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2-Stage Optimal Design and Analysis for Disassembly System with Environmental and Economic Parts Selection Using the Recyclability Evaluation Method

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ABSTRACT

Promotion of a closed-loop supply chain requires disassembly systems that recycle end-of-life (EOL) assembled products. To operate the recycling disassembly system, parts selection is environmentally and economically carried out with non-destructive or destructive disassembly, and the recycling rate of the whole EOL product is determined. As the number of disassembled parts increases, the recycling rate basically increases. However, the labor cost also increases and brings lower profit, which is the difference between the recovered material prices and the disassembly costs. On the other hand, since the precedence relationships among disassembly tasks of the product also change with the parts selections, it is also required to optimize allocation of the tasks in designing a disassembly line. In addition, because information is required for such a design, the recycling rate, profit of each part and disassembly task times take precedence among the disassembly tasks. However, it is difficult to obtain that information in advance before collecting the actual EOL product. This study proposes and analyzes an optimal disassembly system design using integer programming with the environmental and economic parts selection (Igarashi *et al.*, 2013), which harmonizes the recycling rate and profit using recyclability evaluation method (REM) developed by Hitachi, Ltd. The first stage involves optimization of environmental and economic parts selection with integer programming with ε constraint, and the second stage involves optimization of the line balancing with integer programming in terms of minimizing the number of stations. The first and second stages are generally and mathematically formulized, and the relationships between them are analyzed in the cases of cell phones, computers and cleaners.

Keywords: Closed-Loop Supply Chain, Recycling, Sustainable Manufacturing, Combinatorial Optimization, Integer Programming, Disassembly Line Balancing

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1. INTRODUCTION

Promotion of material circulation by closed-loop supply chains has required disassembly systems that recycle end-of-life (EOL) assembly products (Ilgin and Gupta, 2010; Lambert and Gupta, 2005; Pochampally *et al.*, 2008). Recycling is the recovery of materials out of scrap from EOL products (Lambert and Gupta, 2005), and its rate is defined as a rate of recyclable weight to the total weight of a product (Akahori *et al*., 2008). The recycling rate of the whole of EOL product should be considered in the system design phase as an environmental aspect and it should be improved for the material circulation on the earth. Nowadays, that information has been obtained using the Recyclability Evaluation Method (REM) (Hiroshige *et al*., 2002). To operate the recycling disassembly system, parts selection (Kuo, 2013; Wang and Gupta, 2011) is environmentally and economically carried out with non-destructive or destructive disassembly. As the number of disassembled parts increases, the recycling rate basically increases. However, the labor cost also increases and brings lower profit, which is the difference between the recovered material prices and the disassembly costs (Yamada *et al*., 2011). Therefore, the parts selection of non-destructive or destructive disassembly should be optimized in terms of the recycling rate and profit. On the other hand, since the precedence relationships among disassembly tasks of the product also change with the parts selection, it is required to optimize allocation of the tasks in designing a disassembly line (Avikal *et al*., 2013; Aydemir-Karadag and Turkbey, 2013; Kalayci and Gupta, 2013; McGovern and Gupta, 2003). In addition, because information is required for such a design, the recycling rate, profit of each part, and disassembly task times take precedence among the disassembly tasks. However, it is difficult to obtain that information in advance before collecting the actual EOL product.

This study proposes and analyzes an optimal disassembly system design using integer programming with the environmental and economic parts selection (Igarashi *et al*., 2013) which harmonizes the recycling rate and profit using the REM developed by Hitachi, Ltd.

The organization of this paper is as follows: Section 2 explains a disassembly system design problem with an environmental and economic parts selection. First, the relationship between a disassembly parts selection and its subsequent disassembly line balancing is explained. Second, using a 3D-CAD and REM, we explain how to estimate the information required for the disassembly system design in this study. Section 3 proposes a 2-stage optimal design by mixed integer programming at each stage for the disassembly system with the environmental and economic parts selection. In Section 4, an optimization problem of the 2-stage disassembly system design is generally formulated with the environmental and economic parts selection at the first stage and the subsequent disassembly line balancing at the second stage. Section 5 develops a procedure for the 2-stage disassembly system design using the cell phone, computers and cleaners as a case example. Sections 6 adopt the system design procedure to three different types of product examples, such as cell phones, computers and cleaners, and analyze the disassembly parts selection at the first stage and the line balancing at the second stage, respectively. Finally, Section 7 concludes this study and proposes future works.

2. DISASSEMBLY SYSTEM DESIGN PROBLEM WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION

In this section, the disassembly system design problem with the environmental and economic parts selection is explained and the relationship between the parts selection and the disassembly line balancing is addressed.

2.1 Relationship between Environmental and Economic Disassembly Parts Selection and Line Balancing

This section explains relationship between environmental and economic disassembly parts selection and line balancing in disassembly system design.

For the purpose of simultaneous environmental and economic recycling, recycling factories often carry out disassembly parts selection, which either disassembles or disposes of each part. Table 1 shows a change of the recycling rate and cost in relation to decisions regarding recycling or disposing in this study. Disassembling parts can keep recycling rate high and increase material selling profit. However, recycling costs increase. On the other hand, if parts are disposed of, disassembly costs decrease, but the material selling profit and recycling rate also decrease. Since the product/parts structure will be altered after the disassembly parts selection, their disassembly precedence relationship also changes. In Figure 1,

Table 1. Disassembly parts selection by recycling cost and rate

	Disassembly	Dispose
Recycling cost		
Material selling profit	Increase	None
Disassembling cost	Increase	None
Recycling rate	Increase	Decrease

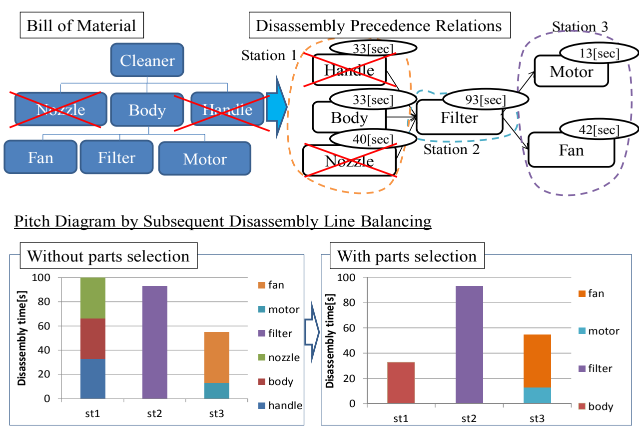

Figure 1. Relationship between environmental and economic disassembly parts selection and subsequent disassembly line balancing.

if Nozzle and Handle are disposed of, the parts will be deleted from the disassembly precedence relationship, since they are not necessary for disassembly. Because the subsequent line balancing, which assigns disassembly tasks to each disassembly station, is also affected, it is necessary for the disassembly system design to carry out the line balancing after the environmental and economic parts selection. In the example of Figure 1, since it is not necessary to assign Nozzle and Handle, which were disposed of, the number of disassembly stations decrease as a result.

2.2 Estimation of Disassembly Information for System Design using 3D-CAD and REM

This section explains the method for estimation of information required for the disassembly system design using the 3D-CAD and REM.

To obtain the disassembly information of the EOL product in advance, REM is used in this study. REM developed by Hitachi, Ltd. (EcoAssist: Akahori *et al*., 2008) is software used to compute and estimate the recycling rate, cost, and disassembly time by inputting product information, such as material type, weight, and disassembly motion at each part as shown in Figure 2.

