Material Based Low-Carbon and Economic Supplier Selection with Estimation of CO₂ Emissions and Cost Using Life Cycle Inventory Database

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Abstract : Recently, supply chains have come to be used globally, not only in developed countries such as Japan but also in emerging countries such as China. Supplier selections are one of the key decisions to be made in a strategic planning of the supply chains, where the manufacturers for assembly products have to select the suppliers that are appropriate for their specific purposes, especially for lower procurement costs of parts. Additionally, global warming is worsening due to increased greenhouse gases (GHG), CO₂ being the major culprit. In order to achieve a low-carbon society that is against global warming, it is necessary to reduce the CO₂ emissions across the globe by means of a low-carbon supply chain; before that, the CO₂ emissions in the supply chains should be visualized and used for any decision making in each process design. However, it is often difficult for assembly companies to share their environmental and cost information with their suppliers since there are other companies in the supply chains. For visualizing the CO₂ emissions, “Life Cycle Assessment (LCA)” and “Life Cycle Inventory (LCI) Database” have been established. According to the LCI database, the CO₂ emissions of the parts depend on types of materials and weights. Therefore, it is important to select the suppliers considering the types of materials and the weights for each part, in order to reduce not only the procurement cost but also the CO₂ emissions. This study proposes a low-carbon supplier selection method with an estimation of CO₂ emissions and cost based on material analysis, so as to aim to achieve both the procurement cost minimization and the CO₂ emissions reduction using the LCI database.

Key Words : Global Warming, Global Supply Chain, Assembly Products, Integer Programming, Life Cycle Assessment, Bills of Materials.

1. Introduction

Supply chain means a series of stages such as suppliers, manufacturers, distributors, retailers, and customers that are physically distinct and geographically separate, with whom inventory is either stored or converted into revenue. In addition, the supply chain consists of a coordinated set of activities, which are concerned with a procurement of raw materials, a production of intermediate and finished products, and a distribution of those products to the customers inside and outside the chain [1]. Operations in the supply chains and logistics are parts of today's most important economic activities, as they remain vital tools for businesses to remain competitive [2]. Furthermore, industries have been gradually shifting towards environmentally friendly supply chains by integrating green technologies into their product designs, productions, and distribution processes [3]. In addition, the supply chains have come to be used globally, not only in developed countries such as Japan but also in emerging countries such as China.

For a relationship between the suppliers and the manufacturers, supplier selections are one of the key decisions to be made

in a strategic planning of the supply chains that has far-reaching implications in subsequent stages of planning and implementations of supply chain strategies [4][5]. Therefore, the manufacturers of assembly products have to select the suppliers that are appropriate for their specific purposes, especially for lower procurement cost of parts. For example, China is Japan's largest trading partner, and many of the materials and the parts are procured from China and Japan [6].

Additionally, global warming is worsening due to increased greenhouse gases (GHG), the CO₂ being major culprits. In order to achieve a low-carbon society that is against the global warming by environmentally conscious manufacturing [7], it is necessary to reduce the CO₂ emissions across the globe by means of a low-carbon supply chain; before that, the CO₂ emissions in the supply chains should be visualized and used for any decision making in each process design [8].

For visualizing the CO₂ emissions, “Life Cycle Assessment (LCA)” and “Life Cycle Inventory (LCI) Database” have been established [9][10][11]. The LCA states that all environmental burdens connected with a product or a service have to be assessed, from the raw materials used to waste removal [12]. In addition, the LCI database demonstrates that representative unit process data on a national level or a regional level cover a wide range of industry [9]. There are mainly two types of the LCI databases: “Process” and “Input-Output (I/O) Tables.” The latter calculates environmental impacts, such as the CO₂ emissions, for certain products from an exchange of value ba-

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sis among industrial sectors based on the I/O tables for each country; Japanese [13] and Chinese [14] LCI databases have also been developed. In order to obtain the CO₂ emissions during each process as foreground data depending on different countries, companies and processes, all resources and energy of the input during each process have to be measured. However, it is not reasonable times, cost and efforts for getting these actual data. Also, it is difficult for assembly companies to share their environmental and cost information with their suppliers since there are other companies in the supply chains. To overcome effort issues in the LCA, in general, the representative and average CO₂ emissions for each material and weight are often obtained and used as background data using the LCI database [15]. According to the LCI database, the CO₂ emissions of the parts depend on the types of the materials and the weights. For reducing the CO₂ emissions in the supply chains, it is considered that one of the key managerial decisions is a low-carbon supplier selection by not only the procurement cost but also by the CO₂ emissions. Each part has a different procurement cost from the suppliers, and the CO₂ emissions for each part/material production depend on each country in the LCI database with the I/O tables because of an energy mix of the electric power [14]. In general, it is well known that the developed countries have the higher procurement cost and the lower CO₂ emissions for each part production, while the emerging countries have the lower procurement cost and the higher CO₂ emissions due to coal-fired power generations.

Recently the CO₂ emissions for each part of the LCI database in each region -such as Europe, Asia and Japan- have been able to be shown on a 3D-CAD such as SolidWorks [16]. However, the CO₂ emissions produced in each country in Asia are not calculated. For example, there is no distinction between China and the other Asian countries because China is included in the Asian region [16]. Moreover, the SimaPro [17] is the most widely used LCA software in the world. In the SimaPro, many inventory databases are equipped to analyze the LCA. However, most of the databases are in Europe and there are very few in Asian countries. For these reasons, the LCI database divided into each country by the I/O tables of China [14] and Japan [13] should be promoted and used for designing the low-carbon supply chain. However, since the information in the LCI database is published as only CO₂ emission intensities by each industrial sector and each material type, the CO₂ emissions for each part cannot be shown. Therefore, an estimation method using the LCI database in each country is also necessary in designing the low-carbon supplier selection.

