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Modeling the Value Recovery of Rare Earth Permanent Magnets at End-of-Life

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Abstract

Permanent magnets containing rare earth elements (REEs) such as Dysprosium and Neodymium offer an advantage over non-REE containing magnets (e.g., ferrite and AlNiCo) in terms of power relative to size. However, REE availability has varied significantly in recent years leading to volatility in the cost of rare earth permanent magnets (REPMs). The supply of REEs can be increased by recycling consumer products and industrial machinery that contain REPMs at product end-of-life (EOL). This paper discusses the REE recovery process for EOL products. The optimal dismantling of products is examined with an emphasis placed on obtaining used REPMs. The challenge of collecting, managing, transporting, and processing used products is addressed through the development of a cost model for REPM recovery. This model is used to investigate several EOL strategies for recovering REPMs. Sensitivity analysis is conducted to identify the key factors that influence value recovery economics. A hard disk drive serves as a case study for model demonstration.
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Keywords: Dismantling; Disassembly; Remanufacturing; Recycling

1. Introduction

Rare earth elements (REEs) such as Dysprosium and Neodymium are often used to create rare earth permanent magnets (REPMs). These REPMs are used in various applications such as hard disk drives (HDDs), electric vehicles, and wind turbines. Darcy et al. [1] estimated that an REPM needs about 1/89 of the size of a ferrite magnet to produce a comparable magnetic field.

In 2009, China provided 94% of the world REE supply [2]; the United States imported 86% of its rare earth metals and compounds from China in 2008-2011 [3]. With recent surges in REE demand and quotas on Chinese exports, the REE supply has been decreased, and this may happen again in the future. Thus, while REPMs offer advantages for various applications, the REE supply is uncertain, leading to volatility in the cost.

Recycling of REEs from EOL products may be an effective way to alleviate the supply risk. Du and Graedel [4] estimated the global in-use stock of Neodymium and Dysprosium in NdFeB permanent magnets to be 62,600t and 15,700t, respectively. Considering the US demand of REE in permanent magnets was 500t in 2011[5], the in-use stock is significant.

This paper discusses the REE recovery challenge associated with product EOL. The optimal disassembly of products is examined with an emphasis placed on obtaining REPMs. A mathematical model is developed to estimate the cost of collecting, managing, transporting, and processing EOL products for REPM recovery. A case study is used to demonstrate the optimal disassembly algorithm and cost

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analysis. A sensitivity analysis is performed to identify the key factors that influence recovery economics.

2. Modeling value recovery of REPMs

As has been noted, it has been suggested that REPMs may be recovered from EOL products. To identify the best strategy, to approach this situation, two related models may be constructed. First, an effective method is needed to find the best way to recover value embedded within a product. This motivates the need for a model for optimal disassembly sequence (a type of dismantling that preserves all components). Dismantling is a general term that may be defined as decomposing a product into pieces or subassemblies. Dismantling includes both preservative and destructive disassembly. Destructive disassembly may be applied to a low value part to recover other more valuable components/subassemblies for reuse, remanufacturing, or recycling. Second, a model is needed for overall dismantling cost; such a model helps to define the target productivity, desired degree of automation, and overall economic feasibility.

2.1. Disassembly model and sequencing methodology

A disassembly model is a representation that describes the relevant features of a product and/or the disassembly process [6]. It incorporates information about product architecture, the value of recovered components and materials, tools, the cost of disassembly tasks and so on. The model is the basis of disassembly process planning (DPP) for determination of disassembly level and sequence. Disassembly level is the product state when disassembly process terminates and sequence indicates the order in which the tasks are arranged and how the resources are used. An effective disassembly plan can always maximize revenue, minimize cost, and/or improve efficiency by recovering the value of components and materials, and employing effective disassembly devices.

An AND/OR graph describes the options available for disassembly as a common visualization model; its advantages include a concise description of the disassembly options (a graph with nodes and arcs is used) [7]. Figure 1 shows a disassembled hard disk drive (HDD). The capital letters represent the parts in the HDD. Figure 2 shows a partial AND/OR graph for the HDD. Each pair of lines connected by an arc denotes a disassembly task and the nodes represent subassemblies resulting from the tasks. Such a graph can be translated into a transition matrix whose rows represent all possible subassemblies and whose columns represent the corresponding disassembly tasks.

