Optimal Disassembly System Design with Environmental and Economic Parts Selection for CO_2 Saving Rate and Recycling Cost

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***Abstract*— Supply chains have been more serious for environmental issues such as material starvation and global warming. It is essential for material circulation to construct and operate recycling factories, where End-of-life (EOL) assembly products are disassembled into each part in order to recover materials. Also, the recycling is able to reduce CO_2 emissions since virgin materials which release CO_2 volumes caused by production and logistics can be saved by the usage of the recovered materials. To design and realize the recycling factories environmentally and economically, this paper proposes a disassembly system design with an optimal environmental and economic parts selection for CO_2 saving rate and recycling cost. The first stage is to conduct the environmental and economic parts selection by the integer programming with ε constraint, and the second stage is to carry out the disassembly line balancing for minimizing the number of stations. The proposed design method contributes to find alternative solutions/designs for harmonizing the CO_2 saving rate and the recycling cost using a Life Cycle Inventory (LCI) database.**

***Keywords*—** *Low-carbon and closed-loop supply chains, Environmentally-conscious manufacturing, Sustainable manufacturing, Disassembly line balancing, Integer programming with ε constraint, Life cycle inventory database, Recyclability evaluation method*

1. Introduction

Since economy and population on our earth is still emerging and growing, environmental issues in supply chains have been more serious for material starvation [1], [2]. For the material circulation by reuse and recycling [3], reverse [4] and closed-loop [2] supply chains have been more essential for assembly products such as home electric appliances, so that disassembly systems [3]-[14] which remove and recover part/material values from End-of-Life (EOL) assembly products should be realized environmentally and economically for sustainability.

At the actual recycling factories [8], the disassembly parts selection for removal or dispose is often carried out to harmonize recycling rate and cost for the economic and sustainable material circulation. In research of part selection [9], [10], a disassembly part selection of reuse, recycling, or cancellation was performed by disassembly cost and reproduction value. However, this parts selection also affect the disassembly line balancing [3] which assign tasks to each work station. Various solving techniques were adopted to the disassembly line balancing [11], [12]. However, there seems no research of the disassembly line balancing by the selected parts, therefore, a disassembly system design integrating the environmental and economic parts selection and the line balancing has been proposed [13], [14].

On the other hand, global warming caused by Greenhouse Gases (GHG) such as CO_2 is another environmental issue [1], [2] and still a challenge for the regular and reverse supply chains to reduce CO_2 emissions in production, logistics and recovery stages as low-carbon supply chains [2]. From a viewpoint of the EOL stage for the assembly products, it is useful to remove and recover the

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parts/materials with higher CO_2 volumes in the disassembly system because they can save the CO_2 volumes comparing to produce the same virgin parts/materials. Then, the CO_2 saving rate at a product is defined and considered in this study as a rate of the CO_2 volumes in their part production for each disassembled and collected part which saves the virgin parts/materials to the total CO_2 volumes of the whole product.

To realize this disassembly parts selection environmentally and economically in the recycling factories, the parts/materials with the higher CO_2 saving rate should be disassembled for the environment if the CO_2 volumes of each part can be estimated. In constant, ones with lower recycling cost should be also disassembled for the economy if the recycling cost of each part can be estimated. Also, as we already discussed, it is known that a disassembly line balancing are affected by the optimal environmental and economic parts selection [13], [14]. However, there is still the other design issue how to obtain product and environmental information such as the disassembly time and the CO_2 saving rate. Moreover, the recycling cost and the CO_2 saving rate depend on material types. To overcome this issue, the Life Cycle Inventory (LCI) database by the input-output tables [15] and Recyclability Evaluation Method (REM) software developed by Hitachi, Ltd. [16], [17] can be used simultaneously in this study.

This paper proposes a disassembly system design with the optimal environmental and economic parts selection which harmonizes the CO_2 saving rate and the recycling cost using the LCI database by the input-output tables. The first step is to optimize the environmental and economic parts selection with the integer programming with ε constraint [18]-[20], and the second step is to carried out the line balancing for minimizing the number of stations with the integer programming [21], [22].

The outline of this paper is as follows: Section 2 overviews a design procedure for a disassembly system with an environmental and economic parts selection for the CO_2 saving rate and the recycling cost. Also, the relationship between the disassembly parts selection and its subsequent disassembly line balancing is explained for the CO_2 saving rate and the recycling cost. In addition, the LCI database and the REM are explained and used how to estimate the information required for the disassembly system design in this study. Section 3 generally formulates an optimization problem by the 2-stage disassembly system design with the environmental and economic parts selection at the first stage for the CO_2 saving rate and the recycling cost, and the subsequent disassembly line balancing at the second stage for minimizing the number of stations. Section 4 develops a design example by the 2-stage disassembly system design for a cleaner using the same example [13] to compare to another case with the disassembly part selection for the recycling rate and cost [14]. Section 5 further analyses and discusses the results in terms of the product vs. line designs, and the CO_2 saving vs. recycling rates [14]. Finally, section 6 concludes this study and identifies future works.

