Decision support model for economical material carbon recovery and reduction by connecting supplier and disassembly part selections

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Abstract

In the Internet of Things (IoT) era, manufacturers collect and share data to provide products that are more functional and less expensive. This embedded manufacturers to construct the global supply chain comprising suppliers, factories and recyclers to assemble products at a lower cost. On the other hand, global warming has become a serious environmental issue, and CO₂ emissions on the global supply chain should be visualized and reduced by life cycle assessment. However, CO₂ emissions vary for each country because of disparities in the energy mix. Therefore, manufacturers need to select appropriate suppliers for specific components, especially to ensure a lower procurement cost of parts and material-based GHG (GreenHouse Gas) emissions. Additionally, the economic model in the world shifts to circular economy which includes recycling the products economically because of the regenerative use for materials. If the parts inside the end-of-life (EOL) products are recycled, CO₂ emissions in the procurement stage can be recovered with recycling cost. Therefore, recyclers need a disassembly part selection that selects recycling or disposal for each part in order to recover CO₂ emission and reduce recycling cost in the EOL stage. Thus, certain product data, such as GreenHouse Gas (GHG) emissions and costs, needs to be shared with not only suppliers/factories but also recyclers by IoT technology on the global supply chain for connecting supplier and disassembly part selections. This study proposes a decision support model for economical carbon recovery by connecting supplier and disassembly part selections on procurement and EOL stages. First, a bill of materials (BOM) is prepared using an Asian supplier selection with the 3D-CAD model and Life Cycle Inventory (LCI) database. Second, disassembled parts of the EOL assembly products from the BOM data are selected for either recycling or disposal using 0-1 integer programming with ϵ constraint method. Finally, the results of the disassembly part selection, in terms of CO₂ emission reduction and costs are discussed.

Keywords: Life cycle inventory database, CO₂ emission, Recycling, Global supply chain, Sharing data, 3D-CAD model, Bill of materials

1. Introduction

The Internet of Things (IoT) technology boosts manufactures to collect and share numerous data to provide the products with more functional and inexpensive (Liu et al., 2017). In order to collect the data, sensor-embedded products are getting available, and the collecting data can be shared with suppliers, factories and recyclers (Tozanli et al., 2019). Not only the suppliers/manufactures for each part but also recyclers can share the data such as procurement costs and CO₂ emissions on the global supply chain. Therefore, in the IoT era, decision-making supports for supplier selection and disassembly part selection on product life cycle can be connected from the procurement to End-of-life (EOL) stages by visualizing the product data. On the other hand, due to mass production and mass consumption throughout the global supply chain, environmental issues such as global warming and resource exhaustion has become a serious global problem (UNFCCC), and manufacturers need to address these problems. In order to solve global warming, the 21st Conference of Parties in 2015 (COP21) which joined 188 countries was held to determine CO₂ reduction targets and related policies to achieve a sustainable society (UNFCCC). On the global supply chain, CO₂ emissions need to be visualized to reduce

ones (Itsubo et al., 2007).

As a visualization method of CO₂ emissions, life cycle assessment is one of the methods used to evaluate the environmental impact in a products' life cycle at procurement, manufacture, use and disposal (Itsubo et al., 2007). From a life cycle inventory (LCI) database, CO₂ emissions on a forward supply chain of assembled products such as TVs, mobile phones, or air conditioners accounted for more than 90% in the supply chain (SHARP, 2002). Additionally, each country has different CO₂ emissions at the material manufacturing stage due to varying energy mixes. A country's energy mix refers to the combination of energy sources, such as coal, gas, wind, and nuclear power, which meet the demands in each country (Kokubu et al., 2015). Generally, there are higher CO₂ emissions and lower procurement costs in emerging countries such as China, but there are lower CO₂ emissions and higher procurement costs in developed countries such as Japan at the parts procurement stage (Kokubu et al., 2015). Supplier selection, which is the process of selecting appropriate suppliers for specific components, is an important decision in the global supply chain, especially to ensure a lower procurement cost of parts and material-based GreenHouse Gas (GHG) emissions (Yoshizaki et al., 2016). Therefore, manufacturers need to construct a global supply chain consisting of suppliers from both emerging and developed countries to reduce procurement cost and CO₂ emissions simultaneously (Yoshizaki et al., 2014).

Moreover, the economic model in the world shifts to a circular economy from a "take, make and dispose" economic model (WORLD ECONOMIC FORUM). The circular economy includes recycling the products economically because of the regenerative use for materials. If the parts inside EOL products are recycled in the EOL stage, CO₂ emissions in the procurement stage can be recovered (Itsubo et al., 2007). This is because if the recycled materials are used for producing new products, procurement of virgin materials can be reduced. However, the recycling cost for each part is different since the recycling costs depend on different recycling operations at varying costs (Hiroshige et al., 2002) (Hitachi Ltd.). Therefore, recyclers need a disassembly part selection which means to either recycling for CO₂ recovery or disposal to reduce recycling cost in the EOL stage (Yamada, 2008). Reuse, remanufacturing, refurbishment, and repair often have higher environmental contribution than recycling. However, reuse of products can be applied to limited parts such as automotive and copiers because of reliability for the parts. Thus, recycling can be adopted for all parts, and the circular economy package which was published in 2015 as an economical strategy in EU contained not only reuse, remanufacturing but also recycling (European Commission). Additionally, if the parts inside the EOL products are recycled in the EOL stage, CO₂ emissions in procurement stage can be recovered according to Life Cycle Assessment (LCA) (Itsubo et al., 2007). This is because if the recycled materials are used for producing new products, procuring virgin materials can be reduced. Thus, this study focuses on recycling firstly instead of reuse.

