Disassembly System Design with Environmental and Economic Parts Selection using the Recyclability Evaluation Method

Kento IGARASHI†1, Tetsuo YAMADA †1 and Masato INOUE†2

Abstract: To promote a closed-loop supply chain for assembled products, disassembly systems are required to recycle End-of-Life (EOL) products. To increase the total recycling rate of products in disassembly systems, it is desirable to keep rather than destroy parts since disassembly costs are increasing. Therefore, a disassembly system design should be considered based on selecting parts for disassembly in order to minimize the recycling cost while maintaining the recycling rate. On the other hand, since the precedence relationships among disassembly tasks also change according to the parts selection, it is required to consider allocation of the tasks in designing a disassembly line. For the disassembly system design, it is also necessary to have disassembled product information such as the recycling rate and profit of each part, disassembly task times and precedence relationships among the disassembly tasks. This study proposes a disassembly system design with environment and economic parts selection, which balances the recycling rate and cost using the Recyclability Evaluation Method (REM) developed by Hitachi, Ltd. The first step is to optimize the environmental and economic parts selection with integer programming, and the second step is line balancing to reduce the number of stations. Next, a design example is shown and discussed by preparing a 3D-CAD model for a computer and a cleaner. Finally, product and line evaluations are carried out by comparing four scenarios; namely 1) all parts disassembled, 2) maximum recycling rate, 3) minimum recycling cost and 4) balance of recycling rate and cost. It is demonstrated that the recycling cost is reduced as a result of maintaining a higher recycling rate and that the number of work stations and the smoothness index are also improved through use of environmental and economic parts selection.

Key words: Closed-loop supply chain, Recycling, Sustainable manufacturing, Integer programming, Line balancing

1 INTRODUCTION

To promote a closed-loop supply chain for assembled products, disassembly systems [1], [2] are required to recycle End-of-Life (EOL) products. However, most EOL products collected have little market value as reused parts due to their obsolescence caused by a long product lifecycle. Therefore, recycling-based disassembly systems are still necessary for economic material circulation [3]. To increase the total recycling rate of products in disassembly systems, it is desirable to disassemble rather than destroy parts, as disassembly costs are increasing. Therefore, a disassembly system design should be considered by based on selecting parts for disassembly in order to minimize the recycling cost while maintaining the recycling rate. For this design, disassembled product information is necessary such as the recycling rate, cost of each part, and the time and procedure for disassembly tasks. Nowadays, the recycling rate and cost of each part and the time for tasks can be calculated using the Recyclability Evaluation Method (REM) developed by Hitachi, Ltd. [4], [5], and the disassembly motion for disassembly tasks can be estimated using 3D-CADs (for example, SolidWorks [6]). In addition, under the disassembly parts selection, the allocation of tasks should be carried out since the precedence relationships among disassembly tasks changes according to the parts selection.

This study proposes a disassembly system design with environment and economic parts selection, which balances the recycling rate and cost using the REM.
2 OUTLINE OF DISASSEMBLY SYSTEM DESIGN WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING RECYCLABILITY EVALUATION METHOD

2.1 Recyclability Evaluation Method (REM)

Figure 1 shows the Recyclability Evaluation Method (REM) developed by Hitachi, Ltd. [4], [5]. The REM is software used to compute and estimate recycling rate and cost and disassembly time by inputting product information such as material type, weight and disassembly motion at each part. Nowadays, this product information can be obtained using 3D-CADs. In this study, we use SolidWorks [6].

In the REM software, the recycling rate is obtained by dividing the sum of the recycled weight of each part by the total weight of the product. In addition, the recycled weight of each part is obtained by the weight of each part and the recycling rate of the part material. On the other hand, the recycling cost is the difference between the recovered material prices and costs, where the costs consist of disassembly (labor), material process and disposal costs, respectively. If the recovered material prices are higher than the costs, the value of the recycling cost becomes negative, which means positive profits are earned as a result of the recycling.

