https://doi.org/10.20965/ijat.2020.p0930

Paper:

Remanufacturing Option Selection with Disassembly for Recovery Rate and Profit

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[Received March 29, 2020; accepted September 11, 2020]

In order to cope with the issue of depletion of natural resources, expectations for economical designs of the closed-loop supply chains of products that include remanufacturing in their lifecycle have recently significantly grown. However, since disassembly of a product to remanufacture it is costly due to high labor costs, the lifecycle option of remanufacturing an end of life product by disassembly and reassembly needs to be established environmentally as well as economically. In this study, we propose a remanufacturing option selection method that takes recovery rates and profits into account. First, a bill of materials of a product is prepared to create data for remanufacturing. Next, its remanufacturing option selection is formulated by using the 0-1 integer programming. Lastly, the proposed remanufacturing option selection method is verified by analyzing the sensitivities of the recovery rates and selling prices of the remanufactured products using the ε constraint method. The proposed method that takes remanufacturing into account has demonstrated a generating larger profits than a conventional method maintaining high recovery rates at the same levels in a case study.

Keywords: product installation reuse, recycling, lifecycle option, reassembly, 0-1 integer programming

1. Introduction

Assembly products such as laptop PCs, smart phones, and television sets are mass-produced and delivered to us through global supply chains [1]. However, the consumption of natural resources to produce and distribute such mass-produced products resulted in resource depletion, posing a significant environmental issue [2]. In order to cope with such resource depletion, expectations for economical designs of the closed-loop supply chains with remanufacturing by disassembling and reassembling products in their lifecycle [3, 4] have significantly grown [2]. Ishigaki et al. [5] used manufacturing and remanufacturing processes in designing the closed-loop supply chains.

Remanufacturing is defined to reproduce a product (or a module) as good as new, in which an end-of-life (EOL) product is completely disassembled into components [3, 4], all the components are inspected, and new components are installed if necessary. The components of remanufactured products, which are installed into it through product installation reuse [2] or which are newly procured, need to go through not only a disassembly process to take components or recycled materials out of an EOL product [6], but also a reassembly process to recompose the taken-out and newly procured components [3, 4]. The above-mentioned remanufacturing process can thus reduce the natural resource consumption for virgin materials. Hiraoka and Tanaka [7] defines the reuse of components as spare parts. This means that the components of an EOL product are reused for maintenance or replacement purposes while maintaining their original functions as components or products [3]. However, since the assembly product [8] is composed of various materials and parts, it needs to be manually disassembled and reassembled by labors for reusing or recycling. In developed countries, however, high labor costs make such remanufacturing process economically impracticable [6, 9].

When reusing and recycling an EOL assembled product, their disassembled components and lifecycle options are accurately selected to ensure that the disassembly process should be environmental and economical [10–14]. The lifecycle option selection, which refers to selecting either reuse, recycling, or disposal for each component of an EOL product, needs to be individually made for every disassembled component in the remanufacturing process [11, 14]. Reuse enables us to save energies and to recover manufacturing materials [15]. Hasegawa et al. [14] took components' lifetime into account, and selected disassembled components with the objective of maximizing the recovery rate and minimizing costs in the three lifecycle options: reuse, recycling, and disposal. However, as the component they selected for reuse were sold as spare parts only, they never considered remanufacturing including reassembly of the reused components or new procurement of components.

This study proposes a remanufacturing option selection method that considers recovery rate and profit and applies the proposed method to a laptop PC as an example. Now, we set up the following research questions (RQ i), ii), iii), iv)).

i) When remanufacturing a product, which components should be selected for product installation reuse or new procurement?

ii) Can the proposed remanufacturing option selection method yield a higher profit than the conventional reuse component selection method [14]?

iii) What effects of any changes in the product's usage years have on its remanufacturing process?

iv) How much should the remanufactured products be sold?

2. Procedure of Remanufacturing Option Selection

2.1. Overview

This study proposes a remanufacturing option selection method with two objective functions of recovery rate and profit. The proposed method is used in the product design stage and the stage of reviewing remanufacturing or redesigning reverse logistics for already distributed products. In this study, recovery rate refers to the total sum of reuse rate and recycling rate [14].

Recovery covers both reuse and recycling [6]. Reuse refers to using the components and modules taken out of an EOL product as spare parts or other components [6], and it can be classified into product installation reuse and spare parts reuse [3]. Recycling refers to recovering raw materials from the scraps of the EOL product [6]. In order to accelerate material circulation, we need to increase the ratio of recovered raw materials to the gross weight of a product as well as the recycling level for recycling electric appliances [16].

Specifically, a lifecycle option is selected for each component of a product: when it is reused, its reuse rate is recorded as a recovery rate of the product; when it is recycled, the recycling rate is also recorded as the recovery rate of the product; however, when it is disposed of, 0 is recorded because there is no contribution to the recovery rate of the product increased.

The respective reuse and recycling rate of each component is defined as a reusable weight ratio of each component to the gross weight of the product [14] and as a recyclable weight ratio of each component to the gross weight of the product [17]. It is assumed that the reusable weight of each component is equal to its weight and that the recyclable weight depends on the recyclable weight of each raw material (Recyclability Evaluation Method [17], etc.).

Profit in this study refers to the total sum of the following: disassembly cost for an EOL product; treatment and disposal cost for recycled components; revenues of reused components; new procurement cost to newly procure components and reassembly cost; revenue of remanufactured products.

STEP1：Construction of a Bill of Materials

1. Determine assembly and disassembly tasks based on each component data.
2. Estimate the assembly and disassembly costs and the recovery rate.
3. Estimate the new procurement cost each component.

↓

STEP2：Formulation and Optimization

1. Formulate the remanufacturing option selection by using 0-1 integer programming.
2. Find the optimal solution by the mathematical programming package.

↓

STEP3：Analysis

1. Experiment on the effect of remanufacturing.
2. Experiment on the effect usage years of the product.
3. Experiment on the effect of the remanufactured product prices.

Fig. 1. Procedure of remanufacturing option selection with disassembly considering recovery rate and profit into account.