There are two critical decision stages: one with supplier selection on the procurement stage, and the other with disassembly part selection on the EOL stage. Therefore, it is important to use IoT technology to share the data for CO₂ emissions and costs with not only suppliers and factories but also recyclers. This will enable a reduction in CO₂ emissions and costs simultaneously across the product life cycle stages and the global supply chain. In this study, a low carbon and economical evaluation is performed, and consider two methods to reduce the CO₂ emission on procurement and EOL stage. In order to pursue lower CO₂ emissions on the procurement stage, manufacturers can pay more to procure the parts from developed countries. On the other hand, to recover CO₂ emissions at the EOL stage, it is necessary to pay a higher recycling cost to recycle more materials from the EOL products. There are design issues:

- I. How to recover and reduce CO₂ emissions decided by both of procurement and EOL stages?
- II. Which ways are more effective for reducing CO₂ emission and cost?

This study proposes a decision support model for economical material-based carbon recovery by connecting supplier and disassembly part selections. The organization of this paper is as follows. Section 2 reviews literatures while section 3 explains the procedures of this study and formulation of both Asian supplier selection and disassembly part selection with ϵ constraint method. Section 4 sets cases and assumptions for using the proposed methods. Section 5 discusses the result of total CO₂ emissions and costs by supplier and disassembly part selection and makes comparisons between variable and fixed lot size. Finally, Section 6 concludes this study and develops future works.

2. Literatures review

This section explained the literatures review in order to clarify the originality of proposed model in this study. Table 1 shows literatures that related carbon recovery and reduction on the supply chain.

In table 1, on the procurement stage, Yoshizaki et al. (2014) proposed supplier selection for assembly products to

reduce CO₂ emissions and procurement costs. Kondo et al. (2017) estimated material-based procurement cost and GHG emissions in Asian countries by the LCI database. Kuo et al. (2017) conducted the low carbon supply chain design with estimated GHG emission by carbon foot print. Khoo et al. (2019) presented the sustainability assessment of various supply chains representing bio production by combining LCA and supply chain approach. Sugiyama et al. (2005) proposed a data treatment procedure for industry-based LCI databases in order to clarify how to use obtained statistical parameters. Nurjanni et al. (2017) designed the supply chain using a mathematical approach to deal with the environmental and financial issues. However, they considered only carbon reduction on the procurement stage.

Moreover, on the EOL stage, Igarashi et al. (2014) proposed a disassembly part selection for assembled products to recover CO₂ emissions and reduce recycling costs. Bringezu (2014) focused on the capture and use of CO₂ from waste management in order to explain the vision of future carbon recycling. Johansson et al. (2009) proposed a manual disassembly pre-step to improve the material recovery and evaluated it by the LCA methodology. Smith et al. (2016) considered sequential disassembly sequences in order to find the disassembly stopping point by mathematical modeling. However, they considered only recycling on the EOL stage. Additionally, Frey et al. (2006) used lifecycle assessment to analyze the CO₂ emissions of a mobile phone in order to clarify the effect of each stage. Ameknassi et al. (2016) developed a programming model with some strategic issues for supply chain management. Blass et al. (2017) compared the modeling approaches of LCA and supply chain management to clarify why LCA was important tool in the supply chain management. However, recovering CO₂ emissions by recycling on the EOL stage was not considered.

Previous studies considered supplier selection on the procurement stage and disassembly part selection on the EOL stage separately. However, it is necessary that two types of selections for supplier and disassembly part should be considered simultaneously. That is why material-based CO₂ emission is decided with selecting supplier for each part on the procurement stage. The originality of the proposed method is to consider both procurement and EOL stages simultaneously in order to recover and reduce carbon emission economically.

Table 1 Literatures that related carbon recovery and reduction on the supply chain

Literature	Life Cycle Stages				Evaluation Indices		Countries/Regions
	Procurement	Manufacturing	EOL		Cost	Environment	
			Dispose	Recycling			
Yoshizaki et al. (2014)	○				○	CO ₂ emissions	Japan and China
Kondo et al. (2017)	○				○	GHG emissions	Japan and China
Khoo et al. (2019)	○				○	GHG emissions, Substance of concern	US, China, Germany, Japan, Singapore and India
Kuo et al. (2017)	○	○			○	GHG emissions	Taiwan
Sugiyama et al. (2005)	○	○				CO ₂ emissions	-
Nurjanni et al. (2017)	○	○			○	CO ₂ emissions	-
Bringezu (2014)				○	○	CO ₂ emissions	Germany
Igarashi et al. (2014)			○	○	○	CO ₂ emissions	Japan
Johansson et al. (2009)			○	○		CO ₂ emissions, Recovering material	Sweden
Smith et al. (2016)			○	○	○	Environmental impact	-
Frey et al. (2006)		○	○	○		Direct land use (Resource consumption)	-
Ameknassi et al. (2016)		○		○	○	GHG emissions	-
Blass et al. (2017)	○		○			Carbon reduction	-
This study	○		○	○	○	CO ₂ emissions	Japan and China

3. Procedure for connecting supplier selection and disassembly part selection

3.1 Overview

In this section, the procedures are explained for integration of the supplier selection in procurement stage and disassembly part selection in the EOL stage. Figure 1 shows the proposed 2-stage method for evaluating Asian supplier selection and disassembly part selection focusing on carbon emissions and costs for this study. The procedures are conducted in two stages: stage 1 is Asian supplier selection for parts procurement, and stage 2 is disassembly part selection from EOL products.