2. Disassembly Design Procedure with Optimal Environmental and Economic Parts Selection for CO_2 Saving Rate and Recycling Cost

2.1 Overview and relationships among input/output information and design results

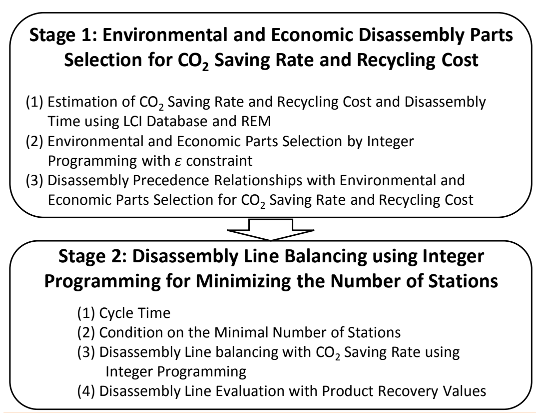

Figure 1. Optimal disassembly design procedure with an environmental and economic parts selection for CO_2 saving rate and recycling cost

To overview a disassembly system design of this paper proposed, the procedure of disassembly system design and the relationships among input/output information and design results are explained in this section. This paper proposes an optimal disassembly design procedure with an optimal environmental and economic parts selection for harmonizing the CO_2 saving rate and the recycling cost as shown in Figure 1.

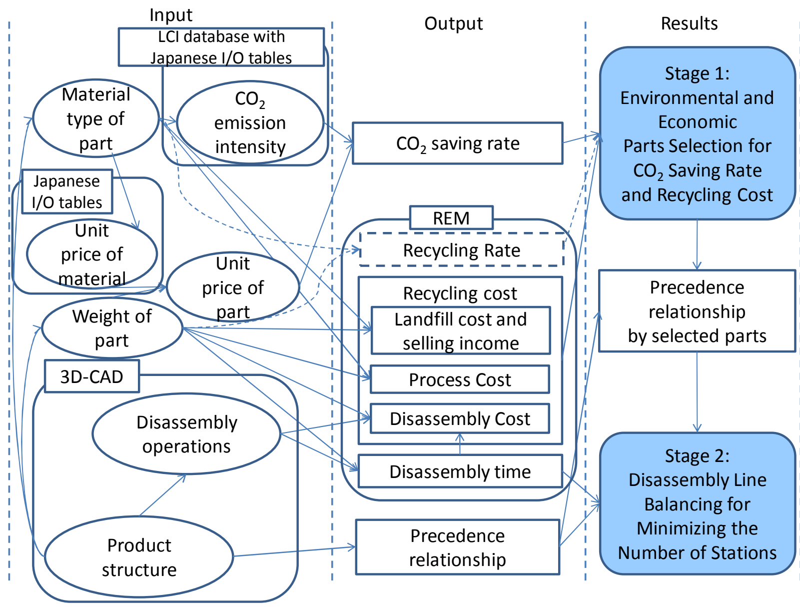

Figure 2. Relationships among types of input/output information and results in disassembly system design for CO_2 saving rates and recycling cost

Table 1. Relationship between CO_2 saving rate and recycling cost by recycling or disposing in an environmental and economic disassembly parts selection at stage 1

Objective functions		Recycling by disassembly	Disposing
Recycling cost	Material selling income	Increase	None
	Landfill, process and disassembly (labor) cost	Increase	None
CO_2 saving rate		Increase	Decrease

A 2-stage disassembly design procedure for the recycling rate and cost [14] is applied to this problem for the CO_2 saving and the recycling cost. The first stage is to optimize the environmental and economic parts selection for the CO_2 saving rate and the recycling cost by the integer programming with ε constraint [18]-[20]. The second step is to carry out the disassembly line balancing for minimizing the number of stations by the integer programming [21], [22] according to the environmental and economic parts selection at Stage 1.

In the environmental and economic parts selection, the LCI database by the input-output tables with the bill of materials [23] is adopted to estimate the CO_2 volumes for each part as the environmental loads. Also, the Recyclability Evaluation Method (REM) software developed by Hitachi. Ltd. [16], [17] is used to estimate the disassembly times of each part.

Based on the both product recovery information obtained by the LCI database and REM, it is noted that a trade-off between the CO_2 saving rate and the recycling cost exists by decisions regarding recycling or disposing as shown in Table 1. The recycling parts by the disassembly can increase not only the CO_2 saving rate but also the material selling revenue while the disposal, process and disassembly (labour) costs increase. In contrast, the disposal, process and disassembly costs become decreased if parts are disposed of. However, the material selling profit and the CO_2 saving rate also decrease.

After this parts selection, product/parts structure for the disassembly are changed, so that the preceding relationships among the disassembly tasks are also changed as well as a case for the recycling rate and cost [13], [14]. Figure 2 shows relationships among types of input/output information and results in the disassembly system design for the CO_2 saving rates and the recycling cost proposed in this study. For example, the material type of a part affects CO_2 emission intensity, landfill cost and process cost. Then, the CO_2 saving rate is calculated by CO_2 emission intensity. Finally, the CO_2 saving rate, disposal cost, and process cost affect the result of parts selection.

2.2 Life cycle inventory (LCI) database by input-output tables and Recyclability evaluation method (REM)

In order to estimate the CO_2 saving rate for each part, this research uses the LCI database by the Japanese input-output (I/O) tables [15]. In general, the input-output tables define economic relationships among sectors by matrix representation based on annual transactions among sectors, so that the carbon dioxide emission intensity is obtained by using the LCI database by the input-output tables. With the LCI database by the I/O tables, the CO_2 volumes at each part are estimated with the product information such as prices and weights [23]. Then the CO_2 saving rate for each part is also calculated as a percentage for the CO_2 volumes of that part per the total volumes at the whole of product.

On the other hand, the disassembly time and recycling cost of each part are estimated by inputting product information such as material type, weight and disassembly motion at each part to the REM software [16], [17]. In the software, the recycling cost is the differences between the recovered material prices and costs, where the costs consist of disassembly, material process and disposal costs, respectively. If the recovered material prices are higher than the recycling costs, the value of the cost becomes negative, which means positive profits earned by the recycling.