Figure 1 shows a procedure of the proposed remanufacturing option selection with disassembly that takes its recovery rate and profit into account. Using an actual product example, we verify the applicability of the proposed procedures to remanufacturing by analyzing the resulted changes in the remanufacturing option selection, profits, and recovery rates.

Step 1 constructs a bill of materials. The object products are actually disassembled to measure its component weights and specify its representative materials. Based on the above-mentioned procedures, assembly tasks are extracted, and the assembly and disassembly contents are determined. In addition, assembly cost, disassembly cost, the treatment and disposal costs and the recovery rate are estimated for each component. Moreover, the procurement cost is estimated to newly procure each component.

In Step 2, the remanufacturing option selection is formulated by using 0-1 integer programming [18] with the recovery rate given as an ε constraint [19] and optimized it with the mathematical programming package Numerical Optimizer [20].

Step 3 conducts numerical experiments to obtain resulted changes in recovery rate and profit, and analyzes the effects of remanufacturing, the usage years for the product, and remanufactured products' prices.

2.2. Evaluations of Recovery Rate and Profit

This study proposes the remanufacturing option selection method with two objective functions for maximizing

Table 1. Relationships among lifecycle options and their effects on profit and recovery rate.

Lifecycle options		Profit						Recovery rate	
		Disassembly cost	Treatment and disposal cost	Spare parts reuse revenue	New procurement cost	Reassembly cost	Remanufactured products revenue	Reuse rate	Recycling rate
With remanufacturing	Product installation reuse	▼				▼	△	△	
	New procurement	▼			▼	▼	△		
Without remanufacturing	Spare parts reuse	▼		△				△	
	Recycling	▼	▼ △						△
	Disposal								

Notes: Items that have positive effects on profit or recovery rate are denoted by △ while they have negative effects are denoted by ▼. The other items that have either positive or negative effects are denoted by △▼.

profit and the total recovery rate by adding new procurement of components and remanufacturing a product to the disassembly part selection method proposed by Hasegawa et al. [14]. Specifically, we propose how to determine the four lifecycle options of remanufacturing, reuse, recycling, and disposal of the EOL product using the mathematical programming by taking into account the product's lifetime, value lifetime, reuse, and recycling rate for each component, in addition to disassembly, new procurement of components, and sales of remanufactured products, reused parts and recycled materials.

When deciding whether an EOL product should be remanufactured, if it is decided to remanufacture it, either product installation reuse or new procurement is selected for each component of the product; if it is decided not to remanufacture it, one of the other lifecycle options, that is, spare parts reuse, recycling, or disposal, is selected.

Table 1 shows the relationships among lifecycle options and their effects on profit and recovery rate: their positive effects on profit and recovery rate are indicated by a triangle; negative effects are indicated by an inverted triangle; either positive or negative effects are indicated by both a triangle and an inverted triangle. For example, if remanufacturing is selected and product installation reuse [3] is selected as a lifecycle option for a certain component, the disassembly and reassembly costs processes should be involved, but the reuse rate should be gone up. In addition, some revenues can be expected from selling remanufactured products.

In the case with remanufacturing in **Table 1**, either product installation reuse or new procurement is selected. Product installation reuse signifies that a component is reused as a component of the remanufactured products, thereby improving its recovery rate.

New procurement means that components are newly procured to reassemble them. When remanufacturing an EOL product, some of its components that exceed their durable years cannot be reused to install into it, and they have to be newly procured, assuming that the newly procured components should be as valuable as ones originally used in it. Remanufacturing the EOL product with newly procured components should involve product installation reuse costs (= disassembly cost + reassembly cost) as well as new procurement costs to purchase new components. However, the recovery rate should not be improved because disassembled components are not reused.

In the case without remanufacturing in **Table 1**, one of the lifecycle options, that is, spare parts reuse, recycling, or disposal, is selected. Spare parts reuse [3] refers to selling the disassembled components as spare parts. Although this process requires disassembly costs, it can produce revenues as a result of selling the disassembled components at their reuse component prices. It can also improve the recovery rate. The reuse component prices are depreciated by the straight line method in accounting [21] based on Hasegawa et al. [14]. In this study, it is assumed that the depreciable period of a component is equal to its lifetime.

Recycling refers to recovering raw materials from the scraps of the EOL product when the product itself or its components have become unable to perform their original functions [6]. The recycling cost is the sum of disassembly cost and treatment and disposal cost. It is assumed that the treatment and disposal costs include sales revenue for the recycled materials [17], thus, positive profits are obtained if profits on sales are higher than costs (**Table 1**). In the case, the recovery rate can be improved because raw materials are recovered, although their original functions as components are lost.

In the case of disposal, it is assumed that the materials components or products will not be recycled and reused, thus, their original values as components are lost, and the recovery rate is not improved.

This study presupposes a piece of a single model product and does not consider any production line for multiple models or quantities. Therefore, any revenue from the sale of remanufactured products is accounted for one. This study also assumes that no disposal costs are involved, which means the worst case by disposing of EOL products rather than reusing or recycling them. Our experimental verification is based on the case of the worst recovery rate. If any disposal costs are considered, this will provide a cost structure where the selected lifecycle option achieves a recovery rate greater than one obtained in the experiments.

2.3. Formulation

This study solves the remanufacturing option selection problem with two objective functions, that is, maximizing the recovery rate and profit by applying the ε constraint method. The ε constraint method, one of the multiple objective optimization methods, obtains the Pareto optimum solutions by formulating the most important objective function as a unique function and other objective functions as constraint equations [19].

In the case without remanufacturing, partial disassembly [6], where either disassembly or no disassembly (disposal) for each component is selected as well as Hasegawa et al. [14] suggested. Specifically, while satisfying its precedence relationships among disassembly components, either spare parts reuse or recycling and disposal for each component can be selected. Thus, using the same assumption as that of Ondemir and Gupta [22], when spare parts reuse or recycling is selected for component j, a corresponding disassembly task must exist and be carried out in accordance with the selected lifecycle options while satisfying its precedence relationships.