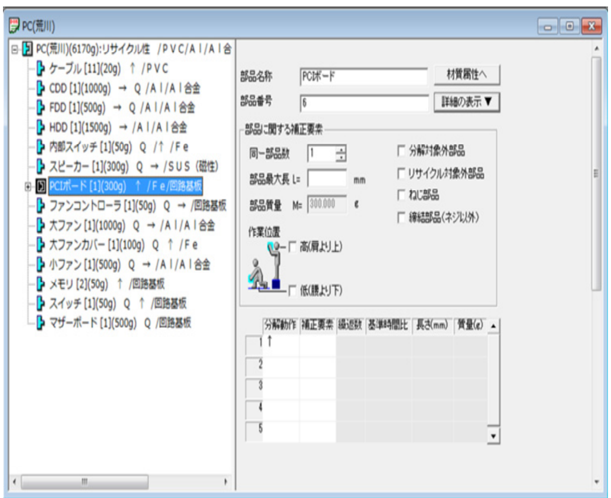

Figure 2. Recyclability Evaluation Method (Hiroshige *et al*., 2002) by EcoAssist (http://www.ecoassist.com/HTML_n/option/rem/remtr/ppframe.htm).

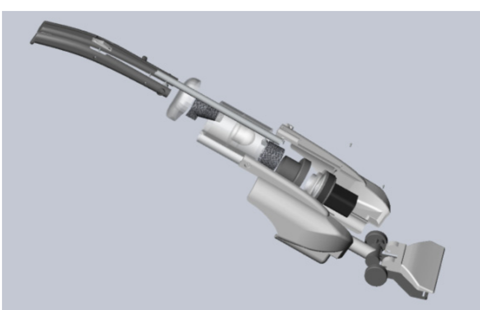

Figure 3. 3D-CAD model (case of the cleaner: Inoue *et al*., 2011).

In the software, the recycling rate is obtained by dividing the sum of the recycled weight of each part by the total weight of the product. The recycled weight of each part is obtained by the weight of each part and the recycling rate of the part material. The recycling cost is the difference between the recovered material prices and costs, where the costs consist of disassembly, material process and disposal costs. If the recovered material prices are higher than the costs, the value of the recycling cost is negative, which means positive profits were earned by recycling. Disassembly operations and procedure relationships are estimated by 3D-CAD as shown in Figure 3.

3. 2-STAGE OPTIMAL DESIGN OF DISASSEMBLY SYSTEM WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION

The 2-stage disassembly system design method for environmental and economic recycling is proposed in this section and the relationships among input-output information and each stage are identified.

Figure 4 shows relationships among types of input/output information and results in the disassembly system design proposed in this study. For example, the material of a part affects recycling rate, disposal cost, and treatment cost. Then, recycling rate, disposal cost, and treatment cost affect the result of parts selection. In this study, the disassembly system design problem with environmental and economic parts selection of Section 2 is treated as a 2-stage problem, and considers solutions from the first stage in order to reach the second stage. Although integrative solutions are theoretically possible, the recycling rate may be defined by the Home Appliances Recycling Law, etc.; therefore, it is necessary to perform disassembly line balancing under disassembly parts selection.

This study proposes a 2-stage design (Yamada and Matsui, 2001) for the disassembly system. The first stage is the environmental and economic parts selection. The second stage is line balancing under the environmental and economic parts selection.

Namely, the 2-stage design method is shown by Figure 5. The first stage is optimization of parts selection that minimizes total recycling cost and maximizes total recycling rate. The total cost is sum of the recycling cost of each part, which consists of disassembly, treatment and disposal costs and sales revenue of materials.

During optimal parts selection, after the first stage, the purpose of the second stage is to optimize work assignment on a disassembly line that minimizes the total number of stations under a given cycle time.

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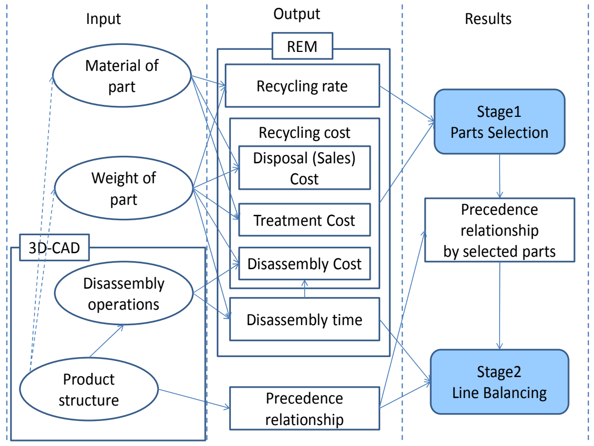

Figure 4. 2-Stage disassembly system design and information with environmental and economic parts selection.

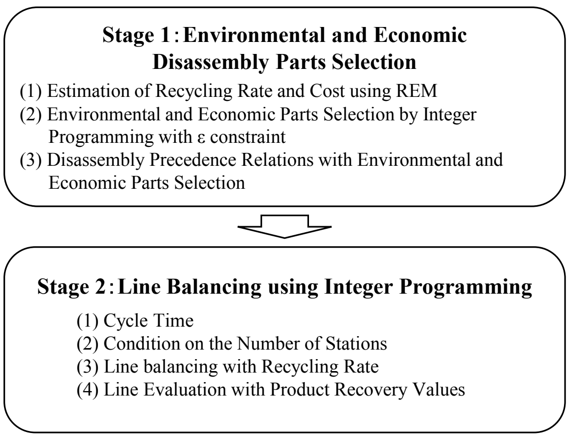

Figure 5. 2-Stage optimal design of disassembly system.

Figure 5 shows the optimal design of the disassembly system with environmental and economic parts selection using REM. The disassembly system design procedure is based on Yamada and Sunanaga (2011) and Igarashi *et al*. (2013). This study attempts to develop environmental and economic parts selection and disassembly line balancing using integer programming.
A summary of the notations in this study is presented below:

i : Index for predecessors of part j with task j
j : Index of parts/tasks ($j = 1, 2, \cdots, N$)
k : Index of stations ($k = K_0, \cdots, K$)
N : Number of parts
J : Set of parts/tasks
J_{select} : Set of selected parts/tasks at Stage 1
J_{cancel} : Set of disposed parts/tasks at Stage 1
c_j : Recycling cost at part j
r_j : Recycling rate at part j
R : Total recycling rate by selected parts
R_{max} : Maximum recycling rate of a product in all parts disassembled
C : Total recycling cost by selected parts
x_j : Binary value; 1 if part j is disassembled, else 0
ε : Constraint of total recycling rate of selected parts
CT : Cycle time
K_0 : Number of necessary stations
K : Total number of stations in a design
p_j : Disassembly (processing) time of task j at part j
$y_{k,j}$: Binary value; 1 if task j at part j is assigned to station k, 0 otherwise
P_j : Set of tasks that immediately precede task j at part j
T_0 : Production planning period
Q : Demands for collected EOL products during T_0
S_0 : Total disassembly time

4. MATHEMATICAL FORMULATION OF 2-STAGE DISASSEMBLY SYSTEM DESIGN WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION

In this section, the 2-stage disassembly system is formulized for optimization.

4.1 Optimization of Environmental and Economic Disassembly Parts Selection

A formulation of environmental and economic disassembly parts selection is shown in this section.

For the purpose of optimal environmental and economic parts selection, the environmental and economic parts selection (Igarashi *et al*., 2013) is here applied to this 2-stage design. Based on the product disassembly data obtained by the REM, 0–1 integer programming (Kubo, 2000) is used in this study for the selection of the parts disassembled or not in terms of the recycling rate and cost. The combinatorial solution, which maximizes the total recycling rate but minimizes the total recycling cost of the product, is examined to satisfy the constraints of the disassembly precedence relationships.

Similar to Igarashi *et al*. (2013), the objective functions for minimizing total recycling cost and maximizing total recycling rate are respectively set as Eqs. (1) and (2):

$$C = \sum_{j=1}^{N} c_j x_j \rightarrow Min \tag{1}$$

$$R = \sum_{j=1}^{N} r_j x_j \rightarrow Max \tag{2}$$

Based on Nof *et al*. (1997), the constraint of precedence relationships in this study are set as Eq. (3):

Subject to:

$$x_j - x_i \le 0 \qquad i \in P_j \tag{3}$$

To solve this multiple purpose optimization, ε constraint method is used. Then R is transposed to

$$R \geq \varepsilon \tag{4}$$

Hence, the total recycling cost C at product is made into the only objective function. Nonlinear optimization is performed on each of those combinations by changing ε gradually, and it looks for the Pareto optimum solution set.