Additional information needs to be attached to the nodes and arcs to generate optimal end-of-life strategies. Such essential information includes the revenue for each subassembly/component and the cost of each disassembly task. The revenue for each subassembly/component depends on its EOL option [8]. Revenue is estimated according to the secondary (recycling) market [9]. The disassembly cost may be estimated based on the cost of the technology employed, and the operator cost (product of the wage rate and disassembly time). The times may be estimated using a scoring system [10], in which disassembly time is proportional to the difficulty in completing a task. This method does not consider destructive disassembly, and the actual disassembly may be performed manually or via automation.

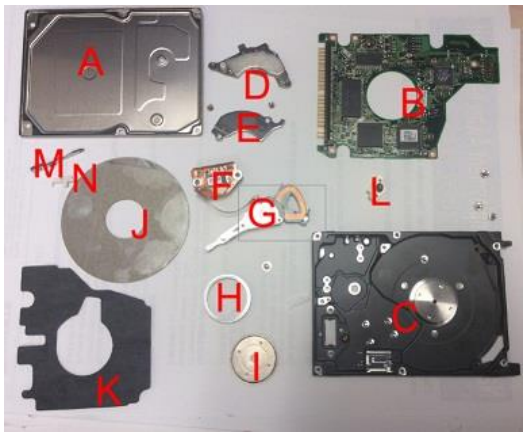

Fig. 1. A small, disassembled hard disk drive.

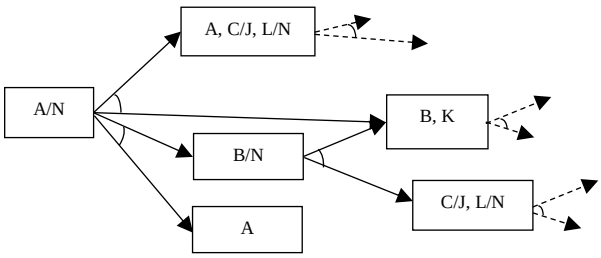

Fig. 2. A partial AND/OR graph based on the product of Fig. 1.

Recently, researchers [11] have designed advanced tools and improved fasteners to preserve the functional value of components as much as possible. The choice as to which dismantling option to pursue (i.e., disassembly or destructive disassembly) depends on the opportunity for recovering value. Fig. 3 illustrates the options that may be available for dismantling.

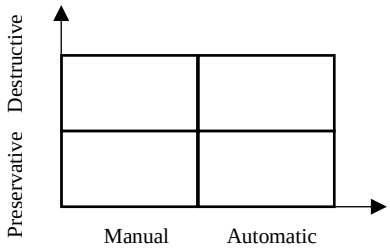

Fig. 3. Dismantling options.

Of course, to generate a product dismantling sequence, constraint information and other product and process data must be available. Given that this information has been secured, Lambert [12] proposed a linear programming method to determine the optimal disassembly sequence for

maximum recovered value. Equations (1)-(3) show this LP formulation:

Maximize: $P = (\mathbf{RT} - \mathbf{C})\mathbf{X}$ (1)

Constraint condition: $\mathbf{TX} => \mathbf{0}$ (2)

$\mathbf{X} = \{0\ OR\ 1\}$ (3)

Where P is the profit gained through disassembly, **T** is the transition matrix derived from the AND/OR graph, **R** is the revenue row vector (with an element in the vector corresponding to the revenue associated with a subassembly /component), **C** is the disassembly cost row vector (an element holds the cost for a dismantling task), and **X** is the decision variable column vector. An element in **X** may assume a value of 0 and 1, depending on whether or not the disassembly task is performed. The LP model may be solved to find the optimal disassembly sequence. Disassembly level can be determined simultaneously.