With the product designs, the LCA is considered to already include material types [18]. With the supply chains, a greening of supply chain network designs and the logistics with the CO₂ emissions have been researched [2][19][20]. In addition, another research projects aim to empirically analysis drivers, practices and outcomes in German automotive suppliers [21] and incentives in British and Dutch subcontractors [22] for carbon emissions. However, a review paper [23] surveyed existing literatures and mentioned effectiveness by LCA-based information for early decision-making stages in procurements. A new green public procurement (GPP) scheme called the CO₂ Performance Ladder (CO₂PL) was introduced in the Netherlands. This result suggests that the (CO₂PL) could contribute significantly [24].

The LCI database has been used for a reverse supply chain for material circulation environmentally and economically [25][26][27][28]. However, the decision at the part procurement stage in a regular supply chain has not been treated for minimizing the procurement cost while reducing the CO₂ emissions. Also, another review paper has been researched to assess how well the existing model-based literature supports the global supply chain design problem [29]. One of the material based papers formulates a mixed integer program that minimizes the sum of the traditional supply chain costs and carbon trading costs with the LCA [30]. In spite thereof, most literature introduced in [29] and [30] have not espoused the CO₂ emissions based on the materials and the weights for each part as specific numerical value criteria even though the CO₂ emissions depend on the material types.

This study proposes the low-carbon supplier selection method with an estimation of CO₂ emissions and cost based on material analysis, so as to aim to achieve both cost minimization and CO₂ emissions reduction using the LCI database [13][14]. The outline of this paper is as follows: Chapter 2 explains the procedure of an environmental and economic supplier selection for the low-carbon supply chain using the LCI database. At first, an overview of a procedure for the environmental and economic supplier selection is explained, and next, the environmental and economic supplier selection is formalized as a 0-1 integer programming with ε constraint. In Chapter 3, a procedure for calculating the CO₂ emissions and selecting a low-carbon supplier is specifically shown. Chapter 4 deals with a design example for estimating the CO₂ emissions along with the proposed procedure. Chapter 5 estimates the CO₂ emissions by constructing the BOM and by identifying the types of material and the weights for each part. Then, we compare a pareto optimal solution for results in the supplier selection of the CO₂ emissions and the procurement cost in the case of cleaners. Finally, Chapter 6 concludes this study and proposes future works.

2. Procedure of Environmental and Economic Supplier Selection for Low-Carbon Supply Chain

2.1 Overview of Procedure for Environmental and Economic Supplier Selection with the I/O tables

In order to select the environmental and economic suppliers for the low-carbon supply chains between the developed and emerging countries, it is important to estimate the CO₂ emissions for each part produced in each country and to select suppliers for minimizing the procurement cost by constraining a targeted reduction ratio of the CO₂ emissions. This chapter explains an overview of the procedure and explains the formulation of the supplier selection.

Figure 1 shows the environmental and economic supplier selection procedure with the I/O tables using the LCI database proposed in this study.

The first stage is a constructed bill of material (BOM) with the CO₂ emissions using the LCI database, which is applied by [27]. In order to estimate the CO₂ emissions of each part for each industrial sector, this study uses the CO₂ emission intensity in the LCI database with the Chinese and Japanese I/O tables developed in [13][14].

The LCI database includes the emission intensity, which is

Fig. 1 The environmental and economic supplier selection procedure using the LCI database

the level of CO₂ emissions per unit of economic activity, measured at the national level as Gross Domestic Product (GDP) [31]. In general, the I/O tables define economic relationships by a matrix representation based on annual transactions among sectors, so that the CO₂ emission intensity for each industrial sector is obtained using the LCI database by the I/O tables. With the LCI database by the I/O tables, the CO₂ emissions at each part in this study are estimated with the product information, such as the material types, the procurement cost and the weights [28]. For estimating the CO₂ emissions of each part, it is also essential to grasp the procurement cost of each part in each country. However, the procurement cost is different for each country since economic conditions, such as exchange rate, are different between developed and emerging countries. Therefore, this study refers to the price level in each country [32], which means a value that represents a general price of a society as a whole on average with the price of an individual product/service.

The second stage is a low-carbon and economic parts/suppliers selection based on [26]. Each part is selected from two suppliers in either the emerging or developed countries. Here, it is assumed that each part is to be assigned to exactly one supplier. This study proposes to minimize the total production cost constrained to a targeted reduction ratio for the CO₂ emissions for one product.

According to the LCA, it is necessary to set a system boundary that shows a range and a limit of an investigation object [15]. A boundary of the LCI database with the Chinese and Japanese I/O tables assumed in this study is shown in Table 1. If the CO₂ emissions for each part are estimated, the stages of the life cycle are represented by a mark “○”, and it is assumed that the other life cycle stages are the same among prepared scenarios. This study focuses on the procurement stage since the CO₂ emissions at the material procurement level account for 39% at the product production level in a home appliance [15]. Also, this study assumes that a function of each part/product produced in different countries is the same and independent of production countries.