2.2 Formulation of Environmental and Economic Disassembly Parts Selection

Based on the product disassembly data obtained using the REM, 0-1 integer programming [7] is used in this study for the selection of the parts disassembled or not in terms of the recycling rate and cost. The combinatorial solution which maximizes the total recycling rate but minimizes the total recycling cost of the product is examined to satisfy the constraints of the disassembly precedence relationships. In this study, it is assumed that there is only one disassembly task for each part. The notations of the disassembly parts selection used for the integer programming are as follows:

\[ c_j \] : Recycling cost of part \( j \)
\[ r_j \] : Recycling rate of part \( j \)
\[ R \] : Total recycling rate of product
\[ R_{\text{MAX}} \] : Maximum recycling rate of a product in all parts disassembled
\[ C \] : Total recycling cost of product
\[ N \] : Number of parts
\[ x_j \] : Binary value; 1 if part \( j \) is disassembled, 0 otherwise
\[ \varepsilon \] : Constraint of total recycling rate of selected parts
\[ P_j \] : Set of tasks that immediately precede task \( j \) at part \( j \)

The objective functions for minimizing the total recycling cost and maximizing the total recycling rate are respectively set as Eqs. (1) and (2):

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

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

Based on Nof et al. [8], the constraint of precedence relationships in this study are set as in Eq. (3). If precedence parts are crushed, their succeeding parts cannot be removed under the constraint in Eq. (3). For example, in case of the cleaner described in section 4, if part #1 is crushed, parts #2-#5 and #15 cannot be selected because they are structurally inside part #1 in the product. This is subject to:

\[
x_j - x_i \leq 0 \quad i \in P_j \tag{3}
\]

To solve this multiple objective optimization, the \( \varepsilon \)-constraint method [9] is used. Then, \( R \) is transposed to:

\[
R \geq \varepsilon \tag{4}
\]

Hence, the total recycling cost \( C \) of the product becomes the only objective function. Then, nonlinear optimization is performed for each of these combinations by changing \( \varepsilon \) gradually, and the function \( R \) searches for the Pareto optimum solution set.
3 DISASSEMBLY DESIGN PROCEDURE WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING REM

3.1 Overview

1) Construction and analysis of product recovery values with BOM
   a) Estimation of recycling rate and cost using REM
   b) Environmental and economic parts selection by integer programming with ε constraint
   c) Disassembly precedence relations with environmental and economic parts selection

2) Maximal cycle time

3) Condition on the number of stations

4) Line balancing with recycling rate

5) Line evaluation with product recovery values

Fig. 2 Design procedure of disassembly system with environmental and economic parts selection using REM

Figure 2 shows the design procedure of the disassembly system with the environmental and economic parts selection using the REM. The disassembly system design with environmental loads for CO₂ using PLM [2] is basically applied to this design and further developed to consider the environmental and economic parts selection using REM.

3.2 Disassembly Design Procedure with Environmental and Economic Parts Selection

According to the procedure shown in Figure 2, the details of the steps are as follows:

1) Construction and analysis of product recovery values with BOM

To realize the environmental and economic design of the disassembly system, this study applies environmental and economic parts selection for recycling rate and cost using the REM. Using the REM and 3D-CAD models as a PLM tool, collected EOL products/parts in the future will be able to be evaluated in advance for their recycling rate and cost as well as disassembly time at step a): estimation of recycling rate and cost using REM.