4.2 Optimization of Disassembly Line Balancing under Environmental and Economic Parts Selection

A Formulation of disassembly line balancing at the second stage under environmental and economic parts selection at the first stage is shown in this section.

In the design of a disassembly line, line balancing, which assigns element tasks to each work station so that the number of work stations may be minimized, is performed. Line balancing is carried out by integer programming (Nof *et al*., 1997). In this study, it is assumed that there is only one disassembly task for each part.

Sets of selected parts/tasks at Stage 1 and of disposed parts (cancelled tasks) at Stage 1 are set as Eq. (5).

$$J = \{J_{select} \cup J_{cancel}\}, \tag{5}$$

where $\quad J_{select} \cap J_{cancel} = \phi.$

Based on Nof *et al*. (1997), the objective function in this study is set as Eq. (6) in order to minimize the total number of stations.

$$\sum_{s=K_0+1}^{K} k y_{k,|J_{select}|} \rightarrow Min \tag{6}$$

Subject to:

$$\sum_{k=1}^{K} y_{k,j} = 1 \qquad j \in J_{select}, \tag{7}$$

$$\sum_{k=1}^{K} k y_{k,i} - \sum_{k=1}^{K} k y_{k,j} \leq 0 \quad j \in J_{select}, \quad i \in P_j, \tag{8}$$

$$\sum_{j=1}^{J_{select}} p_j y_{k,j} \leq CT \qquad k = 1, \cdots, K, \tag{9}$$

$$y_{k,j} = \{0, 1\} \qquad j \in J_{select}, k = 1, \cdots, K. \tag{10}$$

Constraints are set based on Baybars (1986). Constraint (7) requires that each task be assigned to exactly one station. Constraint (8) is the precedence constraint dictating that if $i \in P_j$, i cannot be assigned to a station downstream from task j. Constraint (9) is a cycle time constraint dictating that the total disassembly time for all tasks assigned to a station not exceed the cycle time. Constraint (10) does not allow a task to be assigned to more than one station.

5. 2-STAGE OPTIMAL DISASSEMBLY SYSTEM DESIGN WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION

This section explains the procedure for disassembly system design based on the design method in Section 3 and the formulization in Section 4, and adapts to the examples of cell phone, computer and cleaner.

5.1 The Case of the Cell Phone

This section develops the procedure for disassembly system design, using the example of cell phone.

Stage 1. Environmental and economic disassembly parts selection

(1) Estimation of recycling rate and cost and disassembly time using REM

By using a 3D-CAD model as shown in Figure 6, a product structure is grasped, and its disassembly precedence relationships are created. Based on the product information, such as material type and weight for each part in a 3D-CAD model, the recycling rate and cost, and

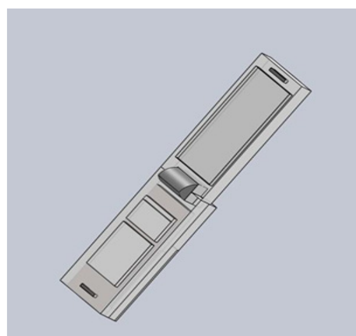

Figure 6. 3D-CAD model in the case of the cell phone.

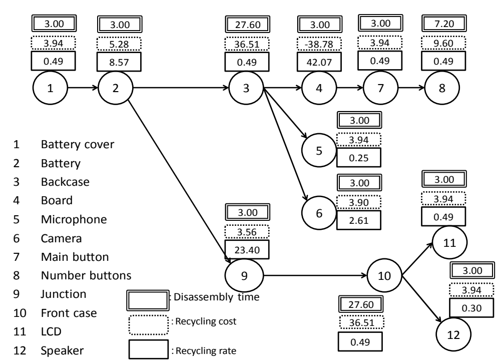

Figure 7. Precedence relationship with the recycling rate and cost, and the disassembly time: case of the cell phone.

disassembly time for each part are estimated using the REM. The data obtained by the REM are added to a bill of materials (BOM) and also described on disassembly precedence relationships as shown in Figure 7. These data and task precedence relationships are used for optimization of the parts selection at Stage 1 and the line balancing at Stage 2.

(2) Environmental and economic parts selection by integer programming with ε constraint

Using integer programming with ε constraint, the Pareto optimal solution is obtained for the recycling rate and cost. To harmonize the environmental and economic aspects in the obtained disassembly parts selection, four scenarios are here considered and discussed as follows: 1) all parts disassembled, 2) maximum recycling rate, 3) minimum recycling cost, 4) recycling rates and cost coexistence as in Figure 8.

To find a coexistence solution for the recycling rate and cost among the alternative solutions obtained in Scenario 4, a recycling efficiency *RE* is set and introduced as Eq. (11).

$$RE = \frac{R}{C} \tag{11}$$

The maximal solution for the *RE* is chosen among the alternative solutions as the coexistence solution for the recycling rate and cost in Scenario 4. In Scenario 2 of the maximum recycling rate, a solution that maximizes the recycling rate was chosen from their solution set when the parts selection was performed.

(3) Disassembly precedence relationships with environmental and economic parts selection

Based on the parts selection at step of stage 1(2), the disassembly precedence relationships are made and updated to show canceled disassembly tasks with the non-selective parts. As in Figure 9, the canceled disassembly tasks with the non-selective parts are marked "x."

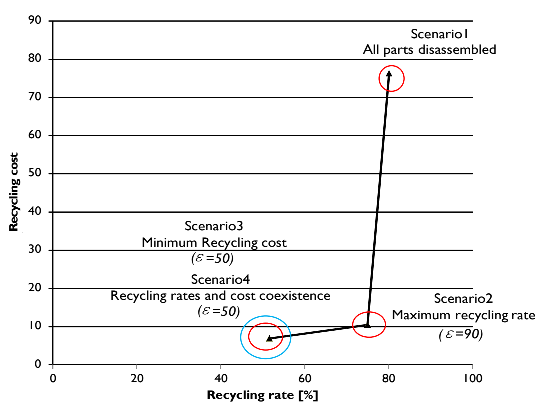

Figure 8. Pareto optimal solutions of environmental and economic parts selection: case of the cell phone.

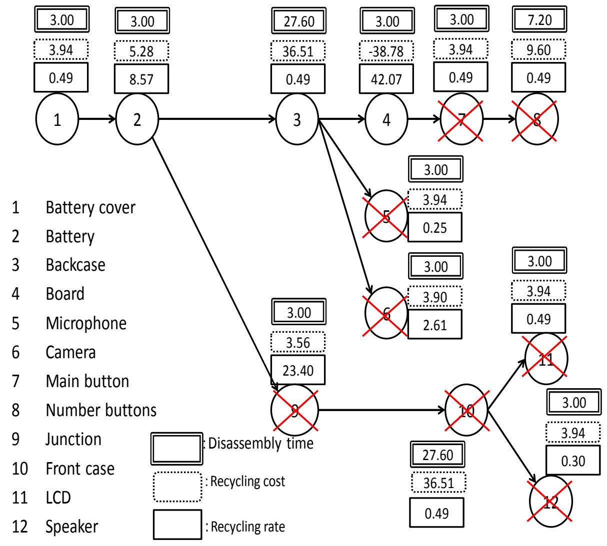

Figure 9. Precedence relationships among disassembly element tasks with environmental and economic parts selection: Scenario 4, recycling rates and cost coexistence in the case of the cell phone.