In the case with remanufacturing, either new procurement or product installation reuse is selected for each component. For component j, therefore, it is assumed that both disassembly and reassembly must be done in accordance with the selected lifecycle options. In the case with remanufacturing, since complete disassembly [6] is made instead of partial disassembly, it is assumed that the precedence among the disassembled components can be ignored.

The symbols used in this study are described below.

2.3.1. Sets and Indices

J: Set of components.

P_j: A set of immediately preceding components in disassembling component j.

j: Index of components.

i: An immediately preceding components in disassembling component j.

2.3.2. Decision Variables

v: Binary value: 1 if product is remanufactured, otherwise 0.

w_j: Binary value: 1 if component j is procured, otherwise 0.

x_j: Binary value: 1 if component j is recycled, otherwise 0.

ys_j: Binary value: 1 if component j is sold as spare parts reuse, otherwise 0.

ya_j: Binary value: 1 if component j is reused as product installation reuse, otherwise 0.

z_j: Binary value: 1 if component j is disposed, otherwise 0.

2.3.3. Parameters

$Crems$: Revenue from remanufactured products (price of remanufactured products).

Crs_j: Revenue from spare parts reuse for component j (price of reused components).

$Cdis_j$: Disassembly cost of component j.

$Ctre_j$: Treatment and disposal cost of component j (inclusive of profits on sales of raw materials).

$Cpro_j$: New procurement cost of component j.

$Casse_j$: Reassembly cost of component j.

rc_j: Recycling rate of component j.

rs_j: Reuse rate of component j.

ε_R: Constraint of target recovery rate.

l_j: Durability of component j.

u: Usage years of a product.

R: Total recovery rate of a product (actual recovery rate).

C: Total profit on a product.

The proposed remanufacturing option selection method has the following two objective functions: maximizing the product's profit (Eq. (1)) and maximizing the recovery rate for the whole of the product (Eq. (2)).

Objective functions:

$$\begin{aligned} C = {} & Crems \times v + \sum_{j\in J} Crs_j \frac{l_j - u}{l_j} ys_j \\ & - \sum_{j\in J} Cdis_j \left(x_j + ys_j + ya_j + w_j\right) - \sum_{j\in J} Ctre_j x_j \\ & - \sum_{j\in J} Cpro_j w_j - \sum_{j\in J} Casse_j \left(w_j + ya_j\right) \rightarrow Max \quad (1) \end{aligned}$$

$$R = \sum_{j\in J} rs_j (ys_j + ya_j) + \sum_{j\in J} rc_j x_j \rightarrow Max \quad . \ . \ . \quad (2)$$

The profit in Eq. (1) is the total sum of revenues and costs. The first member of Eq. (1) refers to revenues from the remanufactured products. The second member refers to revenues from the spare parts reuse, which gets less valued as the usage years increase. The third member refers to the fact that recycling, reuse, or new procurement of components requires disassembly costs in each case. The fourth member refers to the fact that the treatment and disposal costs are involved when components are recycled. The treatment and disposal costs consist of disposal expenses for shredders and so on and their landfill expenses and revenues on sales of recycled materials [17]. The fifth member refers to the procurement costs for newly procuring some components when remanufacturing the EOL product. The sixth member refers to reassembly costs when remanufacturing the EOL product.

Equation (2) represents the sum of the actual recovery rates. The actual recovery rate is the sum of recycling rate and reuse rate. The first member of Eq. (2) refers to the recycling rate of components, and the second member refers to the reuse rate via spare parts reuse or product installation reuse.

In order to solve the two above-mentioned objectives problem, this study apply the well-known ε constraint method [19]. The objective function in Eq. (2) is transported into a constraint in Eq. (3) so that the Pareto optimum solutions can be obtained by varying the target recovery rate ε_R.

Constraints:

$$R \geq \varepsilon_R \quad (3)$$

$$z_i \leq z_j \quad \forall i \in P_j,\ \forall j \in J \quad (4)$$

$$x_j + ys_j + ya_j + z_j + w_j = 1 \quad \forall j \in J \quad (5)$$

$$uys_j < l_j \quad \forall j \in J \quad (6)$$

$$uya_j < l_j \quad \forall j \in J \quad (7)$$

$$w_j + ya_j = v \quad \forall j \in J \quad (8)$$

Next, constraints on the remanufacturing option selection are set up. Eq. (4) shows the precedence relationships among disassembled components. For example, if a preceding component is disposed of, the succeeding component is not disassembled but is also disposed of. Eq. (5) represents the constraints that any one of the recycling, spare parts reuse, product installation reuse, or disposal and new procurement options is always selected for each part.

Equations (6) and (7) mean that when the product's usage years exceeds the durable lifetime of a component, the reuse option is not selected. The durable lifetime refers to the period of time in which the product's failure rate is kept within the specified value [3]. For example, it is specified by guarantee years in development, usage hours, the length of usage years till disposal, or the total usage hours [23]. Eq. (8) shows that either product installation reuse or new procurement is selected only when remanufacturing is selected.

3. Design Example of Remanufacturing Option Selection

3.1. Estimation of Revenues, Costs, and Recovery Rate and Construction of a Bill of Materials

This study uses a laptop PC as a product example. We manually disassembled it to specify the assembly/disassembly work, material type, and weight of each component, and estimate its costs and reuse/recycling rates on various databases.

Specifically, the reassembly cost of each component is estimated by using the assembly reliability evaluation method (AREM) developed by Hitachi, Ltd. [24, 25]. Moreover, the disassembly cost, treatment and disposal costs (inclusive of profits on sales of raw materials), and recycling rate are estimated by using the recyclability evaluation method (REM) [17]. AREM was developed for numerically evaluating the easiness of assembly and the frequency of defects amid the increasingly fierce product development competitions that heavily burdened the design departments, and has been applied to productivity designs [24, 25]. REM, which was developed in accordance with the same concept of AREM in terms of assembly, enables us to quantitatively evaluate the easiness of recycling or disassembly of products/components [17].