2.2. Cost analysis

The method for determining the optimal dismantling sequence above uses a system for task times that assumes preservative dismantling. The system for finding task times does not allow for the possibility of destructive dismantling However, as has been noted, destructive dismantling may offer significant economic advantages. With this in mind, a cost model was created for the system to understand the effects of productivity and system costs on economic feasibility. The proposed model makes no assumption about how the EOL products are processed. In this model, the total annual cost (TC) for recovering EOL products was modeled as the sum of the used product purchase cost (C_p), dismantling cost (C_d), inventory cost (C_h), transportation cost (C_t), and facility cost (C_f).

$$\text{TC} = C_p + C_d + C_h + C_t + C_f \quad (4)$$

A complete nomenclature is provided in Table 1 – the third column in the table applies to the case study that follows in section 3. The parameter values are estimated by industrial partners and researchers for hard disk drives (HDDs). Some discussion of the cost terms in Eq. (4) is followed.

- Purchase

The purchase cost (C_p) is the annual expense for acquiring used products. In some cases, the last owner of a product may pay for an EOL processor to take the used product (in which case the cost is really revenue). The purchase cost is a function of the unit purchase cost (c_p) and the purchase quantity (Q).

$$C_p = c_p \cdot \text{Q} \quad (5)$$

- Dismantling process

Two types of dismantling are considered: a) an automated system with minimal labor, and b) manual dismantling with intensive labor. For an automated system, the dismantling cost includes expenses for machines (amortized capital cost and ongoing O&M cost), electricity, and modest labor. For manual dismantling, the cost is virtually all labor expenses. When the annual work hour is w_h, Eq. (6) indicates that dismantling cost (C_d) is independent of the work hour except for the machine cost.

$$C_d = (c_m + w_h c_e + w_h c_l N_l^{'}) \cdot N_m + w_h c_l N_l$$
$$= \frac{\mu Q}{\eta_m}\left[\frac{c_m}{w_h} + c_e + c_l N_l^{'}\right] + \frac{c_l(1-\mu)Q}{\eta_l} \quad (6)$$

where $N_m = \frac{\mu Q}{w_h \eta_m}$, $N_l = \frac{(1-\mu)Q}{w_h \eta_l}$ (7)

Table 1. Variable Definition.

Term	Definition	Value for HDD
c_p	Unit purchase cost of an EOL product ($/unit)	$0 per HDD for base scenario, ranging from $-0.5 to $1
Q	Processing quantity (units/year)	Q is not used since unit cost is independent of Q.
c_m	Machine cost ($/year/machine)	$8,000/year/machine
w_h	Work hours per year (hour/year)	2080 hours/year
c_e	Electricity cost ($/hour/machine)	$2/hour/machine
c_l	Labor cost ($/hour/worker)	$12/ hour/worker
$N_l^{'}$	Number of workers needed per machine (worker/machine)	1 worker/machine
N_m	Number of machines needed for dismantling	To be determined
μ	Fraction of the EOL products that are dismantled by machine	100%
N_l	Number of workers needed for manual disassembly	N_l is not used since μ=100%
η_m	Machine dismantling rate (units/hour /machine)	900 HDDs/hour/machine for base scenario, ranging from 100 to 1500
η_l	Manual disassembly rate (units/hour/worker)	η_l is not used since μ=100%
I_o	Average inventory level	0.5
c_i	Inventory cost ($/year/HDD)	$0.1/year/HDD
tr	Daily expense of a truck ($/day/truck)	$150/day/truck
w	Mass of an EOL product (kg/unit)	0.5kg/HDD
cp	Truck capacity (kg/truck)	3000kg/truck
k	Number of routes made per day (routes/day/truck)	10 routes/day/truck
δ	Average truck load	1/3 of the truck capacity
c_{sp}	Unit space cost ($/m^2/year)	$120/m^2/year
s_m	Facility space needed for machine operation (m^2/machine)	140m^2/machine
s_l	Facility space needed for worker (m^2/people)	s_l is not used since μ=100%
c	Unit cost of recovering an EOL product ($/unit)	To be determined
TR	Total revenue per year ($/year)	To be determined
p_r	Net revenue from a dismantled EOL product ($/unit)	$1.5 per HDD for base scenario, ranging from $0.5 to $2.5