Based on the estimation at step a), it is necessary to construct a Bill of Materials (BOM) and add that information to the BOM. In the BOM, a product/part structure is shown, and each part in a list has a part number, part name and product recovery values such as recycling rate and cost, and disassembly time simultaneously. Using the BOM with the product recovery values, the environmental and economic parts selection is carried out at step b) via integer programming with ε constraint [7], [9]. The details of steps a) and b) are as follows:

a) Estimation of recycling rate and cost using REM

By inputting the parts information such as material type and weight from the 3D-CAD and the disassembly motion for each part, the REM calculates the recycling rate and cost, and the disassembly time, respectively.

b) Environmental and economic parts selection via integer programming with ε constraint

Using the integer programming with ε constraint [7], [9], the Pareto optimal solution is obtained for the recycling rate and cost. To harmonize the environmental and economic aspects in the obtained disassembly parts selection, four scenarios are considered here and discussed as follows: 1) all parts disassembled, 2) maximum recycling rate, 3) minimum recycling cost and 4) balance of recycling rate and cost.

To find a balanced solution for the recycling rate and cost among the alternative solutions obtained in scenario 4, a recycling efficiency \( RE \) is set and introduced as Eq. (5).

\[
RE = \frac{R}{C} \quad (5)
\]

The maximal solution for the recycling efficiency \( RE \) is chosen from the alternative solutions as the balanced solution for the recycling rate and cost in scenario 4.

c) Disassembly precedence relationships with environmental and economic parts selection

Based on the parts selection at step b), the disassembly precedence relationships are made and updated to show canceled disassembly tasks with the non-selective parts.

2) Maximal cycle time

Similar to Ref. [2], the maximal cycle time \( CT \) is obtained by dividing the production planning quantity \( T_0 \) by the production planning period \( Q \) as well as the assembly/disassembly line designs as in Eq. (6).

\[
CT = \frac{T_0}{Q} \quad (6)
\]
3) Condition of the number of stations
The number of necessary stations $K_0$ is calculated by dividing the mean of total disassembly time $S_0$ by the maximal cycle time $CT$ as in Eq. (7), and rounded to the nearest minimal integer above.

$$K_0 = \left\lceil \frac{S_0}{CT} \right\rceil$$  \hspace{1cm} (7)

4) Line balancing with recycling rate
For the environmental and economic parts selection, the disassembly element tasks satisfying the disassembly precedence relationships are assigned to each station under the maximal cycle time. The disassembly precedence relationships are made and updated at step c): disassembly precedence relationships with the environmental and economic parts selection.

5) Line evaluation with product recovery values
To evaluate the alternatives of the disassembly system design, line and product evaluations are carried out. The balance delay and smoothness index [10] evaluate whether the service times among stations have the appropriate line balance. In addition, the recycling rate and cost and total disassembly time are evaluated as the product evaluation.

4 DESIGN EXAMPLE OF DISASSEMBLY PARTS SELECTION

4.1 Examples of Assembled Products and Environmental and Economic Disassembly Parts Selection using REM

Table 1 Example of BOM with product recovery values in the case of the computer

<table>
<thead>
<tr>
<th>No.</th>
<th>Part name</th>
<th>Recycling rate (%)</th>
<th>Disassembly time [sec]</th>
<th>Recycling cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fan controller</td>
<td>0</td>
<td>28.2</td>
<td>37.71</td>
</tr>
<tr>
<td>2</td>
<td>Cable</td>
<td>4.00</td>
<td>26.4</td>
<td>35.31</td>
</tr>
<tr>
<td>3</td>
<td>PCI board</td>
<td>0</td>
<td>3.0</td>
<td>3.94</td>
</tr>
<tr>
<td>4</td>
<td>HDD</td>
<td>27.27</td>
<td>4.2</td>
<td>-114.51</td>
</tr>
<tr>
<td>5</td>
<td>FDD</td>
<td>9.09</td>
<td>18.0</td>
<td>-15.83</td>
</tr>
<tr>
<td>6</td>
<td>CDD</td>
<td>18.18</td>
<td>18.0</td>
<td>-55.83</td>
</tr>
<tr>
<td>7</td>
<td>Switch</td>
<td>0</td>
<td>15.6</td>
<td>21.09</td>
</tr>
<tr>
<td>8</td>
<td>Big fan</td>
<td>18.18</td>
<td>28.2</td>
<td>-42.29</td>
</tr>
<tr>
<td>9</td>
<td>Big fan cover</td>
<td>1.82</td>
<td>27.6</td>
<td>35.71</td>
</tr>
<tr>
<td>10</td>
<td>Small fan</td>
<td>9.09</td>
<td>28.2</td>
<td>-2.29</td>
</tr>
<tr>
<td>11</td>
<td>Inside switch</td>
<td>0.91</td>
<td>15.6</td>
<td>20.69</td>
</tr>
<tr>
<td>12</td>
<td>Speaker</td>
<td>5.45</td>
<td>28.2</td>
<td>35.31</td>
</tr>
<tr>
<td>13</td>
<td>Memory</td>
<td>0</td>
<td>4.8</td>
<td>6.51</td>
</tr>
<tr>
<td>14</td>
<td>Motherboard</td>
<td>0</td>
<td>56.4</td>
<td>75.09</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>93.99</td>
<td>302.4</td>
<td>40.61</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>6.45</td>
<td>21.6</td>
<td>5.25</td>
</tr>
</tbody>
</table>

