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A Combinatorial Cost-Benefit Analysis Methodology for Designing Modular Electronic Products for the Environment

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Abstract—This paper presents a technique to analyze the efficiency of designing electronic products for the environment. The efficiency of each design is indicated using a Design for Disassembly Index (DfDI). DfDI uses a disassembly tree (DT) which relies on the product's bill of materials as its structural blueprint. DfDI can be used to compare the efficiency among alternative designs, identifying the best alternative for a product retirement plan. In addition, the index offers designers with an important measure to help improve future products.

I. INTRODUCTION

Product designers are usually subject to numerous, but often contradicting demands. Those demands not only include designing for appeal or cost efficiency, but also for assembly, manufacturing, and any of the host of other attributes. This has led to the emergence of a principle called "Design for". The principle covers a wide range of design specialties, for example, "Design for Assembly" (DfA), "Design for Manufacturing" (DfM), etc. Increasingly significant is a new demand for designing environmentally benign products, also known as the "Design for Environment" (DfE) (or *Green Design*). Conceptually, DfE denotes designing products such that their environmental impact is as small as possible. That is, to reduce, reuse and recycle products and their components in the most cost efficient manner.

In the past, the main criticism that surrounded DfE was that it would be enormously expensive because companies would have to overhaul their entire product design or production facilities to implement it. 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.

Major electronic manufacturing companies have taken proactive steps towards the greening of electronic products by emphasizing on reducing parts, rationalizing materials, and reusing components.

Xerox has launched its green manufacturing program with the objective to save costs by reusing its photocopy components [1]. It resulted in a total savings of two hundred million dollars a year. IBM, has established component recovery facilities to disassemble and recover reusable components from computers of various sizes. The facilities work closely with IBM's Engineering Center for Environmentally Conscious Products (ECECP) in Raleigh, North Carolina, to improve future computer designs [2]. Sony has also incorporated the DfE principle into its product development process. At the Sony Disassembly Evaluation Workshop in Stuttgart, Germany, products are taken apart to assess the reuse and recycling potential of electronic parts. During disassembly, every step is clearly documented and recorded. The collected data is later evaluated and shared with the design engineer to help improve future designs [3].

Designing a product to fulfill today's environmental trends requires a designer to look at the whole cycle of the product's life that ranges from the design stage to the end-of-life (EOL) stage (Fig. 1). The factors that may influence the design of products for end-of-life disassembly include: the disassembly sequence, the disassembly time, the disassembly cost, the disposal cost, and the benefit from reuse and recycling.

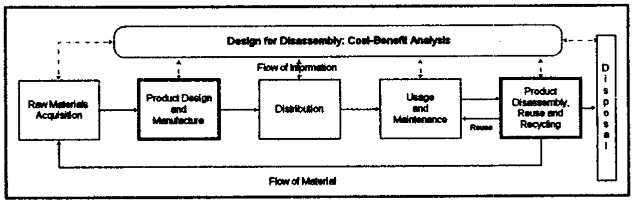

Fig. 1. Product life-cycle.

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Do it right the first time is the ideal phrase to describe the purpose of DfE [4]. Designing products for the ease of disassembly, reuse and recycling is the first priority towards the greening of products, since it has the highest influence on the product's life-cycle [5]. Green design has to account for the basic nature in every step of the product's life-cycle in order to assess its influence on the environment. Present interest on green design generally focuses on one of two major areas: Design for Disassembly (DfD) and Planning For Disassembly (PfD). Research in the area of DfD focuses on designing new products for the ease of end-of-life disassembly. Research in the area of PfD looks at the disassembly of existing products at the disposal stage.

Various analysis tools have been developed to assist and/or evaluate different aspects of product design. Ishii et al. [6] developed a methodology to design a product for retirement using hierarchical semantic network that consists of components and subassemblies. Navin-Chandra [7] presented an evaluation methodology for Design for Disassembly (DfD) which optimizes the component recovery plan. Subramani and Dewhurst [8] investigated procedures to assess service difficulties and the associated costs at the product design stage.

