1. Introduction

Manufacturing, which consumes natural resources, is faced up to a turning point from mass production and heavy consumption to taking a proper environmental management by reducing consumption of limited natural resources. For...
changing of this traditional type manufacturing, environmental conscious manufacturing (Ilgin and Gupta, 2010) has been attention to in order to deal with material starvation. However, in the U.S., end-of-life (EOL) products are thrown away more than 250 million tons, -two-third of what are become the trash despite of still valuable- each year, according to the U.S. Environmental Protection Agency (Nasr, 2017). The assembly products such as computers, cell phones and vacuum cleaners are made of a variety of parts and different types of materials, and proper operations for EOL assembly products are required to remove recyclable materials. 41.8 billion tons of electrical and electronic equipment become an EOL status every year in the world (Wagner et al., 2017). For promoting recycling and waste reduction against the material starvation, circular economy announced as an EU’s economical strategy package by the EU in 2015 (Circular Economy Strategy - Environment - European Commission). The circular economy aims to achieve stable supply of material resources and create new business opportunities including recycling (Circular Economy Strategy - Environment - European Commission). Recycling means the recovery of scrap materials from EOL products (Lambert and Gupta, 2005), and the recycling of the assembly products has become more important to promote material circulation. There is a law about recycling basic home electric appliance such as televisions, air conditioners, washing machines and refrigerators as a Japanese recycling strategy. These appliances are regulated to be recycled more than 50% of the EOL products on weight by the law (Law for the Recycling of Specified Kinds of Home Appliances).

On the other hand, global warming caused by greenhouse gases (GHGs) such as CO$_2$ generated by manufacturing has been recognized as one of the global issues at the COP 21 meeting held in Paris (The Paris Agreement). The Paris agreement has been agreed for implementation by not only the developed nations but also the emerging ones. Each country has the responsibility of setting target values for CO$_2$ reduction, thus undertaking ambitious efforts to curb climate change (The Paris Agreement). For example, by 2030, Japanese government promised to reduce CO$_2$ emissions by 26% compared to one in 2013, while Chinese one set the 60-65% reduction target of CO$_2$ emissions per GDP compared to one in 2005. Since recycling can save additional GHGs at virgin material production phase from natural resources by using recycled materials in manufacturing, it is also expected to reduce the GHGs emissions at the material production stage. The CO$_2$ saving rate can be defined as the rate of the CO$_2$ volumes in part of assembly products production for each disassembled and collected part, which saves the virgin parts/materials to the total CO$_2$ volumes of the whole product (Igarashi et al., 2014).

For material recycling of assembly products, disassembly is an essential phase, and can be defined as the systematic separation of an assembly product into its components, subassemblies or other groupings (Ilgin and Gupta, 2012). There is one unavoidable trade-off problem between cost and recycled weights in material recycling. One of the reasons is that manual disassembly tasks instead of crushing and separating by material type cause higher recycling cost due to labor cost increased. Therefore, disassembly of all parts within the EOL product is difficult in terms of an economic aspect despite a desirable strategy for material circulation. To resolve the trade-off problem, a disassembly parts selection is often carried out at the recycling factories (Yamada, 2008). These factories seek to remove materials from the EOL products with lower recycling cost by disassembly parts selection, which determines the parts selected for material recycling, under achieving higher recycling rate than the lowest limit of one designated by law, and satisfying the target of saving CO$_2$ rate.

To overcome this problem, Smith et al. (2016) propose disassembly sequence planning with disassembly parts selection by considering directions and tools of disassembly tasks, but do not consider environmental loads. Rickli and Camelio (2013) and Seo et al. (2001) address the disassembly parts selection with consideration of environmental impacts, but they do not set CO$_2$ emissions as an objective function. Igarashi et al. (2014) propose an environmentally friendly and economical disassembly parts selection using the ε constraint method by setting bi-objective functions as well as Igarashi et al. (2013) for minimizing the recycling cost and maximizing the CO$_2$ saving rate. The ε constraint method is one of the methods to solve the multi-criteria decision making problem by transposing objective functions to the constraints. With regard to the multi-criteria decision making problem, goal programming is well known as one of the effective ways in solving the multi-criteria decision making problems (Joshi et al., 2014; Ilgin et al., 2015). The goal programming enables us to evaluate different goals simultaneously by setting of 2 targets for each goal, such as tolerable and sufficient levels, so that it obtains some alternative solutions for satisfying preferences of decision makers among the goals (Fushimi et al., 1987). Kinoshita et al. (2016) apply goal programming to the
environmentally friendly and economical disassembly parts selection considering the recycling rate and the cost. The proposed model using goal programming by Kinoshita et al. (2016) can obtain the solutions, which achieve higher recycling rate such as 76% but reduce the recycling cost by 80% from a scenario with all parts disassembly. By changing the target ranges of the goals, the goal programming model can obtain alternative solutions and reduce the number of the numerical experiments by 75% compared with ε constraint method by Igarashi et al. (2014). However, they do not adopt goal programming for minimizing CO₂ saving rate and recycling cost.

There are 3 indices including the recycling rate, CO₂ saving rate and cost used in Igarashi et al. (2014), Igarashi et al. (2016) and Kinoshita et al. (2016). The environmental indices such as the recycling and CO₂ saving rates contribute to different but related global environmental issues such as material starvation and global warming. However, the recycling and CO₂ saving rates depend on material types and weights. With respect to the recycling cost, it depends on not only material types and weights but also disassembly tasks such as screwing and moving up (Hiroshige et al., 2001; Hitachi Ltd.). These material types and weight are included a bill of materials (BOM) built at an assembly phase. BOM is listing of all the subassemblies, parts, raw materials, components, bulk products (Institute of Industrial and Systems Engineers). By adding environmental and disassembly information such as cost, CO₂ saving and recycling rates, BOM also plays an important role for environmentally friendly and economical disassembly parts selection. Hence, it is desirable to construct BOM including cost, CO₂ saving and recycling rates at recycling factories for promoting material circulation economically.

In addition to 3 different indices such as recycling rate, CO₂ saving rate and cost for each part, there are disassembly precedence relationships among disassembly tasks/parts. In other words, to remove a certain part, which has some preceding parts, the preceding parts also have to be disassembled in advance. Thus, the obtained material types and weights based on the disassembly parts selection with CO₂ saving/recycling rates and cost also depend on disassembly tasks and disassembly precedence relationships.

It is known that each metal has different amount of underground stock, which can be mined economically. Also, for some metals such as gold, silver, lead and zinc, the amount of surface stocks including assembly products at not only EOL but also usage phases, which have already mined for manufacturing called as an urban mining, is much larger than one of underground stock (Halada et al., 2009). Japan has one of the huge urban mining consisted of assembly products. Japanese surface stock of gold and silver are 2.7 and 3.0 times larger than world annual consumption (Halada et al., 2009). In a case of Aluminum, a rate of recycled weights becomes only 1.9% at 2006 in Japan against the amount of surface stock (Halada et al., 2009). There is a possibility to provide more recycled materials where there are poor natural resources in Japan.