- Inventory

Inventory cost includes the cost of storage, inventory holding and maintenance.

$$C_h = I_o \cdot c_i \cdot Q \quad (8)$$

- Transportation

The transportation cost includes the cost of securing a truck (e.g., payment made to a shipping company) and loading/unloading a truck. Assuming the aggregated cost of a truck is tr and the truck covers k routes per day, the transportation cost is as follows.

$$C_t = (\text{tr} \cdot Q \cdot w/cp)/(k \cdot \delta) \quad (9)$$

- Facility

The facility cost is mainly composed of the cost of using the space needed for the dismantling system.

$$C_f = c_{sp}(s_m N_m + s_l N_l) = c_{sp} Q\left[\frac{s_m \mu}{w_h \eta_m} + \frac{s_l(1-\mu)}{w_h \eta_l}\right] \quad (10)$$

In summary, the total cost (TC) and the associated unit cost (c) can be expressed as follows:

$$\mathrm{TC} = C_p + C_d + C_h + C_t + C_f$$
$$= c_p \mathrm{Q} + \frac{\mu Q}{\eta_m}\left[\frac{c_m}{w_h} + c_e + c_l N_l{}'\right] + \frac{c_l(1-\mu)Q}{\eta_l} + I_o\, c_i Q + \frac{\mathrm{tr}\cdot Q\cdot w}{k\cdot\delta\cdot cp} + c_{sp} Q\left[\frac{s_m \mu}{w_h \eta_m} + \frac{s_l(1-\mu)}{w_h \eta_l}\right] \quad (11)$$

$$\mathrm{c} = \frac{TC}{Q} = c_p + \frac{\mu}{\eta_m}\left[\frac{c_m}{w_h} + c_e + c_l N_l{}'\right] + \frac{c_l(1-\mu)}{\eta_l} + I_o\, c_i + \frac{\mathrm{tr}\cdot w}{k\cdot\delta\cdot cp} + c_{sp}\left[\frac{s_m \mu}{w_h \eta_m} + \frac{s_l(1-\mu)}{w_h \eta_l}\right] \quad (12)$$

When Q products are dismantled, the total revenue (TR) and the associated unit revenue (r) are as follows.

$$\mathrm{TR} = p_r \mathrm{Q} \quad (13)$$

$$\mathrm{r} = \frac{TR}{Q} = p_r \quad (14)$$

Note that the total cost modeled here is the EOL product recovery cost, which does not include additional processing associated with remanufacturing, recycling, etc. Thus, the revenue here captures only the value associated with selling dismantled components and materials.

3. Case study

In 2008, REPMs accounted for 21% of all REE use in terms of volume, and 38% in terms of value [13]. NdFeB permanent magnets for hard disk drives (HDDs) constitute 8-35% of REPMs [14]. Owing to their abundance, hard disk drives have potential as a source of recovered REPMs. In addition to harvesting the value from the magnets, other components and materials may be recovered, e.g., gold and aluminum.

3.1. Hard disk drive EOL strategy

A specific hard disk drive (HDD) was selected for study. The HDD components are shown in Table 2. For the analysis that follows, the following assumptions were made:

- Some parts are treated as stable subassemblies to disassemble, namely BK, FG, MN and HIJ (the letters refer to the part code in Table 2).
- The printed circuit board (PCB) is dismantled first. This is because the PCB contains valuable materials, e.g., gold and silver. Removal of the PCB obviates the need to flip the HDD, thus reducing dismantling time.
- Composition and price of components are estimated based on references and market price.

The transition matrix for the indicated HDD was constructed and applied; however, owing to its large size, it is not shown here. The assumed end-of-life options and revenue for the subassemblies/components are listed in Table A.1 in the Appendix. The disassembly cost vector is shown in Table A.2. As has been noted, the time required to remove a fastener comes from the Kroll and Hanft scoring system – this applies for manual disassembly (no automation). If a greater degree of automation is employed, it is assumed that the disassembly time will be reduced by some factor φ which is defined explicitly by equation (15).

$$t_a = \varphi \cdot t_m \quad (15)$$

where t_m is the time required to complete a given task manually (according to the scoring system), t_a is the task time with some amount of automation, and φ is the fraction that when multiplied by t_m gives the automation time t_a (φ may be considered the degree of automation).

