, they can be reused in the production line, as raw materials or parts. Salvage profit is one of the function of weight, volume, or another property, like capacity, *etc.*

$$(C_S)_{V^q_{(\sigma_q)_i}} = P \times W_i + P_2 \times V_i + ... + P_i \times Y_i$$

i: index of component i
SB_i: salvage benefit for component i
P_j: weighted value of recycled method, where $j=1,...,n$
W_i: weight of component i
V_i: volume of component i
Y_i: other physical property of component i

Total recycling cost $(CT_R)_i$: Total recycling cost is calculated by summing the total disassembly cost, total material reprocessing cost, total disposal cost and total regainable benefit.

$$(CT_R)_i = X_1 \times (C_D)_{V^q_{(\sigma_q)_i}} + X_3 \times (C_P)_{V^q_{(\sigma_q)_i}} + X_2 \times ((C_M)_{V^q_{(\sigma_q)_i}} - (C_S)_{V^q_{(\sigma_q)_i}})$$

i: index of component i
$(CT_R)_i$:Total recycling cost for each component i
$(C_D)_{V^q_{(\sigma_q)_i}}$: Disassembly cost for component i
$(C_M)_{V^q_{(\sigma_q)_i}}$: Material recycling cost for component i
$(C_S)_{V^q_{(\sigma_q)_i}}$: Salvage benefit for component i
$(C_P)_{V^q_{(\sigma_q)_i}}$: Disposals cost for component i
X_i: Decision variable, where $i = 1,2,3$

4. Conclusion and Future Research

Recycling is increasingly gaining attention world-wide. The importance of recycling is recognized by most industrially developed countries, with varying emphases on issues concerning legislation, standardization, basic research, and industrial implementation. Nonetheless, research on recycling is in its infancy. In this paper, research activities concerning the recycling of end-of-life products and the disassembly model were developed. Based on the developed technique, numerous EOL products can be recycled effectively. The model is currently focused on PC recycling; however, it has great potential to be developed for other products such as TVs, telephones, automobiles, etc. As preliminary research, this project is one of the pioneers for computer recycling. The research project will impact the current computer industry by means of raising environmental conscious in manufacturing.

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