In general, decision makers for selecting the suppliers often consider some specific costs such as customs and import duty in the global supply chain management. However, the customs and the import duty have already been visualized in interna-

tional trades. At the same time, they also need to know the non-visualized relationships between the CO₂ emissions and the procurement cost. Therefore, this study focuses on the visualizing relationships between the CO₂ emissions and the procurement cost, so that it is assumed that there is no customs and import duty. On the other hand, there are other cases for “Free Trade Agreement (FTA)”, “Economic Partnership Agreement (EPA)” and “Regional Comprehensive Economic Partnership (RECP)” discussed in recent years [33], where the customs and the import duty is not required for the trades among those countries. Our study can be applied to these cases.

Table 1 Boundary of LCI database in this study

Life Cycle Flow	Procurement					Product		Usage	Disposal
	Raw Material Level	Material Logistics Level	Material Production Level	Part Production Level	Part Logistics Level	Product Production Level	Product Logistics Level	Use Level	Disposition and Recycling Level
CO ₂ Emissions	○	○	○	–	–	–	–	–	–

Figure 2 shows relationships among input/output information and results in the low-carbon and economic supplier selections proposed in this study. As for input, there are 3D-CAD data, a China-Japan I/O sectorial correspondence table, I/O tables in Japan, a LCI database using Chinese I/O tables and a LCI database using Japanese I/O tables. Then, a unit price of material, a procurement cost of parts in China and Japan, and CO₂ emissions of parts in China and Japan are obtained and used for stages 1 and 2.

For example, the material of parts affects the department name in Japan. The department name in Japan also affects the value of shipment, the quantity of shipment, the CO₂ emission intensity in Japan and the department name in China, respectively. As a result, the BOM with the CO₂ emissions is constructed by the procurement cost and the CO₂ emissions of the parts in China and Japan in stage 1. Then, each part is selected from each supplier in stage 2.

2.2 Formulation of Environmental and Economic Supplier Selection

Section 2.2 defines a method and formulation of the environmental and economic supplier selection to evaluate the low-carbon supply chain. In this study, the environmental and economic supplier selection for the low-carbon supply chain is treated at stage 2 as shown in Figure 1.

In order to minimize the total procurement cost within the constraints of the targeted CO₂ reduction ratio, the 0-1 integer programming [34] with ε constraint [35] is used in this study for a decision at each part, whether or not one of two alternative suppliers in each country is selected. A summary of the notation used in this study is set below:

J : Set of parts, $J = \{1, 2, \dots, j, \dots, |J|\}$

L : Set of suppliers, $L = \{1, 2, \dots, l, \dots, |L|\}$

M : Set of material, $M = \{1, 2, \dots, m, \dots, |M|\}$

l : Index of suppliers

j : Index of parts

m : Index of material

UP_{jm} : Unit price of material m at part j

Fig. 2 Relationships among input/output information and results in the low-carbon and economic supplier selection

PC_{jl} : Procurement cost of part j at supplier l

e_{jl} : CO₂ emissions of part j at supplier l

I_{CO_2jl} : CO₂ emission intensity of part j at supplier l

$P_{valuejm}$: Production value of material m at part j

$P_{volumejm}$: Production volume of material m at part j

n_j : Number of parts at part j

w_j : Weight of part j

PL_{jl} : Price level part j at supplier l

x_{jl} : Binary value; 1 if part j at supplier l is selected, 0 otherwise

R_{max} : Total CO₂ emissions of the initial configuration

$\varepsilon_{CO_2,c}$: Constraint of total CO₂ emissions

TPC : Total procurement cost

E : Total CO₂ saving rate at product

The objective functions for minimizing the sum of the procurement cost at each part and minimizing the total CO₂ emissions of the product consisting of each part are respectively set as Equations 1 and 2:

$$TPC = \sum_{j \in J} \sum_{l \in L} PC_{jl} x_{jl} \rightarrow \text{Min} \quad (1)$$

$$E = \sum_{j \in J} \sum_{l \in L} e_{jj} x_{jl} \rightarrow \text{Min} \quad (2)$$

Also, the constraint for not selecting the same parts from more than one supplier is set as Equation (3):

$$\sum_{l \in L} x_{jl} = 1 \quad \forall j \in J \quad (3)$$

To solve this multiple objective optimization, ε constraint method [35] is used in a similar manner to [26]. Then E is transposed to

$$E \leq \varepsilon_{CO_2,c} \times R_{max} \quad (4)$$

The objective function TPC is made into the only objective function; the optimization is performed to each of those combinations by changing ε gradually, such as to 94, 90, 80, ..., i.e., 50 (%) for each targeted reduction ratio. The optimization looks for the pareto optimum solution set.

3. Procedure of Environmental and Economic Supplier Selection for Low-Carbon Supply Chain Using LCI Database

3.1 Stage 1: BOM with Estimation of CO₂ Emissions and Cost

Chapter 3 first develops an estimation method for the CO₂ emissions using the LCI database to construct a BOM, which has the CO₂ emission information for each part on one product. After that, the low-carbon and economic supplier selection is conducted with the I/O tables in section 3.2.

As shown in Figure 1, the details of calculating the CO₂ emissions using the LCI database are as follows:

i) Identification of Department Name in Each I/O Table

The I/O tables in Japan have the information for production value and volume according to product/part types with the industrial sector names and numbers. The production value and volume mean the value and volume of industrial shipments per year on the I/O table in Japan. Also, the industrial sector number and name are different between the Chinese LCI database and the Japanese LCI database. Therefore, the Japanese industrial sector number and name are assigned to the Chinese industrial sector number and name using the correspondence table and the material type. Then, this information is added to the BOM of the product.

ii) Estimation of Procurement Cost for Each Part

Since the Japanese and Chinese procurement cost cannot be obtained from the 3D-CAD model as a cleaner [36], it is necessary to estimate the Japanese and Chinese procurement cost. By using the I/O table in Japan [28], the Japanese procurement cost is estimated in this study. Then, the Chinese procurement cost can be estimated using a price level in each country [32]. By referring to the price level in each country, the exchange rate assumes that the Chinese procurement cost is 0.500 times lower than Japanese procurement cost in this study.