The degree of automation will impact not only task times, but also the disassembly costs. The LP model was run in CPLEX version 12.6 for several values of φ. The profit associated with preservative disassembly was calculated and is shown in Fig. 4. The figure reveals that the profit (revenue minus labor cost) from a 92.29 gram HDD ranges from 0.022 dollars to 0.373 dollars with a wage rate of $12 dollars/hour when the automation factor φ changes from 1 to 0.2.

Table 2. Parts list for HDD.

Part code	Part name	Part code	Part name
A	Cover	H	Spacer
B	Printed Circuit Board	I	Lid
C	Base casting	J	Platter
D	Actuator top	K	Pad insulator
E	Actuator bottom	L	Plastic 1
F	Flex circuit	M	Arm
G	Head stack assembly	N	Plastic 2

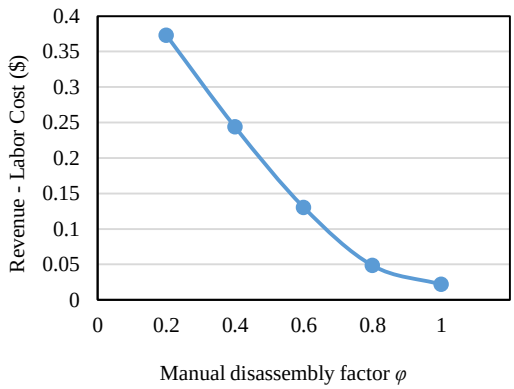

Fig. 4. Recovered profit variation with manual disassembly factor φ.

For pure manual disassembly, the optimal disassembly sequence for the HDD is B, K, and AC/JL/N. Component B, the printed circuited board, is sent for mixed recycling, component K, the pad insulator, is reused, and the remaining assembled components are disposed. This result demonstrates that for a 92.29g HDD, with manual disassembly the profit is very small, and the REPM is not recovered. This situation changes with automation, since the times and costs with reduce, and the sequence and disassembly level will change. The next sub-section considers a more general approach to HDD processing that does not necessarily consider preservative disassembly.

3.2. Cost model of hard disk drive recovery

Many data centers frequently change out their HDDs, and are willing to give up their used HDDs under the

condition that any data is destroyed. For example, Google replaces about 300,000 HDDs every month. With such a concentrated source of EOL products, transportation costs decrease and inventory costs can be minimized. In addition, the acquisition (or purchase) cost of EOL HDDs is reduced or may even become revenue. All these factors contribute to a cost reduction in hard disk drive recovery.

Hard disk drives may be disassembled manually using tools such as screwdrivers. However, HDDs may also be dismantled (perhaps destructively) with automated equipment. For example, Hitachi developed a machine that can dismantle 100 units per hour by shaking and pranging HDDs [15]. Automated equipment is being developed by Oak Ridge National Lab for the value recovery of HDD components and materials. It is envisioned that the machine (Fig. 5) will perform the tasks of aligning, shearing off the PCB, sorting, separating magnets by punching, heating the punched section to demagnetize the magnets and defeat adhesives, and finally collecting the various output streams from hard disk drives. The cost model presented in section 2.2 may be used to assess the economic feasibility of value recovery from HDDs for such a process.

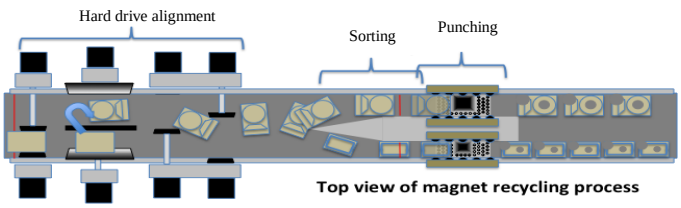

Fig. 5. Dismantling system

Using the data in Table 1, it is found that the unit recovery cost significantly depends upon the purchase cost and dismantling cost. Therefore, the unit purchase cost (c_p) and dismantling rate (η_m) were studied via a sensitivity analysis. Fig. 6 shows the effect of changing c_p and η_m on the unit recovery cost. As dismantling rate increases, its effect on unit recovery cost diminishes. In particular, when the rate exceeds 300HDDs/hour, the unit recovery cost does not change much. On the contrary, purchase cost always has a significant impact on the recovery cost.