Therefore, types of materials and weights become essential information for the environmentally friendly and economical disassembly parts selection. In order to pursue cost effectiveness of recycled weights by each material, one of the design issues about disassembly parts is come up with as follows: (1) Which types of materials are recycled by increasing the recycling or the CO₂ saving rates? How much weights is recycled for each material? How much cost is required for recycling?, (2) Are there the same or different cost effectiveness for recycled weights by types of materials between the recycling and the CO₂ saving rates? and (3) Are there any bottlenecks to drive down the cost effectiveness for recycled weights? Which parts or disassembly tasks are the bottlenecks? Which parts or tasks should be improved? However, the previous studies treating the cost and recycling rate or CO₂ saving rate in Igarashi et al. (2014), Igarashi et al. (2016) and Kinoshita et al. (2016) neither analyze of the collected material types and weights nor identify bottlenecks to drive down cost effectiveness for recycled weights.

This study focusses on the EOL assembly product, applies goal programming to environmentally friendly and economical disassembly parts selection for minimizing the total recycling cost, while maximizing the total CO₂ saving/recycling rates based on Kinoshita et al. (2016), and analyzes collected materials for types and weights by the disassembly parts selection. This paper is organized as follows: section 2 explains and formulates a proposal for environmentally friendly and economical disassembly parts selection by goal programming based on Igarashi et al. (2014) and Kinoshita et al. (2016). In section 3, a design example in the case of a vacuum cleaner is demonstrated and results are discussed. Section 4 compares 2 types of bi-objective optimizations by goal programming, such as the recycling cost vs. the rate in Kinoshita et al. (2016) and
2. Overviews of material based analysis with disassembly parts selection using goal programming

Section 2 explains the design procedures of material based analysis method with environmentally friendly and economically disassembly parts selection for CO\textsubscript{2} saving rate and recycling cost, and formulates the disassembly parts selection by using goal programming introduced from Kinoshita et al. (2016).

2.1 Procedures of material based analysis based on disassembly parts selection

Figure 1 shows overview of material based analysis method with environmentally friendly and economically disassembly parts selection by using goal programming. The procedures are consisted of 5 steps as shown in Fig. 1. The steps 1 and 3 are introduced from Igarashi et al. (2014), and the step 2 is introduced from Kinoshita et al. (2016), respectively. The detailed explanation for each step is as follows:

**Step 1: Construct Disassembly Precedence Relationships and BOM based on 3D-CAD model**

(1) Grasp disassembly precedence relationships, material type, weight and disassembly task
(2) Estimate CO\textsubscript{2} saving rate and recycling cost by using LCI database and REM, respectively

**Step 2: Carry out the Environmentally Friendly and Economical Disassembly Parts Selection by using Goal Programming**

(1) Set respective CO\textsubscript{2} saving rate and recycling cost target ranges
(2) Select parts to harmonize CO\textsubscript{2} saving rate and recycling cost

**Step 3: Update Disassembly Precedence Relationships with Environmental Friendly and Economic Disassembly Parts Selection**

(1) Evaluate the obtained Pareto optimal solutions in terms of environmental and economical aspects
(2) Cancel disassembly tasks and crash parts without cost

**Step 4: Analyze Recycled Materials Types, Weights and Cost**

(1) Pick up solution for detailed material analysis and calculate recycled weight for each part
(2) Compare the unit recycling cost [cost/weight] and recycled material weight

**Step 5: Suggest Improvement Plans for Identified Bottlenecks**

(1) Focus on the lighter recycled weight or worse cost effectiveness for identifying bottlenecks
(2) Propose improved plans for designers by using the disassembly precedence relationships and BOM

Figure 1 shows overview of material based analysis method with environmentally friendly and economically disassembly parts selection by using goal programming. The procedures are consisted of 5 steps as shown in Fig. 1. The steps 1 and 3 are introduced from Igarashi et al. (2014), and the step 2 is introduced from Kinoshita et al. (2016), respectively. The detailed explanation for each step is as follows:

**Step 1: Construct disassembly precedence relationships and BOM based on 3D-CAD model**

To visualize the disassembly precedence relationships, the CO\textsubscript{2} emissions and recycling cost for each part, the step 1 is introduced from Igarashi et al. (2014). The step 1 uses 3D-CAD model, life cycle inventory (LCI) database and Recyclability Evaluation Method (REM) (Hiroshige et al., 2001; Hitachi Ltd.) as well as Igarashi et al. (2014). From the 3D-CAD model, product data such as weights, material types and disassembly tasks for each part is obtained, and the disassembly precedence relationships are constructed. The LCI database (Itsubo Laboratory) has been developed for
measuring the GHGs emissions and consists of a wide range of industry representative unit process data on the national or regional levels (Sugiyama et al., 2005). According to the LCI database (Itsubo Laboratory), GHGs emissions at the material production stage of the parts depends on the type of material and the weights (Yoshizaki et al., 2016). By matching the material types from the 3D-CAD model and the unit process data in the LCI database (Itsubo Laboratory), the CO$_2$ saving rate is calculated for each part. With regard to the recycling cost, the REM software estimates the recycling cost consisted of disassembly cost, disposal cost, sales of materials and landfill cost quantitatively by inputting disassembly tasks, weights and material type (Hirosighe et al., 2001; Hitachi Ltd.). Moreover, BOM, including the recycling cost and environmental information, is prepared as the input data of the environmentally friendly and economical disassembly parts selection.

Step 2: Carry out environmentally friendly and economical disassembly parts selection by using goal programming

This study applies the bi-objective disassembly parts selection by Kinoshita et al. (2016) to another bi-objective for CO$_2$ saving rate and recycling cost. The environmentally friendly and economical disassembly parts selection has 2 objective functions: minimizing the total recycling cost and maximizing the total CO$_2$ saving rate. To obtain solutions satisfying both values of objective functions by using goal programming, it requires to set the tolerable and sufficient levels for each goal. The tolerable level is defined as a level, where a decision maker is eager to achieve at least (Fushimi et al., 1987). Therefore, value of objective function must be equal to or greater (or lower) than the tolerable level. Hence, the target range, which is the difference between the sufficient and the tolerable levels, is set for each goal. The detailed formulation is explained in subsection 2.2.

Step 3: Update disassembly precedence relationships with the results of disassembly parts selection

In order to update the disassembly precedence relationships, the step 3 evaluates the obtained solutions in the step 2 in terms of the CO$_2$ saving rate and recycling cost. The obtained solutions are Pareto optimal solutions since the CO$_2$ saving rate and recycling cost have trade-off relationships. Therefore, solutions harmonizing CO$_2$ saving rate and cost can be defined as solution with over 50% higher total CO$_2$ saving rate $E$ and lower total recycling cost $C$ by 50% than one when all parts disassembled. Based on the results of the environmentally friendly and economical disassembly parts selection, canceled parts are removed from the disassembly precedence relationship. The updated disassembly precedence relationship indicates that the selected parts are disassembled manually for recycling, otherwise the canceled ones are destroyed without time and costs.

