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DESIGNING ELECTRONIC PRODUCTS FOR DISASSEMBLY USING COST/BENEFIT ANALYSIS

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ABSTRACT

This paper presents a technique to analyze the design efficiency of a product at both ends of the life-cycle. The design efficiency is measured using a Design for Disassembly Index (DfDI). DfDI uses a disassembly tree (DT) which relies on product's structural blueprint. The DT can be used to identify precedent relationships that define the structural constraints in terms of the order in which components can be retrieved. DfDI can be used to compare the merits and drawbacks of different product designs. The index offers designers with an important measure to help improve future products. We provide a comprehensive procedure for developing the index and demonstrate its application through an example.

INTRODUCTION

Environmental design initiatives address the environmental concerns of product life-cycle and production processes. During the past decade, interest has started to generate in designing products that not only satisfy functional specifications, but are also easy to assemble, disassemble and possess any of the host of other attributes. This has led to the emergence of a concept called "Design for". The concept covers a wide range of design specialties e.g., "Design for Assembly" (DfA), "Design for Manufacturing" (DfM), etc. Lately, there have been efforts to incorporate environmental considerations into the "Design for" concept and is known as the "Design for Environment" (DfE) (or *Green Design*).

Originally, many companies were skeptical to incorporate the DfE concept into their products and production facilities because they felt that this would be enormously expensive as they would have to overhaul their entire operation. However, with positive experiences of many companies, the current consensus is that, with proper design, not only is DfE more cost efficient, in many cases, it could actually generate positive income in the long run. Moreover, it is necessary because of competition, consumer demand and the prevailing laws.

A perfect phrase to describe how today's businesses synchronize both ends of products' life-cycles is '*Making ends meet*'—that is, the design of products on one end and the end-of-life reclamation on the other. If expensive

materials or components were used to design products, then one would have to guarantee that it would be economically feasible to remove and reuse parts and materials from the products. This paper provides a technique to analyze the design efficiency of a product at both ends of the life-cycle. The design efficiency is measured using a Design for Disassembly Index (DfDI).

DfDI uses a disassembly tree (DT) which relies on product's structural blueprint [8], [9]. The DT can be used to identify precedent relationships that define the structural constraints in terms of the order in which components can be retrieved. DfDI can be used to compare the merits and drawbacks of different product designs. The development of this index involves the analysis of the disassembly paths and a logic disassembly table to find the combination of components and materials together with their layout in the product so as to provide the optimum cost-benefit ratio for end-of-life retrieval. The cost considerations in this analysis include disassembly labor costs and tooling requirements, while the benefit is derived from the sales of recovered components. As a result, the methodology offers the best combination of components (with the highest cost-benefit ratio) to incorporate in the design of the product.

LITERATURE REVIEW

Since the design of a product has the highest influence on the product's life-cycle, it is the first priority towards the greening of products [2]. "Do it right the first time" is the phrase used to describe the objective of green design [1]. Green design has to capture the essence in every step of the product's life-cycle in order to assess its impact on the environment.

Various analysis tools have been developed to assist and/or evaluate different aspects of product design. Ishii et al. [4] developed a methodology to design a product for retirement using hierarchical semantic network that consists of components and subassemblies. Navin-Chandra [6] presented an evaluation methodology for Design for Disassembly (DfD). He developed a software called ReStar which optimizes the component recovery plan. Subramani and Dewhurst [7] investigated procedures to assess service difficulties and the associated costs at the product design stage. Isaacs and Gupta [3] have suggested an evaluation methodology that enables an automobile designer to

measure disassembly and recycling potential for different automobile designs. Johnson and Wang [5] used a disassembly tree (DT) in designing products to enhance material recovery opportunities. Vujosevic et al. [10] have studied the design of products that can be easily disassembled for maintenance.

MODEL FORMULATION

Nomenclature

A_{ik}	subassembly node k in product i ;
D_j	vector representing the total demand for component P_j (unit);
DC	component disposal cost (\$/unit of index scale);
DW_j	disposal cost index of component j (index scale 1= lowest, 10 = highest);
I_{ii}	identity matrix of rank i ;
$LS^S(Root_i)$	set of selected leaf successors of the root node in product i ;
P_j	component j ;
PC	Processing (disassembly) cost (\$/unit time)
Q_{ij}	multiplicity matrix representing the number of each type of component P_j obtained from each type of product i ;
$Root_i$	root node of the product i ;
RV_j	resale value of component j (\$/unit);
s_i	number of subassembly nodes in product i ;
S_i	vector representing the supply of product i from all sources;
$T(A_{ik})$	time to disassemble subassembly k from product i (unit time);
$T(Root_i)$	time to disassemble root node of the product i (unit time);
TC_i	cost of acquisition and transportation for product i (\$/unit);
TD_i^S	total disassembly time for a set of selected components in product i (unit time);
TDC	total disposal cost (\$);
TPC	total processing cost (\$);
TRR	total resale revenue (\$);
W_{ij}	matrix representing the number of units of component P_j obtained from product i that will require disposal;
W_j	vector representing the total number of units of component P_j that will require disposal;
X_{ij}	matrix representing the number of units of component P_j retrieved from product i used to fulfill the total demand for components;
Y_i	vector representing the number of each of product i in the batch to be disassembled;
Y_{ij}	matrix representing the total yield of the number of component P_j retrieved from

$[a]$	product i ;
	gives the smallest integer that is larger than or equal to a ;
$\{b_{ij}\}$	element in row i and column j of matrix b_{ij} ; and
$\{g\}$	the i^{th} element in vector g .