3. Formulation of Optimal Disassembly System Design with Environmental and Economic Parts Selection for CO_2 Saving Rate and Recycling Cost

3.1 Notation and assumptions

With the product disassembly data and the CO_2 saving rate obtained by the LCI database [15] and the REM [16], [17], 0-1 integer programming with ε constraint [18]-[20] is used in this study for the selection of the parts disassembled or not in terms of the CO_2 saving rate and the recycling cost similar to [13], [14]. The combinatorial solution which maximizes the CO_2 saving rate but minimizes the total recycling cost of the product is examined to satisfy the constraints of the disassembly precedence relation. It is assumed that there is only one disassembly task j for each part j. The notation of the disassembly parts selection at stage 1 and the line balancing at stage 2 used for the integer programming is as follows:

i	:	Index for predecessors of part j with task j
j	:	Index of parts/tasks (j=1,2,…,N)
k	:	Index of stations (k=K_0,…,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
e_j	:	CO_2 saving rate at part j
E	:	Total CO_2 saving rate by selected parts
E_{max}	:	Maximum CO_2 saving 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_{CO_2}	:	Constraint of total CO_2 saving 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

3.2 Optimization for environmental and economic parts selection and for disassembly line balancing

Similar to [13], [14], the bi-objective functions for maximizing CO_2 saving rate and minimizing total recycling cost with the disassembly parts selection at Stage 1 are respectively set as Eq. (1) and (2). Also, the constraint of the disassembly precedence relations are set as Eq. (3) based on Nof et al. [21]:

$$C = \sum_{j=1}^{N} c_j x_j \rightarrow Min \quad (1)$$

$$E = \sum_{j=1}^{N} e_j x_j \rightarrow Max \quad (2)$$

Subject to:

$$x_i - x_j \leq 0 \qquad i \in P_j \ . \quad (3)$$

To solve this multiple purpose optimization, ε-constraint method [18]-[20] is used as well as [13], [14]. The objective function E is made into the only objective function, a nonlinear optimization is performed to each of those combinations by changing ε gradually similar to [13], [14]. The function E looks for the Pareto optimum solution set. Then E is transposed to

$$E \geq \varepsilon_{CO_2} \ . \quad (4)$$

Based on [21], the objective function for the disassembly line balancing at Stage 2 is set as Eq. (5) for minimizing total number of stations as well as [14].

$$\sum_{s=K_0+1}^{K} k y_{k,|J_{select}|} \rightarrow Min \quad (5)$$

Subject to:

$$J = \{J_{select} \cup J_{cancel}\} \quad (6)$$

where $J_{select} \cap J_{cancel} = \phi$,

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

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

$$\sum_{j=1}^{J_{select}} p_j y_{k,j} \leq CT \qquad k = 1, \ldots, K, \quad (9)$$

$$y_{k,j} = \{0,1\} \qquad j \in J_{select}, k = 1, \ldots, K. \quad (10)$$

Similar to Igarashi, et al. (2014) [14], sets of selected parts/tasks and of disposed parts (cancelled tasks) at Stage 1 are set as Eq. (6). As the constraints of line balancing based on Baybars (1986) [22], constraint (7) requires that each task be assigned to exactly one station. Constraint (8) is the precedence constraint that if task i cannot be assigned to a station downstream from task j. Constraint (9) is cycle time constraint where the total disassembly time for all tasks assigned to a station does not exceed the cycle time. Constraint (10) does not allow a task to be assigned to more than one station.

4. Design Procedure Example of Disassembly System with Optimal Environmental and Economic Parts Selection for CO_2 Saving Rate and Recycling Cost

4.1 A disassembly design problem and scenarios

To validate the proposed design procedure of the disassembly system by comparing to another design case for the recycling rate and cost [14] in Section 5 later, the same example of the assembly product and the production plan [13], [14] is here prepared for a cleaner by a 3D-CAD model [24]. Table 2 shows the production plan prepared in [13], [14].

Table 2. Example of disassembly problem for cleaner [13], [14]

Production Planning Period T_0	Demands Q for Collected EOL products during T_0
504,000 [sec] (=20 [days] × 7 [hours] ×3,600 [sec])	12,000

To harmonize the CO_2 emissions and the recycling cost in the obtained disassembly part selection with the integer programming [18]-[20], four scenarios similar to [13], [14] are here considered and discussed for the product evaluation as follows: 1) All parts disassembled, 2) CO_2 volumes maximum, 3) CO_2 volumes and cost coexistence, and 4) Recycling cost minimum. In the scenario of 2) CO_2 volumes maximum, a solution with the highest value of the total collected CO_2 volumes at the product E is selected within the candidates whom their collected CO_2 volumes is higher than 50 [%]. For the line evaluation, the disassembly line balancing is carried out by the integer programming [18] for minimizing the number of stations based on the selected disassembly parts at each scenario, respectively.