The Asian supplier selection at stage 1 includes two steps. Step 1 calculates material-based CO₂ emissions and

procurement cost for each part at the material procurement stage using the 3D-CAD model and the LCI database with Asian international input/output (I/O) tables (Horiguchi et al., 2012). According to SHARP company's environmental report (SHARP, 2002), the CO₂ emissions of home appliance in the material production level accounts for more than 90% in the forward supply chain among logistics and manufacturing of material and product. Thus, the CO₂ emissions on the material production and transportation are considered using an international LCI database (Horiguchi et al., 2012) though parts transportation were not treated because of the limitation of the database. In step 2, a multi-criteria of optimal order quantity and the supplier selection for each part are carried out to minimize both CO₂ emissions at procurement stage and procurement costs based on Kondo et al. (2019).

After that, the disassembly part selection in stage 2 is conducted in three steps based on Igarashi et al. (2014). At step 1, the CO₂ saving rate for disassembly part selection is calculated by dividing total CO₂ emissions by emissions for each part which are indicated by the results of stage 1. Step 2 calculates the recycling costs for each part by using the Recyclability Evaluation Method (REM) (Hiroshige et al., 2002) (Hitachi Ltd.). Input data for REM are the weights, material types, and disassembly task types for each part. Finally, in step 3 the disassembly part selection is conducted to minimize recycling costs and achieve the target CO₂ saving rates by using 0-1 integer programming (Hiller and Lieberman, 2005) with ε constraint method (Eskandarpour et al., 2015).

Fig. 1 Proposed 2-stage method for evaluating Asian suppliers and disassembly part selections with carbon emissions and costs in this study

3.2 Evaluation of total CO₂ and cost

This section explains CO₂ and cost information with supplier and disassembly part selections. Table 2 shows the method of designing supplier and disassembly part selections. This is a bi-objective problem for lower CO₂ emission and cost. In this study, CO₂ and cost information are collected from the LCI database and REM. To solve the bi-objective problems in both stages, objective functions of CO₂ are changed by ε constraint method (Eskandarpour et al., 2015).

At stage 1, the bi-objective problem of supplier selection is to minimize CO₂ emission and procurement cost by deciding the order quantity for each part on the procurement stage. Stage 1 is to decide order quantities for each part by selecting the supplier to clarify how many parts should be procured from which supplier and country for minimizing CO₂ emission and procurement cost. Next, at stage 2, the bi-objective problem of disassembly part selection is to maximize CO₂ recovery volume and minimize recycling cost by selecting recycling or disposal for each part on the EOL stage. The objective of stage 2 is to select whether to recycle or dispose for each part. This is to clarify which lifecycle option is optimal, recycling or disposal, for maximizing CO₂ recovery volume and minimizing recycling cost. Additionally, for the total evaluation of the two stages, the bi-objective problem of this study is to achieve lower total CO₂ emission and total cost. Total CO₂ emission is calculated by the difference between procurement CO₂ emissions and CO₂ recovery volume, and total cost is calculated by the sum of procurement cost and recycling cost. Finally, the results are analyzed to clarify how to procure and recycle the parts economically and environmentally.

Table 2 Evaluation of supplier and disassembly part selections

		Stage 1: Supplier selection	Stage 2: Disassembly parts selection	Total evaluation for two stages
Bi-objective problems	CO ₂	Minimize material-based CO ₂ emission at procurement stage	Maximize recovered CO ₂ emission at disassembly stage	Pursue lower total CO ₂ emission on two stages
	Cost	Minimize procurement cost	Minimize recycling cost	Pursue lower total cost on two stages
Design parameter		Decide order quantity for each part by selecting suppliers	Select either recycle or dispose for each part	—
Decisions		How many parts procured from which supplier and country for minimizing CO ₂ emission and procurement cost?	Which lifecycle option is selected between recycling or disposal for maximizing recovery CO ₂ value and minimizing recycling cost?	How to procure and recycle the parts economically and environmentally?
Database		The 3D-CAD model and the LCI database with Asian international I/O tables	Recyclability Evaluation Method (REM)	—

The notation is explained in detail below:

j : Index of parts J

l : Index of supplier L

i : Index for predecessors of part j

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

e_{lj} : CO₂ emission at procurement stage of part j at supplier l

c_j : Recycling cost at part j

g_j : CO₂ saving rate at part j

x_{lj} : Quantity of part j transported at supplier l

y_j : Binary value; 1 if part j is recycling, or else 0

n_j : Quantity of part j needed for a product

$K_{product}$: Quantity of product demands

$Q_{min, lj}$: Minimum order quantity from supplier l for part j

P_j : Set of tasks that immediately precede task j at part j

$\varepsilon_{CO_2, s}$: Constraint of CO₂ emission in supplier selection

$\varepsilon_{CO_2, d}$: Constraint of CO₂ saving rate in disassembly part selection

$E_{procurement}$: CO₂ emission at procurement stage by product

$E_{procurement\ max}$: Maximum CO₂ emission of the initial configuration

$E_{recovery}$: CO₂ saving rate at EOL stage

TE : Total CO₂ emission on two stage

TPC : Total procurement cost

TRC : Total recycling cost

TC : Total cost on two stage

3.3 Formulation

Asian supplier and disassembly part selections are formulated in this section. Supplier and disassembly part selection are formulated to minimize the total CO₂ emission and cost in this study. Equations (1) and (2) are the objective functions in this study. Equation (1) represents the sum of procurement and recycling costs, while equation (2) shows the total CO₂ emissions on two stages which formulate the difference between procurement CO₂ emissions and recovery CO₂ volumes.

$$TC = TPC + TRC \rightarrow Min \quad (1)$$

$$TE = E_{procurement} - E_{recovery} \rightarrow Min \quad (2)$$

Then, The formulation of supplier and disassembly part selections as below:

Stage 1: Asian supplier selection for parts procurement

In stage 1, Asian supplier selection is formulated with ϵ constraint method. The problem has the bi-objectives to minimize CO₂ emissions and procurement cost based on the method by Kondo et al. (2019).