Stage 2: Disassembly line balancing using integer programming

(1) Cycle time

Similar to Yamada and Sunanaga (2011), the cycle time is obtained by dividing the production planning quantity by the production planning period as well as the assembly/disassembly line designs. In the case of the cell phone, the cycle time *CT* is obtained as Eq. (12) when production planning period T_o = 50,400 and demands Q = 15,750.

$$CT = \frac{T_0}{Q} = \frac{504{,}000}{15{,}750} = 32[\text{sec}] \tag{12}$$

(2) Condition of the number of stations

The number of necessary stations is calculated by dividing the mean of total disassembly time by the *CT*, and rounded to the nearest minimal integer above. In case of the cell phone, the minimal number of stations K_0 is calculated as Eq. (12) when total disassembly time S_0 = 89.4 sec.

$$K_0 = \left\lceil \frac{S_0}{CT} \right\rceil = \left\lceil \frac{89.4}{32} \right\rceil = 3 \tag{13}$$

(3) Line balancing using integer programming

With the environmental and economic parts selection, the disassembly element tasks satisfying the disassembly precedence relations are assigned to each station under the maximal cycle time, as in Figures 10 and 11.

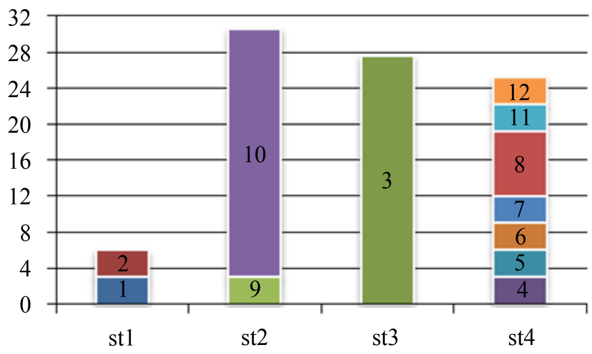

Figure 10. Pitch diagram without environmental and economic parts selection: Scenario 1, all parts disassembled in the case of the cell phone.

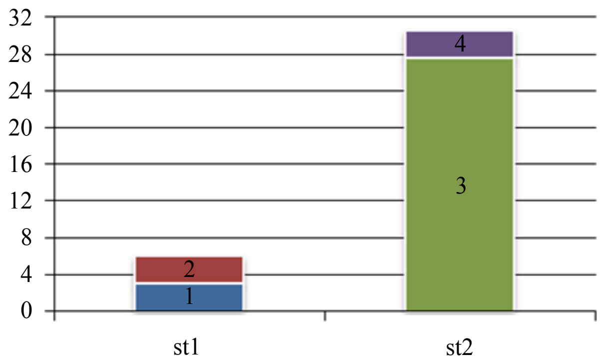

Figure 11. Pitch diagram with environmental and economic parts selection: Scenario 4, recycling rate and cost coexistence in the case of the cell phone.

(4) Line evaluation with product recovery values

To evaluate the alternatives of the disassembly system design, the line and product evaluations are carried out. The balance delay and smoothness index evaluate whether the service times among stations have the appropriate line balance. In addition, the recycling rate and cost and total disassembly time are evaluated as the product evaluation.

5.2 The Case of the Computer

After the example of the cell phone, this section shows the example of disassembly system design in the case of the computer.

Using integer programming with ε constraint, the Pareto optimal solution is obtained for the recycling rate and cost as well as the case of the cell phone. Based on the parts selection, the disassembly precedence relationships are made and updated to show canceled disassembly tasks with the non-selective parts, as in Figure 12 in the case of computer.

With the environmental and economic parts selection, the disassembly element tasks satisfying the disassembly precedence relations are assigned to each station under the maximal cycle time, as in Figures 12–14.

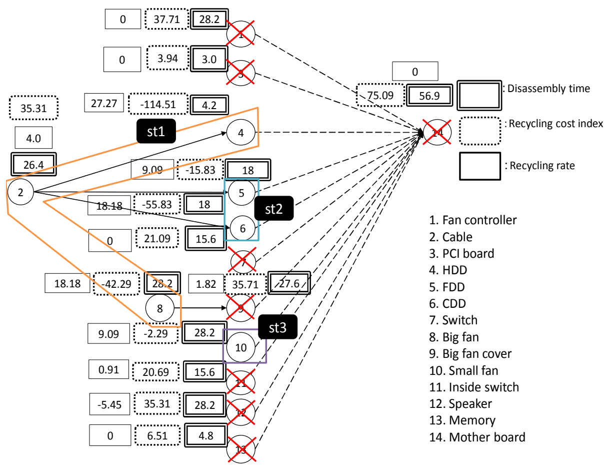

Figure 12. Precedence relationships among assignment of tasks by integer programming with environmental and economic parts selection: case of the computer (Scenario 4).

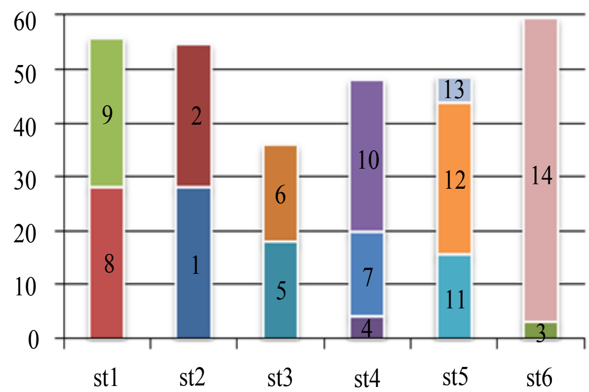

Figure 13. Pitch diagram without environmental and economic parts selection: Scenario 1, all parts disassembled in the case of the computer.

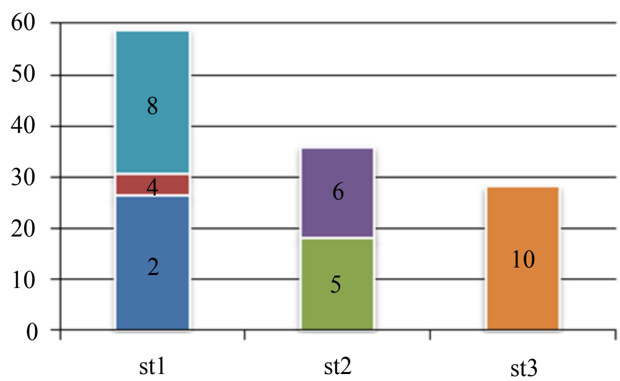

Figure 14. Pitch diagram with environmental and economic parts selection: Scenario 4, recycling rate and cost coexistence in the case of the computer.

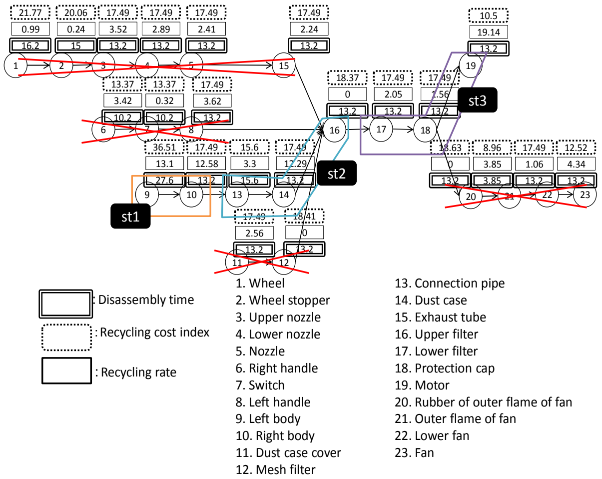

Figure 15. Precedence relationships among assignment of tasks by integer programming with environmental and economic parts selection: case of the cleaner (Scenario 4).

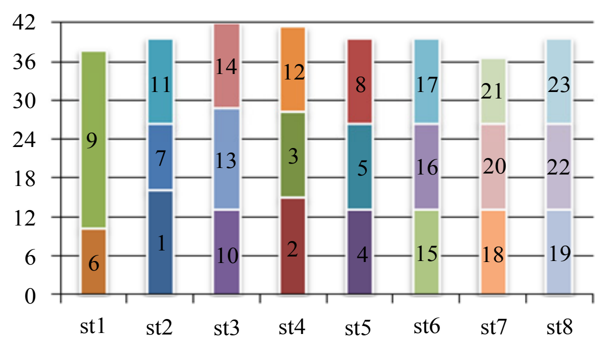

Figure 16. Pitch diagram without environmental and economic parts selection: Scenario 1, all parts disassembled in the case of the cleaner.