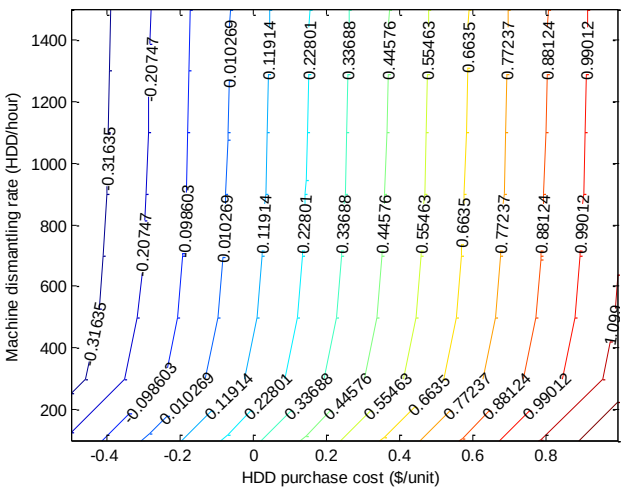

Fig. 6. Sensitivity analysis on c_p and η_m (lines are unit recovery costs)

Sensitivity analysis was also performed on the unit revenue from the dismantled HDD components and materials. Fig. 7 shows the effect of varying unit purchase cost (c_p) and unit revenue (p_r) on the profit. As unit revenue increases or unit purchase cost decreases, the profit increases for the same amount.

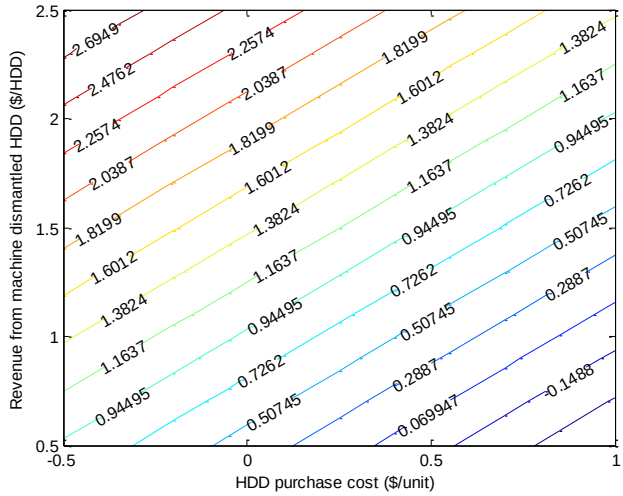

Fig. 7. Sensitivity analysis on c_p and p_r (lines are profits)

The effect of changing the truck loading level (δ) and inventory level (I_o) was also considered. Table 3 shows the parameter values that were examined: low cost condition, and high cost condition for the 2 parameters. The analysis indicates a total cost change of $0.102/unit ($0.144/unit–$0.042/unit). This is a relatively small number considering the extreme cases. The reason is that inventory holding cost and transportation cost are relatively small in this case study.

Table 3. An extreme case scenario.

Variable	Low cost	High cost
δ	0.9	0.1
I_o	0.1	0.9

4. Summary and Conclusions

One strategy for increasing the supply of REEs is to recover value from EOL products that contain REPMs. A model for disassembly was constructed that allows the optimal EOL strategy to be determined. A model based on AND/OR graph was built and an optimal disassembly sequence was determined using linear programming method. Besides, effect of automation level of preservative disassembly on the recovered value has been investigated. It shows that automation level has great impact on the EOL value of HDDs.

A cost model was developed to quantify the challenge of collecting, managing, transporting, and processing EOL products. When applied to HDDs, the model reveals that purchasing and dismantling are the major costs. Since the relevant parameter values in Table 1 were estimated, sensitivity analysis was conducted to embrace different ranges of these uncertain variables. It is found that HDD recovery can be profitable assuming purchase and dismantling costs are reduced; in fact, if purchasing cost is

zero or negative (i.e., revenue is received for taking used HDDs) the economic situation is very favorable. Moreover, even more value may be captured if additional materials are recycled and valuable components are remanufactured/ reused.