Isaacs and Gupta [9] have suggested an evaluation methodology that enables an automobile designer to measure disassembly and recycling potential for different automobile designs. Johnson and Wang [10] used a disassembly tree (DT) in designing products to enhance material recovery opportunities. Vujosevic et al. [11] have studied the design of products that can be easily disassembled for maintenance.

Literature in the area of planning for disassembly can be classified based on the technique that is applied to solve the problem. Brennan et al. [12] addressed operations planning issues in an assembly/disassembly production environment. Gupta and Taleb [13] presented an algorithm for scheduling disassembly to calculate the number of products (root items) to disassemble in order to fulfill the demand. The algorithm was improved by Taleb et al. [14] and Taleb and Gupta [15] by accommodating the ability to handle the disassembly of complex product structures that have multiple occurrences of parts.

Veerakamolmal and Gupta [16] applied planning and sequencing techniques to create an efficient disassembly plan, that minimizes the total processing time or the cost of disassembly. Moore et al. [17] used Petri Nets to study the problem of disassembly process planning.

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 [16]. 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 disposal and disassembly labor/tooling requirements costs, while the benefit is derived from the sales of recovered components in terms of reuse and recycling revenue. As a result, the methodology offers the best combination of components (with the highest net benefit) to recover from the product. In sum, this methodology allows designers to improve each product design with regard to the maximum benefit obtainable from product disassembly, even before it is put into production. Designers will also be able to incorporate the information (electronically) [18], as an EOL product retirement plan, into the product.

II. MODEL FORMULATION

For the disassembly of products, the operations begin with disassembling the first component from a product, which usually is the outer casing. The steps that follow are to disassemble the successive components until the last one in the product structure is reached. If we represent the product as the root node, the successive subassemblies as the subassembly nodes, and the last retrievable set of components as the leaf nodes, we can use the product's bill of materials (BOM) to represent the product's Disassembly Tree (DT) [16]. DT is a hierarchical representation of the "predecessor-successor" relationships between its various nodes. In Fig. 2, for instance, $ROOT_A$ is the root node, $Sub_{A,1}$ is a subassembly node, and P_1, P_2, P_3 are component nodes.

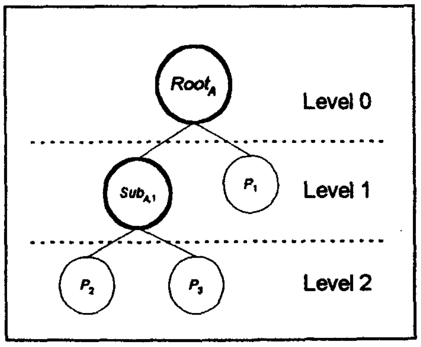

Fig. 2. A Graphical Representation of a DT.

A. Nomenclature

A_{ik}	subassembly node k in product i;
CF	recycling revenue factor (\$/unit of index scale);
CI_j	recycling revenue index of component P_j (index

	scale 0 = lowest, 10 = highest);
CRP_j	percentage of recyclable contents by weight in component P_j;
DF	disposal cost factor ($/unit of index scale);
DI_j	disposal cost index of component P_j (index scale 0 = lowest, 10 = highest);
DW_j	weight of component P_j (lb.);
$LS^s(A_{ik})$	set of selected leaf successors of subassembly node k in product i;
$LS^s(Root_i)$	set of selected leaf successors of the root node in product i;
P_j	component j;
PC	processing (e.g. disassembling, sorting, cleaning, identification and packaging) cost per unit time ($/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;
$T(A_{ik})$	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 ($/unit);
TD_i^s	total disassembly time for a set of selected components in product i (unit time);
TCR	total recycling revenue ($);
TDC	total disposal cost ($);
TPC	total processing cost ($);
TRR	total resale revenue ($);
X_{ij}	matrix representing the (mutually exclusive combination) selection of component P_j retrieved from product i for reuse (X_{ij} = 1) or recycle and/or disposal (X_{ij} = 0);
Z	revenue of retrieved;
$\lceil \alpha \rceil$	gives the smallest integer that is larger than or equal to α;
$\{\beta_{ij}\}$	element in row i and column j of matrix β_{ij}; and
$\{\gamma_i\}$	the i^{th} element in vector γ_i.