Step 4: Analyze recycled material types, weights and cost

Material analysis for the results of the disassembly parts selection is conducted to obtain information about recycled materials in order to pursue the cost effectiveness for the recycled weights by each material type. The materials, which are contained within 10% against the whole EOL product on weight should be excluded from the material analysis because the cost effectiveness is eager to be lower due to lighter contained weight. First, the step 4 picks up some solutions based on the evaluation in the step 3 for analysis. Next, the recycled weight for each material type is calculated by using BOM to calculate the cost effectiveness for recycled materials. The cost effectiveness [cost/weight] is defined to divide the total recycling cost $C$ by the recycled weight. Finally, to evaluate the cost effectiveness for each recycled material, step 4 compares the recycled material weight and unit recycling cost. By conducting the detailed material analysis, it is expected to find out that recycled weights of a certain material is much lighter than one contained of the products. Additionally, it is also expected that the a certain material with worse cost effectiveness than ones of other materials is found.

Step 5: Suggest improvement plans for identified bottlenecks

To promote material recycling, it requires to remove materials/parts more easily or with lower cost by improving the bottlenecks such as disassembly tasks, material types or preceding disassembly parts. First, the step 5 focuses on the materials with lighter collected materials or worse cost effectiveness for recycling material found in the analysis in the
step 4. Next, to identify bottlenecks to drive down the recycled weight or cost effectiveness, step 5 uses the disassembly precedence relationships and BOM. Especially, the disassembly tasks and preceding parts are focused on. Finally, improvement plans of the identified bottleneck are suggested to production/product designers for reviewing the material type, disassembly tasks and disassembly precedence relationships.

2.2 Formulation of disassembly parts selection by goal programming

This study explores the environmentally friendly and economical disassembly parts selection with the \( \varepsilon \) constraint method in order to apply goal programming, based on the works of Igarashi et al. (2014) and Kinoshita et al. (2016).

A summary of the notations used in this study is listed below:

\( i \) : Index for the predecessors of the part \( j \) with the task \( j \)
\( j \) : Index of the parts/tasks \( (j=1,2,\ldots,N) \)
\( N \) : Number of the parts
\( J \) : Set of the parts/tasks
\( c_j \) : Recycling cost for part \( j \)
\( e_j \) : CO\(_2\) saving rate for part \( j \)
\( P_j \) : Set of the tasks that immediately precede task \( j \) at part \( j \)
\( C \) : Total recycling cost
\( C_0 \) : Tolerable total recycling cost
\( C_s \) : Sufficient total recycling cost
\( E \) : Total CO\(_2\) saving rate
\( E_{max} \) : CO\(_2\) saving rate when all parts are disassembled for material recycling
\( E_0 \) : Tolerable total CO\(_2\) saving rate
\( E_s \) : Sufficient total CO\(_2\) saving rate
\( x_j \) : Binary variable; 1 if part \( j \) is disassembled, else 0
\( d'_j \) : Positive deviation from the sufficient recycling cost \( C_s \)
\( d_j \) : Negative deviation from the sufficient recycling cost \( C_s \)
\( d'_i \) : Positive deviation from the sufficient CO\(_2\) saving rate \( E_s \)
\( d_i \) : Negative deviation from the sufficient CO\(_2\) saving rate \( E_s \)
\( d \) : Maximum deviational variable
\( \beta \) : Parameter to weight the average and the maximum of \( d \)

The proposed environmentally friendly and economical disassembly parts selection has bi-objective functions: to minimize the total recycling cost \( C \) and to maximize the total CO\(_2\) saving rate \( E \) as shown in Eqs. (1) and (2). Part \( j \) represents component \( j \). On the other hand, task \( j \) represents removal or disassembly of part \( j \). Therefore, it is assumed that each part \( j \) is removed or disassembled by task \( j \) from an EOL product. If the part \( j \) is selected for disassembly for material recycling \( (x_j=1) \), both total recycling cost \( C \) and CO\(_2\) saving rate \( E \) can be increased. Otherwise \( (x_j=0) \), neither of them is increased.

\[
C = \sum_{j}^{N} c_j x_j \rightarrow \text{Min} \tag{1}
\]

\[
E = \sum_{j}^{N} e_j x_j \rightarrow \text{Max} \tag{2}
\]

The constraint of the precedence relationships among the disassembly tasks is set based on Nof et al. (1997). Indices \( i \) and \( j \) represent part or task. Part or task \( i \) precedes part or task \( j \) respectively. For example, in a case of the cleaner, the preceding part #1 wheel of the part #2 wheel stopper is one element of \( P_2 \) as shown in Fig. 3.
Therefore, the part #1 wheel also has to be disassembled in order to disassemble the part #2 wheel stopper. Then, the constraint for disassembly precedence relationships is as shown in Eq. (3).

\[
x_j \leq x_i \quad i \in P_j
\]

(3)

\[
x_j = \{0,1\} \quad j \in J
\]

(4)

Similar to Kinoshita et al. (2016), these objective functions as shown in Eqs. (1) and (2) are transposed to the constraints by setting tolerable and sufficient levels for the target ranges. Goal programming seeks solutions by minimizing the differences between the value of the objective functions and the sufficient levels. Additionally, goal programming can propose alternative solutions easily by changing the target ranges. The detailed formulation is shown below:

1. The first goal is to minimize the total recycling cost \( C \).

The total recycling cost \( C \) denotes the total cost, including the disassembly cost, disposal cost, landfill cost and sales of materials, for material recycling. The sufficient total recycling cost \( C_s \) is set to be lower than the tolerable total recycling cost \( C_0 \) as shown in Eq. (5). The total recycling cost \( C \) is equal to or lower than the tolerable total recycling cost \( C_0 \), with the aim to reach the sufficient total recycling cost \( C_s \) as shown in Eqs. (6) and (7). The terms \( d^+_1 \) and \( d^-_1 \) are the deviation variables that show the differences between the sufficient total recycling cost \( C_s \) and the total one \( C \). By minimizing the deviation variable \( d^+_1 \), the total recycling cost \( C \) approaches the sufficient one \( C_s \). The coefficient \((C_0 - C_s)\) in Eq. (7) is set to normalize each goal, since the bi-objective functions have different unit or scales such as cost and CO\(_2\) saving rate. The first goal is formulated as follows:

Goal: minimize \( d^+_1 \),

Subject to:

\[
C_s < C_0
\]

(5)

\[
C \leq C_0
\]

(6)

\[
C + (C_0 - C_s)(d^-_1 - d^+_1) = C_s
\]

(7)

2. The second goal is to maximize the total CO\(_2\) saving rate \( E \).

The total CO\(_2\) saving rate \( E \) is maximized and formulated with goal programming, along with the total recycling cost \( C \). The sufficient total CO\(_2\) saving rate \( E_s \) is set to be greater than the tolerable total CO\(_2\) saving rate \( E_0 \) as shown in Eq. (8). The total CO\(_2\) saving rate \( E \) is equal to or greater than the tolerable CO\(_2\) saving rate \( E_0 \), with the aim to reach the sufficient total CO\(_2\) saving rate \( E_s \) as shown in Eqs. (9) and (10). Similar to Eq. (7), the deviation variables \( d^-_2 \) and \( d^+_2 \), and the coefficient \((R_s - R_0)\) are set in Eq. (10). By minimizing \( d^-_2 \), the total CO\(_2\) saving rate \( E \) tries to reach the sufficient total CO\(_2\) saving rate \( E_s \). The second goal is formulated as follows:

Goal: minimize \( d^-_2 \),

Subject to:

\[
E_s > E_0
\]

(8)

\[
E \geq E_0
\]

(9)

\[
E + (E_s - E_0)(d^-_2 - d^+_2) = E_s
\]

(10)
Similar to Kinoshita et al. (2016), the whole objective function is set as Eq. (11), and the constraints are set as Eqs. (12), (13), (14) and (15) to solve this bi-objective problem by goal programming. The term \( d_i^+ \) represents the difference between the total recycling cost \( C \) and the sufficient total recycling cost \( C_s \). Also, the term \( d_j^- \) shows the differences between the total CO\(_2\) saving rate \( E \) and the sufficient total CO\(_2\) saving rate \( E_s \). In Eq. (11), the term \( \frac{d_i^+ + d_j^-}{2} \) represents deviations, which represent the differences from the sufficient total recycling or CO\(_2\) saving rate, while the term \( d \) denotes the maximum of \( d_i^+ \) and \( d_j^- \) as shown in Eqs. (12) and (13) (Kinoshita et al., 2016). To achieve solutions satisfying both objective functions simultaneously, this study minimizes the average of the deviation \( \frac{d_i^+ + d_j^-}{2} \) in former of Eq. (11), and the maximum deviation \( d \) in latter of Eq. (11).

The parameter \( \beta \) is used to weight the average and maximum of the deviation variables \( d \), and set as 0.5 in this study.

\[
\beta \frac{d_i^+ + d_j^-}{2} + (1 - \beta) d \rightarrow \text{Minimize} \quad (11)
\]

\[
d \geq d_i^+ \quad (12)
\]

\[
d \geq d_j^- \quad (13)
\]

\[
d_i^+, d_i^-, d_j^+, d_j^- \geq 0 \quad (14)
\]

\[
0.0 \leq \beta \leq 1.0 \quad (15)
\]

3. Design example of disassembly parts selection by goal programming

Section 3 describes input data such as material type, CO\(_2\) saving rate, recycling cost and disassembly precedence relationships, shows design example for setting the target ranges for each objective function, and evaluates the obtained Pareto optimal solutions from viewpoints of both CO\(_2\) saving rate and cost.

3.1 Product example and goal programming adaptation

(1) Product example

![Fig. 2a Input data of material weights in the case of a vacuum cleaner](image1)

![Fig. 2b Results of recycled weights in a case of recycling rate and cost at all ranges](image2)

![Fig. 2c Results of recycled weights in a case of CO\(_2\) saving rate and cost at all ranges](image3)
This subsection adopts a vacuum cleaner as an example of a product to test the environmentally friendly and economical disassembly parts selection for the CO\textsubscript{2} saving rate and the recycling cost by goal programming. The vacuum cleaner has 23 original parts without any missing part, with the assumption that the conditions for all parts are good and available. The total recycling cost and the CO\textsubscript{2} saving rate with all parts disassembled are 402.17 and 100% (=E\textsubscript{max}), respectively. Figure 2a shows each material weight and percentage against for the whole product weight in the case of the vacuum cleaner, with the total product weight being 1,421[g] and 8 types of materials, namely Polypropylene (PP), polyvinyl chloride (PVC), Poly methyl methacrylate (PMMA), Cloth/Fiber, Al/Al alloy, Acrylonitrile butadiene styrene (ABS), Motor, and Rubber. It is shown that PP which the 11 out of 23 parts of the vacuum cleaner are made of is the heaviest material at 647.07[g]. Figure 3 shows the disassembly precedence relationships with the recycling cost, material type and weights in the case of the vacuum cleaner. Each element shows each part connected with plain-line or dotted-line arrows each other. The plain-line arrows means disassembly preceding relationships, while dotted-line arrows means no constraint relationships among parts (Igarashi et al., 2013). The disassembly precedence relationships provide a visual representation of ordering disassembly tasks/parts based on immediate predecessors. (McGovern and Gupta, 2011). The selection of environmentally friendly and economical disassembly parts is carried out using the relationships in Fig. 3.

(2) Goal programming adaptation

Similar to Kinoshita et al. (2016), this study adopts goal programming to the proposed bi-objective disassembly parts selection for CO\textsubscript{2} saving rate and recycling cost. It requires setting of the sufficient and tolerable levels for each goal. To compare the results with the recycling rate and cost in Kinoshita et al. (2016), the CO\textsubscript{2} saving rate target ranges are changed to 4 patterns as well as Kinoshita et al. (2016) in order to obtain Pareto optimal solutions harmonizing the total recycling cost $C$ and the total CO\textsubscript{2} saving rate $E$. According to
Kinoshita et al. (2016), the division into 4 areas are enough to obtain the best and alternative solutions. Therefore, this study also set patterns 1) all ranges, 2) division into 2 areas, 3) division into 3 areas and 4) division into 4 areas as combinations of target rages of CO₂ saving rate. The changing patterns are set to divide the feasible CO₂ saving rate range equally, which are defined from 0% (no disassembly parts) to 100% (=E_{max}: all parts disassembled). The details of the patterns of CO₂ saving rate target ranges are as follows:

Pattern 1) All ranges from 0% to 100% (E_0=0%, E_r=E_{max})
Pattern 2) Division into 2 areas from 0% to 50% (E_0=0%, E_r=E_{max/50}) and from 50% to 100% (E_0=50%, E_r=E_{max})
Pattern 3) Division into 3 areas from 0% to 33% (E_0=0%, E_r=E_{max/33}), from 33% to 66% (E_0=E_{max/33}, E_r=E_{max/66}) and from 66% to 100% (E_0=E_{max/66}, E_r=E_{max})
Pattern 4) Division into 4 areas from 0% to 25% (E_0=0%, E_r=E_{max/25}), from 25% to 50% (E_0=E_{max/25}, E_r=E_{max/50}), from 50% to 75% (E_0=E_{max/50}, E_r=E_{max/75}) and from 75% to 100% (E_0=E_{max/75}, E_r=E_{max})

In contrast to the CO₂ saving rate target ranges, the steady target range of the recycling cost is set from a sum of negative cost parts (=C_0) to a sum of positive profit parts (=C_0), so that the recycling cost is minimized. Then the environmentally friendly and economical disassembly parts selection is carried out with the above recycling cost and CO₂ saving rate target ranges under the disassembly precedence relationships as shown in Fig. 3. By using the mathematical programming package developed by Numerical Optimizer (NTT DATA Mathematical System Inc.), all numerical experiments are performed by the same desktop PC with the following specifications: Windows 7 with Intel(R) Core(TM) i7-2600 CPU@3.40GHz.