Table 2 Example of BOM with product recovery values in the case of the cleaner

<table>
<thead>
<tr>
<th>No.</th>
<th>Part name</th>
<th>Recycling rate (%)</th>
<th>Disassembly time [sec]</th>
<th>Recycling cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wheel</td>
<td>0.99</td>
<td>16.2</td>
<td>21.77</td>
</tr>
<tr>
<td>2</td>
<td>Wheel stopper</td>
<td>0.24</td>
<td>15.0</td>
<td>20.06</td>
</tr>
<tr>
<td>3</td>
<td>Upper nozzle</td>
<td>3.52</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>4</td>
<td>Lower nozzle</td>
<td>2.89</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>5</td>
<td>Nozzle</td>
<td>2.41</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>6</td>
<td>Right handle</td>
<td>3.42</td>
<td>10.2</td>
<td>13.37</td>
</tr>
<tr>
<td>7</td>
<td>Switch</td>
<td>0.32</td>
<td>10.2</td>
<td>13.37</td>
</tr>
<tr>
<td>8</td>
<td>Left handle</td>
<td>3.62</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>9</td>
<td>Left body</td>
<td>13.10</td>
<td>27.6</td>
<td>36.51</td>
</tr>
<tr>
<td>10</td>
<td>Right body</td>
<td>12.58</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>11</td>
<td>Dust case cover</td>
<td>2.56</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>12</td>
<td>Mesh filter</td>
<td>0</td>
<td>13.2</td>
<td>18.41</td>
</tr>
<tr>
<td>13</td>
<td>Connection pipe</td>
<td>3.30</td>
<td>15.6</td>
<td>17.31</td>
</tr>
<tr>
<td>14</td>
<td>Dust case</td>
<td>12.29</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>15</td>
<td>Exhaust tube</td>
<td>2.24</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>16</td>
<td>Upper filter</td>
<td>0</td>
<td>13.2</td>
<td>18.37</td>
</tr>
<tr>
<td>17</td>
<td>Lower filter</td>
<td>2.05</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>18</td>
<td>Protection cap</td>
<td>1.56</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>19</td>
<td>Motor</td>
<td>19.14</td>
<td>13.2</td>
<td>10.50</td>
</tr>
<tr>
<td>20</td>
<td>Rubber of outer frame</td>
<td>0</td>
<td>13.2</td>
<td>18.63</td>
</tr>
<tr>
<td>21</td>
<td>Outer frame of fan</td>
<td>3.85</td>
<td>10.2</td>
<td>8.96</td>
</tr>
<tr>
<td>22</td>
<td>Lower fan</td>
<td>1.06</td>
<td>13.2</td>
<td>17.49</td>
</tr>
<tr>
<td>23</td>
<td>Fan</td>
<td>4.34</td>
<td>13.2</td>
<td>12.52</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>95.48</td>
<td>316.2</td>
<td>402.17</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>4.15</td>
<td>13.7</td>
<td>17.49</td>
</tr>
</tbody>
</table>

To validate the proposed design procedure of the disassembly system in sections 3 and 4, examples of assembled products are prepared. The prepared product examples in this study are a computer [11] and a cleaner [12]. The basic product/parts information is obtained via precedence relationships [11] and 3D-CAD [11], [12].