Equations (3) and (4) are the bi-objective functions for Asian supplier selection. Equation (3) minimizes the procurement cost. Equation (4) minimizes the CO₂ emissions from the procurement stage. To solve the bi-objective problem for the supplier selection, 0-1 integer programming (Hiller and Lieberman, 2005) with ϵ constraint method (Eskandarpour et al., 2015) is used. The objective function (4) is changed to constraint (5) to solve the bi-objective optimization. Optimization is performed by changing the target CO₂ saving rates to 20%, 40%, ..., 80%.

Equation (6) constrains the quantity of part x_{lj} which represents the number of parts needed to assemble the product. Additionally, equation (7) ensures that the amount transported, x_{lj} , is equal or over minimum order quantity, $Q_{min, lj}$.

$$TPC = \sum_{j \in J} \sum_{l \in L} PC_{lj} x_{lj} \rightarrow Min \quad (3)$$

$$E_{procurement} = \sum_{j \in J} \sum_{l \in L} e_{lj} x_{lj} \rightarrow Min \quad (4)$$

Subject to:

$$E_{procurement} \leq \epsilon_{CO_2, s} E_{procurement}^{max} \quad (5)$$

$$\sum_{l \in L} x_{lj} = n_j K_{product} \quad \forall j \in J \quad (6)$$

$$x_{lj} \geq Q_{min, lj} \quad \forall l \in L, \forall j \in J \quad (7)$$

Stage 2: Disassembly part selection for EOL products

Disassembly part selection of EOL products is conducted in stage 2. This section also formulizes disassembly part selection by using 0-1 integer programming (Hiller and Lieberman, 2005) with another ϵ constraint method (Eskandarpour et al., 2015) based on the method of Igarashi et al. (2014). Disassembly part selection is formulated in a bi-objective problem for minimizing total recycling costs and maximizing the CO₂ saving rate. It is solved with ϵ constraint method (Eskandarpour et al., 2015). The CO₂ saving rate is calculated as a rate of the CO₂ emission for each part in assembled products (Igarashi et al., 2014).

Equations (8) and (9) represent the bi-objective functions for the disassembly part selection. Equation (8) minimizes the sum of recycling cost. Equation (9) maximizes the sum of CO₂ saving rate. To solve the bi-objective problem, equation (9) is transposed to equation (10). Additionally, equation (11) represents the disassembly precedence relationship between tasks.

$$TRC = \sum_{j \in J} c_j y_j \rightarrow Min \quad (8)$$

$$E_{recovery} = \sum_{j \in J} g_j y_j \rightarrow Max \quad (9)$$

Subject to:

$$E_{recovery} \geq \epsilon_{CO_2, d} \quad (10)$$

$$y_i - y_j \geq 0 \quad i \in P_i \quad (11)$$

4. Product case and supply chain scenario for vacuum cleaner

4.1 Product example

In this section, a case study for a vacuum cleaner (Inoue et al., 2014) as shown at Figure A1 in Appendix A is applied to validate the proposed methods in this study. The proposed model can be applied to not only vacuum cleaner but also other assembly product. This is because the product parameters are based on the 3D-CAD model, and the CO₂ emission and costs for each part are calculated from the LCI database with Asian international input/output tables and REM. In this study, the case study of vacuum cleaner is verified in order to illustrate the effectiveness of the proposed model. Moreover, recycling for automotive and large home appliances such as TV, refrigerator, air conditioner and washing machine are already regulated, collected and operated by the laws in Japan. However, the small home appliances such as vacuum cleaner are not obligated to be recycled. Thus, it is known that the recovery amount was about 50% only to the target one (Ministry of Internal Affairs and Communications, 2017). Therefore, it is also important to illustrate the effect by recycling the small home appliance such a vacuum cleaner.

Table 3 shows the BOM of the vacuum cleaner (Kondo et al., 2019) (Igarashi et al., 2014) including part names, material types, weights, procurement costs, CO₂ emissions, and recycling costs for each part. These parameters are estimated by using the 3D-CAD model, LCI database with Asian international I/O tables (Horiguchi et al., 2012) and REM (Hiroshige et al., 2002) (Hitachi Ltd.). Additionally, table 3 indicates that part #9 (Left body) has the highest recycling cost of all parts, and part #21 (Outer flame of the fan) has the lowest recycling cost of all parts in the vacuum cleaner. The assumptions of the case study are set as follows:

Table 3 The bill of materials for vacuum cleaner (Kondo et al., 2019) (Igarashi et al., 2014)