B. Cost-Benefit Function

In order to design products for environmental compatibility, we develop a cost-benefit function (representing the revenue of retrieval) that can be used to assess designs for disassembly. The cost-benefit function consists of four terms, (viz., total resale revenue (*TRR*), total recycling revenue (*TCR*), total processing cost (*TPC*), and total disposal cost (*TDC*)) as follows.

$$Z = TRR + TCR - TPC - TDC$$

Each term is described below.

1) Total Resale Revenue

TRR is directly influenced by RV_j and TC_i. RV_j is the resale value of component j, and TC_i is the cost per unit of acquiring and transporting product i from the distribution centers (or collection sources) to the disassembly facility. The revenue equation represents revenue less the cost of product acquisition, which can be formulated as

$$TRR = \sum_{j \exists P_j \in LS^S(Root_i)} \left(RV_j \cdot \left\{Q_{ij}\right\} \cdot \left\{X_{ij}\right\}\right) - TC_i$$

2) Total Recycling Revenue

TCR is calculated by multiplying the component recycling revenue factors by the number of component units not recycled for materials content as follows:

$$TCR = \sum_{j \exists P_j \in LS^S(Root_i)} \left(CI_j \cdot DW_j \cdot CRP_j \cdot \{Q_{ij}\} \cdot (1 - \{X_{ij}\})\right) \cdot CF$$

Note that each component has a percentage of recyclable contents (CRP_j) (the portion not recycled must be properly disposed of). CI_j is the recycling revenue index (varying in value from 1 to 10) representing the degree of benefit generated by the recycling of component P_j (the higher the value of index, the more profitable it is to recycle the component), DW_j is the weight of the component, and CF is the recycling revenue factor.

3) Total Processing Cost

TPC can be calculated from the process makespan (TD_i^s) and the processing cost per unit time (*PC*) as follows:

$$TPC = TD_i^s \cdot PC$$

and, in turn, TD_i^s can be obtained using the following equation:

$$TD_i^s = \left(\underset{\forall Pj \in LS^s(Rooti)}{Max} \{X_{ij}\} \right)\left(T(Root_i) \right) + \sum_{k=1}^{Si} \left\{ \left(\underset{\forall Pj \in LS^s(Aik)}{Max} \{X_{ij}\} \right)\left(T(A_{ik}) \right) \right\}$$

4) Total Disposal Cost

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

$$TDC = \sum_{j \exists P_j \in LS^S(Root_i)} \left(DI_j \cdot DW_j \cdot (1 - CRP_j) \cdot \{Q_{ij}\} \cdot (1 - \{X_{ij}\})\right) \cdot DF$$

Note that DI_j is the disposal cost index (varying in value from 1 to 10) representing the degree of nuisance created by the disposal of component P_j (the higher the value of index, the more nuisance the component creates and hence it costs more to dispose it of), DW_j is the weight of the component, and DF is the disposal cost factor.

III. DFDI CALCULATION PROCEDURE

The DfDI can be calculated using the following steps:

Procedure:

Step 1: List each component by its ID, predecessor, resale value, multiplicity, weight, recyclable percentage, recycle index, and disposal index.

Step 2: Assess the disassembly times.

Step 3: Generate mutually exclusive combinations for component(s) selection.

Step 4: Calculate total benefit, total cost, DfDI and net benefit for each combination.