The procurement cost of each part is estimated by multiplying the unit price of each material by the material weight of each part by the number of parts for each part. The unit price of each material is calculated by dividing the production value by the production volume on the I/O table in Japan [28]. Then, the procurement cost of the Japanese and Chinese parts is estimated with reference to the price level of each country [32]. The unit price of material m at part j , UP_{jm} , is set as Equation 5:

$$UP_{jm} = \frac{P_{value\ jm}}{P_{volume\ jm}} \quad (5)$$

The procurement cost of part j at supplier l , PC_{jl} , is set as Equation 6:

$$PC_{jl} = UP_{jm} \times n_j \times w_j \times PL_{jl} \quad (6)$$

iii) Estimation of CO₂ emissions for Each Part

Based on the sector name of each part in the product, CO₂ emission intensity [t-CO₂/million yen] is identified for each part on the I/O table in Japan [28]. Then, the CO₂ emissions [t-CO₂/ten thousand RMB] are identified for each part on the I/O table in China [14]. Finally, the value [t-CO₂/ten thousand RMB] is transformed to the value [t-CO₂/million yen]. The CO₂ emissions of part j at supplier l , e_{jl} , are set and introduced as Equation 7:

$$e_{jl} = PC_{jl} \times I_{CO_2\ jl} \quad (7)$$

3.2 Stage 2: Material Based Low-Carbon and Economic Supplier Selection

Section 3.2 designs a method for the low-carbon and economic supplier selection to decide whether the supplier within two countries is selected. As shown in Figure 1, the details of the steps for the low-carbon supplier selection are as follows:

iv) Integer Programming Formulation for Supplier Selection

As mentioned in Section 2.2, a supplier selection problem is here formulated by the integer programming [34] with ε constraint [35] in order to minimize the total procurement cost within the constraints of the targeted CO₂ reduction ratio, using the procurement cost of each part and the CO₂ emissions for each part.

v) Optimization by Mathematical Programming Package

By using the mathematical programming package developed by Numerical Optimizer [37], the supplier selection problem is optimized to minimize the total procurement cost under the targeted CO₂ reduction ratio.

4. Example of Estimation for CO₂ emissions Using LCI Database in China and Japan

4.1 Example Problem for Estimating CO₂ emissions Using LCI Database

Chapter 4 extracts data from the 3D-CAD to construct a BOM with CO₂ emissions. The product example is adapted to a cleaner model [36], which is assumed as a functional unit in the LCA [15]. Its basic product/parts information is obtained with a 3D-CAD such as SolidWorks [16]. In this study, part names, material names of part, numbers of part, and weights of parts are utilized with SolidWorks. Then, the BOM of an assembly product is constructed by using the parts, and Figure 3 shows the 3D-CAD data for the cleaner model [36].

Fig. 3 3D-CAD data: Case of cleaner model [36]
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Table 2 shows the BOM obtained with the 3D-CAD for the cleaner model [36]. In the case of the cleaner shown in Table 2, there are 23 parts and it is mostly composed of plastic parts such as polypropylene. With a weight for each part, a motor (#19) is the heaviest one and accounts for 20% of the total weight of the product. Moreover, the standard deviation of the CO₂ emissions and the production cost is larger because the material and weight are different depending on the parts.

4.2 An Example of Procedure for Estimating CO₂ Emissions Using LCI Database

Section 4.2 calculates the CO₂ emissions using the LCI database to set a supplier selection problem. According to the steps in Figure 1, the calculation results of the CO₂ emissions for a part at the proposed steps are developed and shown as

Table 2 BOM of cleaner obtained with 3D-CAD

PartNumber	Part Name	Material Number	Material Name	Number[piece]	Weight[g]
1	Wheel	1	Polypropylene	2	7.07
2	Wheel stopper	1	Polypropylene	2	1.71
3	Upper nozzle	1	Polypropylene	1	50.35
4	Lower nozzle	1	Polypropylene	1	41.25
5	Nozzle	1	Polypropylene	1	34.5
6	Right handle	1	Polypropylene	1	48.93
7	Switch	2	Polyvinyl chloride	1	4.65
8	Left handle	1	Polypropylene	1	51.7
9	Left body	1	Polypropylene	1	187.27
10	Right body	1	Polypropylene	1	179.88
11	Dust case cover	3	Methacrylate resin	1	36.57
12	Mesh filter	4	Carbon fiber	1	18.45
13	Connection pipe	5	Aluminum alloy	1	47.17
14	Dust case	3	Methacrylate resin	1	175.69
15	Exhaust tube	2	Polyvinyl chloride	1	32.04
16	Upper filter	4	Carbon fiber	1	17.74
17	Lower filter	1	Polypropylene	1	29.33
18	Protection cap	6	Polystyrene(ABS)	1	22.29
19	Motor	7	DC motors	1	279.27
20	Rubber of outer frame of fan	8	Synthetic rubber	1	22.85
21	Outer frame of fan	1	Polypropylene	1	55.11
22	Lower fan	1	Polypropylene	1	15.08
23	Fan	5	Aluminum alloy	1	62.1
Total				25.00	1421.00
Average				1.09	61.78
Standard deviation				0.29	71.77

a part example for the left side of the body (Part number: 9; Weight: 187.27 [g]; Number of parts: 1 [piece]; Material Number: 1 = Polypropylene; Supplier number: 1 = Japan or 2 = China) in the cleaner as follows:

i) Identification of Department Name in Each I/O Table

The material name “polypropylene” is related to the sector name in Japan, which is “thermoplastic resin” on the correspondence table and in the material type [28]. The sector name in Japan is related to the sector name in China, which is “manufacturer of synthetic materials” by the [14].