Table. 1 Bill of materials with disassembly parts selection for recycling cost and CO₂ saving rate: case of a vacuum cleaner

<table>
<thead>
<tr>
<th>No.</th>
<th>Part name</th>
<th>Material type</th>
<th>Disassembly operation</th>
<th>Weight [g]</th>
<th>CO₂ saving rate [%]</th>
<th>Recycling rate [%]</th>
<th>Recycling cost [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wheel</td>
<td>PP</td>
<td>[move right]</td>
<td>7.07</td>
<td>0.62</td>
<td>0.99</td>
<td>21.77</td>
</tr>
<tr>
<td>2</td>
<td>Wheel stopper</td>
<td>PP</td>
<td>[move up]</td>
<td>1.71</td>
<td>0.15</td>
<td>0.24</td>
<td>20.06</td>
</tr>
<tr>
<td>3</td>
<td>Upper nozzle</td>
<td>PP</td>
<td>[move up]</td>
<td>30.35</td>
<td>2.22</td>
<td>3.52</td>
<td>17.49</td>
</tr>
<tr>
<td>4</td>
<td>Lower nozzle</td>
<td>PP</td>
<td>[move up]</td>
<td>41.25</td>
<td>1.82</td>
<td>2.89</td>
<td>17.49</td>
</tr>
<tr>
<td>5</td>
<td>Nut</td>
<td>PP</td>
<td>[move up]</td>
<td>34.50</td>
<td>1.52</td>
<td>2.41</td>
<td>17.49</td>
</tr>
<tr>
<td>6</td>
<td>Right handle</td>
<td>PP</td>
<td>[screw][move up]</td>
<td>48.93</td>
<td>2.18</td>
<td>3.42</td>
<td>13.37</td>
</tr>
<tr>
<td>7</td>
<td>Switch</td>
<td>PVC</td>
<td>[screw][move up]</td>
<td>4.65</td>
<td>0.60</td>
<td>0.32</td>
<td>13.37</td>
</tr>
<tr>
<td>8</td>
<td>Left handle</td>
<td>PP</td>
<td>[move up]</td>
<td>51.70</td>
<td>2.28</td>
<td>3.62</td>
<td>17.40</td>
</tr>
<tr>
<td>9</td>
<td>Left body</td>
<td>PP</td>
<td>[screw][move up]</td>
<td>107.27</td>
<td>0.80</td>
<td>1.30</td>
<td>36.51</td>
</tr>
<tr>
<td>10</td>
<td>Right body</td>
<td>PP</td>
<td>[move up]</td>
<td>179.88</td>
<td>7.92</td>
<td>12.58</td>
<td>17.49</td>
</tr>
<tr>
<td>11</td>
<td>Dust case</td>
<td>PMMA</td>
<td>[move up]</td>
<td>36.57</td>
<td>3.08</td>
<td>2.56</td>
<td>17.40</td>
</tr>
<tr>
<td>12</td>
<td>Motor</td>
<td>PP</td>
<td>[move up]</td>
<td>28.33</td>
<td>1.29</td>
<td>2.05</td>
<td>17.40</td>
</tr>
<tr>
<td>13</td>
<td>Exhaust tube</td>
<td>PVC</td>
<td>[move up]</td>
<td>32.04</td>
<td>1.27</td>
<td>2.24</td>
<td>17.49</td>
</tr>
<tr>
<td>14</td>
<td>Upper pipe</td>
<td>PVC</td>
<td>[move up]</td>
<td>17.74</td>
<td>18.55</td>
<td>0.00</td>
<td>18.57</td>
</tr>
<tr>
<td>15</td>
<td>Lower pipe</td>
<td>PP</td>
<td>[move up]</td>
<td>30.98</td>
<td>2.05</td>
<td>3.79</td>
<td>17.40</td>
</tr>
<tr>
<td>16</td>
<td>Protection pipe</td>
<td>ABS</td>
<td>[move up]</td>
<td>22.29</td>
<td>1.39</td>
<td>1.56</td>
<td>17.49</td>
</tr>
<tr>
<td>17</td>
<td>Motor</td>
<td>Motor</td>
<td>[move up]</td>
<td>270.27</td>
<td>0.00</td>
<td>19.14</td>
<td>16.50</td>
</tr>
<tr>
<td>18</td>
<td>Rubber</td>
<td>Rubber</td>
<td>[move up]</td>
<td>22.85</td>
<td>0.00</td>
<td>18.63</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Outer frame of fan</td>
<td>PP</td>
<td>[move up]</td>
<td>55.11</td>
<td>2.64</td>
<td>3.85</td>
<td>8.96</td>
</tr>
<tr>
<td>20</td>
<td>Lower fan</td>
<td>PP</td>
<td>[move up]</td>
<td>13.08</td>
<td>0.66</td>
<td>1.06</td>
<td>17.49</td>
</tr>
<tr>
<td>21</td>
<td>Fan</td>
<td>PP</td>
<td>[move up]</td>
<td>62.10</td>
<td>2.85</td>
<td>4.34</td>
<td>12.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pattern 1)</th>
<th>Pattern 2)</th>
<th>Pattern 3)</th>
<th>Pattern 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all ranges</td>
<td>2 areas</td>
<td>3 areas</td>
<td>4 areas</td>
</tr>
<tr>
<td>CO₂ saving rate [%]</td>
<td>Recycling rate [%]</td>
<td>Recycling cost [%]</td>
<td></td>
</tr>
<tr>
<td>Target ranges of the CO₂ saving rate [%]</td>
<td>0~100%</td>
<td>33%~66%</td>
<td>50~75%</td>
</tr>
<tr>
<td>0~25%</td>
<td>25~50%</td>
<td>75~100%</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Design example

This subsection explains the solutions obtained from the experiments. Table 1 shows the input data such as the recycling cost and the CO₂ saving rate for each part, and the results of the disassembly parts selection. The circles “○” in Table 1 denote the selected parts for recycling, while the non-marked indicates the destroyed parts without the recycling cost. 10 solutions are obtained from the numerical experiments since 10 target ranges of
the CO₂ saving rate are set in 4 patterns. The 3 solutions in patterns 3) from 0% to 33% and from 33% to 66%, 4) from 50% to 75% are duplicated with ones of other solutions as shown in Table 1. It is assumed that the part #19 motor is always disassembled and removed from the percentage of CO₂ saving rate as well as Igarashi et al. (2014) since it has too high CO₂ volumes (95% of the whole volumes). To disassemble #19 motor in the parts selection, the 3 parts including #16 upper filter, #17 lower filter and #18 protection are selected in all solutions because the 3 parts are preceded to #19 motor as shown in Fig. 3.

From Table 1, it observes that a solution at pattern 1) all ranges selects 54% of the whole weight for recycling, and has the total CO₂ saving rate \( E = 59.80\% \) and total recycling cost \( C = 153.75 \), respectively. In addition, PP is recycled by 396.48 [g], while all parts made of Al/Al alloy are not selected. Figure 3 shows that the updated disassembly precedence relationships in bi-objective for CO₂ saving rate and cost at pattern 1) all ranges. The parts with slash line shows the canceled parts by the disassembly parts selection. That is, these canceled parts are crushed without cost for disposal.