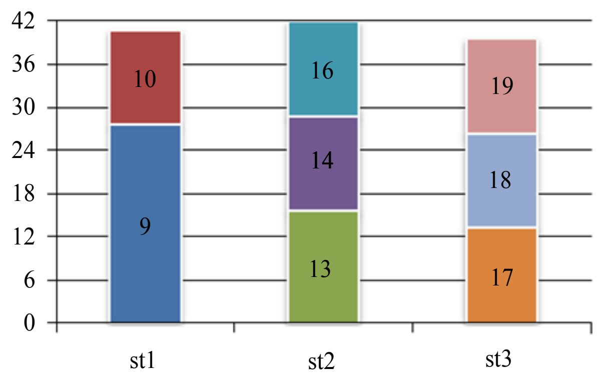

Figure 17. Pitch diagram with environmental and economic parts selection: Scenario 4, recycling rate and cost coexistence in the case of the cleaner.

5.3 The Case of the Cleaner

This section also shows the example of disassembly system design in the case of the cleaner.

Like the cases of the cell phone and the computer, the Pareto optimal solutions of environmental and economic parts selection are obtained, and the precedence relationships by selected parts is shown in Figure 15. With the environmental and economic parts selection, the assignment of tasks to each station under the cycle time, as in Figures 15–17.

6. ANALYSIS OF 2-STAGE OPTIMAL DISASSEMBLY SYSTEM DESIGN WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION

This section analyzes the 2-stage optimal design examples for cell phones, computers and cleaners.

6.1 Analysis of Recycling Rate and Cost by Environmental and Economic Disassembly Parts Selection at Stage 1

An analysis of environmental and economic disassembly parts selection at stage 1 for the procedure of Section 5 is performed in this section.

(1) Estimation of recycling rate and cost and disassembly time using REM

In order to validate the proposed design procedure of the disassembly system, an example of the assembly product and the disassembly is prepared. The prepared product examples in this study are a cellphone, computer and cleaner. Their basic product/parts information is obtained with 3D-CAD (Arakawa and Yamada, 2009; Inoue *et al*., 2011).

(2) Environmental and economic parts selection by integer programming with ε constraint

Similar to Igarashi *et al*. (2013), using the integer programming with ε constraint, the Pareto optimal solution is obtained for the recycling rate and cost by GLPK (GNU Linear Programming Kit). The GLPK package is intended for solving large-scale linear programming, mixed integer programming (MIP) and other related problems (GLPK-GNU Project). Figure 18 shows the Pareto optimal solution for the recycling rate and cost in the cases of the computer, cleaner and cell phone. While the recycling rate is shown on the horizontal axis, the recycling cost is shown on the vertical one. Each solution is obtained by each ε constraint.

(3) Disassembly precedence relationships with environmental and economic parts selection

With the cleaner, it turns out that the selected disassembly tasks/parts are divided by each product module.

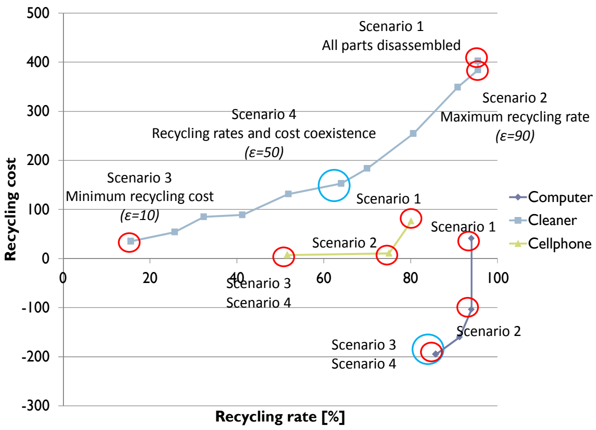

Figure 18. Behaviors of recycling cost for recycling rate.

One of the reasons is that these precedence relationships are arrayed in series by each module like as Figure 15.

Tables 3–5 show examples of parts selection in the case of cell phone, computer and cleaner. It is shown that the parts with positive recycling cost (negative recycling profit) and low recycling rate, such as Front case in cell phone, Switch in computer and Mesh filter in cleaner are preferentially disposed as a constraint ε for the total recycling rate decreases from Scenarios 1 to 4. On the other hand, in order to disassemble parts with a high recycling rate (cell phone: #4 board; computer: #4 HDD; #5 FDD; #6 CDD; cleaner: #14 dust case; #19 motor), the other parts with a low recycling rate or high cost (cell phone: #1 battery cover; #3 back case; computer: #2 cable; cleaner: #13 connection pipe; #16 upper filter; #17 lower filter; #18 protection cap) seem to disassembled.

6.2 Analysis of Optimal Disassembly Line Balancing at Stage 2

Another analysis of disassembly line balancing optimized at stage 2 according to the procedure of Section 5 and its comprehensive consideration are performed in this section.

An example of the disassembly problem is set as Table 2 in this study.

Table 2. Example of disassembly problem for computer, cleaner and cell phone (Igarashi *et al*., 2013)

Product type	Production planning period T_0 (sec)	Demands Q for collected EOL products during T_0
Computer	504,000	8,400
Cleaner	(= 20 day×7 hr	12,000
Cell phone	×3,600 sec)	15,750

EOL: end-of-life.

(1) Line balancing using integer programming

As explained in Section 6.2, in order to disassemble parts with a higher recycling rate, it was observed that the parts with longer disassembly times, which brought higher disassembly costs, are also disassembled, such as #4 board and #3 cack case in the case of the cell phone in Figure 11 (cell phone). In addition, when a solution other than those presented in the four scenarios (cleaner: ε = 70, ε = 30) is selected, line balancing is performed. If the constraint ε decreases in the first stage, in order that selection parts decrease proportionally with ε, the number of stations in the second stage also decreases proportionally.

Table 3. Bill of materials with example of parts selection: case of the cell phone

No.	Part name	Material type	Disassembly operation	Weight (g)	Recycling rate (%)	Disassembly Time (sec)	Recycling cost	Scenario 1: All parts disassembled	Scenario 2: Recycling rate maximum	Scenario 4: Recycling rate and cost coexistence	Scenario 3: Recycling cost minimum
1	Battery cover	PC	[move up]	1.00	0.49	3.00	3.94	○	○	○	○
2	Battery	Battery	[move up]	58.10	8.57	3.00	5.28	○	○	○	○
3	Backcase	PC	[screw 4]	1.00	0.49	27.60	36.51	○	○	○	○
4	Board	Circuit board	[move up]	85.40	42.07	3.00	-38.78	○	○	○	○
5	Microphone	SUS	[move up]	0.50	0.25	3.00	3.94	○	×	×	×
6	Camera	Zinc alloy	[move up]	5.30	2.61	3.00	3.90	○	×	×	×
7	Main button	PC	[move up]	1.00	0.49	3.00	3.94	○	×	×	×
8	Number buttons	PC	[move up 12]	1.00	0.49	7.20	9.60	○	×	×	×
9	Junction	SUS	[move up]	47.50	23.40	3.00	3.56	○	○	×	×
10	Front case	PC	[screw 4] [move up]	1.00	0.49	27.60	36.51	○	×	×	×
11	LCD	Glass	[move up]	1.00	0.49	3.00	3.93	○	×	×	×
12	Speaker	SUS	[move up]	0.60	0.30	3.00	3.94	○	×	×	×
Total				203.40	80.14	89.40	76.27				
Average				16.95	6.68	7.45	6.36				
Standard deviation				28.15	12.46	9.08	18.05				