ii) Estimation of Procurement cost for Each Part

First, according to Equation 5, the unit price for material #1 at part #9, $UP_{9,1}$, is calculated as Equation 8. This is obtained from the BOM of the cleaner model [36] using the part number, $j = 9$, and the material number, $m = 1$, when the production value of material #1 at part #9, $P_{value9,1} = 408,459$ [million yen], and the production volume of material #1 at part #9, $P_{volume9,1} = 2,947,399$ [t].

$$UP_{9,1} = \frac{P_{value9,1}}{P_{volume9,1}} = \frac{408,459 \text{ [million yen]}}{2,947,399 \text{ [t]}} \quad (8)$$

$$\approx 0.1385 \text{ [yen/g]}$$

Second, according to Equation 6, the production cost of part #9 at supplier #1 and #2, $PC_{9,1}$ and $PC_{9,2}$, are calculated as Equation 9 and 10. This is obtained from the supplier number in Japan as 1 and in China as 2 respectively, when the unit price of material #1 at part #9, $UP_{9,1} = 0.1385$ [yen/g], the number of part #9, $n_9 = 1$ [piece], the weight of part #9, $w_9 = 187.27$ [g],

the price level part #9 at supplier #1, $PL_{9,1} = 1.00$, and the price level part #9 at supplier, $PL_{9,1} = 0.50$.

$$PC_{9,1} = UP_{9,1} \times n_9 \times w_9 \times PL_{9,1}$$

$$= 0.1385 \text{ [yen/g]} \times 1 \text{ [piece]} \times 187.27 \times 1.00 \quad (9)$$

$$= 25.95 \text{ [yen]}$$

$$PC_{9,2} = UP_{9,1} \times n_9 \times w_9 \times PL_{9,2}$$

$$= 0.1385 \text{ [yen/g]} \times 1 \text{ [piece]} \times 187.27 \times 0.50 \quad (10)$$

$$= 12.98 \text{ [yen]}$$

ii) Estimation of Procurement cost for Each Part

According to Equations 7, the CO₂ emissions of part #9 at supplier #1 and #2, $e_{9,1}$ and $e_{9,2}$, are estimated as Equations 11 and 12, when the production cost of part #9 at supplier #1, $PC_{9,1} = 25.95$ [yen], the production cost of part #9 at supplier #2, $PC_{9,2} = 12.98$ [yen], the CO₂ emission intensity of part #9 at supplier #1, $I_{CO_2,9,1} = 7.46$ [g/yen], and the CO₂ emission intensity of part #9 at supplier #2, $I_{CO_2,9,2} = 28.21$ [g/yen].

$$e_{9,1} = PC_{9,1} \times I_{CO_2,9,1}$$

$$= 25.95 \text{ [yen]} \times 7.46 \text{ [g/yen]} = 193.59 \text{ [g]} \quad (11)$$

$$e_{9,2} = PC_{9,2} \times I_{CO_2,9,2}$$

$$= 12.98 \text{ [yen]} \times 28.21 \text{ [g/yen]} = 366.17 \text{ [g]} \quad (12)$$

5. Material-based Analysis of CO₂ Emissions and Procurement Cost Using LCI Database in China and Japan: Case of Cleaner

5.1 Results of CO₂ Emissions of Each Part in China and Japan

Chapter 5 discusses the results of estimating the CO₂ emissions including their product characteristics and differences among

each part. Table 3 shows the BOM with the CO₂ emissions for each part in China and Japan in the case of the cleaner. In addition, Figure 4 shows the CO₂ emissions and percentage of the procurement cost for each part without a motor in the example of the cleaner. The percentage of the procurement cost means a proportion of the procurement cost of each part, with total procurement cost being 100%. These proportions are same for the cases between Japan and China. It is noted that the motor (#19) is removed as an exceptional value in Figure 4 since its CO₂ volumes are more than 100 times larger on average.

In Japan, it is shown at Figure 4 that the CO₂ emissions for part #12 mesh filter is 4.5 times higher than the average. The production cost for the part is the highest in all parts of the cleaner, so that the proportion of the production cost of the mesh filter (#12) is 19%. Similarly, the CO₂ emissions of the mesh filter (#12) are 5.6 times higher on average than in China. It is found that the parts with higher CO₂ emissions also have the higher proportion of production cost for each part. For this reason, if it is difficult to estimate the CO₂ emissions of some products/parts in other countries, but it may be partly predicted using characteristics with known LCI data in other countries.

Figure 5 shows the comparison of the CO₂ emissions between China and Japan by each material without a DC motor on the cleaner. A straight line indicates a level where the CO₂ emissions are the same considering the cost difference between China and Japan. As the distance from the straight line becomes longer on the upper side, the CO₂ emissions for the material produced in China are higher than those in Japan, considering the cost difference. In addition, some materials such as the carbon fiber and the aluminium alloy in Figure 5, their CO₂ emissions in China are higher than that in Japan by a respective 151% and 154% on average between China and Japan for each material. Thus, magnitude relation of CO₂ emissions is also identified within each material type.

