DISASSEMBLY SYSTEM DESIGN WITH OPTIMAL ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING LIFE CYCLE INVENTORY DATABASE BY INPUT-OUTPUT TABLES

Tetsuo Yamada*, The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan, tyamada@uec.ac.jp, (+)81-42-443-5269
Kento Igarashi, The University of Electro-Communications, Tokyo, Japan
Norihiro Itsubo, Tokyo City University, Yokohama, Japan
Masato Inoue, Meiji University, Kawasaki, Japan

ABSTRACT

To prevent global warming by supply chain, End-of-Life (EOL) assembly products should be disassembled environmentally and economically for material circulation (Wang and Gupta, 2011). This paper proposes a disassembly system design with an optimal environmental and economic parts selection which harmonizes collected CO2 volumes and recycling cost using a Life Cycle (LC) inventory database by the input-output tables (Yamada et al., 2012). The first step is to optimize the environmental and economic parts selection with the integer programming, and the second step is to carried out the line balancing for minimizing the number of stations.

Keywords: Low-carbon and closed-loop supply chain, Recycling, Environmentally-conscious manufacturing, Sustainable manufacturing, Integer Programming

INTRODUCTION

To prevent global warming by supply chains, End-of-Life (EOL) assembly products should be disassembled not only environmentally but also economically for material circulation [1]. With disassembly parts selection in recycling factories, parts/materials with higher CO2 volumes should be disassembled for environment if the CO2 volumes of each part can be estimated. On the other hand, ones with lower recycling cost should be also disassembled for economy if the recycling cost of each part can be estimated. In addition, a disassembly line balancing should be also carried out based on the optimal environmental and economic parts selection [2]. However, there is another design issue how to obtain product and environmental information such as the disassembly time and CO2 volumes. To overcome this issue, the Life Cycle (LC) inventory database by the input-output tables [3] and Recyclability Evaluation Method (REM) software developed by Hitachi. Ltd. [4] can be used.

This paper proposes a disassembly system design with the optimal environmental and economic parts selection which harmonizes collected CO2 volumes [3] and recycling cost [4] using the LC inventory database by the input-output tables. The first step is to optimize the environmental and economic parts selection with the integer programming [5], and the second step is to carried out the line balancing for minimizing the number of stations with the ranked positional weight heuristic [6].

DISASSEMBLY DESIGN PROCEDURE WITH OPTIMAL ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING LIFE CYCLE INVENTORY DATABASE BY INPUT-OUTPUT TABLES
This paper proposes a design procedure for a disassembly system with an optimal environmental and economic parts selection using LC inventory database by the input-output tables as shown in Figure 1. This design procedure consists of 2 main flows from upstream to downstream for the disassembly system design on the left side [3] and the environmental and economic parts selection on the right side [2]. In the environmental and economic parts selection, the LC inventory database by the input-output tables with the bill of materials [2] are adopted to estimate the CO2 volumes for each part as the environmental loads, while the Recyclability Evaluation Method (REM) software developed by Hitachi Ltd. [4] is used to estimate the disassembly times and recycling rates of each part.

The LC inventory database used in this study is calculated by the Japanese input-output tables [3]. 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 LC inventory database by the input-output tables. With the LC inventory database by the I/O tables, the CO2 volumes at each part are estimated with the product information such as prices and weights [3]. 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 [4]. 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 costs, the value of the recycling cost is negative which means positive profits earned by the recycling.

**FORMULATION OF OPTIMAL ENVIRONMENTAL AND ECONOMIC DISASSEMBLY PARTS SELECTION**

With the product disassembly data and CO2 volumes obtained by the LC inventory database [3] and the REM [4], 0-1 integer programming [4] is used in this study for the selection of the parts disassembled or not in terms of the CO2 volumes and the recycling cost similar to [2]. The combinatorial solution which
maximizes the collected CO2 volumes but minimizes the total recycling cost of the product is examined to satisfy the constraints of the disassembly precedence relation. The notation of the disassembly parts selection used for the integer programming is as follows:

- \( c_j \): Recycling cost at part \( j \)
- \( e_j \): CO2 volumes at part \( j \)
- \( E \): Total collected CO2 volumes at a product
- \( E_{\text{max}} \): Maximal CO2 volumes of a product in all parts disassembled
- \( C \): Total recycling cost at a product
- \( N \): Number of parts
- \( x_i \): Binary value; 1 if part \( i \) is disassembled, else 0
- \( \varepsilon \): Constraint of total CO2 volumes of selected parts
- \( A_1 \): An arc with constraints of disassembly precedence relation
- \( A_2 \): An arc without constraints of disassembly precedence relation
- \( P_j \): set of tasks that immediately precede part \( j \)

Similar to [2], the objective functions for minimizing total recycling cost and maximizing total CO2 volumes are respectively set as equations (1) and (2):

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

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

The constraint of the disassembly precedence relations are set as equations (3), (4) and (5) [2] based on Nof et al. [6]:

Subject to:  
\[ x_i - x_j \leq 0 \quad i \in P_j \]  \( \tag{3} \)

\[ A = A_1 \cup A_2 \quad (i, j) \in A \]  \( \tag{4} \)

To solve this multiple purpose optimization, \( \varepsilon \)-constraint method is used as well as [2]. The objective function \( E \) is made into the only objective function, a nonlinear optimization is performed to each of those combinations by changing \( \varepsilon \) gradually. The function \( E \) looks for the Pareto optimum solution set. Then \( E \) is transposed to

\[ E \geq \varepsilon \]  \( \tag{5} \)

DESIGN EXAMPLE OF DISASSEMBLY SYSTEM WITH OPTIMAL ENVIRONMENTAL AND ECONOMIC PARTS SELECTION USING LCI DATABASE BY INPUT-OUTPUT TABLES

To validate the proposed design procedure of the disassembly system, an example of the assembly product is prepared. A cleaner is prepared as an example of 3D-CAD model [7]. The production plan is also prepared as shown in Table 1.