Table 4. Bill of materials with example of parts selection: case of the computer

No.	Part name	Material type	Disassembly operation	Weight (g)	Recycling rate (%)	Disassembly Time (sec)	Recycling cost	Scenario 1: All parts disassembled	Scenario 2: Recycling rate maximum	Scenario 4: Recycling rate and cost coexistence	Scenario 3: Recycling cost minimum
1	Fan controller	Circuit board	[screw 4] [move right]	50.00	0.00	28.20	37.71	○	×	×	×
2	Cable	PVC	[move up 2]	20.00	4.00	26.40	35.31	○	○	○	○
3	PCI board	Fe	[move up]	300.00	0.00	3.00	3.94	○	×	×	×
4	HDD	Al/Al alloy	[move right]	1500.00	27.27	4.20	-114.51	○	○	○	○
5	FDD	Al/Al alloy	[move right] [screw 2]	500.00	9.09	18.00	-15.83	○	○	○	○
6	CDD	Al/Al alloy	[move right] [screw 2]	1000.00	18.18	18.00	-55.83	○	○	○	○
7	Switch	Circuit board	[screw 2] [move up]	50.00	0.00	15.60	21.09	○	×	×	×
8	Big fan	Al/Al alloy	[screw 4] [move right]	1000.00	18.18	28.20	-42.29	○	○	○	○
9	Big fan cover	Fe	[screw 4] [move up]	100.00	1.82	27.60	35.71	○	○	×	×
10	Small fan	Al/Al alloy	[screw 4] [move right]	500.00	9.09	28.20	-2.29	○	○	○	○
11	Inside switch	Fe	[screw 2] [move left]	50.00	0.91	15.60	20.69	○	○	×	×
12	Speaker	SUS	[screw 4] [move right]	300.00	5.45	28.20	35.31	○	○	×	×
13	Memory	Circuit board	[move up]	50.00	0.00	4.80	6.51	○	×	×	×
14	Mother board	Circuit board	[screw 9]	500.00	0.00	56.40	75.09	○	×	×	×
Total				5920.00	93.99	302.40	40.61				
Average				422.86	6.45	21.60	5.25				
Standard deviation				438.92	8.40	13.29	46.23				

Table 5. Bill of materials with example of parts selection: case of the cleaner

No.	Part name	Material type	Disassembly operation	Weight (g)	Recycling rate (%)	Disassembly Time (sec)	Recycling cost	Scenario 1: All parts disassembled	Scenario 2: Maximum recycling rate	Scenario 4: Recycling rate and cost coexistence	Scenario 3: Minimum recycling cost
1	Wheel	PP	[move right]	7.07	0.99	16.20	21.77	○	○	×	×
2	Wheel stopper	PP	[move up]	1.71	0.24	15.00	20.06	○	○	×	×
3	Upper nozzle	PP	[move up]	50.35	3.52	13.20	17.49	○	○	×	×
4	Lower nozzle	PP	[move up]	41.25	2.89	13.20	17.49	○	○	×	×
5	Nozzle	PP	[move up]	34.50	2.41	13.20	17.49	○	○	×	×
6	Right handle	PP	[screw] [move up]	48.93	3.42	10.20	13.37	○	○	×	×
7	Switch	PVC	[screw] [move up]	4.65	0.32	10.20	13.37	○	○	×	×
8	Left handle	PP	[move up]	51.70	3.62	13.20	17.49	○	○	×	×
9	Left body	PP	[screw 4] [move up]	187.27	13.10	27.60	36.51	○	○	○	○
10	Right body	PP	[move up]	179.88	12.58	13.20	17.49	○	○	○	×
11	Dust case cover	PMMA	[move up]	36.57	2.56	13.20	17.49	○	○	×	×
12	Mesh filter	cloth/Fibre	[move up]	18.45	0.00	13.20	18.41	○	×	×	×
13	Connection pipe	Al/Al alloy	[screw 2] [move up]	47.17	3.30	15.60	17.31	○	○	○	×
14	Dust case	PMMA	[move up]	175.69	12.29	13.20	17.49	○	○	○	×
15	Exhaust tube	PVC	[move up]	32.04	2.24	13.20	17.49	○	○	×	×
16	Upper filter	cloth/Fibre	[move up]	17.74	0.00	13.20	18.37	○	○	○	×
17	Lower filter	PP	[move up]	29.33	2.05	13.20	17.49	○	○	○	×
18	Protection cap	ABS	[move up]	22.29	1.56	13.20	17.49	○	○	○	×
19	Motor	Motor	[move up]	279.27	19.14	13.20	10.50	○	○	○	×
20	Rubber of outer frame of fan	Rubber	[move up]	22.85	0.00	13.20	18.63	○	○	×	×
21	Outer frame of fan	Al/Al alloy	[screw] [move up]	55.11	3.85	10.20	8.96	○	○	×	×
22	Lower fan	PP	[move up]	15.08	1.06	13.20	17.49	○	○	×	×
23	Fan	Al/Al alloy	[move up]	62.10	4.34	13.20	12.52	○	○	×	×
Total				1421.00	95.48	316.20	402.17				
Average				61.78	4.15	13.70	17.49				
Standard deviation				70.19	4.97	3.27	4.98				

(2) Line evaluation with product recovery values

Table 6 show the examples of the disassembly system design in the cases of the computer, cleaner and cell phone. By comparing among four scenarios, it turned out that both cases with the environmental and economic parts selection reduced the recycling cost. In the case of the computer, the recycling cost at Scenario 4 is drastically smaller than that at scenario 1 by 355%. On the other hand, with the cleaner, the differences between the maximal and minimal recycling rates among the scenarios are within 82.4%, which is larger than those within 8.2% for the computer. It is considered that there is lower flexibility of the economic parts selection because these precedence relationships are arrayed in series by each module.

Moreover, the numbers of work stations in all scenarios were reduced by comparing all disassembled parts to Scenario 1. One of the reasons is that most of the parts with higher costs also have longer disassembly times, and these tasks can become a bottleneck in line balancing. Therefore, the bottleneck can be solved with destructive disassembly by using the environmental and economic parts selection. However, in the following cases, it is observed that parts with a longer disassembly time still remain at the second stage. It is thought that the parts with a long disassembly time have high recycling costs. However, when the material is of high value, sales exceed disassembly cost, serve as negative cost, and are disassembled (computer: #8 bigfan, #5 FDD, #6 CDD). In order to disassemble parts with a high recycling rate in the first stage, those with higher recycling costs, which also means longer disassembly times, are disassembled, such as part #3 backcase in cell phone, #2 cable in computer, and #9 left body in cleaner.

In a product design phase, it is desirable to arrange parts with a high recycling rate as much as possible to the front side on the disassembly precedence relationships. It is seen that some succeeding parts with a higher recycling rate cannot be disassembled physically because their precedence parts are disposed of due to their higher recycling cost. In case of the cleaner, it is considered that the recycling cost can be reduced if the motor in part #19 can be arranged from front to back side in the product design phase.

Unlike the case of the cleaner, the smoothness index *SI* in the case of the computer is not improved. There are many tasks that require longer disassembly time as compared to the case of the cleaner. Even if they perform the parts selection, tasks with longer disassembly time still remain, because they often have higher profit, which means negative values of cost. Therefore, it may be a bottleneck of the line. Also, in the case of tandem type precedence relationships like a cleaner, the assignment of tasks almost becomes the same among the scenarios. When parts with long disassembly time are contained in the module, the number of stations will increase. Therefore, it is easier to assigns tasks to each station when the longer disassembly time is independent and outside modules.

6.3 Integer Programming vs. Ranked Positional Weight Heuristic for Disassembly Line Balancing

In order to validate the effectiveness of line balancing by integer programming proposed in this study, the proposal method with integer programming is compared with the ranked positional weight heuristic in the previous study (Igarashi *et al*., 2013).