Procurement costs in this study are estimated using the Input-Output Table in 2015 [26]. The representative materials of each component are corresponded to the names in the domestic production output tables by sector and by item in the Input-Output Table. After that, their prices per gram from the production quantities and outputs of corresponding materials are estimated to seek the components' prices in their respective weights.

Regarding the reuse of components, their obsolescent values have depreciated using the straight line method in accounting in consideration of consistent with Hasegawa et al. [14].

Next, a bill of materials is prepared. **Table 2** shows a bill of materials (five usage years), which is used as input data in the experiments: component name, component number, representative material name, weight, costs, reuse rate, and the component lifetime are given in respective lines. Regarding the component lifetime, as followed by Hasegawa et al. [14] for their desktop PC, the lifetime of #6 HDD and #21 fan are set at five years each while the lifetime of other components is also set at ten years each.

From **Table 2**, for example, it is shown that #4 back plate is made of Al/Al alloy, and its disassembly costs 13.37 Japanese Yen. The reuse component price of #6 HDD is zero Yen because its lifetime is five years. The reuse rate of #1 lithium ion battery is 12.26%, and its recycling rate is 7.01%. It is found that the reuse rate for #1 lithium ion battery is higher than the recycling rate. This is because only a part of their weights is recyclable in some components depending on their raw materials. Therefore, their recycling rates become lower than their reuse rates.

In this study, given remanufactured product prices, remanufacturing option selections are carried out to maximize profits with the constraint that the actual recovery rate R should not be less than the target recovery rate ε_R. The price of remanufactured products at Yen 2,000 and the usage years at five years are set. The set price of remanufactured products (Yen 2,000) exceeds the total sum of disassembly cost (Yen 736) and reassembly cost (Yen 1,009.2) (Yen 1,745.2 = Yen 736 + Yen 1,009.2) for every component. Thus, this amount assures us of positive profit when selling remanufactured products (**Table 2**).

Figure 2 shows the disassembly precedence relationships of the laptop PC used in the numerical experiments. In this study, disposing of a component means that it is not manually disassembled but is crushed and it is assumed that all other components in their subsequent relations are also disposed of. From **Fig. 2**, for example, #17 bottom cover precedes subsequent 29 parts. If #17 bottom cover

Table 2. Input data used for remanufacturing option selection (five usage years).

No	Component name	Material type	Weight [g]	Disassembly cost [Yen]	Treatment and disposal cost [Yen]	Procurement cost [Yen]	Assembly cost [Yen]	Spare parts reuse price [Yen]	Recycling rate [%]	Reuse rate [%]	Component lifetime [Year]
1	Lithium ion battery	ABS	305.00	17.49	31.81	93.35	10.00	46.68	7.01	12.26	10
2	Key + Top cover	PC/ABS	51.00	17.49	0.00	15.61	10.00	7.81	2.05	2.05	10
3	Membrane plug board	PET	11.00	13.37	0.00	2.77	26.73	1.39	0.44	0.44	10
4	Back plate	Al/Al alloy	32.00	13.37	−2.56	8.78	26.73	4.39	1.29	1.29	10
5	Stabilizer	SUS (magnetic)	3.00	17.49	−0.02	0.45	10.00	0.23	0.12	0.12	10
6	HDD	Al/Al alloy	111.00	36.51	−8.88	30.44	76.92	0.00	4.46	4.46	5
7	RAM	Epoxy resin	14.00	20.06	0.00	6.24	10.00	3.12	0.23	0.56	10
8	Case body	Al/Al alloy	49.00	17.49	−3.92	13.44	10.00	6.72	1.97	1.97	10
9	Case body	Al/Al alloy	8.00	13.37	−0.64	2.19	10.00	1.10	0.32	0.32	10
10	Case body + Board + Cord	SUS (magnetic)	52.00	13.37	−0.42	7.86	26.73	3.93	2.09	2.09	10
11	Case body	ABS	26.00	17.49	0.00	7.96	10.00	3.98	1.05	1.05	10
12	Pad part	PC/ABS	16.00	13.37	0.00	4.90	26.73	2.45	0.64	0.64	10
13	Board component	Circuit board	15.00	13.37	2.25	3.95	26.73	1.98	0.00	0.60	10
14	CPU	Circuit board	7.00	17.49	1.05	1.84	10.00	0.92	0.00	0.28	10
15	Top cover	PC/ABS	104.00	17.49	0.00	31.83	10.00	15.92	4.18	4.18	10
16	Top cover	SUS (magnetic)	193.00	36.51	−1.54	29.18	76.92	14.59	7.76	7.76	10
17	Bottom cover	PC/ABS	177.00	113.66	0.00	54.17	244.22	27.09	7.12	7.12	10
18	Bottom cover	PC/ABS	18.00	17.49	0.00	5.51	10.00	2.76	0.72	0.72	10
19	Resin frame	PC/ABS	5.00	17.49	0.00	1.53	10.00	0.77	0.20	0.20	10
20	Metal frame	SUS (magnetic)	28.00	17.49	−0.22	4.23	10.00	2.12	1.13	1.13	10
21	Fan	PC/ABS	7.00	17.49	0.00	2.14	10.00	0.00	0.28	0.28	5
22	Heat sink	Cu/Cu alloy	63.00	36.51	−6.30	151.56	76.92	75.78	2.53	2.53	10
23	Liquid crystal module	Glass	425.00	13.37	-4.25	852.63	26.73	426.32	17.09	17.09	10
24	Front cover	Glass	242.00	17.49	−2.42	37.04	10.00	18.52	9.73	9.73	10
25	Rear cover	PC/ABS	233.00	21.09	0.00	71.31	43.46	35.66	9.37	9.37	10
26	Connecting cable	Cu/Cu alloy	7.00	17.49	−0.70	5.02	10.00	2.51	0.28	0.28	10
27	Antenna cable	Cu/Cu alloy	5.00	17.49	−0.50	3.59	10.00	1.80	0.20	0.20	10
28	Frame	SUS (magnetic)	59.00	36.51	−0.47	8.92	76.92	4.46	2.37	2.37	10
29	WEB camera + Board	Circuit board	7.00	17.49	1.05	1.84	10.00	0.92	0.00	0.28	10
30	Mother board	Circuit board	171.00	13.37	25.65	45.01	26.73	22.51	0.00	6.88	10
31	Cushioning	Polyurethane	3.00	17.49	0.00	0.00	10.00	0.00	0.12	0.12	10
32	Speaker	PC/ABS	30.00	17.49	0.00	9.18	10.00	4.59	1.21	1.21	10
33	Wireless LAN card	Circuit board	4.00	13.37	0.60	1.05	26.73	0.53	0.00	0.16	10
34	Cords	Cu/Cu alloy	6.00	17.49	−0.60	4.31	10.00	2.16	0.24	0.24	10
	Total	–	2487.00	736.00	28.97	1519.83	1009.20	743.63	86.20	99.98	–
	Average	–	73.15	21.65	0.85	44.70	29.68	21.87	2.54	2.94	–
	Standard deviation	–	100.82	17.39	7.32	144.09	43.03	72.15	3.78	4.05	–