IV. EXAMPLE

This example considers two environmentally friendly computer designs, *DX*1 and *DX*2 (Fig. 3 (a) and (b)) each consisting of six identical components.

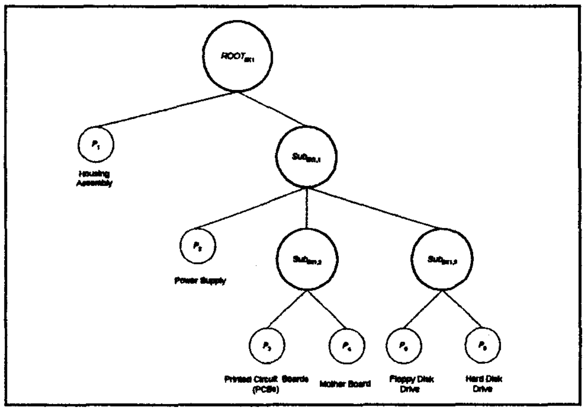

Fig. 3 (a). DT of computer design *DX*1.

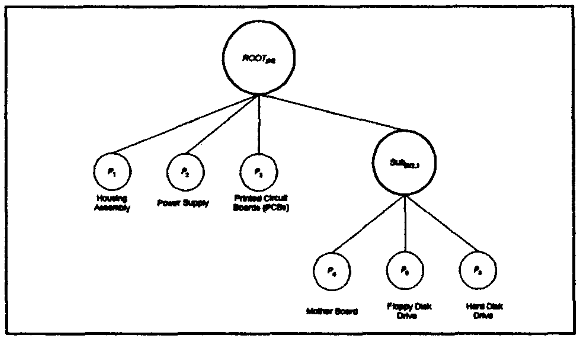

Fig. 3 (b). DT of computer design *DX*2.

The following steps demonstrate the calculation of the DfDI for product design *DX*1.

Step 1. The component IDs, predecessor IDs, and other relevant information are listed in columns (A) through (H) of Table 1.

Step 2. Suppose $T(Root_{DX1}) = 3$, $T(Sub_{DX1,1}) = 5$, $T(Sub_{DX1,2}) = 1.5$, $T(Sub_{DX1,3}) = 8$, $T(Root_{DX2}) = 3.5$, $T(Sub_{DX2,1}) = 6.5$. Let $TC_1 = \$ 12$, $TC_2 = \$ 12$, $PC = 0.55$ \$/min, $CF = 1.5$ \$/lb., and $DF = 0.1$ \$/lb. The disassembly times can be calculated by assessing the selection of reused components in each of the corresponding mutually exclusive combination. For instance, subassembly module $Root_{DX1}$, $Sub_{DX1,1}$ and $Sub_{DX1,2}$ must be disassembled for combination number 29 (to obtain components P_2, P_3 and P_4). Therefore, *TPC* for the combination is $(T(Root_{DX1}) + T(Sub_{DX1,1}) + T(Sub_{DX1,2}))\cdot PC = (9.5)(0.55) = \$ 5.23$.

Step 3. Table 2 shows the mutually exclusive combinations in column (J). A value of "1" indicates that the part is sold (reused) for its value, and a value of "0" indicates that the part is recycled for its material content and/or the part is disposed of.

Step 4. In Table 2, for each combination, the total benefit (*TRR* + *TCR*), and the total cost (*TPC* + *TDC*), the DfDI (calculated by dividing column (O) by (P)) and the net benefit (calculated by subtracting column (P) from column (O)) are shown in columns (O), (P), (Q) and (R) respectively.

Table 1. Data of product design *DX*1.