5.2 Results of Supplier Selection and Pareto Optimal Solution for Procurement Cost and CO₂ Emissions

Section 5.2 summarizes the results of supplier selection to make differences clear in each country.

In the manufacturing of the cleaner, this study deals with a pair of procurement for Chinese and Japanese suppliers. As a baseline, it is assumed that Chinese suppliers are selected in all parts to minimize the procurement cost of parts. By using the procurement cost and the CO₂ emissions, the minimization of the procurement cost is formulated constrained to a targeted reduction ratio for the CO₂ emissions as the integer programming. This experiment of the supplier selection problem was conducted with a mathematical programming package, Numerical Optimizer developed by [37]. A pareto optimal solution is obtained by the bi-objective optimization [35]. Here, a data set for the optimal design of the low-carbon and economic supplier selection is prepared as follows:

The total CO₂ emissions of the initial configuration, $R_{max}=6024.20$, and Constraint of the total CO₂ emissions $\varepsilon_{CO_2,c} = \{94, 90, 80, 70, 60, 50\}$.

In constraint of the total CO₂ emissions of supplier selection as $\varepsilon_{CO_2,c} = \{94, 90, 80, 70, 60, 50\}$, there is no change in the appearance of supplier selection. This is because by changing the motor's supplier from China to Japan, more than 50% of

the CO₂ emissions can be reduced. One of the reasons is that the procurement cost and the CO₂ emissions for the motor are significantly high. For this reason, a supplier selection in this study is conducted without the motor (#19) to analyse a feature among the other parts.

Table 4 shows the bill of materials with the CO₂ emissions for each part in China and Japan without a DC motor in the case of cleaner. The selected supplier of Japan is represented by a mark "○", and the no mark means that the supplier of China is selected. It indicates that the suppliers are changed for 9 and 13 parts in the respective targeted CO₂ reduction ratios of 40% and 50% from China to Japan as the CO₂ emissions reduction rate is increased. In contrast, there are a few parts made in Japan for the mesh filter (#12), the connection pipe (#13), and the outer frame of the fun (#21) at the targeted CO₂ reduction ratio of 20%, and for the mesh filter (#12) and the upper filter (#16) at the reduction ratio of 30%. In addition, there is no supplier change for some parts like there was for the dust case cover (#11) in all cases. This is due to a different balance of the procurement cost and the CO₂ emissions for the whole product.

At Table 4, the Japanese mesh filter (#12) and the Japanese upper filter (#16) are continuously selected at the targeted CO₂ reduction ratio from 20% to 50% and from 30% to 50%, respectively. The mesh filter (#12) and the upper filter (#16) have the higher CO₂ emissions such as 1378.60 [g-CO₂] and 1325.66 [g-CO₂] in China, respectively. One of the reasons is that their material type is the carbon fiber. Since the carbon fiber has the higher CO₂ emission intensity, the parts made by the carbon fiber also have the higher CO₂ emissions. Therefore, when the targeted CO₂ reduction ratio is higher such as 20% and 30%, the Japanese parts are often selected in order to reduce the total CO₂ emissions.

On the other hand, some parts are non-monotonously selected even if the targeted CO₂ reduction ratio is monotonously increased. For example, the switch (#7) and the fan (#23) are selected from the Japanese supplier at the targeted CO₂ reduction ratio of 6% and 10%. However, these parts are not selected at the reduction ratio of 20% and 30%. After that, these parts are selected again at the reduction ratio of 40% and 50%. The similar selection behavior is seen for the connection pipe (#13).

Moreover, there are the parts selected once from Japanese suppliers such as the wheel stopper (#2) and the lower fan (#22). The wheel stopper (#2) and the lower fan (#22) are selected once from Japanese suppliers at the targeted CO₂ reduction ratio 10% or 40%, respectively. Since their CO₂ emissions and procurement cost are lower than ones in the other parts, it is considered that this is caused by adjusting the balance of both the CO₂ emissions and the procurement cost to satisfy the targeted CO₂ reduction ratio. For instance, it is difficult to satisfy the targeted CO₂ reduction ratio by selecting only the parts with the higher CO₂ emissions such as the mesh filter (#12) and the upper filter (#16) from Japan. In that case, the parts which have the lower CO₂ emissions are also selected for satisfying the targeted CO₂ reduction ratio.

Thereafter, Figure 6 shows a proportion of supplier selection by material types between China and Japan using Table 4. It indicates that there is no supplier change for the methacrylic resin and the synthetic rubber, and that the Chinese suppliers are always chosen. On the other hand, the proportion of Japanese supplier selection for the carbon fiber and the aluminium alloy

Table 3 The BOM with the CO2 emissions of each part in China and Japan: Case of cleaner