is disposed of, then 29 parts in subsequent relations are all disposed of. Though #17 bottom cover requires the highest disassembly cost (Yen 113.66) as seen from **Table 2**, disposal is not selected for reusing or recycling any other components with higher recovery values in their subsequent relations.

All numerical experiments are conducted on a Windows 10 desktop computer, Intel® CoreTM i5-9400 CPU @ 2.90 GHz, using the optimization solver Numerical Optimizer [20].

3.2. Remanufacturing Option Selection Results (RQ i))

The ε constraint method is used to obtain the Pareto optimal solutions by varying the target recovery rates by 1%, 2%, 3%,…, 99%. **Table 3** shows the remanufacturing option selection results for the remanufactured components (five usage years; remanufactured products' price: Yen 2,000). In **Table 3**, the lifecycle option selection results for each part are described in reference to the target recovery rates given in the second row at the top of the table. At the bottom of the table, the respective actual recovery rates and profits are shown. For example, when the target recovery rate is 76%–77%, remanufacturing is not selected, the actual recovery rate is 77.55%, and the profit is Yen 284.645. As a result of selecting the remanufacturing option, spare parts reuse is selected for #2 key + top cover and #5 stabilizer while disposal is selected for #7 RAM and #20 metal frame.

When the target recovery rate is 92%–95%, remanufacturing is selected, the actual recovery rate is 95.24%, and the profit is Yen 222.22. In the remanufacturing, product installation reuse is selected for #22 heat sink and #24 front cover while new procurement is selected for #6 HDD and #21 fan.

From **Table 3**, it is found that remanufacturing is selected only when the target recovery rate is 92%–95%. On the other hand, remanufacturing is not selected when

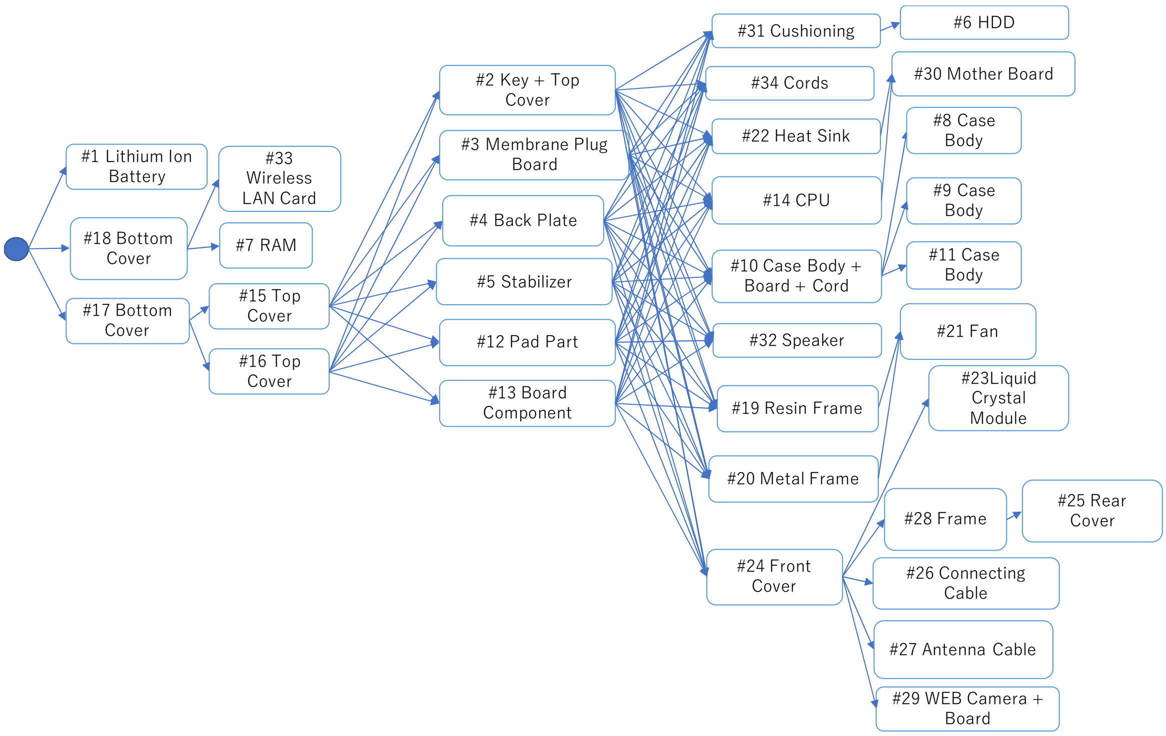

Fig. 2. Precedence relationships among disassembled components: laptop PC.

the target recovery rate is 96% or more, which seems attributable to the lifetime and weight of #6 HDD. Since the numerical experiments were conducted for the components' five usage years, product installation reuse or spare parts reuse could not be selected for #6 HDD, the lifetime of which is five years according to **Table 2**.