No.	Part name	Material type	Weight [g]	Procurement cost [US\$]		CO ₂ emission [g CO ₂ -eq]		Recycling cost [US\$]
				Japan	China	Japan	China	
1	Wheel	PP	7.07	0.020	0.010	13.52	42.39	0.22
2	Wheel stopper	PP	1.71	0.005	0.002	3.27	10.25	0.20
3	Upper nozzle	PP	50.35	0.070	0.036	48.14	150.95	0.17
4	Lower nozzle	PP	41.25	0.057	0.030	39.44	123.67	0.17
5	Nozzle	PP	34.50	0.048	0.025	32.98	103.43	0.17
6	Right handle	PP	48.93	0.068	0.035	46.78	146.69	0.13
7	Switch	PVC	4.65	0.006	0.003	4.02	12.59	0.13
8	Left handle	PP	51.70	0.072	0.037	49.43	154.99	0.17
9	Left body	PP	187.27	0.260	0.134	179.04	561.43	0.37
10	Right body	PP	179.88	0.249	0.129	171.98	539.27	0.17
11	Dust case cover	PMMA	36.57	0.096	0.050	66.52	208.60	0.17
12	Mesh filter	Cloth/Fiber	18.45	0.599	0.310	390.38	2249.44	0.18
13	Connection pipe	Al/Al alloy	47.17	0.101	0.052	39.85	316.01	0.17
14	Dust case	PMMA	175.69	0.463	0.239	319.59	1002.14	0.17
15	Exhaust tube	PVC	32.04	0.040	0.021	27.67	86.76	0.17
16	Upper filter	Cloth/Fiber	17.74	0.576	0.298	375.36	2162.88	0.18
17	Lower filter	PP	29.33	0.041	0.021	28.04	87.93	0.17
18	Protection cap	ABS	22.29	0.044	0.023	30.15	94.54	0.17
19	Motor	Motor	279.27	112.089	57.950	29465.72	207446.13	0.11
20	Rubber of outer flame of fan	Rubber	22.85	0.056	0.029	50.44	235.83	0.19
21	Outer flame of fan	Al/Al alloy	55.11	0.118	0.061	46.55	369.20	0.09
22	Lower fan	PP	15.08	0.021	0.011	14.42	45.21	0.17
23	Fan	Al/Al alloy	62.10	0.133	0.069	52.46	416.03	0.13

- The CO₂ emissions for each part are different by a procured and manufactured country on the procurement stage.
- The procurement CO₂ emissions for each part can be recovered by recycling parts at EOL stage.
- Japanese and Chinese suppliers are available for each part to constitute the vacuum cleaner, China is the largest importer of Japanese products and also the second largest exporter of products to Japan (JETRO).
- Japan is the developed country which has higher cost and lower CO₂ emissions, while China is the emerging country which has lower cost and higher CO₂ emissions.
- Part #19 (Motor) is excluded in the case study for supplier and disassembly part selections. It means #19 (Motor) is always procured from Japan and the part #19 (Motor) are always recycled. This is because the CO₂ emissions of part #19 (Motor) accounts for more than 90% of the whole product.
- There are the precedence relationships among disassembly tasks of the vacuum cleaner as shown in Fig. 2 (Igarashi et al., 2014). The disassembly precedence relationship indicates that all precedence parts need to be disassembled before the subsequent parts are disassembled (Alqahtani et al., 2019). In Fig. 2, the solid arrows represent constrained precedence while the dotted arrows represent unconstrained relationships. This disassembly precedence relationship shown in Fig. 2 is addressed in Equation (11) at section 3.3. For example, to recycle part #2 (Wheel stopper), part #1 (Wheel) firstly has to be disassembled due to the precedence relationship.

Fig. 2 Disassembly precedence relationship: case of vacuum cleaner (Igarashi et al., 2014)

4.2 Scenarios of supplier selection and disassembly part selection

This section prepares cases of supplier selection and disassembly part selection. Four different cases for the supplier selection with variable lot sizes are evaluated in this study: 1) All Chinese supplier, 2) Supplier selection for 6% CO₂ reduction, 3) Supplier selection for 26% CO₂ reduction and 4) All Japanese supplier. The assumptions for supplier selection are as follows:

- The manufacturer assembles a total of 1,000 products, so that each part should be supplied to assemble 1,000 products.
- The parts #2 (Wheel) and #3 (Wheel stopper) are used for two parts per one product. Thus, the aforementioned parts are supplied for 2,000 parts.
- The initial suppliers are Chinese for all parts, with the highest CO₂ emission and lowest cost on procurement stage.

Scenario A) ‘All Chinese supplier’ refers to when all the parts are supplied from the Chinese suppliers. Due to the high CO₂ emissions and low cost of the Chinese suppliers, this scenario indicates the highest CO₂ emission (9,120 [kg CO₂-eq]) but the lowest procurement cost (1,620 [US\$]) within all scenario. On the other hand, the Scenario D) ‘All Japanese supplier’ refers to when all the parts are supplied from the Japanese suppliers. This scenario has the lowest CO₂ emission (2,030 [g CO₂-eq]) but the highest procurement cost (3.14 [US\$]) of all scenarios because the Japanese suppliers have the lowest CO₂ emission and highest procurement cost. Therefore, the scenarios B) ‘Supplier selection for 6% CO₂ reduction’ and C) ‘Supplier selection for 26% CO₂ reduction’ are compared to scenario A).

Moreover, the scenarios of the disassembly part selection are explained. In this study, six cases are presented where the target CO₂ saving rates are respectively 0%, 20%, 40%, 60%, 80% and 100% for each scenario in the supplier selection.

It is noted that 100% collection rate for the consumed assembled products is difficult in reality, and there is a lack of the material for the process of recycling. However, this study also assumes that all products are collected at the EOL stage, and all the parts in assembled products can be recycled without any material loss in the recycling process.

Therefore, four scenarios of the supplier selection and, six scenarios of disassembly part selection are prepared. Thus, 24 different cases with the supplier and disassembly part selections are examined and evaluated in terms of total CO₂ emissions and cost by connecting the two stages between procurement and EOL stages.

5. The results by 2-stage model: vacuum cleaner case

5.1 Total CO₂ emission and cost of the two stages

In this section, total CO₂ emissions and cost on two stages are analyzed to discuss the relationship of CO₂ emissions and cost between the procurement and EOL stages. Table 4 shows the results of total CO₂ emissions and cost at procurement and EOL stage. The total cost of the two stages represents the sum of the procurement and recycling costs as equation (1). Additionally, total CO₂ emissions of the two stages indicate the difference between the CO₂ emissions in the procurement stage and the CO₂ recovery volume in EOL stage as equation (2). In case 1) where all parts are procured from Chinese suppliers and discarded without recycling, the total cost was the lowest at 1,620 [US\$] while the total CO₂ emissions were highest at 9,120 [kg CO₂-eq]. On the other hand, in case 19) where all parts are procured from Japanese suppliers and discarded without recycling, the total cost increased by 95% from case 1) at 3,140 [US\$] but the total CO₂ emissions were reduced by 78% at 2,030 [kg CO₂-eq]. Without recycling, the total CO₂ emissions decreased by 78% due to a change in parts procurement from the Chinese to the Japanese suppliers.