Table 3. Bill of materials (BOM) with CO_2 saving rate and recycling cost: Case of the cleaner

No.	Part name	Material type	Weight [g]	CO_2 saving rate (%)	Recycling cost	Disassembly Time [sec]
1	Wheel	PP	7.07	0.62	21.77	16.20
2	Wheel stopper	PP	1.71	0.15	20.06	15.00
3	Upper nozzle	PP	50.35	2.22	17.49	13.20
4	Lower nozzle	PP	41.25	1.82	17.49	13.20
5	Nozzle	PP	34.50	1.52	17.49	13.20
6	Right handle	PP	48.93	2.18	13.37	10.20
7	Switch	PVC	4.65	0.60	13.37	10.20
8	Left handle	PP	51.70	2.28	17.49	13.20
9	Left body	PP	187.27	8.31	36.51	27.60
10	Right body	PP	179.88	7.92	17.49	13.20
11	Dust case cover	PMMA	36.57	3.08	17.49	13.20
12	Mesh filter	cloth/Fiber	18.45	19.28	18.41	13.20
13	Connection pipe	Al/Al alloy	47.17	2.16	17.31	15.60
14	Dust case	PMMA	175.69	15.21	17.49	13.20
15	Exhaust tube	PVC	32.04	1.27	17.49	13.20
16	Upper filter	cloth/Fiber	17.74	18.54	18.37	13.20
17	Lower filter	PP	29.33	1.29	17.49	13.20
18	Protection cap	ABS	22.29	1.39	17.49	13.20
19	Motor	Motor	279.27		10.50	13.20
20	Rubber of outer flame of fan	Rubber	22.85	4.00	18.63	13.20
21	Outer flame of fan	Al/Al alloy	55.11	2.64	8.96	10.20
22	Lower fan	PP	15.08	0.66	17.49	13.20
23	Fan	Al/Al alloy	62.10	2.85	12.52	13.20
Total			1421.00	100.00	402.17	316.20
Average			61.78	4.55	17.49	13.70
Standard deviation			70.19	5.62	4.98	3.27

4.2 Design example for environmental and economic parts selection for CO_2 saving rate and recycling cost

This section develops a procedure for a bi-criteria disassembly system design for the CO_2 saving rate and recycling cost using a cleaner as a case example.

4.2.1 Environmental and economic disassembly parts selection for CO_2 saving rate and recycling cost at stage 1

(1) Estimation of CO_2 saving rate, recycling cost and disassembly time using LCI database and REM

Similar to [13], [14], the prepared product example in this study is a cleaner, and their basic products/parts information is obtained with 3D-CAD [24]. A bill of materials with the CO_2 saving rate, disassembly time, recycling cost and required for the disassembly system design are estimated and assumed using the LCI database and the REM as shown in Table 3. It is found that the CO_2 saving rate of the parts #12 “Mesh filter”, #14 “Dust case” and #16 “Upper filter” are higher than its average value by 14.7%, 10.7% and 14.0%, respectively. Since the CO_2 saving rate of part #19 “motor” is too large (95% of the whole) in this example, it is assumed that the motor is certainly disassembled and is removed from the percentage of the CO_2 saving rate. Therefore, the CO_2 saving rate has been taken and shown percentage except the motor as shown in Table 3.

Figure 3 shows the precedence relationships of the cleaner with the estimated disassembly time, recycling cost and CO_2 saving rate. In this figure, solid or dotted line links mean the constrained or non-constrained precedence relationships among the disassembly tasks by Eq. (3), respectively

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

Using the Integer Programming with ε constraint [18]-[20], the pareto optimal solution is obtained for the CO_2 saving rate and recycling cost by GLPK [25] which is a package for the linear programming, mixed integer programming and other related problems. Figure 4 shows the pareto optimal solutions for the CO_2 saving rate and the recycling cost in the case of the cleaner. It is observed that recycling cost monotonically increases as the CO_2 saving rate increases.

In order to choose the parts selection for the disassembly line balancing of the Stage 2, four scenarios are here considered and discussed as follows: 1) All parts disassembled, 2) Maximum CO_2 saving rate, 3) CO_2 saving rate and cost coexistence, 4) Minimum recycling cost. To choose coexistence solution as Scenario 3 by the pareto optimum solutions, a recycling efficiency *RE* is set as Eq. (13) as well as [13], [14]. The maximal solution for the recycling efficiency RE is chosen at ε=50 among the alternative solutions as the coexistence solution for the CO_2 saving rate and cost in Scenario 3 in Figure 4.

$$RE = \frac{E}{C} \tag{13}$$

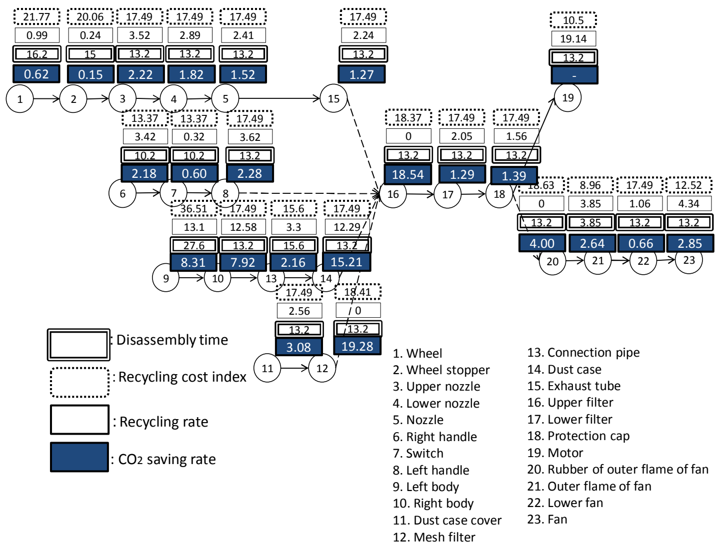

Figure 3. Precedence relationship with CO_2 saving rate and recycling rate and cost: Case of the cleaner