The reuse rate and recycling rate of #6 HDD, the weight of which is 111 grams, one and a half times heavier than average, are as high as 4.46% each. Although #6 HDD with a reuse/recycling rate of 4.46% needs to be reused or recycled when the target recovery rate is 96% or more, it cannot be reused due to its lifetime. Therefore, it is not remanufactured but recycled to improve its recovery rate of 4.46%.

The remanufacturing option selection results demonstrate that new procurement has been selected only for #6 HDD and #21 fan, which are not reusable due to their lifetime. In other words, new procurement seems to be selected for a component with no remaining lifetime while product installation reuse is selected for a component with some remaining lifetime.

Additionally, it is also found that there were few changes in the lifecycle option selection results for heavy components of 100 g or more, such as #1 lithium ion battery, #6 HDD, #23 liquid crystal module, #24 front cover, #25 rear cover, and so on, with different target recovery rates. Thus, the proposed method almost uniquely determine which lifecycle option is appropriate for the components regardless of their target recovery rates, which enable us to effectively support prompt decision making.

However, light components (#9 case body, etc.) which involve low cost and reuse/recycling rates, enable us to achieve the target recovery rates by frequently altering their lifecycle options. When the proposed method is used, it is not desirable in some cases that disposal and reuse are sensitively changed when the target recovery rate is altered. In actual operations, therefore, it is necessary to flexibly respond to the actual situations, for instance, by providing some tolerance in changing the lifecycle options.

4. Verification of Proposed Method

4.1. Effects of Remanufacturing (RQ ii))

Figure 3 compares the profits and actual recovery rates of the proposed method and the conventional method used by Hasegawa et al. [14] that does not take remanufacturing into consideration. When the target recovery rates are 91% or less and 97% or more, the proposed method and the conventional method by Hasegawa et al. [14] gain the same profits and actual recovery rates because no remanufacturing is selected for any components as shown in **Table 3**. Thus, **Fig. 3** only shows the profits and actual recovery rates when the target recovery rates are between 91% and 96% by altering the target rate by 1% because they should represent profits and actual recovery rates that reflect the remanufacturing options selected for some components. It is noted that there are some differences in the number of plots or obtained solutions between the proposed method and the conventional method. This is because a plurality of same solutions was obtained for the

Table 3. Remanufacturing option selection results (five usage years; remanufactured products' price: Yen 2,000).

		Target recovery rate [%]														
No	Component name	0~65	66~72	73~75	76~77	78~84	85~86	87~88	89	90	91	92~95	96	97	98	99
1	Lithium ion battery	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
2	Key + Top cover	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
3	Membrane plug board	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
4	Back plate	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
5	Stabilizer	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
6	HDD	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	New procurement	Recycling	Recycling	Recycling	Recycling
7	RAM	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Spare parts reuse	Spare parts reuse
8	Case body	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
9	Case body	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Disposal	Product installation reuse	Spare parts reuse	Spare parts reuse	Disposal	Spare parts reuse
10	Case body + Board + Cord	Disposal	Disposal	Spare parts reuse	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
11	Case body	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Spare parts reuse	Product installation reuse	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse
12	Pad part	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
13	Board component	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
14	CPU	Disposal	Spare parts reuse	Spare parts reuse	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
15	Top cover	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
16	Top cover	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
17	Bottom cover	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
18	Bottom cover	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Spare parts reuse	Spare parts reuse
19	Resin frame	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Disposal
20	Metal frame	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
21	Fan	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	New procurement	Disposal	Disposal	Disposal	Disposal
22	Heat sink	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
23	Liquid crystal module	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
24	Front cover	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
25	Rear cover	Disposal	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
26	Connecting cable	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Spare parts reuse
27	Antenna cable	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Disposal
28	Frame	Disposal	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
29	WEB camera + Board	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Disposal
30	Mother board	Disposal	Spare parts reuse	Spare parts reuse	Disposal	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
31	Cushioning	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Recycling	Recycling	Recycling	Recycling
32	Speaker	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Spare parts reuse	Spare parts reuse	Product installation reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse	Spare parts reuse
33	Wireless LAN card	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Spare parts reuse
34	Cords	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Disposal	Product installation reuse	Disposal	Disposal	Disposal	Spare parts reuse
	Actual recovery rate [%]	65.81	72.97	75.06	77.55	84.71	86.8	88.77	89.09	90.3	91.03	95.24	96.01	97.06	98.02	99.02
	Profit [Yen]	302.13	294.70	285.26	284.65	277.21	267.77	257.00	244.73	231.83	230.59	222.22	171.33	157.82	138.42	82.99

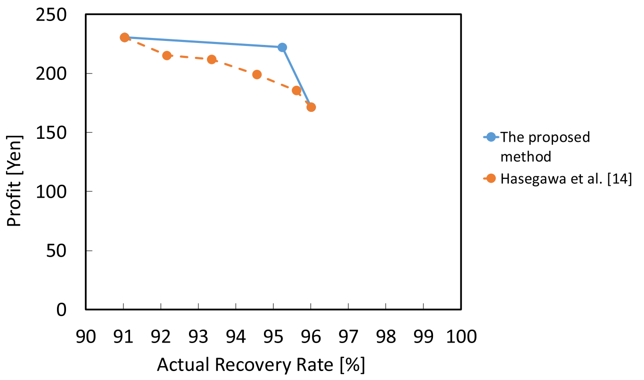

Fig. 3. Comparison between the actual recovery rate and profit by the proposed and conventional methods.

combination of profit and actual recovery rate when maximizing the profit even with different target recovery rates.

From **Fig. 3**, the proposed method can gain higher profits than the conventional method with target recovery rates between 92% and 95% because remanufacturing is selected for some components. Specifically, while the conventional method without remanufacturing selected obtained an average actual recovery rate of 93.9% and an average profit of Yen 202.8, the proposed method with remanufacturing selected for some components obtained an average actual recovery rate of 95.2% and an average profit of Yen 222.2. In other words, the proposed method that takes remanufacturing into account improved the profit by about Yen 20.