Additionally, case 13) shows that CO₂ emissions were reduced by 2,371 [kg CO₂-eq], a reduction of 26% from one of case 1), by procuring some parts from Japanese suppliers and without recycling of any parts. In case 13), the total cost is 1,990 [US\$], and total CO₂ emission is 6,749 [kg CO₂-eq]. A similar CO₂ emission amount is observed in case 8) which showed emission of 6,748 [kg CO₂-eq], and it means that case 8) achieved almost 26% CO₂ reduction at the procurement and EOL stages. However, the total cost of case 8) was only 1,891 [US\$], and it shows the total cost at case 8) was 5% lower than the cost at case 13). Therefore, it was observed that there was a case where the same CO₂ emissions amount with a lower cost was achieved by connecting supplier and disassembly part selection compared to only selecting suppliers (Kondo et al., 2019).

5.2 Total recycling cost and CO₂ emission of the supplier and disassembly part selections

This section discusses the results of supplier and disassembly part selections for each scenario to investigate the case study of a vacuum cleaner. Table 5 shows the results of supplier selection for each case at stage 1. In scenario B) ‘supplier selection for achieving 6% CO₂ reduction’, 13 units of the part #13 (Connection pipe), 189 units of the part #16 (Upper filter) and 999 units of the part #20 (Rubber of outer flame of fan) were switched from Chinese to Japanese suppliers. By switching the suppliers, 6% of the CO₂ emissions (8,573 [kg CO₂-eq]) were reduced, though the procurement cost increased by 1,707 [US\$]. Next, in scenario C) ‘supplier selection for achieving 26% CO₂ reduction’, the supplier for 371 units of the part #13 (Connection pipe), 837 units of the part #16 (Upper filter) and 1,000 units of the part #20 (Rubber of outer flame of fan) were changed from the Chinese to Japanese suppliers. This resulted in CO₂ emissions as 6,749 [kg CO₂-eq] and 1,990 [US\$] for the procurement cost.

Table 4 Total CO₂ emission and cost of procurement and EOL stage

Case Number		1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)	12)	13)	14)	15)	16)	17)	18)	19)	20)	21)	22)	23)	24)
Stage 1 :Scenario of Green Procurement		A) All Chinese supplier						B) Supplier selection for achieving 6% CO ₂ reduction						C) Supplier selection for achieving 26% CO ₂ reduction						D) All Japanese supplier					
Stage 2: Scenario of CO ₂ Recovering		Target CO ₂ saving rate						Target CO ₂ saving rate						Target CO ₂ saving rate						Target CO ₂ saving rate					
		0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%
CO ₂	Procurement CO ₂ emission [kg CO ₂ -eq]	9,120						8,573						6,749						2,030					
	Stage 1																								
	Stage 2	0	2,162	4,624	5,728	7,360	9,120	0	1,825	4,259	5,360	6,912	8,573	0	1,518	2,765	4,425	5,404	6,749	0	422	832	1,230	1,642	2,030
	Total stage	9,120	6,959	4,496	3,393	1,760	0	8,573	6,748	4,314	3,213	1,661	0	6,749	5,231	3,984	2,324	1,345	0	2,030	1,608	1,198	800	388	0
Cost	Procurement cost [US\$]	1620						1707						1990						3140					
	Stage 1																								
	Stage 2	0	184	543	1,083	1,873	3,917	0	184	543	1,083	1,739	3,917	0	184	857	1,205	2,056	3,917	0	320	543	1,247	1,873	3,917
	Total stage	1,620	1,804	2,163	2,703	3,493	5,537	1,707	1,891	2,250	2,790	3,446	5,624	1,990	2,174	2,847	3,195	4,046	5,907	3,140	3,460	3,683	4,387	5,013	7,057
Total CO ₂ emission / cost		5.63	3.86	2.08	1.26	0.50	0.00	5.02	3.57	1.92	1.15	0.48	0.00	3.39	2.41	1.40	0.73	0.33	0.00	0.65	0.46	0.33	0.18	0.08	0.00
Total cost / CO ₂ emission		0.18	0.26	0.48	0.80	1.98	-	0.20	0.28	0.52	0.87	2.08	-	0.29	0.42	0.71	1.38	3.01	-	1.55	2.15	3.08	5.49	12.93	-

Table 6 shows the result of disassembly part selection for each result of the supplier scenarios at stage 2. In table 6, the circles signify that the parts are recycled in the case at stage 2. It is found that the part #16 (Upper filter) is always recycled for all scenarios in procurement when the target CO₂ saving rate is over 20%. This is because the part #16 (Upper filter) has either the 1st or 2nd highest CO₂ saving rate of all parts and has a higher recycling cost by only 3.4% more than the average recycling cost among all scenarios of supplier selection at stage 1. Additionally, according to the disassembly precedence relationship in Fig. 2, part #16 (Upper filter) has no preceding disassembly task and is not constrained by other parts. Thus, part #16 (Upper filter) can be recycled without removing other parts which would incur an additional recycling cost. It means that the target CO₂ saving rate can be achieved effectively if the parts with a higher CO₂ saving rate have no precedence task. Therefore, it was found that by considering the disassembly precedence relationship during the supplier selection at the procurement stage, the target CO₂ saving rate could be achieved with lower cost.