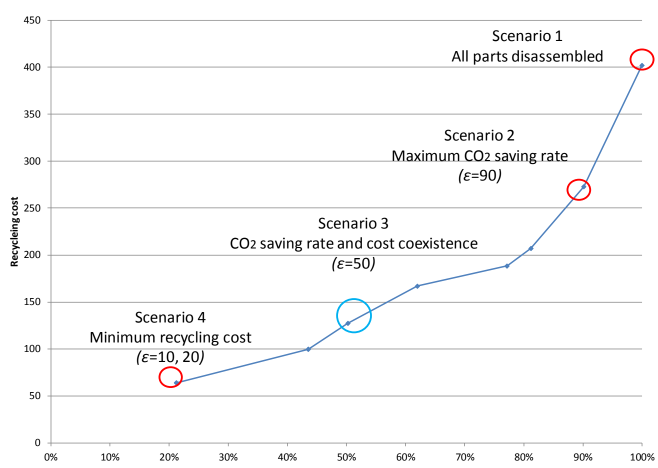

Figure 4. Behaviour of recycling cost for CO_2 saving rate: Case of the cleaner

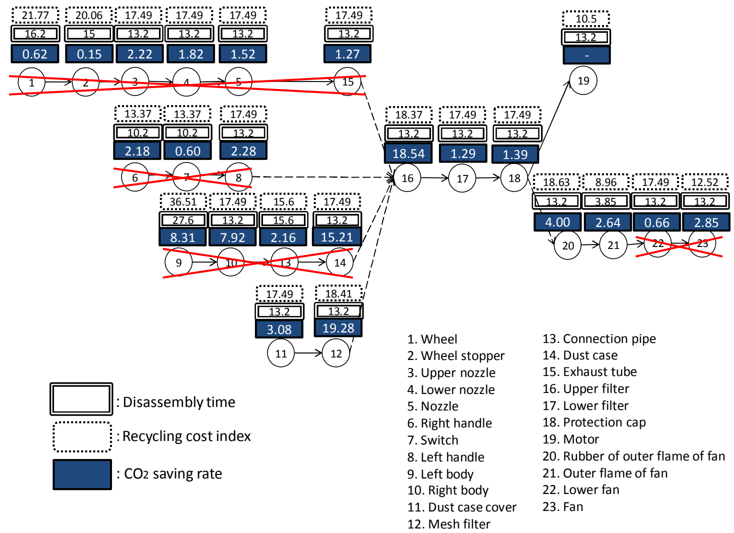

Figure 5. Precedence relations among disassembly element tasks with optimal environmental and economic parts selection: Scenario 3) CO_2 saving rate and recycling cost coexistence

(3) Disassembly precedence relationships with environmental and economic parts selection for CO_2 saving rate and recycling cost

Figure 5 shows the precedence relations among disassembly element tasks after the environmental and economic parts selection in the scenario 3 for the CO_2 saving rate and recycling cost coexistence. A mark “x” in the figure means the cancelled disassembly tasks with the non-selective parts. Similar to [13], [14], it is observed that the cancelled parts are collected by a module, for example, part #1 to #5 and #15 because of their precedence relationships.

4.2.2 Disassembly line balancing using integer programming at stage 2

(1) Cycle time

The cycle time is obtained by dividing the production planning quantity Q by the production planning period T_0 as well as the assembly/disassembly line designs. From the given production planning period and demands in Table 3, the cycle time CT is calculated as Eq. (14).

$$CT = \frac{T_0}{Q} = \frac{50{,}400[\text{sec}]}{8{,}400[\text{units}]} = 42[\text{sec}]. \qquad (14)$$

(2) Condition of the number of stations

The minimal number of stations K_0 is obtained by dividing the total disassembly time S_0 by the cycle time CT. In case of scenario 3 for the CO_2 saving rate and cost coexistence, the total disassembly time becomes 102.6 [sec]. Then, the minimal number of stations K_0 is calculated as Eq. (15).

$$K_0 = \left\lceil \frac{S_0}{CT} \right\rceil = \left\lceil \frac{102.6[\text{sec}]}{42[\text{sec}]} \right\rceil = 3. \qquad (15)$$

(3) Disassembly line balancing with CO_2 saving rate using integer programming

By using the disassembly precedence relations among the selected tasks, the disassembly line balancing is carried out by the integer programming [18] for minimizing the number of stations. The assignment of each task to stations are also shown in Figure 6, and the pitch diagram with the optimal environmental and economic parts selection at scenario 3 for the CO_2 saving rate and recycling cost coexistence are drawn as shown in Figure 7.

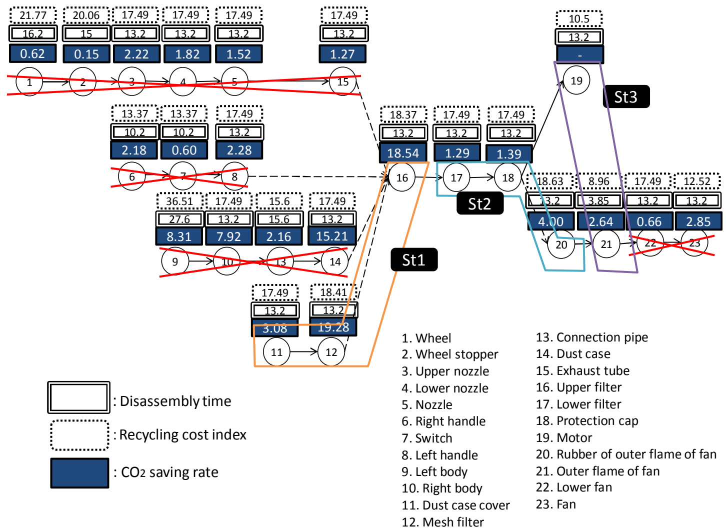

Figure 6. Precedence relationships among assignment of tasks by integer programming: With selected parts for CO_2 saving rate and recycling cost