However, in the target recovery rates of 96% or more where remanufacturing is not selected for any components, the proposed method produced the same part selection results as the conventional method. Therefore, the proposed method may obtain the same or higher revenue and recovery rate than ones by the conventional method but can never produce any lower revenue or recovery rate than the conventional method in the experiments. It demonstrates that the proposed method, which takes remanufacturing into account, is superior to the conventional method.

4.2. Effects of Usage Years (RQ iii))

The effects of differences in the usage years of a product on its recovery rate and profit are examined. With the price of remanufactured products set at Yen 2,000, numerical experiments are conducted by varying the usage years of the product from one year to nine years. **Fig. 4** shows the actual recovery rates and profits at respective usage years: ◯ indicates the point where remanufacturing is selected. It is noted that plurality of solutions to the combination of profit and actual recovery rate at the time of maximizing the profit can be obtained even with different target recovery rates. Therefore, the number of plots and obtained solutions varies according to the usage years.

Remanufacturing has been selected at two points only. The first one is when the product's usage years are four, the recovery rate is 99.9%, and the profit is Yen 254.8. The second one is when the product's usage years are five, the recovery rate is 95.2%, and the profit is Yen 222.2. In the case of usage four years of the product, product installation reuse is selected for every component. In the case of five usage years of the product, new procurement is selected for #6 HDD and #21 fan only while the product installation reuse is selected for all the remaining components, as shown in **Table 3**.

4.2.1. Usage Years: One to Five Years

From **Fig. 4**, when the number of usage years is five years or less, as the actual recovery rate is increased, the profit is decreased gradually: a horizontal line graph. In both cases where remanufacturing is selected, it is noticed that it does not excessively increase or decrease the profit.

From **Fig. 4**, as the usage years increase, the profit decreases, because as the usage years increase, the price of the reused parts falls. In other words, when the usage years is from one to five years, whether remanufacturing is selected or not seems to have few effects on the increase or decrease in profit. However, the actual recovery rate and the usage years seem to have greater effects.

4.2.2. Usage Years: Six to Nine Years

In each of the cases of six to nine usage years, remanufacturing is selected to obtain a recovery rate of 95.2% and a profit of Yen 222.2. When the usage years are six years or more, as the actual recovery rate is increased, the profit becomes negative. In some cases, the involved costs bring the profit down to negative. This can be attributed to the fact that as the usage years increase, the price of the reused components for spare parts reuse falls and the disassembly cost exceeds the revenues on sales of spare parts or recycled materials.

Nonetheless, in the case of six to nine usage years, the proposed method realized some profits by selecting remanufacturing. For example, in the case of eight usage years, when the actual recovery rate is 95.2%, the profit is Yen 222.2. However, when the actual recovery rate is 96%, the profit is Yen −261.4 because no remanufacturing is selected. Likewise, the involved costs have made the profits negative for the larger actual recovery rates more than 96%. In the case from seven to nine usage years, it is found that remanufacturing also brings in some profits. We, therefore, demonstrate that whether remanufacturing is selected or not has great effects on profit.

4.3. Effects of Remanufactured Products' Prices (RQ iv))

In this section, the effects of remanufactured products' prices are examined on the selection of remanufacturing. We conducted experiments by varying the remanufactured products' prices by Yen 500 from Yen 1,000 to Yen 5,000, with the 5 usage years and the target recovery rate at 0%.

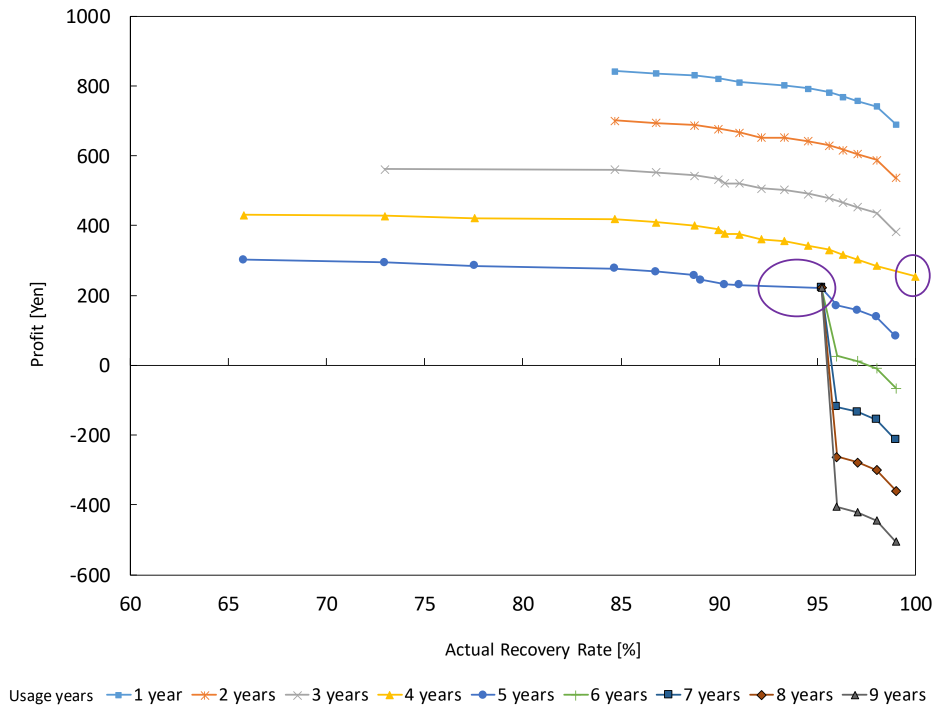

Fig. 4. Relationship between actual recovery rate and profit in respective usage years: remanufactured products' price: Yen 2,000.