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Component ID	Predecessor ID	Resale Value (RV_i)	Multiplicity ($\{Q_i\}$)	Weight (DW_i)	Recycle Percentage (CRP_i)	Recycle Index (CI_i)	Disposal Index (DI_i)
P_1	$Root_{DX1}$	0.00	2	3.00	90%	8.00	4.00
P_2	$Sub_{DX1,1}$	5.00	1	7.00	65%	5.50	5.00
P_3	$Sub_{DX1,2}$	1.75	4	0.50	30%	6.00	6.00
P_4	$Sub_{DX1,2}$	17.00	1	1.00	20%	6.00	6.00
P_5	$Sub_{DX1,3}$	0.00	1	1.80	70%	8.00	0.90
P_6	$Sub_{DX1,3}$	3.50	1	2.50	40%	3.00	2.00

For design *DX*1, the maximum value of the net benefit is \$ 19.07 (combination number 29). By following a similar procedure, we can show that the maximum value of the net benefit for design *DX*2 is \$ 23.17 (Table 2) (for combination number 30). Since design *DX*2 has a higher value of the net benefit than design *DX*1, the design *DX*2 is preferred.

With today's computer consumption growing at an astronomical rate, manufacturers are entertaining different alternatives for designing computers that would be economical to dispose of [19]. This example demonstrated that with respect to the optimal design (i.e., *DX*2) the list of components recommended for recovery and reuse are P_2, P_3, P_4 and P_6 which corresponds to the power supply, PCBs, mother board and hard disk drive respectively. The remaining components (i.e., P_1, housing assembly and P_5,

Table 2. Analysis of designs *DX*1 and *DX*2.