(4) Disassembly line evaluation with product recovery values

Product and line evaluations are here conducted to the obtained disassembly system. The CO_2 saving rate and the recycling cost are simultaneously used for the product evaluation. The number of disassembly stations, balance delay *BD* which indicates a percentage of idol times and smoothness index *SI* as a variation of the total disassembly task time among disassembly stations are evaluated for the line evaluations. Table 4 shows the examples of the disassembly system design with the environmental and economic parts selection for the CO_2 saving rate and recycling cost in the case of the cleaner.

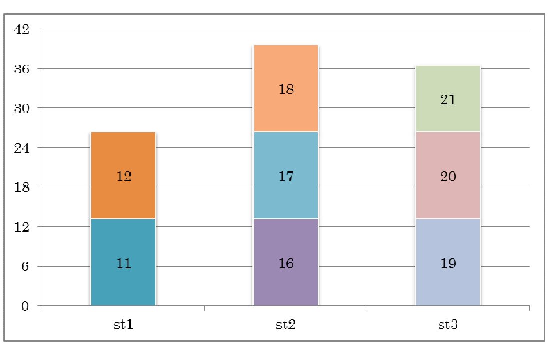

Figure 7. Pitch diagram with optimal environmental and economic parts selection: Scenario 3) CO_2 saving rate and recycling cost coexistence

5. Results of Product and Line Design Evaluation

5.1 Product vs. line designs

This section discusses the results of the product vs. line designs as shown in Table 4. With the product evaluation, the recycling cost was reduced by 32.15% at scenario 2 for the recycling and CO_2 saving rates maximum, by 68.34% at scenario 3 for the CO_2 saving rate and cost coexistence, and by 84.12% at scenario 4 for the recycling cost minimum as compared with the scenario 1 for the all parts disassembled. However, the CO_2 saving rate was maintained on more than 50% at scenario 2 for the recycling and CO_2 saving rates maximum and at scenario 3 for the CO_2 saving rate and cost coexistence.

With the line evaluation, 16.7% of the Balance Delay *BD* and 61.6% of the Smoothness Index *SI* were increased at the scenario 3 for the CO_2 saving rate and cost coexistence compared with the scenario 1 for the all parts disassembled. One of the reasons is that they did not consider to these evaluations for the optimization at stage 2 in the proposed model of this study after the parts selection. However, the other all scenarios 2, 3 and 4 could reduce respective 2, 5 and 6 disassembly stations as compared with the scenario 1.

Table 4. Example of disassembly system design with environmental and economic parts selection for CO_2 saving rate and recycling cost

			scenario 1: All parts disassmbled	scenario 2: CO2 saving rate maximum	scenario 3: CO2 saving rate and recycling cost coexistence	scenario 4: Recycling cost minimum
Product evaluation	Total disassembly time [sec]		316.20	219.00	102.6	52.8
	Number of parts		23	16	8	4
	CO2 saving rate [%]		100.00	90.12	50.21	21.22
	Recycling cost		402.17	272.89	127.34	63.85
Line evaluation	Number of stations	Minimal	8	6	3	2
		Actual	8	6	3	2
	Balance delay *BD*		0.06	0.18	0.07	0.37
	Smoothness index *SI*		8.38	22.55	13.54	26.40

Table 5. Comparison of disassembly system design for recycling [14] vs. CO_2 saving rates and cost

			scenario 1: All parts disassmbled	scenario 2: CO2 saving rate maximum (or Reycling rate maximum)			scenario 3: CO2 saving rate and recycling cost coexistence (or Recycling rate and cost coexistence [14])			scenario 5: Recycling cost minimum		
	Objective		-	Recycling rate and cost [14]	CO2 saving rate and cost	Difference [%]	Recycling rate and cost [14]	CO2 saving rate and cost	Difference [%]	Recycling rate and cost [14]	CO2 saving rate and cost	Difference [%]
Product evaluation	Total disassembly		316.20	303.00	219.00	28%	122.40	102.6	16%	27.60	52.8	-91%
	Number of parts		23	22	16	27%	8	8	0%	1	4	-300%
	Recycling rate [%]		95.48	95.48	79.57	17%	64.02	29.16	54%	13.10	22.75	-74%
	CO2 saving rate [%]		100.00	80.72	90.12	-12%	54.83	50.21	8%	8.31	21.22	-155%
	Recycling cost		402.17	383.76	272.89	29%	152.65	127.34	17%	36.51	63.85	-75%
Line evaluation	Number of stations	Minimal	8	8	6	25%	3	3	0%	1	2	-100%
		Actual	8	8	6	25%	3	3	0%	1	2	-100%
	Balance delay *BD*		0.06	0.10	0.18	-80%	0.03	0.07	-133%	0.34	0.37	-9%
	Smoothness index *SI*		8.38	17.75	22.55	-27%	2.68	13.54	-404%	0.00	26.40	-

5.2 CO_2 saving vs. recycling rates and cost

In order to consider the characteristic of the system design by the difference of the objective functions, the optimal disassembly parts selection of bi-objective in the previous study for the recycling rate and cost [14], and for the CO_2 saving rate and cost in Section 5.1 are compared and analysed in this section.