(1) Comparison among environmental and economic scenarios

Tables 7–9 show evaluation of the line balancing by the integer programming in this study and the ranked positional weight heuristic with the hand calculation (Igarashi *et al*., 2013). There is no difference in the number of stations and balance delay *BD*. On the other hand, differences are seen in *SI*. By comparison with *SI* in the integer programming and the positional weight heuristic, on average there is a difference of 75.75% in the case of the computer and only by 1.25% in the case of the cleaner. It seems that the smoothness index is increased when the variation in disassembly time is larger. Therefore, it is observed that the variations of disassembly time are 10 in the case of the cleaner and 176 in the case of computer. One of the reasons is that the objective function in this study does not include minimization of the smoothness index. However, it can be easily introduced in the case of Integer Programming, and it can take *SI* into consideration by adding constraints

Table 6. Examples of system evaluation

			Scenario 1: All parts disassembled			Scenario 2: Recycling rate maximum			Scenario 3: Recycling cost minimum			Scenario 4: Recycling rate and cost coexistence		
Name of products			Computer	Cleaner	Cell phone	Computer	Cleaner	Cell phone	Computer	Cleaner	Cell phone	Computer	Cleaner	Cell phone
Product evaluation	Total disassembly time (sec)		302.40	316.20	89.40	194.40	316.20	39.60	123.00	27.60	36.60	123.00	122.40	36.60
	Number of parts		14	23	12	9	23	5	5	2	4	5	8	4
	Recycling rate (%)		94.00	95.48	80.15	94.00	95.48	75.02	85.82	13.10	51.62	85.32	64.02	51.62
	Recycling cost index		40.61	402.17	76.27	-103.73	402.17	10.51	-195.44	36.51	6.95	-195.44	152.65	6.95
Line evaluation	Cycle time (sec)		60.00	42.00	32.00	60.00	42.00	32.00	60.00	42.00	32.00	60.00	42.00	32.00
	Number of stations	Minimal	6	8	3	4	8	2.00	3	1	2	3	3	2.00
		Actual	6	8	4	4	8	2.00	3	1	2	3	3	2.00
	Balance delay *BD*		0.16	0.06	0.30	0.19	0.06	0.38	0.31	0.34	0.43	0.31	0.03	0.43
	Smoothness index *SI*		28.81	8.38	21.61	21.58	8.38	21.60	38.16	0.00	24.60	38.16	2.68	24.60

Table 7. Example of disassembly line design: case of the cell phone

		Scenario 1: All parts disassembled			Scenario 2: Recycling rate maximum			Scenario 3: Recycling cost minimum			Scenario 4: Recycling rate and cost coexistence		
		Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)
Number of stations	Minimal	3	3	0	2	2	0	2	2	0	2	2	0
	Actual	4	4	0	2	2	0	2	2	0	2	2	0
Balance delay *BD*		0.30	0.30	0	0.38	0.38	0	0.43	0.43	0	0.43	0.43	0
Smoothness index *SI*		21.61	24.42	-13	21.60	21.60	0	24.60	24.60	0	24.60	24.60	0

Table 8. Example of disassembly line design: case of the computer

		Scenario 1: All parts disassembled			Scenario 2: Recycling rate maximum			Scenario 3: Recycling cost minimum			Scenario 4: Recycling rate and cost coexistence		
		Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%]	Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)
Number of stations	Minimal	6	6	0	4	4	0	3	3	0	3	3	0
	Actual	6	6	0	4	4	0	3	3	0	3	3	0
Balance delay *BD*		0.16	0.16	0	0.19	0.19	0	0.31	0.31	0	0.31	0.31	0
Smoothness index *SI*		28.81	7.59	74	21.58	6.75	69	38.16	7.55	80	38.16	7.55	80

Table 9. Example of disassembly line design: case of the cleaner

		Scenario 1: All parts disassembled			Scenario 2: Recycling rate maximum			Scenario 3: Recycling cost minimum			Scenario 4: Recycling rate and cost coexistence		
		Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)	Integer Programming	Ranked Positional Weight heuristic	Difference (%)
Number of stations	Minimal	8	8	0	8	8	0	1	1	0	3	3	0
	Actual	8	8	0	8	8	0	1	1	0	3	3	0
Balance delay *BD*		0.06	0.06	0	0.10	0.10	0	0.34	0.34	0	0.31	0.31	0
Smoothness index *SI*		8.38	8.80	-5	17.75	17.75	0	0.00	0.00	0	2.68	2.68	0

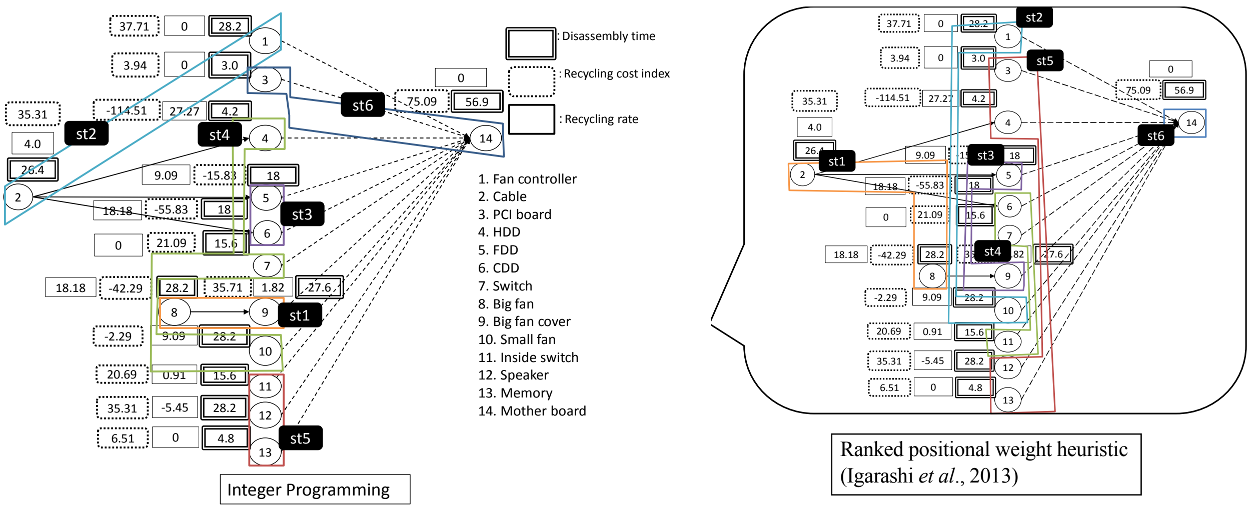

Figure 19. Precedence relationships among assignment of tasks by integer programming and ranked positional weight heuristic: case of the computer (Scenario 1).

(McGovern and Gupta, 2003).

As a result, it is thought that the disassembly line balancing by the integer programming in this study is practical because a more complicated and larger-scale problem can be solved efficiently with integer programming. In addition, the computation time by the integer

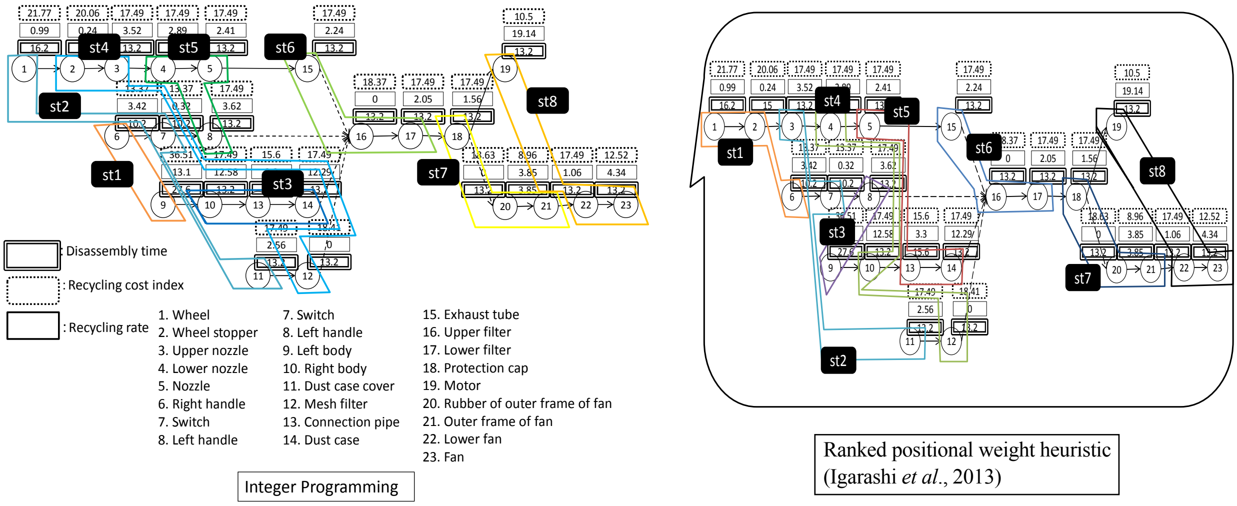

Figure 20. Precedence relationships among assignment of tasks by integer programming and ranked positional weight heuristic: case of the cleaner (Scenario 1).

programming was less than 0.1 second in the experiments. According to the ranked positional weight heuristic with the hand calculation, the computation time was more than about 5 minutes. Therefore, the disassembly line balancing with the integer programming is more useful than that with the ranked positional weight heuristic.