(I)	(J)						(K)	(L)	(M)	(N)	(O)	(P)	(Q)	(R)	(S)	(T)
Combination	Parts Reused, Recycled and/or Disposed of (X_i)						Design *DX*1								Design *DX*2	
							Reuse Revenue (*TRR*)	Recycling Revenue (*TCR*)	Processing Cost (*TPC*)	Disposal Cost (*TDC*)	Total Benefit (K) + (L)	Total Cost (M) + (N)	DFDI (O)/(P)	Net Benefit (O) - (P)	DFDI	Net Benefit
	P1	P2	P3	P4	P5	P6										
1	0	0	0	0	0	0	-12.00	12.05	0.00	3.13	0.05	3.13	0.02	-3.08	0.02	-3.08
2	0	0	0	0	0	1	-8.50	11.63	8.80	2.83	3.13	11.63	0.27	-8.50	0.54	-2.62
3	0	0	0	0	1	0	-12.00	10.64	8.80	3.09	-1.36	11.89	-0.11	-13.24	-0.23	-7.37
4	0	0	0	0	1	1	-8.50	10.22	8.80	2.79	1.72	11.59	0.15	-9.86	0.30	-3.99
5	0	0	0	1	0	0	5.00	11.89	5.23	2.65	16.89	7.88	2.14	9.01	3.03	11.31
6	0	0	0	1	0	1	8.50	11.47	9.63	2.35	19.97	11.98	1.67	7.99	3.78	14.69
7	0	0	0	1	1	0	5.00	10.48	9.63	2.61	15.48	12.23	1.27	3.25	2.80	9.95
8	0	0	0	1	1	1	8.50	10.06	9.63	2.31	18.56	11.93	1.56	6.63	3.55	13.33
9	0	0	1	0	0	0	-5.00	11.55	5.23	2.29	6.55	7.52	0.87	-0.97	1.69	2.68
10	0	0	1	0	0	1	-1.50	11.13	9.63	1.99	9.63	11.62	0.83	-1.99	1.48	3.14
11	0	0	1	0	1	0	-5.00	10.14	9.63	2.25	5.14	11.87	0.43	-6.73	0.76	-1.61
12	0	0	1	0	1	1	-1.50	9.72	9.63	1.95	8.22	11.57	0.71	-3.36	1.28	1.77
13	0	0	1	1	0	0	12.00	11.38	5.23	1.81	23.38	7.04	3.32	16.34	3.70	17.07
14	0	0	1	1	0	1	15.50	10.96	9.63	1.51	26.46	11.14	2.38	15.32	4.40	20.45
15	0	0	1	1	1	0	12.00	9.97	9.63	1.77	21.97	11.39	1.93	10.58	3.51	15.71
16	0	0	1	1	1	1	15.50	9.55	9.63	1.47	25.05	11.09	2.26	13.96	4.20	19.09
17	0	1	0	0	0	0	-7.00	8.56	4.40	1.91	1.56	6.31	0.25	-4.76	0.45	-1.93
18	0	1	0	0	0	1	-3.50	8.13	8.80	1.61	4.63	10.41	0.44	-5.78	0.76	-1.48
19	0	1	0	0	1	0	-7.00	7.14	8.80	1.86	0.14	10.66	0.01	-10.52	0.02	-6.22
20	0	1	0	0	1	1	-3.50	6.72	8.80	1.56	3.22	10.36	0.31	-7.14	0.53	-2.84
21	0	1	0	1	0	0	10.00	8.38	5.23	1.43	18.38	6.65	2.76	11.73	3.10	12.45
22	0	1	0	1	0	1	13.50	7.96	9.63	1.13	21.46	10.75	2.00	10.71	3.81	15.83
23	0	1	0	1	1	0	10.00	6.97	9.63	1.38	16.97	11.01	1.54	5.97	2.89	11.09
24	0	1	0	1	1	1	13.50	6.55	9.63	1.08	20.05	10.71	1.87	9.35	3.59	14.47
25	0	1	1	0	0	0	0.00	8.05	5.23	1.07	8.05	6.29	1.28	1.76	3.04	5.40
26	0	1	1	0	0	1	3.50	7.63	9.63	0.77	11.13	10.39	1.07	0.73	2.11	5.86
27	0	1	1	0	1	0	0.00	6.64	9.63	1.02	6.64	10.65	0.62	-4.01	1.20	1.12
28	0	1	1	0	1	1	3.50	6.22	9.63	0.72	9.72	10.35	0.94	-0.63	1.86	4.50
29	0	1	1	1	0	0	17.00	7.88	5.23	0.59	24.88	5.81	**4.28***	**19.07***	4.89	19.79
30	0	1	1	1	0	1	20.50	7.46	9.63	0.29	27.96	9.91	2.82	18.05	**5.84***	**23.17***
31	0	1	1	1	1	0	17.00	6.47	9.63	0.54	23.47	10.17	2.31	13.30	4.66	18.43
32	0	1	1	1	1	1	20.50	6.05	9.63	0.24	26.55	9.87	2.69	16.68	5.60	21.81
33	1	0	0	0	0	0	-12.00	6.01	1.65	2.89	-5.99	4.54	-1.32	-10.54	-1.34	-10.46
34	1	0	0	0	0	1	-8.50	5.59	8.80	2.59	-2.91	11.39	-0.26	-14.31	-0.41	-10.01
35	1	0	0	0	1	0	-12.00	4.60	8.80	2.85	-7.40	11.65	-0.64	-19.05	-1.01	-14.75
36	1	0	0	0	1	1	-8.50	4.18	8.80	2.55	-4.32	11.35	-0.38	-15.67	-0.61	-11.37