Figure 8 shows the respective behaviour of the recycling cost for the CO_2 saving rate at the four scenarios of the bi-objective for the recycling rate and cost in [14] and for the CO_2 saving rate and cost in this study. With the both cases, the recycling cost basically increases as the CO_2 saving rate increases. Also, it is observed that these solutions were plotted nearly on the similar lines at scenarios 1, 3 and 4. However, the CO_2 saving rate of the bi-objective for the recycling rate and cost is lower than that for the CO_2 saving rate and cost by 12% at the scenario 2. It is considered that the part #12 "Mesh filter" with higher CO_2 saving rate for 19.28% was cancelled in the case for the bi-objective between the recycling rate and cost. One of the reasons is that the recycling rate is 0% [14] for the part #12 although the CO_2 saving rate is 19.28%. Therefore, it is considered that the part #12 is preferentially cancelled in the case when the recycling rate and cost are the bi-objectives.

Table 5 shows the differences of the product and line evaluations between two bi-objective cases for the recycling vs. the CO_2 saving rates and the cost. At the scenario 3 for the recycling or the CO_2 saving rates and the cost coexistence, the total disassembly time in the case of the bi-objective for the recycling rate and cost are longer than the optimization for the CO_2 saving rate and cost by 16% with the product evaluation. However, the number of stations was not changed between the both cases with the line evaluation.

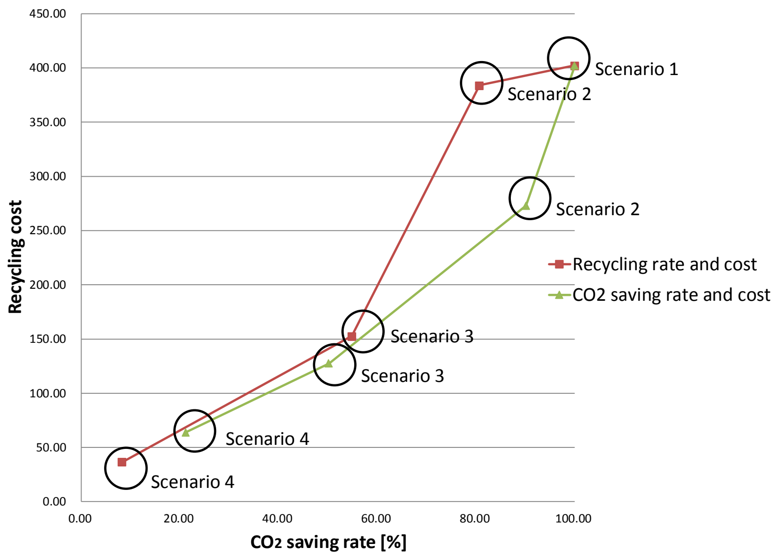

Figure 8. Behaviour of recycling cost for CO_2 saving rate: Cases of bi-objective optimization for CO_2 saving vs. recycling rates and cost

6. Conclusions

This paper proposed the disassembly system design with the optimal environmental and economic parts selection which harmonized the CO_2 saving rate and the recycling cost using the Life Cycle Inventory database by the input-output tables and the Recyclability Evaluation Method. The design example demonstrated that the recycling cost was minimized in spite of maintaining the CO_2 saving rate by selecting disassembled parts with the higher CO_2 saving rate. The main conclusions are as follows:

- By constructing a bill of materials with the CO_2 saving rate and recycling cost, the characteristics for each part are quantitatively identified environmentally and economically. In the example, it is found that the CO_2 saving rate of the parts #12 “Mesh filter”, #14 “Dust case” and #16 “Upper filter” are higher than its average value by 14.7%, 10.7% and 14.0%, respectively.

- With the product evaluation, the recycling cost was reduced by 32.15% and by 68.34% at respective scenarios 2 and 3 for the CO_2 saving rate considered by comparing with the scenario 1 for the all parts disassembled in the experiments.

- With the line evaluation, the number of the disassembly stations at scenarios 2, 3 and 4 was minimized after the parts selection and could be reduced for respective 2, 5 and 6 stations as compared with the scenario 1 though the balance delay and smoothness index were not improved.

- With the both cases of bi-objective for the CO_2 saving/recycling rates and cost, these solutions were plotted nearly on the similar lines between bi-objectives for the CO_2 saving rate and cost and for the recycling rate and cost at scenarios 1, 3 and 4. However, the CO_2 saving rate of the bi-objective for recycling rate and cost is lower than that for the CO_2 saving rate and cost by 12% at the scenario 2. It is considered that the part #12 “Mesh filter” with higher CO_2 saving rate for 19.28% was canceled in the case for the recycling rate and cost, but was not canceled in another case for the CO_2 saving rate and cost. One of the reasons is that there is a part where the recycling rate is 0% but the CO_2 saving rate is 19.28% like a part #12 depending on material types. Therefore, the proposed method could have the CO_2 saving rate higher.

- At the scenario 3 for the CO_2 saving or the recycling rate and the cost coexistence, there are no difference for the number of disassembly stations with the line evaluation, while the total disassembly time in the case of the bi-objective for the recycling rate and cost are longer than that in the optimization for the CO_2 saving rate and cost by 16%.

Further study should optimize the multi criteria design [7], [20] for the cost, recycling and CO_2 saving rates, consider a simultaneous design for the assembly and disassembly systems, etc.

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References

[1] Wang, H.-F. and Gupta, S. M., *Green Supply Chain Management: Product Life Cycle Approach*, New York, NY: McGraw Hill, USA, 2011.