(2) Comparison among product types

In this section, in order to analyze the relationships between each disassembly line balancing method and part structure, a comparison among product types is considered. From Figures 19 and 20, it is observed that the positional weight of an element task affects the line balancing in case of the ranked positional weight heuristic. The situation is identical in Scenarios 2–4. By comparing the positional weight of element tasks become larger in the case of in-series component formation, like the computer, and also become smaller in the case of parallel component formation, like the cleaner. In addition, since parts are disposed of like part #14 at scenario 2 and 4, parallel component formation is more emphasized in the case of the computer. In the case of the cleaner, parts #9, #10, #13, #14, #16 to #19 are selected at Scenario 4. Also, in-series component formation is emphasized in case of the cleaner. Therefore, component formations, precedence relationships of disassembly tasks, and disassembly parts selection have influence on line balancing using ranked positional weight heuristic. On the other hand, in the case of integer programming, line balancing is performed without being influenced by positional weight.

7. CONCLUSIONS

This study proposed and analyzed the 2-stage optimal design of disassembly system with the environmental and economic parts selection, which harmonized the recycling rate and profit using the REM. The first stage was to optimize environmental and economic parts selection by the integer programming with ε constraint, and the second stage was to optimize the line balancing with integer programming for minimizing the number of disassembly stations. Next, the optimal design example was shown and discussed. Finally, the line and product evaluations were carried out and analyzed in the cases of cell phones, computers and cleaners. The main conclusions are as follows:

- In the environmental and economic disassembly parts selection, 1 out of 12 parts in the case of the cell phone and 5 out of 14 parts in the case of the computer have negative costs, which mean profits earned. One of the reasons is that those parts are heavy and consisted of valuable metal. On the other hand, all costs became a positive value in the case of the cleaner because there were a few heavy parts with valuable material.
- Like the cleaner, when part structure is in series, the percentage decrease of the recycling rate by part selection becomes larger than the computer with a parallel part structure. Although the cell phone also had an in series part structure, the percentage decrease of the recycling rate was lower than the cleaner 53.87% because of their negative cost (profits) unlike the cleaner.
- By comparing the 4 scenarios of environmental and economic disassembly parts selection, it is demonstrated that the recycling cost was reduced 355% in the case of computer maintaining recycling rates, because the crushing parts recycling rate was zero.

- Smoothness index *SI* was increased when the variation in disassembly time was larger. In the case of integer programming, one should take the *SI* into consideration by adding constraints.
- Component structures, precedence relationships of disassembly tasks, and disassembly parts selection have quantitatively influenced on line balancing.

Future studies should optimize multi criteria (Tanaka *et al*., 2013) for recycling rate and CO_2 emissions and cost by disassembly parts selection, and adapt to regular supply chains.

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APPENDIX

Construction and Analysis of Product Recovery Values with Bill of Materials

Tables A1–A3 show the examples of the bill of materials with the product recovery values in the cases of computer and cleaner (Igarashi *et al*., 2013). By inputting the part information, such as material type and weight from the 3D-CAD and the disassembly motion for each part, the recyclability evaluation method (REM) calculated the recycling rate and cost, and the disassembly time, respectively.

With the recycling rate, it is found that several parts have zero recycling rates for both cases of computer and cleaner. With disassembly time, there are the complicated tasks with longer disassembly times, such as the mother board in the case of the computer. Unlike the case of the computer, many tasks/parts in the case of the cleaner have the same disassembly times because of the same simple motions.

With the recycling cost, it is noted that 5 out of 14 parts have the negative costs, which means profits earned in the case of computer. One of the reasons is that those parts are heavy and consisted of valuable metal. On the other hand, all costs became a positive value in the case of the cleaner because there were a few heavy parts with valuable material.

Table A1. Example of bill of materials with product recovery values: case of the cell phone

No.	Part name	Recycling rate (%)	Disassembly time (sec)	Recycling cost
1	Battery cover	0.49	3.00	3.94
2	Battery	8.57	3.00	5.28
3	Backcase	0.49	27.60	36.51
4	Circuit board	42.07	3.00	-38.78
5	Microphone	0.25	3.00	3.94
6	Camera	2.61	3.00	3.90
7	Main button	0.49	3.00	3.94
8	Number buttons	0.49	7.20	9.60
9	Junction	23.40	3.00	3.56
10	Front case	0.49	27.60	36.51
11	LCD	0.49	3.00	3.93
12	Speaker	0.30	3.00	3.94
	Total	80.14	89.40	76.27
	Average	6.68	7.45	6.36

Table A2. Example of bill of materials with product recovery values: case of the computer (Igarashi *et al*., 2013)

No.	Part name	Recycling rate (%)	Disassembly time (sec)	Recycling cost
1	Fan controller	0	28.2	37.71
2	Cable	4	28.2	35.31
3	PCI board	0	15.6	3.94
4	HDD	27.27	4.2	-114.51
5	FDD	9.09	26.4	-15.83
6	CDD	18.18	26.4	-55.83
7	Switch	0	4.8	21.09
8	Big fan	18.18	27.6	-42.29
9	Big fan cover	1.82	28.2	35.71
10	Small fan	9.09	15.6	-2.29
11	Inside switch	0.91	18	20.69
12	Speaker	5.45	18	35.31
13	Memory	0	28.2	6.51
14	Motherboard	0	56.4	75.09
	Total	93.99	302.4	40.61
	Average	6.45	21.6	5.25

Table A3. Example of bill of materials with product recovery values: case of the cleaner (Igarashi *et al*., 2013)

No.	Part name	Recycling rate (%)	Disassembly time (sec)	Recycling cost
1	Wheel	0.99	16.2	21.77
2	Wheel stopper	0.24	15	20.06
3	Upper nozzle	3.52	13.2	17.49
4	Lower nozzle	2.89	13.2	17.49
5	Nozzle	2.41	13.2	17.49
6	Right handle	3.42	10.2	13.37
7	Switch	0.32	10.2	13.37
8	Left handle	3.62	13.2	17.49
9	Left body	13.1	27.6	36.51
10	Right body	12.58	13.2	17.49
11	Dust case cover	2.56	13.2	17.49
12	Mesh filter	0	13.2	18.41
13	Connection pipe	3.3	15.6	17.31
14	Dust case	12.29	13.2	17.49
15	Exhaust tube	2.24	13.2	17.49
16	Upper filter	0	13.2	18.37
17	Lower filter	2.05	13.2	17.49
18	Protection cap	1.56	13.2	17.49
19	Motor	19.14	13.2	10.5
20	Rubber of outer frame of fan	0	13.2	18.63
21	Outer frame of fan	3.85	10.2	8.96
22	Lower fan	1.06	13.2	17.49
23	Fan	4.34	13.2	12.52
	Total	95.48	316.2	402.17
	Average	4.15	13.7	17.49