In another case of pattern 4) division into 4 areas from 25% to 50%, the selected parts have 79% of the whole product weight, and bring the total CO₂ saving rate \( E = 50.21\% \) and recycling cost \( C = 127.34 \), respectively. With respect to the total CO₂ saving rate, the differences between them is only 9.59%. The recycled weights of PP and Al/Al alloy are different by 367.15 [g] and 55.1 [g], respectively. In a rate of recycled weight against contained weight, the differences of them becomes 56.74% and 33.63%, respectively. Thus, it is found that obtained types of materials, recycled weights for each material and cost are different by each target range given.

### 4. Comparison of bi-objectives for CO₂ saving rate vs. recycling cost and recycling rate vs. cost

This section compares the results of 2 different bi-objectives for recycling rate and cost in Kinoshita et al. (2016) and for CO₂ saving rate and recycling cost in order to find whether there are any similar or different cost effectiveness for recycled materials between CO₂ saving and recycling rates. As shown in Table 1, each part has different CO₂ saving and recycling rates and cost. By adding recycling rate \( r_j \) of selected parts, the total recycling rate \( R \) is also obtained in this study for CO₂ saving rate and recycling cost. For example, the total recycling rate \( R \) at pattern 1) all ranges in this study becomes 50.99% by adding the recycling rate \( r_j \) of the selected 8 parts as shown in Table 1. As using the similar way, the total CO₂ saving rate \( E \) in Kinoshita et al. (2016) is also calculated.

The total CO₂ saving and recycling rates for the total recycling cost in this study and Kinoshita et al. (2016) are shown in Figs. 4a and 4b, respectively. The marks “□” and “△” in Figs. 4a and 4b indicate the plots for recycling rate and cost by Kinoshita et al. (2016), and for CO₂ saving rate and cost in this study. The both of vertical axises mean the total recycling cost \( C \), while the horizontal axises mean the total CO₂ saving and recycling rates, respectively. All solutions in Fig 4a are the same as ones in Fig. 4b. However, all plotted locations are different between Figs. 4a and 4b since the horizontal axises are different.

From Figs. 4a and 4b, it can be observed that the recycling cost generally increases as the recycling and CO₂ saving rates increase in both cases. Also, it turns out the green line with triangle marks is generally located under the blue line with square marks in Fig. 4a since the bi-objective in this study has priority to select the parts with higher CO₂ saving rate but lower recycling cost. For example, the part #12 mesh filter with higher CO₂ saving rate by 19.28% but recycling rate by 0% has more priority than ones of the parts #9 left and #10 right bodies and is selected in all solutions except the solution with the lowest total CO₂ saving rate.

On the other hand, the blue line with square marks is generally located under the green line with triangle marks in Fig. 4b due to the similar reasons. Hence, the #9 left and #10 right bodies are selected for all solutions in Kinoshita et al. (2016). The sum of the recycling rate of these parts are 25.68% with recycling cost by 54.00.

Even though the general behaviors in both cases in Figs. 4a and 4b become similar, there are not the same plots in both Figs. 4a and 4b. One of the reasons is that the combinations of the selected parts for CO₂ saving rate and recycling cost are not duplicated with ones for recycling rate and cost in Kinoshita et al. (2016). Figures 2b and 2c show that results of recycled materials in bi-objectives for recycling rate and cost and for CO₂ saving rate and cost at pattern 1) all ranges, respectively. By comparing the selected materials at the pattern 1) all ranges in the bi-objectives for CO₂ saving rate and cost and for recycling rate and cost as shown in Figs. 2b and 2c, it turns out that the selected material and weight are different. For example, parts made of Al are selected by 47.17
[g] for recycling in the bi-objective for recycling rate and cost in Kinoshita et al. (2016), while these parts made of Al are not selected in this study.

By setting the different environmental objective functions such as maximizing CO$_2$ saving and recycling rates, the different recycled materials are obtained, even though the similar trends such as increasing the total recycling cost as the CO$_2$ saving or recycling rates increase are observed.

![Fig. 4a Trends of the recycling cost for CO$_2$ saving rate: case of bi-objective optimization by goal programing](image-a)

![Fig. 4b Trends of the recycling cost for recycling rate: case of bi-objective optimization by goal programing](image-b)

Additionally, a square shaped plot with the highest CO$_2$ saving rate is located under than one with the 2nd highest CO$_2$ saving rate as shown in Fig. 4a. This is caused that the differences between CO$_2$ saving and recycling rates of #11 dust case cover made of PMMA. As shown in Table 1, the CO$_2$ saving rate about 17 out of 23 parts is lower than the recycling rate for each part. The solution with highest total CO$_2$ saving rate contains #11 dust case cover, while one with the 2nd highest CO$_2$ saving rate contains #7 switch and #8 left handle instead of #11 dust case cover. It finds out from Table 1 that the CO$_2$ saving rate of #11 dust case cover is higher than the sum of the CO$_2$ saving rate of #7 switch and #8 left handle, while the recycling cost of #11 dust case cover is lower than the sum of the recycling cost of them. Therefore, the differences between CO$_2$ saving and recycling rates
can increase total CO\(_2\) saving rate in the bi-objective optimization for recycling rate and cost despite decreasing the recycling cost.

By focusing on the differences between the CO\(_2\) saving and recycling rates for each part as shown in Table 1, the parts made of cloth/fiber and rubber have the higher CO\(_2\) saving rate than the recycling rate. The rubber and cloth/fiber are difficult for material recycling, and the recycling rate of the parts made of them become 0%. By setting CO\(_2\) saving rate as an objective function, it is found that these parts made of rubber and cloth/fiber seem to be prioritized for recycling.

To investigate relationships between the recycling cost and recycled weights of these materials quantitatively in both results of CO\(_2\) saving rate and recycling cost and of recycling rate and cost, the more detailed material analysis is conducted in section 5.

5. Material based analysis of the results of disassembly parts selection

Section 5 conducts material based analysis for examining cost effectiveness for each recycled material by comparing the different bi-objectives for CO\(_2\) saving rate and cost and for recycling rate and cost. Additionally, bottlenecks, where drive down the cost effectiveness, are identified. Furthermore, improvement plans for the bottlenecks are suggested by using the disassembly precedence relationships and BOM.

5.1 Analysis of unit recycling cost for each material

From discussions of the subsection 3.2 and section 4, it finds out that the different target ranges and environmental objective functions collect the different material types and weights. Moreover, it finds out that there can be different recycled weights and cost for each part between CO\(_2\) saving and recycling rates. To identify the types of recycled materials, weight and recycling cost, subsection 5.1 conducts detailed material analysis of the disassembly parts selection based on the information obtained in Fig. 3 and Table 1. The recycling cost and recycled weights are used as indices to analyze each material type so as to pursue the cost effectiveness for recycled weights (= total recycling cost/recycled weight [cost/weight]) by the material type.