Part Number	Partname	Material Number	Material Name	Number [piece]	Weight [g]	Production Cost [yen]		CO2 Emissions [g-CO ₂]	
						Japan	China	Japan	China
1	Wheel	1	Polypropylene	2	7.07	1.96	0.98	14.62	27.65
2	Wheel stopper	1	Polypropylene	2	1.71	0.47	0.24	3.51	6.77
3	Upper nozzle	1	Polypropylene	1	50.35	6.98	3.49	52.07	98.45
4	Lower nozzle	1	Polypropylene	1	41.25	5.72	2.86	42.67	80.68
5	Nozzle	1	Polypropylene	1	34.5	4.78	2.39	35.66	67.42
6	Right handle	1	Polypropylene	1	48.93	6.78	3.39	50.58	95.63
7	Switch	2	Polyvinyl chloride	1	4.65	0.58	0.29	4.33	8.18
8	Left handle	1	Polypropylene	1	51.7	7.16	3.58	53.41	100.99
9	Left body	1	Polypropylene	1	187.27	25.95	12.98	193.59	366.17
10	Right body	1	Polypropylene	1	179.88	24.93	12.46	185.98	351.5
11	Dust case cover	3	Methacrylate resin	1	36.57	9.64	4.82	72.3	135.97
12	Mesh filter	4	Carbon fiber	1	18.45	59.9	29.95	452.84	1378.6
13	Connection pipe	5	Aluminum alloy	1	47.17	10.12	5.06	50.8	171.84
14	Dust case	3	Methacrylate resin	1	175.69	46.32	23.16	347.4	653.34
15	Exhaust tube	2	Polyvinyl chloride	1	32.04	4.01	2.01	29.91	56.7
16	Upper filter	4	Carbon fiber	1	17.74	57.59	28.8	435.38	1325.66
17	Lower filter	1	Polypropylene	1	29.33	4.06	2.03	30.29	57.27
18	Protection cap	6	Polystyrene(ABS)	1	22.29	4.37	2.18	32.6	61.5
19	Motor	7	DC motors	1	279.27	11208.93	5604.47	45284.08	157821.88
20	Rubber of outer frame of fan	8	Synthetic rubber	1	22.85	5.56	2.78	93.91	76.31
21	Outer frame of fan	1	Polypropylene	1	55.11	11.82	5.91	59.34	200.7
22	Lower fan	1	Polypropylene	1	15.08	2.09	1.04	15.59	29.34
23	Fan	5	Aluminum alloy	1	62.1	13.32	6.66	66.87	226.17
Total				25.00	1421.00	11523.04	5761.53	47607.73	163398.72
Average				1.09	61.78	501.00	250.50	2069.90	7104.29
Standard deviation				0.29	71.77	2334.31	1167.16	9421.28	32857.44

Fig. 4 The CO2 emissions and the percentage of the procurement cost of each part without the motor: Case of cleaner

are more than 50% as shown in Figure 6. This is caused by the fact that the CO₂ emissions in China are higher than those in Japan by 151% for the carbon fiber and 154% for the aluminium alloy, respectively, in considering the cost difference in Figure 5.

In Figure 7, the total procurement cost and the total CO₂ emissions of each optimization are confirmed as a trade-off relationship, while the total CO₂ emissions decrease as the total procurement cost increases. For example, the total procurement cost and the total CO₂ emissions are increased by 10.71 [yen]

and decreased by 196.33 [g-CO₂] from the targeted CO₂ reduction ratio from 6% to 10%, respectively.

As a result, managers are able to switch supplier in accordance with the targeted CO₂ reduction ratio using the bill of materials with the CO₂ emissions for each part. For example in this study, managers can identify and change the supplier for switch (#7), exhaust tube (#15), outer frame of fan (#21), and fan (#23) in order to decrease the CO₂ emissions by 6% at the cleaner.

Fig. 5 Comparison the CO₂ emissions between China and Japan by each material without the DC motor

Table 4 The BOM with the environmental impact of each part in China and Japan without DC Motor:
Case of cleaner

Part Number	Part Name	Material Name	Targeted Reduction Ratio for CO ₂ Emissions						
			0%	6%	10%	20%	30%	40%	50%
			Japan	Japan	Japan	Japan	Japan	Japan	Japan
1	Wheel	Polypropylene							
2	Wheel stopper	Polypropylene			○				
3	Upper nozzle	Polypropylene						○	○
4	Lower nozzle	Polypropylene						○	
5	Nozzle	Polypropylene							
6	Right handle	Polypropylene			○				○
7	Switch	Polyvinyl chloride		○	○			○	○
8	Left handle	Polypropylene							○
9	Left body	Polypropylene							○
10	Right body	Polypropylene							○
11	Dust case cover	Methacrylate resin							
12	Mesh filter	Carbon fiber				○	○	○	○
13	Connection pipe	Aluminum alloy			○	○		○	○
14	Dust case	Methacrylate resin							
15	Exhaust tube	Polyvinyl chloride		○	○				○
16	Upper filter	Carbon fiber					○	○	○
17	Lower filter	Polypropylene			○				○
18	Protection cap	Polystyrene (ABS)							
20	Rubber of outer frame of fan	Synthetic rubber							
21	Outer frame of fan	Aluminum alloy		○	○	○		○	○
22	Lower fan	Polypropylene						○	
23	Fan	Aluminum alloy		○	○			○	○
Total Procurement Cost [yen]			157.06	171.92	182.63	197.98	215.8	241.12	273.65
Total CO ₂ Emissions [g-CO ₂]			5576.84	5245.54	5049.21	4388.68	3760.8	3237.11	2804.37

Fig. 6 Proportion of supplier selection by material type between China and Japan: Case of cleaner

5.3 Supplier Switch Scenario by Material Type: CO₂ Emissions vs. Procurement Cost

According to the LCA [15], the CO₂ emissions for the parts depend on their material. Therefore, this section analyses the scenario of supplier switch by material type. By referring to Section 5.1 and Section 5.2, supplier change scenarios made in China for Japan are prepared as A) ~ E):

A) DC motor

Fig. 7 Pareto optimal solutions without the DC motor: Case of cleaner

B) Carbon fiber

C) Polypropylene

D) Methacrylic resin

E) Aluminium alloy

For example, the scenario B) Carbon fiber means that the mesh filter (#12) and the upper filter (#16) are switched at the same time from the Chinese to Japanese suppliers.