To harmonize the environmental and economic aspects in the obtained disassembly part selection with the integer programming [2][8], four scenarios as well as [2] are here considered and discussed for the
product evaluation as follows: 1) All parts disassembled, 2) CO2 volumes maximum, 3) CO2 volumes and cost coexistence and 4) Recycling cost minimum. In the scenario 2) CO2 volumes maximum, a solution with the highest value of the total collected CO2 volumes at the product, $E$, is selected within the candidates whom their collected CO2 volumes is higher than 50 %. For the line evaluation, the disassembly line balancing is carried out by the ranked positional weight heuristic [6] for the selected disassembly parts at each scenario, respectively.

Table 1 Example of disassembly problem for cleaner

<table>
<thead>
<tr>
<th>Production Planning Period $T_0$</th>
<th>Demands $Q$ for Collected EOL products during $T_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,400 [min] ($= 20 \text{ days} \times 7 \text{ hours} \times 60 \text{ min}$)</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Figure 2 Behaviors of Recycling Cost for CO2 Volumes

Figure 3 Precedence relations among disassembly element tasks with optimal environmental and economic parts selection: Scenario 3) CO2 volumes and cost coexistence
Figure 4 Pitch diagram with optimal environmental and economic parts selection:
Scenario 3) CO2 volumes and cost coexistence

Figure 2 shows the Pareto optimal solution for the recycling cost and CO2 volumes in the experiment. While the collected CO2 volumes from the disassembled parts in one product are shown on the horizontal axis, the recycling cost is shown on the vertical one, where each solution is obtained by each ε constraint. Figure 3 shows the precedence relations among disassembly element tasks after the environmental and economic parts selection in the scenario 2, CO2 volume maximum. “x” marks in the figure means the canceled disassembly tasks with the non-selective parts. By using the disassembly precedence relations among the selected tasks, the disassembly line balancing is carried out by the ranked positional weight heuristic [5]. The assignment of each task to stations are also shown in Figure 3, and the pitch diagram with the optimal environmental and economic parts selection are drawn as shown in Figure 4.

Table 2 Example of disassembly system design using LC inventory database with input-output tables

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Scenario 1: All parts disassembled</th>
<th>Scenario 2: CO2 volumes maximum</th>
<th>Scenario 3: CO2 volumes and cost coexistence</th>
<th>Scenario 4: Recycling cost minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total disassembly time (sec)</td>
<td>316.2</td>
<td>219</td>
<td>102.6</td>
<td>52.8</td>
</tr>
<tr>
<td>Number of parts</td>
<td>23</td>
<td>16</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Constraint of required CO2 volumes [%]</td>
<td>100</td>
<td>90</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Actual CO2 volumes [g-CO2]</td>
<td>47579.28</td>
<td>47347.30</td>
<td>45729.71</td>
<td>46410.44</td>
</tr>
<tr>
<td>Recycling cost index</td>
<td>402.17</td>
<td>272.89</td>
<td>127.34</td>
<td>63.85</td>
</tr>
</tbody>
</table>

Table 2 show an example of the disassembly system design using the LC inventory database with the input-output tables. In the product evaluation, the total disassembly time and the number of disassembled parts basically decrease in order to reduce the recycling cost from scenario 1 to 4, so that the collected CO2 volumes also decrease as the recycling cost decreases. From the viewpoint of the CO2 volumes, there are a few differences between the scenarios within only 3.9%. However, the recycling cost at the scenarios 2 to 4 is 1.5 to 6.3 times lower than one at the scenario 1. One of the reasons is that a part “Motor” is the largest CO2 volumes among the all parts, therefore, the total CO2 volumes at the product is almost maintained as long as a part with the largest CO2 volumes such as the motor is selected and disassembled.
In the line evaluation, the disassembly line balancing is carried out by the ranked positional weight heuristic [6] for the selected disassembly parts at each scenario, respectively. As the total disassembly time and the number of disassembled parts basically decrease, the minimal and actual number of stations is decreased.

SUMMARY AND FUTURE STUDIES

This paper proposed the disassembly system design with the optimal environmental and economic parts selection which harmonized collected CO2 volumes and recycling cost using the LC 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 total collected CO2 volumes by selecting a disassembled part with the largest CO2 volumes.

Further study should evaluate the CO2 volumes of each part by the process base inventory database, use the LC inventory database by the input-output tables in the other countries, optimize the line balancing under the optimal environmental and economic parts selection, etc.

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REFERENCES