The target ranges and objective functions are set by a production designer. How does a production designer set targets ranges to express his/her objectives such as environment conscious for the CO\(_2\) saving or recycling rate, cost sensitive for the recycling cost or both of them? In order to examine the recycled materials among the different target ranges in both bi-objectives, 6 scenarios such as A) highest CO\(_2\) saving rate, B) highest recycling rate, C) harmonizing CO\(_2\) saving rate and cost, D) harmonizing recycling rate and cost, E) lowest recycling cost in this study and F) lowest recycling cost in Kinoshita et al. (2016) are set for the both bi-objectives for CO\(_2\) saving rate and cost or for recycling rate and cost, respectively to compare 6 solutions.

One solution is selected for each scenario as shown in Figs 4a and 4b. The harmonizing solution is defined as a solution with over 50% CO\(_2\) saving or recycling rates and lower by 50% than one when all parts disassembled. Those 2 solutions are obtained at pattern 1) all ranges respectively. According to Kinoshita et al. (2016), the pattern 1) all ranges for bi-objectives is expected to obtain the better solution than the other ones. Actually, the solutions allocated to the scenarios C) and D) harmonizing CO\(_2\) saving/recycling rates and cost are located on just middle of both CO\(_2\) saving or recycling rates and cost as shown in Figs. 4a and 4b.

That is, solutions for the scenarios A) highest CO\(_2\) saving rate, C) harmonizing CO\(_2\) saving rate and cost and E) lowest recycling cost are obtained at patterns 4) from 75% to 100%, 1) from 0% to 100% and 4) from 0% to 25% in this study, respectively. In contrast, the solutions for the scenarios B) highest recycling rate, D) harmonizing recycling rate and cost and F) lowest recycling cost in Kinoshita et al. (2016) are obtained at patterns 4) from 75% to 100%, 1) from 0% to 100% and 4) from 0% to 25% in Kinoshita et al. (2016), respectively.

After that, the obtained 6 scenarios are analyzed in terms of the recycled material type, weights and recycling cost, respectively. It is noted that acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), cloth/fiber and rubber are excluded from this material analysis since the weights of these material contained is too lighter than 100 [g] as shown in Fig. 2a. The motor is also excluded from the material analysis since it is contained by only part such as #19 motor in the whole product. Therefore, this material analysis is conducted for 16 parts with
3 types of materials, namely PP, PMMA and Al/Al alloy in this study.

Figure 5 shows recycled weights [g] for each material in 6 scenarios. It is observed that both PMMA and Al/Al alloy are not recycled at the scenarios E) lowest recycling cost in this study and F) lowest recycling cost in Kinoshita et al. (2016). Table 2 shows unit recycling cost [cost/weight] for each material in 6 scenarios. The unit recycling cost for each material is shown in Table 2 from the 2nd to 4th columns, and is calculated by dividing the total recycling cost with recycled weights for each material as shown in Fig. 5. Thus, the unit recycling cost can be also considered as an unit urban mining cost. If the unit recycling cost can be lower than the unit virgin material production cost, it means that circular economy is boosted by recycling. The lower unit recycling cost is obtained when the heavier recycled weights is gotten at the same cost. In order to identify scenarios to have higher or lower cost effectiveness for the recycled weights, the unit recycling cost in Table 2 are divided into 3 groups: (I) Lowest, (II) Middle and (III) Highest unit recycling cost. Therefore, the 5 unit recycling cost without underline are belonged to group (I) lowest unit recycling cost. The 4 unit recycling cost with underline are belonged to group (II). The rest of 4 unit recycling cost with dashed underline are belonged to group (III) highest unit recycling cost.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Unit recycling cost per weight [cost/weight]</th>
<th>PP</th>
<th>PMMA</th>
<th>Al/Al alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A) Highest CO₂ saving rate</td>
<td>0.52</td>
<td>1.08</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>Scenario B) Highest recycling rate</td>
<td>0.50</td>
<td>1.45</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>Scenario C) Harmonizing CO₂ saving rate and cost</td>
<td>0.39</td>
<td>4.20</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Scenario D) Harmonizing recycling rate and cost</td>
<td>0.39</td>
<td>0.87</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td>Scenario E) Lowest recycling cost in this study</td>
<td>2.81</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Scenario F) Lowest recycling cost in Kinoshita et al. (2016)</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Fig.5 Recycled weights for each material in 6 scenarios

Group (I) Lowest unit recycling cost

The 5 unit recycling costs from 0.15 to 0.52, which are shown without underline, belong to the group (I) lowest recycling cost. The unit recycling cost at scenario F) lower recycling cost in Kinoshita et al. (2016) is the lowest such as 0.15. It is shown that all unit recycling cost at group (I) lowest recycling cost are obtained by PP. Thus, the cost effectiveness for the recycled weights at PP can be higher than the other materials because a rate of the recycled PP on weight becomes more than 55% (≒ 355 [g]) at any scenarios except the scenario E) lowest recycling cost in this study.
There are 3 reasons of the higher rate of recycled PP. One reason is that 11 out of 23 parts of the vacuum cleaner are made of PP. Another one is the 1st and 2nd heaviest parts are made of PP (#9 left and #10 right bodies) with higher CO$_2$ saving and recycling rates. The environmental indices such as CO$_2$ saving and recycling rates become higher as the weights become heavier generally. For example, the CO$_2$ saving and recycling rates of #9 left body is 1.9 and 3.1 times higher than average of them, respectively. The last reason is that the 1st and 2nd heaviest parts made of PP have only 0 and 1 preceding part as shown in Fig. 3. Therefore, it is considered that they are not constrained by the disassembly precedence relationships. For the 3 reasons, the recycled weights of the heaviest material PP is collected economically. Consequently, the unit recycling cost of PP is the lowest in all scenarios in both bi-objective cases. It is considered that the heaviest materials can be collected environmentally friendly and economically to set either maximizing recycling rate as an objective function or environmental target ranges higher such as from 75% to 100%.

Therefore, it is found that the unit recycling cost of the heaviest material becomes the lowest in spite of setting different environmental objective functions such as maximizing the total CO$_2$ saving or recycling rates.

**Group (II) Middle unit recycling cost**

The group (II) middle unit recycling cost is consisted from the 6th to 9th lowest unit recycling cost such as 0.87, 1.08, 1.45 and 1.55 in Table 2. These unit recycling costs have underline as shown in Table 2. Also, 3 out of them are obtained by PMMA. From Fig. 3, it is found that there are only 2 parts made of PMMA. Even though the heavier one made of PMMA, namely #14 dust case, has 3 preceding parts, it is selected for recycling as shown in Fig. 5 at 3 scenarios. One of the reasons is that the average CO$_2$ saving and recycling rates of parts made of PMMA is 2.1 times and 1.8 times higher such as 9.15% and 7.43% than average ones for all parts, respectively. For this reason, it seems that materials such as PMMA, which have higher average of CO$_2$ saving or recycling rates than one of the whole product, are selected for recycling. Therefore, the parts made of PMMA are selected and the 3 out 4 unit recycling cost of PMMA belong to group (II).