On the other hand, the results of disassembly part selection with cases 1) to 6) at scenario A) 'all Chinese supplier' and case 7) to 12) at scenario B) 'supplier selection for achieving 6% CO₂ reduction' are the same. However, the results with case 1) to 6) at scenario A) 'all Chinese supplier' and case 13) to 18) at scenario C) 'supplier selection for achieving 26% CO₂ reduction' differs slightly. For example, parts #11 (Dust case cover) and #12 (Mesh filter) are recycled in cases 4) and 10). However, parts #6 (Right handle), #13 (Connection pipe) and parts #14 (Dust case) are recycled instead of parts #11 (Dust case cover) and #12 (Mesh filter) in case 16). This is because there is a CO₂ saving rate of 35.5% of CO₂ for parts #11 (Dust case cover), #12 (Mesh filter) and #16 (Upper filter) in case 16) when 371 units of part #12 (Mesh filter) are procured from Japan. Additionally, when the parts are procured from China, they are often recycled, which enables greater recovery of CO₂ emissions. The reason is that the CO₂ saving rate can be decreased by selecting the Japanese parts when the parts are procured from Japan. At the same time, the CO₂ saving rate for the other parts procured from China was increased since the total CO₂ emissions of the vacuum cleaner was reduced. Therefore, if a company decides to recycle the parts, the parts should be procured from emerging countries to achieve a target CO₂ saving rate effectively.

Table 5 The results of supplier selection for each scenario at stage 1

Scenario of Green procurement		A) All Chinese supplier		B) Supplier selection for achieving 6% CO ₂ reduction		C) Supplier selection for achieving 26% CO ₂ reduction		D) All Japanese supplier	
No.	Part name	Japan	China	Japan	China	Japan	China	Japan	China
1	Wheel	0	2,000	0	2,000	0	2,000	2,000	0
2	Wheel stopper	0	2,000	0	2,000	0	2,000	2,000	0
3	Upper nozzle	0	1,000	0	1,000	0	1,000	1,000	0
4	Lower nozzle	0	1,000	0	1,000	0	1,000	1,000	0
5	Nozzle	0	1,000	0	1,000	0	1,000	1,000	0
6	Right handle	0	1,000	0	1,000	0	1,000	1,000	0
7	Switch	0	1,000	0	1,000	0	1,000	1,000	0
8	Left handle	0	1,000	0	1,000	0	1,000	1,000	0
9	Left body	0	1,000	0	1,000	0	1,000	1,000	0
10	Right body	0	1,000	0	1,000	0	1,000	1,000	0
11	Dust case cover	0	1,000	0	1,000	0	1,000	1,000	0
12	Mesh filter	0	1,000	13	987	371	629	1,000	0
13	Connection pipe	0	1,000	0	1,000	0	1,000	1,000	0
14	Dust case	0	1,000	0	1,000	0	1,000	1,000	0
15	Exhaust tube	0	1,000	0	1,000	0	1,000	1,000	0
16	Upper filter	0	1,000	189	811	837	163	1,000	0
17	Lower filter	0	1,000	0	1,000	0	1,000	1,000	0
18	Protection cap	0	1,000	0	1,000	0	1,000	1,000	0
20	Rubber of outer flame of fan	0	1,000	999	1	1,000	0	1,000	0
21	Outer flame of fan	0	1,000	0	1,000	0	1,000	1,000	0
22	Lower fan	0	1,000	0	1,000	0	1,000	1,000	0
23	Fan	0	1,000	0	1,000	0	1,000	1,000	0
CO ₂ emission [kg CO ₂ -eq]		9,120		8,573		6,749		2,030	
Procurement cost [US\$]		1,620		1,707		1,990		3,140	

Table 6 The result of disassembly part selection for each supplier scenario at stage 2

Case Number	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)	12)	13)	14)	15)	16)	17)	18)	19)	20)	21)	22)	23)	24)
Stage 1: Scenario of Green Procurement	A) All Chinese supplier						B) Supplier selection for achieving 6% CO ₂ reduction						C) Supplier selection for achieving 26% CO ₂ reduction						D) All Japanese supplier					
Stage 2: Scenario of CO ₂ Recovering	Target CO ₂ saving rate						Target CO ₂ saving rate						Target CO ₂ saving rate						Target CO ₂ saving rate					
	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%	0%	20%	40%	60%	80%	100%
1) Wheel						○						○						○						○
2) Wheel stopper						○						○						○						○
3) Upper nozzle						○						○						○						○
4) Lower nozzle						○						○						○						○
5) Nozzle						○						○						○						○
6) Right handle					○	○					○	○			○	○		○		○		○	○	○
7) Switch					○	○					○	○						○					○	○
8) Left handle					○	○					○	○						○					○	○
9) Left body				○	○	○				○	○	○			○	○	○	○				○	○	○
10) Right body				○	○	○				○	○	○			○	○	○	○				○	○	○
11) Dust case cover			○	○	○	○			○	○	○	○					○	○			○	○	○	○
12) Mesh filter			○	○	○	○			○	○	○	○					○	○			○	○	○	○
13) Connection pipe					○	○					○	○				○	○	○					○	○
14) Dust case					○	○					○	○				○	○	○					○	○
15) Exhaust tube					○	○						○						○						○
16) Upper filter		○	○	○	○	○		○	○	○	○	○		○	○	○	○	○		○	○	○	○	○
17) Lower filter						○						○					○	○						○
18) Protection cap						○						○					○	○						○
20) Rubber of outer flame of fan						○						○					○	○						○
21) Outer flame of fan						○						○					○	○						○
22) Lower fan						○						○						○						○
23) Fan						○						○						○						○
Total recycling cost [US\$]	0	184	543	1,083	1,873	3,917	0	184	543	1,083	1,739	3,917	0	184	857	1,205	2,056	3,917	0	317	543	1,216	1,873	3,917
CO ₂ recovery value [kg CO ₂ -eq]	0	2,162	4,624	5,728	7,360	9,120	0	1,825	4,259	5,360	6,912	8,573	0	1,518	2,765	4,425	5,404	6,746	0	422	832	1,230	1,642	2,030