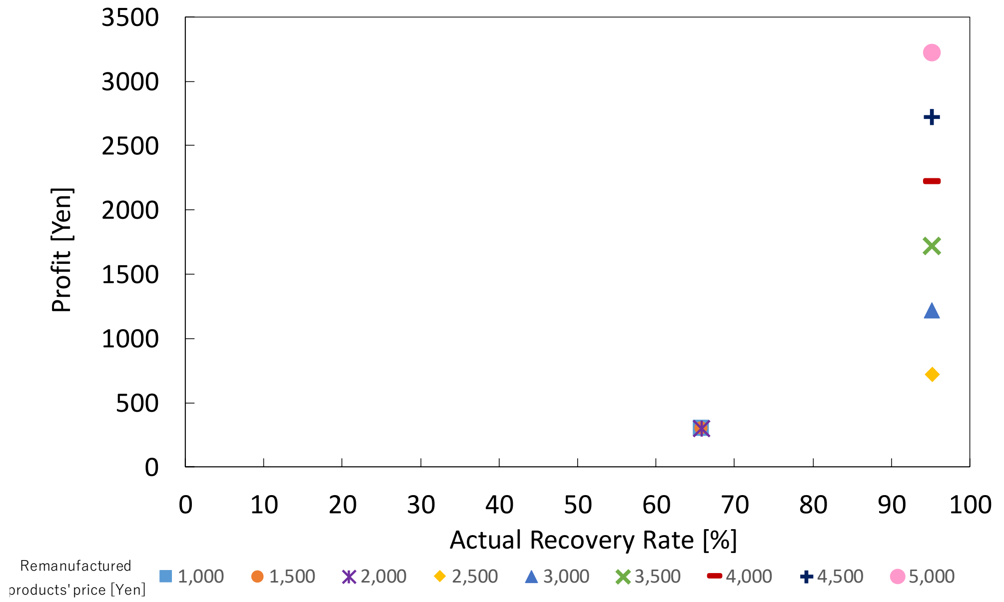

Fig. 5. Relationship between actual recovery rate and profit at different remanufactured products' prices: five usage years.

Figure 5 shows the relationship between the actual recovery rate and profit at different prices of remanufactured products. In the case of not selecting remanufacturing, when the remanufactured products' prices are Yen 1,000, Yen 1,500, and Yen 2,000, the actual recovery rate is 65.82% and the profit is Yen 302. On the other hand, when the remanufactured products' price is Yen 2,500 or more, remanufacturing is selected at every such remanufactured products' price to make an actual recovery rate of 95.24% in each case. When the remanufactured products' price was Yen 2,500, the actual recovery rate and the profit increased by 29.43% and Yen 420, respectively, as compared with those when the remanufactured products' price was up to Yen 2,000. When the remanufactured products' price was Yen 3,000 or more, the profit increased by Yen 500 for every increase of Yen 500 in the remanufactured products' price. This demonstrates that if we can sell a remanufactured PC at the price of Yen 2,500 or more, a higher profit can be achieved than one if we select spare parts reuse or recycling. The remanufactured products' price of Yen 2,500 represents a price 1.4 times as high as the maximum profit solution within the sum (Yen 1,745.2) of disassembly and reassembly costs for every part (**Table 3**).

In **Fig. 4**, we turn our attention to one usage year and to the remanufactured products' price of Yen 3,000 in **Fig. 5**. In **Fig. 4**, the maximum profit is Yen 843 with an actual recovery rate of 85%, due to the usage year of the product being one year. Since the product has been used for a short period of time, the reused components for spare parts reuse are highly priced, thus, making the profit from spare parts reuse or disposal become higher than the revenue from remanufacturing products. Hence, remanufacturing has not been selected. On the other hand, in **Fig. 5**, remanufacturing has been selected with the remanufactured products' price being Yen 3,000 and a profit of Yen 1,222, about Yen 350 higher than the maximum profit in **Fig. 4**. In addition, the actual recovery rate is around 95%, which means about 10% higher than that in **Fig. 4**.

5. Conclusion and Future Issues

This study proposed and verified a remanufacturing option selection method that took recovery rates and profits into account by applying it to a laptop PC as a product example. Main findings of this paper are as follows.

$<$ i) Relationship between recovery rate and profit $>$

- While remanufacturing and spare parts reuse can raise the actual recovery rate, they can reduce profit. This is because when disassembling a product and taking out some components according to the precedence relationships, we also need to disassemble other components which have the preceding relations among them.

$<$ ii) Changes in recovery rate $>$

- When the target recovery rate is high, remanufacturing is an effective option, in addition to the conventional product lifecycle options.
- When the target recovery rate changes, the reason why remanufacturing is selected in addition to the other conventional lifecycle options is that revenues from remanufactured products can bring in higher profits.

$<$ iii) Remanufacturing and usage years $>$

- In the case of the usage years increased, the conventional lifecycle options such as recycling, spare parts reuse, and disposal are difficult to be selected, while remanufacturing is easy to be selected.
- Remanufacturing in the proposed method enables a resale of the remanufactured products as a whole rather than in component units, which produces higher profits, thus, remanufacturing becomes easier to be selected.

$<$ iv) Remanufactured products' prices $>$

- When the prices of remanufactured products are increased, remanufacturing becomes easier to be selected because it enables us to achieve higher profits.
- On the other hand, when remanufactured products cannot effectively generate any profits, it is more economical and environmentally friendly to generate profits from spare parts reuse for individual components.

The following studies are listed as future considerations: 1) to consider not only individual components' lifetime but also products' lifetime, as well as lot production and upgrading options [27]; 2) to take into account the disposal and cleaning costs in the remanufacturing process. Specifically, the proposed remanufacturing option selection model should introduce disposal costs by setting a disposal cost coefficient for component j and adding it to the objective function of profit (Eq. (1)).

Acknowledgements

We hereby express our sincere thanks to Ms. Yumiko Ueno and Mr. Seiichi Fujita of Hitachi, Ltd. who generously provided their assembly reliability evaluation method (AREM) and recyclability evaluation method (REM) for this study. This study was partially supported by the Japan Society for the Promotion of Science (JSPS), KAKENHI, Grant-in-Aid for Scientific Research (A), JP18H03824, from 2018 to 2021.

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Main Works:
• Y. Kinoshita, T. Yamada, S. M. Gupta, A. Ishigaki, and M. Inoue, "Decision Support Model of Environmentally Friendly and Economical Material Strategy for Life Cycle Cost and Recyclable Weight," Int. J. of Production Economics, Vol.224, 107545, 2020.
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