In order to design products simultaneously for environmental compatibility and commercial viability, a cost-benefit model that can be used to assess the DfE, is proposed. The cost-benefit model consists of three major components, viz., TRR , TPC , and TDC .

TRR is directly influenced by RV_j and TC_i . The revenue equation can be formulated as follows

$$TRR = \sum_i \sum_{\substack{j \in D_j > 0 \\ \text{and} \\ P_j \in LS^S(Root_i)}} (RV_j \cdot \{X_{ij}\}) - \sum_i (TC_i \cdot \{Y_i\})$$

TPC can be calculated from PC and TD_i^S as follows:

$$TPC = PC \cdot \sum_i TD_i^S$$

where, TD_i^S is obtained using the following equation:

$$TD_i^S = \left(\underset{\forall P_j \in LS^S(Root_i)}{Max} \left[\frac{\{D_j\}}{\{Q_{ij}\}} \right] \right) \left(T(Root_i) \right) + \sum_{k=1}^{S_i} \left(\underset{\forall P_j \in LS^S(Root_i)}{Max} \left[\frac{\{D_j\}}{\{Q_{ij}\}} \right] \right) \left(T(A_{ik}) \right)$$

TDC is calculated by multiplying the component disposal cost by the number of components disposed as follows:

$$TDC = DC \cdot \left(\sum_i \sum_{\substack{j \in D_j > 0 \\ \text{and} \\ P_j \in LS^S(Root_i)}} (DW_j \cdot \{W_{ij}\}) \right) + DC \cdot \left(\sum_i \sum_{\substack{j \in D_j = 0 \\ \text{and} \\ P_j \in LS^S(Root_i)}} (DW_j \cdot \{Y_i \cdot I_{ii} \cdot Q_{ij}\}) \right)$$

Note that DW_j is the disposal cost index representing the degree of nuisance created by the disposal of component j . The higher the value of index, the more nuisance the component creates and hence it costs more to dispose it of.

The five steps for calculating DfDI are as follows:

- Step 1:** List all components with their predecessors, values, multiplicity and disposal costs.
- Step 2:** Assess the disassembly times.
- Step 3:** Generate mutually exclusive combination table for component(s) selection.
- Step 4:** Calculate the benefits and costs for each mutually exclusive combination.
- Step 5:** Calculate the DfDI and the net benefit for each mutually exclusive combination.

EXAMPLE

Consider two product designs, G and H (see Figure 1). Each consisting of four identical components (the values, multiplicity, and disposal costs of the components are the equal in each design). Next, we demonstrate the calculation of the DfDI for product design G .

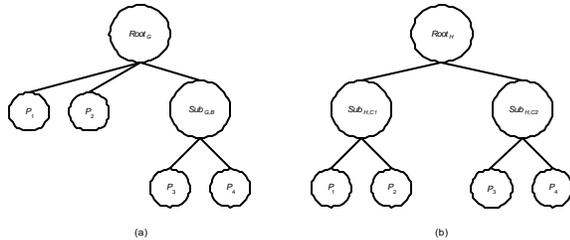


Figure 1. Product structure G and H .

Step 1: Table 1 lists every component with its predecessor, value, multiplicity and disposal cost.

Table 1. DT Data.

(A) Component ID	(B) PredecessorID	(C) Value	(D) Multiplicity	(E) Disposal Cost/Unit
P_1	$Root_G$	5	1	2
P_2	$Root_G$	3	1	1
P_3	$Sub_{G,B}$	5	2	4
P_4	$Sub_{G,B}$	10	1	3

Step 2: Let $T(Root_G) = 5$, $T(Sub_{G,B}) = 5$, $T(Root_H) = 5$, $T(Sub_{H,C1}) = 7$, and $T(Sub_{H,C2}) = 5$. Also, let $TC_i = \$3$ and $PC = \$0.20/\text{minute}$.

Step 3: Table 2 shows the mutually exclusive combinations in column (G). “1” indicates that the part is sold (recycled) for its value while “0” indicates that the part is disposed of.

Table 2. Mutually Exclusive Combination.

(F) Mutually Exclusive Combination	(G) Parts Recycled				(H) Total Benefit	(I) Total Cost	(J) DFDI	(K) Net Benefit
	P_1	P_2	P_3	P_4				
1	0	0	0	0	0	14	0.00	-14
2	0	0	0	1	7	13	0.54	-6
3	0	0	1	0	7	8	0.88	-1
4	0	0	1	1	17	5	3.40	12
5	0	1	0	0	0	14	0.00	-14
6	0	1	0	1	10	12	0.83	-2
7	0	1	1	0	10	7	1.43	3
8	0	1	1	1	20	4	5.00	16
9	1	0	0	0	2	13	0.15	-11
10	1	0	0	1	12	11	1.09	1
11	1	0	1	0	12	6	2.00	6
12	1	0	1	1	22	3	7.33	19
13	1	1	0	0	5	12	0.42	-7
14	1	1	0	1	15	10	1.50	5
15	1	1	1	0	15	5	3.00	10
16	1	1	1	1	25	2	12.50	23

Step 4: In Table 2, for each mutually exclusive combination, the total benefit, TRR is shown in column (H), and the total cost, $TPC + TDC$ is shown in column (I).

Step 5: As shown in Table 2, the DfDI is calculated by dividing column (H) by column (I) and the net benefit is calculated by subtracting column (I) from column (H).

For product G , the maximum value of the DfDI is 12.50. By following a similar procedure, we can show that the maximum value of the DfDI for product H is 7.35. Since, product G has a higher value of the DfDI than product H , the former design is preferred. A similar conclusion can be reached by considering the net benefits of design G (\$23) and design H (\$21.6).

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