Base line

○...The parts are recycled

5.3 The relationship with total CO₂ emissions and costs of the two stages

This section explains the relationship between total CO₂ emissions and costs of the two types by supplier and disassembly part selections. The relationship between the total CO₂ emissions and cost on the two stages are shown in Fig. 3. The reason why this study compares scenarios A) to D) is that the effect for connecting two types of decisions between the supplier selection on the procurement stage and disassembly part selection on the EOL stage are clarified. This is because in the previous studies the supplier or disassembly parts selection is separately evaluated. In Fig. 3, the vertical axis represents the total CO₂ emissions in the two stages, while horizontal axis represents the total cost in the two stages. As the total CO₂ emissions decrease, the total cost increases monotonically in all scenarios. Additionally, these results indicate the total CO₂ emissions of the two stages are almost similar for each scenario in terms of cost when the assembled product has higher CO₂ emissions can be reduced with only a little increase. For example, on case 2), the total CO₂ emissions are reduced by 2,162 [kg CO₂-eq] for a reduction of 23%, while the total cost increased by 184 [US\$] for an increase of 11% from case 1). However, in case 14), the total CO₂ emissions are reduced by only 1,518 [kg CO₂-eq] for a reduction of 23%, and the total cost increased by 184 [US\$] for an increase of 10% from case 13).

Additionally, scenario D) 'all Japanese supplier' has the lowest cost in all green procurement scenarios with the same total CO₂ emissions. Scenario D) 'all Japanese supplier' incurs the highest procurement cost but the lowest CO₂ emissions on the procurement stage. Moreover, cases 19) to 23) in the scenario D) produces lower CO₂ emissions with the same cost as well as the other scenarios from Fig. 3. Therefore, if the CO₂ emissions need to be reduced by more than 70%, it is recommended that the parts are procured from Japan and are recycled at EOL stage in order to obtain lower total cost.

5.4 Discussions

This section discusses about the theoretical contributions and the data quality of this study.

Theoretical contribution in this study is to clarify the effect by considering both supplier and disassembly part selections simultaneously. There are two points of the theoretical contributions in this study. At first, we found a case where the same CO₂ volumes emitted with lower costs were obtained by connecting the supplier selection on procurement stage and disassembly part selection on the EOL stage compared to the supplier selection only (Yoshizaki et al., 2014). Therefore, it is suggested that the product data such as CO₂ emissions and costs should be shared with not only suppliers/factories but also recyclers by IoT technology on the global supply chain. Secondly, it is demonstrated that if the parts are recycled on the EOL stage, the parts can be maintained to procure with lower costs from emerging countries

Fig. 3 The relationship between total CO₂ emissions and costs of the two selections across the all case

to achieve the target CO₂ saving rate economically.

As one of the validities for the results, the data quality is here discussed. Similar to Kondo et al. (2017), weights and number of each part can have higher accuracy by using the 3D-CAD models in this study. On the other hand, the unit material prices are used from the census of manufacture with the LCI database. Therefore, it is said that the unit material prices are not real at a process but is considered as representative unit process data (Horiguchi et al., 2012). Moreover, the recycling cost was also estimated value using REM (Hiroshige et al., 2002) (Hitachi Ltd.). Therefore, if actual data for the material price and the recycling cost are available, the result may become more precise.

6. Conclusions

This study proposed a decision support model for economical carbon recovery by connecting supplier and disassembly part selections. First, a BOM was provided by a 3D-CAD model and an LCI database with the Asian international I/O tables. Secondly, the disassembled parts selection of EOL assembly products was carried out by using 0-1 integer programming with ϵ constraint method to recover CO₂ emissions. Finally, the results of the supplier and disassembly part selection were discussed in terms of the product lifecycle.

- It was observed that there was a case where the same CO₂ emission at a lower cost was obtained by connecting supplier and disassembly part selections compared to only supplier selection. Therefore, the data of products such as GHG emissions and costs should be shared with not only suppliers/factories but also recyclers by IoT technology on the global supply chain to consider two types of selections simultaneously.
- To consider the disassembly precedence relationship at the supplier selection on the procurement stage, the target CO₂ saving rate can be achieved at a lower cost. For example, if the parts which have no precedence tasks are procured from emerging countries, the parts have a high CO₂ recovery volume and can recover the CO₂ volume without the incurring of an additional recycling cost of certain parts.
- If a company decides to recycle certain parts, the parts should be procured from emerging countries to achieve the target CO₂ saving rate effectively. This is because the CO₂ saving rates of the parts which are procured from developed countries can be decreased. At the same time, the CO₂ saving rates of the other parts procured from emerging countries are increased since the total CO₂ emissions of products are reduced. Therefore, if the company

decides to recycle the parts and the parts are procured from emerging countries, the procurement CO₂ emissions can be recovered on the EOL stage while saving the procurement cost.

Further study should apply the proposed model to the other product and consider the CO₂ emissions and costs in the transportation of the parts. Additionally, the disassembly precedence relationship should be considered on the procurement stage to reduce the total cost on two stages.

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Appendix A

Fig. A1 The structure of the vacuum cleaner (Inoue et al., 2014)

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