1) Construction and analysis of product recovery values with BOM

a) Estimation of recycling rate and cost using REM

Tables 1 and 2 show examples of BOM with the product recovery values in the cases of the computer and cleaner, respectively. By inputting the parts information such as material type and weight from the 3D-CAD and the disassembly motion for each part, the REM calculates the recycling rate and cost, and the disassembly time, respectively. For the recycling rate, it is found that several parts have a zero recycling rate in the cases of both the computer and cleaner. For the disassembly time, in the case of the computer, there are complicated tasks with longer disassembly times such for the motherboard.
Unlike the case of the computer, many tasks/parts in the case of the cleaner have the same disassembly times because of the same simple motions.

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

4.2 Environmental and Economic Parts Selection using Integer Programming with ε Constraint

Through use of integer programming with ε constraint, the Pareto optimal solution for the recycling rate and cost in the cases of the computer and cleaner, respectively.

The recycling rate is shown on the horizontal axis and the recycling cost is shown on the vertical axis. Each solution is obtained via each ε constraint.

c) Disassembly precedence relationships with environmental and economic parts selection

Based on the parts selection at step b), the disassembly precedence relationships are shown in Figures 5 and 6 with canceled disassembly tasks by the non-selective parts.

5 DESIGN EXAMPLE OF DISASSEMBLY SYSTEM WITH ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING REM

5.1 A Disassembly Problem of Disassembly System with Environmental and Economic Disassembly Parts Selection using REM

Based on the example of the assembled products for the computer and cleaner in section 4, an example of the disassembly problem is set and shown in Table 3 to analyze the effectiveness of the proposed design procedure.

Table 3 Example of disassembly problem for the computer and cleaner

<table>
<thead>
<tr>
<th>Product type</th>
<th>Production planning period (T_0)</th>
<th>Demands (Q) for collected EOL products during (T_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer</td>
<td>504,000 [sec] (=20 [days] (\times) 7 [hours] (\times) 3,600 [sec])</td>
<td>8,400</td>
</tr>
<tr>
<td>Cleaner</td>
<td>7 [hours] (\times) 3,600 [sec]</td>
<td>12,000</td>
</tr>
</tbody>
</table>

5.2 Design Example of Disassembly Line

2) Maximal cycle time

From the given production planning period and demands in Table 3, the maximal cycle time \(CT\) in the case of the computer is calculated as

\[
CT = \frac{504,000}{8,400} = 60 \text{[sec]}.
\]

(9)

Similar to the case of computer, the maximal cycle time in the case of the cleaner is obtained as \(CT=42\) [sec].

3) Condition of the number of stations

The minimal number of stations \(K_0\) is obtained by dividing the total disassembly time by maximal cycle time \(CT\). In case of the computer, total disassembly time is 302.4 [sec] as shown in Table 1. The minimal number of stations \(K_0\) calculated as

\[
K_0 = \left\lfloor \frac{302.4 \text{[sec]}}{60 \text{[sec]}} \right\rfloor = 6.
\]

(10)
Similar to the case of computer, the minimal number of stations in the case of the cleaner is obtained as $K_0=8$.