[2] Yamada, T., "*Part 6, 6.2 Design of Closed-loop and Low-carbon Supply Chains for Sustainability*" in Takakuwa, S., Son, N. H., Minh, N. D. (Eds.), *Manufacturing and Environmental Management*, National Political Publishing House, Hanoi, Vietnam, pp.211-221, 2012.

[3] Lambert, A. J. D. and Gupta, S. M., *Disassembly Modeling for Assembly, Maintenance, Reuse, and Recycling*, Florida, CRC Press, 2005.

[4] Gupta, S. M., *Reverse Supply Chains: Issues and Analysis*, Florida, CRC press, USA, 2013.

[5] Nakashima, K., Kojima, M. and Gupta, S. M., "*Management of a Disassembly Line using Two Types of Kanbans*", International Journal of Supply Chain Management, Vol.1, No.3, pp.11-19, 2012.

[6] Yamada, T., Mizuhara, N., Yamamoto, H. and Matsui, M., "*A Performance Evaluation of Disassembly Systems with Reverse Blocking*", Computers and Industrial Engineering, Vol.56, Issue 3, pp. 1113-1125, 2009.

[7] Ondemir, O., Gupta, S. M., *"A Multi-Criteria Decision Making Model for Advanced Repair-Toorder and Disassembly-to-Order System"*, European Journal of Operation Research, Vol. 233, Issue 2, pp.408-419, 2014.

[8] Yamada, T., *"Design Issues for Inverse Manufacturing Systems in Japanese Cases"*, Northeast Decision Sciences Institute 2008 Annual Conference, NY, USA, pp.551-556, March, 2008.

[9] Veerakamolmal, P. and Gupta, S. M., *"Analysis of Design Efficiency for the Disassembly of Modular Electronic Products"*, Journal of Electronics Manufacturing, Vol. 9, No. 1, pp.79-95, 1999.

[10] Kuo, T. C., "*Waste Electronics and Electrical Equipment Disassembly and Recycling using Petri Net Analysis: Considering the Economic Value and Environmental Impacts"*, Computers & Industrial Engineering, Vol. 65, pp.54-64, 2013.

[11] McGovern, S. M. and Gupta, S. M., *"2-Opt Heuristic for the Disassembly Line Balancing Problem"*, Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing III, Providence, pp.71-84, 2003.

[12] Kalayci, C. B. and Gupta, S. M., *"Artificial Bee Colony Algorithm for Solving Sequence-Dependent Disassembly Line Balancing Problem"*, Expert Systems with Applications, Vol. 40, pp.7231-7241, 2013.

[13] Igarashi, K., Yamada, T. and Inoue, M., "*Disassembly System Design with Environmental and Economic Parts Selection using the Recyclability Evaluation Method"*. Japan Industrial Management Association, Vol. 64 No. 2E, pp.293-302 (on CD-ROM), 2013.

[14] Igarashi, K., Yamada, T. and Inoue, M., *"2-Stage Optimal Design and Analysis for Disassembly System with Environmental and Economic Parts Selection using the Recyclability Evaluation Method"*, Industrial Engineering and Management Systems, Vol. 13, No. 1, pp.52-66, 2014.

[15] Prof. Norihiro Itsubo Laboratory, "LCA inventory database", Available at http://www.yc.tcu.ac.jp/~itsubo-lab/# on March 18 in 2014.

[16] Recyclability Evaluation Method (REM), © Hitachi, Ltd., EcoAssist, Available at http://www.ecoassist.com/HTML_n/option/rem/rem_tr/ppframe.htm on May 20, 2014 (in Japanese)

[17] Hiroshige, Y., Nishi, T. and Ohashi, T. *"Recyclability Evaluation Method"*, 2002 ASME International Mechanical Engineering Congress & Exposition, November., New Orleans, Louisiana, USA, pp.835-839, 2002.

[18] Kubo, M., *Combinatorial Optimization and Algorithm*, Tokyo: Kyoritsu Shuppan, 2000 (in Japanese).

[19] Yoshimura, M.: System Design Optimization for Product Manufacturing, Yokendo, Tokyo (in Japanese), 2007.

[20] Liu, S. and Papageorgiou, L. G., "*Multiobjective Optimization of Production, Distribution and Capacity Planning of Global Supply Chains in the Process Industry*", Omega, Vol. 41, pp. 369-382, 2013.
[21] Nof, S.Y., Wilhelm, W.E. and Warnecke, H., *Industrial Assembly*, CHAPMAN & HALL, 1997.
[22] Baybars, I., *"A Survey of Exact Algorithms for the Simple Assembly Line Balancing Problem"*, Management Science, Vol. 32, No. 8, pp.909-932, 1986.
[23] Yamada, T., Suzuki, Y., Masui, T., Itsubo, N. and Inoue, M., *"Disassembly System Design with Environmental and Economic Parts Selection using Life Cycle Inventory Database by Input-Output Tables"*, 10th Global Conference on Sustainable Manufacturing, Sustainable Product Development and Life Cycle Engineering, *CIRP*, Istanbul, Turkey, pp.321-326, Oct, 2011.
[24] Inoue, M., Akiyama, T. and Ishikawa, H. *"Lifecycle Design Support System Based on 3D-CAD using Set-Base Design Method"*, The Japan Society of Mechanical Engineers, 21th Conference on Design Engineering and System Department, Osaka, 420-423, Oct, 2011 (in Japanese).
[25] GLPK - GNU Project, http://www.gnu.org/software/glpk/ (Available on Jan 9, 2012)