The lowest unit recycling cost for Al/Al alloy is obtained from the group (II) at the scenario B) such as 1.55. However, the total recycling cost $C$ of Al/Al alloy at the scenario B) is the highest by 254.48 among ones at all scenarios. Therefore, it is considered that the unit recycling cost of materials such as PMMA, which have higher CO$_2$ saving and recycling rates, becomes higher than one of the heaviest contained materials but lower than one of other materials as shown in Table 2.

**Group (III) Higher unit recycling cost**

The group (III) higher unit recycling cost is consisted of 4 elements. 2 of them are obtained by Al/Al alloy. By focusing on the recycled weights of Al/Al alloy as shown in Fig. 5, it seems that collecting Al/Al alloy is more difficult compared to the other materials. One of the reasons is that averages of the CO$_2$ saving and recycling rates of part made of Al/Al are lower by 41% and 7% than ones of the whole product. Consequently, at scenarios A) highest CO$_2$ saving and B) recycling rates, the unit recycling costs with Al/Al alloy become higher than other materials even though the recycling cost for metals is cheaper generally. Furthermore, it can be considered that there are some bottlenecks preventing from collection Al/Al alloy with the cheaper recycling cost.

By analyzing the unit recycling costs for each group, there are 3 observed findings. One finding is that the unit recycling cost of the heaviest material becomes lowest regardless of an environmental objective function set for maximizing CO$_2$ saving or recycling rates. The next finding is that the unit recycling cost of materials, which have higher average of CO$_2$ saving or recycling rates, become higher than one of heaviest contained material but lower than ones of other materials. The last finding is that the unit recycling cost of metal can be higher than other ones of materials even though the recycling cost of metals is generally cheaper.

### 5.2 Identify bottlenecks and evaluate improvement plans

Based on the material analysis in subsection 5.1, it was found that the collecting Al/Al alloy was economically difficult in the case of the vacuum clear. This subsection identifies the bottlenecks by using BOM and disassembly precedence relationships as shown in Table 1 and Fig. 3 in order to collect Al/Al alloy economically.
By focusing on the recycling cost of 3 parts made of Al/Al alloy in Table 1, it finds out that each recycling cost of them is lower by 1.00%, 48.76% and 28.40% than the average cost, respectively in spite of 2 out of them requiring screwing as disassembly tasks. The recycling cost of these parts which require screwing task for disassembly tends to be higher because the task has longer disassembly time than other tasks such as moving up. The highest recycling cost is observed to disassemble #9 left body due to the 4 times screwing. Thus, it is said that the disassembly tasks of 3 parts made of Al/Al alloy are not bottleneck in this case. Also, it is found that the recycling cost of parts made of Al/Al alloy with screwing as disassembly tasks would not be higher due to higher material revenue.

Based on discussion about the disassembly tasks of 3 parts made of Al/Al alloy, there is a possibility that the number of preceding disassembly parts of them brings the higher recycling cost. By focusing on the 3 parts made of Al/Al alloy, it is found that each part has 2, 4 and 6 preceding parts, respectively. Specially, #23 fan containing heaviest Al/Al alloy of them has 6 preceding parts. Even though #23 fan contains the heaviest Al/Al alloy with the lower recycling cost by 28.40% than the average cost, the part could be recycled only scenario B) higher recycling rate in bi-objective for recycling rate and cost.

Therefore, it turns out that the number of preceding parts is bottlenecks for collecting Al/Al alloy economically in this case. For improving the bottlenecks in product design, it is considered to change the current disassembly precedence relationships as shown in Fig. 3 in order to decrease the number of disassembly preceding parts for the #23 fan. There is a fan module in the vacuum cleaner consisted of 4 parts including #20 rubber of outer flame of fan, #21 outer flame of fan, #22 lower fan and #23 fan. The fan module has 2 parts made of Al/Al alloy such as #21 outer flame of fan and #23 fan. However, there are 3 preceding disassembly parts such as #16 upper and #17 lower filters and #18 protection cap to disassemble the fan module as shown in Fig. 3. Thus, it is considered as one improvement plan to remove the 3 preceding disassembly parts by changing product structures. As the effect of the improved plan, the recycling cost to disassemble #23 fan could be lower by 48.08% than cost of current product structures. As another improved plan in production design is that the recycling cost of 3 parts such as #21 outer flame of fan, #22 lower fan and #23 fan is reduced by shorting the disassembly time of them with operation KAIZEN. Especially, the disassembly time of the immediate preceding part #22 lower fan should be shortened in order to remove succeeding #23 fan economically.

6. Conclusions

This study focused on materials removed from the EOL assembly products, conducted the environmentally friendly and economical disassembly parts selection by using goal programming. Next, the recycled material types, weights and recycling cost were analyzed in order to identify the bottlenecks for enhancing the cost effectiveness by comparing the bi-objectives for CO$_2$ saving rate and recycling cost and for recycling rate and cost. Finally, the improvement plans of identified bottleneck were proposed. The main findings of this study were as follows:

- Different targets ranges of CO$_2$ saving or recycling rates by goal programming obtained different types of materials, recycled weights for each material and cost in spite of setting the same objective functions for the CO$_2$ saving rate and recycling cost and for recycling rate and cost.
- There were different recycled weights and cost obtained from the disassembly parts selection between bi-objectives for CO$_2$ saving rate and recycling cost and for recycling rate and cost. The bi-objective for recycling rate and cost obtained the heaviest materials contained of the EOL assembly products, while the bi-objective for CO$_2$ saving rate and recycling cost obtained PMMA, which emits more GHGs emissions at material production phase.
- It found out that it was not found the obvious differences between the total CO$_2$ saving $E$ and recycling rates $R$ in terms of the total recycling cost in environmentally friendly and economical disassembly parts selection.
- The same trends were observed that the total recycling cost $C$ increased as the total CO$_2$ saving $E$ or recycling rates $R$ increased. However, there were not the same combinations of the selected parts in bi-objectives for CO$_2$ saving rate and cost for recycling rate and cost in Kinoshita et al. (2016).
The unit recycling cost of materials such as PMMA, which have higher CO\textsubscript{2} saving and recycling rates, became higher than one of the heaviest contained materials but lower than one of other materials.

The unit recycling cost of metal could be higher than other ones of materials even though the recycling cost of metals was generally cheaper due to disassembly precedence relationships or disassembly operations.

Even though the screwing as disassembly task causes higher recycling cost generally, the task was not bottleneck for the parts made of Al/Al alloy owing to higher revenue of materials in this case.

The cost effectiveness for the recycled materials such as Al/Al alloy can be higher by improving only related disassembly times and disassembly precedence relationships.

Future studies should expand the proposed bi-objective disassembly parts selection to a multi-objective one considering not only the recycling cost and the CO\textsubscript{2} saving rate but also the recycling rate, take into account the revenue of materials for the disassembly parts selection and material analysis, and apply Linear Physical Programming which is other method to solve multi-objective problems (Messac et al., 1996; Gupta and Ilgin, 2017).

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References