Acknowledgments

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Appendix

Table A.1. Revenue for subassemblies/components and associated end of life option (SA: subassembly/component, RT: EOL option, Rev: unit revenue; DS: disposal, PR: primary recycling, SR: mixed recycling, RE: reuse).

SA	Mass (gram)	RT	Rev ($)	SA	Mass (gram)	RT	Rev ($)
A	8.552	PR	0.013	C/G	61.069	DS	-0.004
B	11.640	SR	0.150	CE/GL	52.052	DS	-0.003
C	40.300	SR	0.040	CEH/J	53.195	SR	0.053
D	9.347	RE	0.301	CH/JL	50.240	DS	-0.003
E	3.285	PR	0.005	CEL/N	44.833	DS	-0.003
F	2.441	SR	0.000	C/GL	61.399	DS	-0.004
G	5.696	SR	0.006	CE/GMN	52.640	DS	-0.003
H	2.410	PR	0.004	CEH/JL	53.525	DS	-0.003
I	2.481	PR	0.004	CH/JMN	50.828	DS	-0.003
J	4.719	PR	0.007	C/GMN	61.987	DS	-0.004
K	0.173	RE	0.010	CE/GL/N	52.970	DS	-0.003
L	0.330	PR	0.000	CE/J	61.332	DS	-0.004
M	0.849	PR	0.001	CEH/JMN	54.113	DS	-0.003
N	0.069	PR	0.000	CH/JL/N	51.158	DS	-0.003
FG	8.137	DS	0.000	C/GL/N	62.317	DS	-0.004
BK	11.813	DS	-0.001	C/J	70.679	DS	-0.004
MN	0.918	DS	0.000	CE/JL	61.662	DS	-0.004
HIJ	9.610	SR	0.010	CEH/JL/N	54.443	DS	-0.003
CL	40.630	DS	-0.002	C/JL	71.009	DS	-0.004
CE	43.585	SR	0.044	CE/JMN	52.640	DS	-0.003
CEL	43.915	DS	-0.003	C/JMN	71.597	DS	-0.004
CMN	41.218	DS	-0.002	CE/JL/N	62.580	DS	-0.004
CE/G	51.722	DS	-0.003	C/JL/N	71.927	DS	-0.004
CH/J	49.910	SR	0.050	AC/JL/N	80.479	DS	-0.005
CL/N	41.548	DS	-0.002	A/N	92.292	DS	-0.006
CEMN	44.503	DS	-0.003				

Table A.2. Costs of manual disassembly tasks (DT is short for disassembly task).

DT code	Cost ($)	DT code	Cost ($)	DT code	Cost ($)	DT code	Cost ($)
1	0	21	0.083	41	0.067	61	0.067
2	0.117	22	0.067	42	0.083	62	0.083
3	0.217	23	0.083	43	0.217	63	0.217
4	0.217	24	0.083	44	0.067	64	0.083
5	0.067	25	0.083	45	0.067	65	0.067
6	0.067	26	0.167	46	0.167	66	0.067
7	0.167	27	0.217	47	0.067	67	0.067
8	0.083	28	0.167	48	0.167	68	0.167
9	0.067	29	0.217	49	0.083	69	0.083
10	0.083	30	0.083	50	0.083	70	0.067
11	0.167	31	0.067	51	0.067	71	0.083
12	0.217	32	0.167	52	0.217	72	0.083
13	0.067	33	0.067	53	0.067	73	0.067
14	0.167	34	0.083	54	0.067	74	0.067
15	0.083	35	0.083	55	0.083	75	0.033
16	0.167	36	0.067	56	0.067	76	0.017
17	0.067	37	0.167	57	0.067	77	0.017
18	0.217	38	0.083	58	0.167	78	0.017
19	0.083	39	0.167	59	0.083		
20	0.167	40	0.067	60	0.167		