37	1	0	0	1	0	0	5.00	5.84	5.23	2.41	10.84	7.64	1.42	3.20	1.57	3.93
38	1	0	0	1	0	1	8.50	5.42	9.63	2.11	13.92	11.74	1.19	2.18	2.10	7.31
39	1	0	0	1	1	0	5.00	4.43	9.63	2.37	9.43	11.99	0.79	-2.56	1.37	2.56
40	1	0	0	1	1	1	8.50	4.01	9.63	2.07	12.51	11.69	1.07	0.82	1.91	5.94
41	1	0	1	0	0	0	-5.00	5.50	5.23	2.05	0.50	7.28	0.07	-6.78	0.14	-3.13
42	1	0	1	0	0	1	-1.50	5.08	9.63	1.75	3.58	11.38	0.31	-7.80	0.57	-2.67
43	1	0	1	0	1	0	-5.00	4.09	9.63	2.01	-0.91	11.63	-0.08	-12.54	-0.14	-7.41
44	1	0	1	0	1	1	-1.50	3.67	9.63	1.71	2.17	11.33	0.19	-9.16	0.35	-4.03
45	1	0	1	1	0	0	12.00	5.33	5.23	1.57	17.33	6.80	2.55	10.54	2.85	11.26
46	1	0	1	1	0	1	15.50	4.91	9.63	1.27	20.41	10.90	1.87	9.52	3.54	14.64
47	1	0	1	1	1	0	12.00	3.92	9.63	1.53	15.92	11.15	1.43	4.77	2.64	9.90
48	1	0	1	1	1	1	15.50	3.50	9.63	1.23	19.00	10.86	1.75	8.15	3.32	13.28
49	1	1	0	0	0	0	-7.00	2.50	4.40	1.67	-4.50	6.07	-0.74	-10.57	-1.39	-7.74
50	1	1	0	0	0	1	-3.50	2.08	8.80	1.37	-1.42	10.17	-0.14	-11.59	-0.24	-7.29
51	1	1	0	0	1	0	-7.00	1.09	8.80	1.62	-5.91	10.42	-0.57	-16.33	-0.97	-12.03
52	1	1	0	0	1	1	-3.50	0.67	8.80	1.32	-2.83	10.12	-0.28	-12.95	-0.49	-8.65
53	1	1	0	1	0	0	10.00	2.34	5.23	1.19	12.34	6.41	1.92	5.92	2.17	6.65
54	1	1	0	1	0	1	13.50	1.92	9.63	0.89	15.42	10.51	1.47	4.90	2.86	10.03
55	1	1	0	1	1	0	10.00	0.92	9.63	1.14	10.92	10.77	1.01	0.16	1.94	5.28
56	1	1	0	1	1	1	13.50	0.50	9.63	0.84	14.00	10.47	1.34	3.54	2.62	8.66
57	1	1	1	0	0	0	0.00	2.00	5.23	0.83	2.00	6.05	0.33	-4.06	0.83	-0.40
58	1	1	1	0	0	1	3.50	1.58	9.63	0.53	5.08	10.15	0.50	-5.07	1.01	0.05
59	1	1	1	0	1	0	0.00	0.59	9.63	0.78	0.59	10.41	0.06	-9.82	0.11	-4.69
60	1	1	1	0	1	1	3.50	0.17	9.63	0.48	3.67	10.11	0.36	-6.44	0.74	-1.31
61	1	1	1	1	0	0	17.00	1.83	5.23	0.35	18.83	5.57	3.38	13.26	3.88	13.98
62	1	1	1	1	0	1	20.50	1.41	9.63	0.05	21.91	9.67	2.27	12.24	4.82	17.36
63	1	1	1	1	1	0	17.00	0.42	9.63	0.30	17.42	9.93	1.76	7.50	3.63	12.62
64	1	1	1	1	1	1	20.50	0.00	9.63	0.00	20.50	9.63	2.13	10.88	4.56	16.00

floppy disk drive) from the product can be pulverized and recycled and/or processed for environmentally benign disposal.

By incorporating the information into the product, or providing it to recyclers and/or waste collection agencies in some appropriate way, the products can be handled in the way the designers had originally envisioned.

V. SUMMARY

This paper introduced a technique to measure the design efficiency using a Design for Disassembly Index (DfDI). The development of DfDI involves the analysis of the trade-off between the costs and benefits of EOL disassembly to find the combination of components that provides the optimum cost-benefit ratio for end-of-life retrieval. The cost considerations in this analysis include the costs of disassembly (labor) and disposal, while the benefit is derived from the sale of recovered components and materials. The index offers designers with an important measure to help improve future products.

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