Figures 5 and 6 show the precedence relationships among disassembly element tasks after the environmental and economic parts selection in the cases of the computer and cleaner at scenario 4. The "x" marks in the figures indicate canceled disassembly tasks with the non-selective parts. In this study, disassembly parts arrayed in series are subject to the constrained precedence as shown in the constraint of Eq. (3) in section 2, while there are no constraints among parallel tasks. In Figures 5 and 6, the precedence relationships constrained by Eq. (3) are shown as solid-line arrows, while dotted-line arrows show no constrained relationships among the tasks. With the cleaner, it turns out that the selected disassembly tasks/parts are divided by each product module. One of the reasons is that its precedence relationships are arrayed in series.
4) Line balancing with recycling rate

Figures 7 and 8 show the respective results of the pitch diagram with and without the environmental and economic parts selection in the case of the computer. It is observed that the actual number of stations is decreased from six in scenario 1 to three in scenario 4 via the environmental and economic parts selection. Similar to Figures 7 and 8.

Figures 9 and 10 show the results for the case of the cleaner.

The actual disassembly task assignments to each station are carried out as shown in Figures 11 and 12 in the case of the computer and Figures 13 and 14 in the case of the cleaner.
5) Line evaluation with product recovery values

Tables 4 and 5 show the examples of the disassembly system design in the cases of the computer and cleaner, respectively. For the product evaluation, based on comparing the four scenarios it turned out that cases with the environmental and economic parts selection reduced the recycling cost by more than 355.4% in the case of the computer and 4.58% in the case of the cleaner. In the case of the computer, the recycling cost in scenario 4 is drastically smaller (581.2% smaller) than that in scenario 1 as a result of maintaining higher recycling rates (85.82% higher) because there are crushed parts with zero recycling rates such as the motherboard and PCI board. From the viewpoint of the recycling rate, the differences between the maximal and minimal recycling rates were within 82.38% for the four scenarios in the case of the cleaner, 10 times the figure of 8.18% in the case of the computer. It is considered that there is lower flexibility of the economic parts selection because precedence relationships are arrayed in series by each module in the case of the cleaner.

For the line evaluation, the number of work stations and the smoothness index in scenario 4, and the balance of recycling rate and cost were reduced and improved in the cases of both the computer and the cleaner as shown by
Fig.13 Precedence relations among assigned tasks for scenario 1: all parts disassembled in the case of the cleaner

Fig.14 Precedence relations among assigned tasks for scenario 4: balance of recycling rate and cost in the case of the cleaner

comparisons to scenario 1: all parts disassembled. One of the reasons is that most of the parts with higher costs also have longer disassembly times, and these tasks can form a bottleneck in line balancing. Therefore, it is considered that the bottleneck can be removed with destructive disassembly using the environmental and economic parts selection.

Finally, for all the product and line evaluations in this study, the possible influences of part/component structures and precedence relationships of the selected disassembly tasks can be quantitatively measured to evaluate not only the collected EOL products but also the disassembly line. It is well known that environmentally conscious product design promotes adoption of a parallel structure and/or sets the valuable parts outside structurally [14]. However, it is considered that a part of the possible influences on the disassembly system design could be quantitatively measured using the proposed design procedure.

6 CONCLUSIONS

This study proposed a disassembly system design with the environment and economic parts selection using the REM. The main conclusions were as follows:
• For the product evaluation, by comparing scenario 1 to 4, in the cases of both the computer and the cleaner, the environmental and economic parts selection reduced the recycling cost by more than 35.54% in the case of the computer and 4.58% in the case of the cleaner.
• By comparing the four scenarios, it was demonstrated that higher recycling rates were maintained in the case of the computer (85.82% higher) and of the cleaner (64.02% higher) in scenario 4. One of the reasons is that there were crushed parts with zero/lower recycling rates.
• For the disassembly line evaluation, the number of work stations and the smoothness index could be reduced because tasks with removed parts were the cause of bottlenecks in line balancing.
• The possible influences of part/component structures and precedence relationships among selected disassembly tasks in the product design phase could be quantitatively measured by evaluating not only the collected EOL products but also the disassembly line.

Future studies should focus on issues such as optimizing the task assignment in line balancing or minimizing CO₂ emissions through disassembly parts selection.

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