The supplier change scenarios are compared to consider the CO₂ emissions and the pareto optimal solution by a mathematical programming package, Numerical Optimizer [37]. At scenario A) DC motor, the CO₂ emissions are reduced by 67.2%.

However, the procurement cost increased by 97.2% because the proportion of the procurement cost and the CO₂ emissions for the DC motor is significantly high. Therefore, the supplier change scenarios are here discussed without the DC motor.

Figure 8 shows the pareto optimal solutions between the CO₂ emissions and the total cost without the DC motor. The selected points with the longer distance from the line on the upper right side mean a point with both the higher CO₂ emissions and procurement cost. It is observed that a supplier change for the aluminium alloy from the Chinese to the Japanese supplier is suitable at Scenario E) Aluminium alloy if the 6% reduction ratio of the CO₂ emissions is required.

In terms of the cost effectiveness for the CO₂ emissions, it is not stated that the CO₂ emissions are ineffective in reducing the CO₂ emissions in scenarios C) Polypropylene and D) Methacrylic resin. One of the reasons is that the CO₂ emissions are reduced by 10.8% and 5.5% while the procurement cost is increased by 28.9% in scenario C) Polypropylene and by 14.7% in scenario D) Methacrylic resin, respectively.

On the other hand, at scenario B) Carbon fiber, the CO₂ emissions cannot be partially reduced because their reduction ratio is 32.6% while their procurement costs increased by 37.4%. Within the prepared scenarios, it is said that the CO₂ emissions can be effectively reduced by 7.6% while the procurement cost increased by 11.2% at scenario E) Aluminium alloy. This is because the CO₂ emission intensity for the Chinese aluminium alloy is not significantly higher than that for the other materials. For example, the CO₂ emission intensity for the Chinese aluminium alloy and the carbon fiber is 33.96 [g/yen] and 221.77 [g/yen], respectively. In addition, the parts made of the aluminium alloy are not significantly heavier than the other parts. For example, the weights for the connection pipe (#13) and the fan (#23) are 47.17 [g/yen] and 62.10 [g/yen], respectively. Consequently, this enables a reduction of the total CO₂ emissions by changing the supplier from China because the CO₂ emission intensity of the material and the weights for those parts are lower, such that the CO₂ emissions also become lower.

Fig. 8 Comparison of pareto optimal solutions between scenarios of supplier switch without the DC motor

6. CONCLUSIONS

This study proposed the low-carbon supplier selection method with the estimation of CO₂ emissions and cost based on material analysis, so as to aim to achieve both cost minimization and CO₂ emissions reduction using the LCI database. At first, an overview of a procedure for an environmental and economic supplier selection was explained, and next, the environmental and economic supplier selection was formalized as a 0-1 integer programming with ϵ constraint. Finally, a pareto optimal

solution and supplier selection considering the CO₂ emissions and the procurement cost in cases of cleaner. The main conclusions are as follows:

- Product/Material values with BOM were constructed and analysed using the LCI database to design a low-carbon and economic supplier selection. For example, the material, the weight, and the CO₂ emissions for the left body in Japan are shown as the polypropylene, 187.27 [g] and 193.59 [g-CO₂], respectively. These results demonstrated that it was possible to calculate the CO₂ emissions using the LCI database.
- The parts with higher CO₂ emissions also had the higher proportion of the production cost of each part. For example, the CO₂ emissions of the mesh filter of part 12 was 4.5 times higher than average, and the proportion of the production cost of the mesh filter was 19%.
- The total procurement cost and the total CO₂ emissions of each supplier selection were confirmed as a trade-off relationship. In other words, as the total procurement cost increased, the total CO₂ emissions decreased. The total procurement cost had increased to 14.86 [yen], from 157.06 [yen] to 171.92 [yen], and the total CO₂ emissions had been decreased to 331.3.28 [g/CO₂], from 5576.84 [g/CO₂] to 5245.54 [g/CO₂], in order to achieve 6% reduction of the CO₂ emissions. These results showed that managers were able to switch suppliers in accordance with the reduction rate of the CO₂ emissions using the bill of materials with the CO₂ emissions of each part.
- This enabled us to reduce the total CO₂ emissions by selecting a supplier for the types of material while reducing the total procurement cost. The supplier change for the aluminium alloy was best for the 6% CO₂ reduction among the prepared scenarios, and the cost effectiveness for the CO₂ reduction ratio was also good in this study ' s example of cleaner in the experiments. It could effectively reduce The CO₂ emissions could be effectively reduced by 7.6% while the procurement cost increased by 11.2%. These results indicated that magnitude relation of CO₂ emissions is also identified within each material type.

One of further studies should consider the customs and the import duty for the international trades and the global supply chain management.

Another study should adopt the LCI database obtained at the other future years. One of the reasons is that the CO₂ intensity is changed by economic conditions and electric energy mixes among nuclear power, coals, oils, natural gas, renewable energy and so on. For example, all nuclear power plants were stopped in Japan since the great east Japan earthquake in 2011. Therefore, the CO₂ emission intensities for most of industries using the electric power might be increased at that year. Also, the Chinese one might be decreased if their main electric power switches from the coals to the natural gas with the lower CO₂ emissions.

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