Problem of Modeling Global and Closed-Loop Supply Chain Network Design

Hiromasa Ijuin and Tetsuo Yamada

Abstract Nowadays, the economic activities cause some environmental problems for not only the global warming by Greenhouse Gas (GHG), but also the material starvation by mass consumption of resources. In order to resolve their problems simultaneously, Japanese government took effect with the plastic regulation and announced that GHG emissions became zero by 2050. In order for manufacturing companies to develop sustainably, they are required to design the Global Closed-Loop Supply Chain (GCLSC) network to recycle End-of-Life (EOL) products and reduce GHG emissions. The GCLSC network integrates the global supply chain network, which is a series of cross-border transaction of product, and the local reverse supply chain network, which is a domestic transaction for collecting and recycling EOL products. However, it is necessary to select appropriate global suppliers considering GHG emissions because the amount of material-based GHG emissions in EOL product is dependent on manufacturing country. On the other hand, the GCLSC network is costly for procurement, manufacturing, transportation, recycling and opening facilities costs. Thus, the decision maker who designs designing GCLSC network should consider not only cost, but also environmental aspects such as recycling EOL product and GHG saving weight simultaneously. This study designs the GCLSC network to minimize total cost and to maximize entire recycling rate on global and local supply chain network. Furthermore, the GHG emission from components procurement and the GHG saving weight by recycling EOL product is evaluated. First, the GCLSC network is modeled. Next, the objective function for minimizing total cost and maximizing entire recycling rate are formulated with integer programming. Finally, a numerical experiment is conducted and evaluated in terms of costs, entire recycling rate, and GHG emission.

Keywords Global supply chain · Reverse logistics · Lifecycle inventory database · BOM (bill of materials) · 0–1 integer programming

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1   Introduction

Nowadays, the assembled product, such as vacuum cleaner and smartphone is delivered to users through a global supply chain that spans procurement, manufacturing, and sales in multiple countries [1]. The economic activities such as those have caused the Marine-Plastic-Issue and global warming [2]. The Marine-Plastic-Issue is caused by disposing End-of-Life (EOL) product made from plastic materials, and global warming is occurred by Greenhouse Gas (GHG) emission in manufacturing. In order to resolve their problems, governments and manufacturing companies are taking action in around the world. For example, EU adopt the low "the reduction of impact of certain plastic products on the environment" in 2018 and decided to ban the single-used plastic products, which was not recycled, such as straw and cutlery by 2021 [3]. The Coca-Cola Company announced that they would collect as much cans and plastic bottles as the world's product sales volume by 2030 [4]. Japanese government took effect with the plastic regulation and announced that GHG emissions became zero by 2050 [2]. In order for manufacturing companies to develop sustainability, they are required to design the Global Closed-Loop Supply Chain (GCLSC) network for reducing GHG emissions and recycling EOL products in manufacturing stages [5].

The GCLSC integrates the global supply chain network [6], which is a series of cross-border transaction of products, and the local reverse supply chain network [7], which is a local transaction for collecting and recycling EOL products because as accordance with the Basel Convention [8], the collection center, the recovery facility, and the disposal facility must be located in the same country as the place of market. However, GCLSC network is costly for procurement, manufacturing, transportation, recycling and opening facilities costs. Thus, the decision maker who designs configuration of GCLSC network should consider to select appropriate global suppliers considering material-based GHG emissions because the amount of material-based GHG emissions in products is dependent on power generation methods such as thermal power generation, hydroelectricity, and solar photovoltaics in each country [6]. As a previous study, Armin et al. [9] proposed CLSC model to determine facility location decisions and lateral transshipment quantities that minimize the total supply chain cost across different disruption scenarios. However, they did not evaluate the environmental impacts such as recycling rate and GHG emissions. Aldoukhi and Gupta [10] designed CLSC considering to minimize total cost and carbon emission and to maximize service level of retailers. However, they did not consider materials such as plastic and aluminum obtained from recycling EOL product. Polat et al. [11] integrated forward and reverse logistics network design. However, they did not take into account that different countries have different costs and GHG emissions when procuring and manufacturing components.

This study designs the GCLSC network to (1) minimize total cost and (2) maximize the entire recycling rate by Integer Programming (IP) [12] with ε constraint for entire recycling rate on global supply chain network and domestic closed-loop, where the GHG emission from components procurement and the GHG saving weight by

recycling EOL product is calculated. First, the GCLSC network is draw and modeled. Next, the objective functions for minimizing total cost and the environmental evaluation for entire recycling rate and GHG emission are formulated with IP [12]. Finally, a numerical experiment is conducted and evaluated in terms of costs, entire recycling rate, and material-based GHG emission weight.

2 Model

2.1 Assumption and Notation

Figure 1 shows a GCLSC network model proposed in this study. That integrates a global supply chain network [6] and a local reverse supply chain network [7]. In the global supply chain network, the component j is procured from supplier o and transported to factory p for manufacturing an assembly product. After that, the assembly product is transported from factory p to market q. In the market q, assembly product is sold to an user and returned by the user as the EOL product. When component j is procured from supplier o, the material-based GHG emission GHG_{oj} is generated, and the amount of it is depends on the country where supplier o is in.

In the local reverse supply chain network, EOL products are transported from market q to collection center g. In a collection center g, EOL products are identified and divided status s based on user situation. Furthermore, EOL product with status s is transported from collection center g to recovery facility r or disposal facility h.
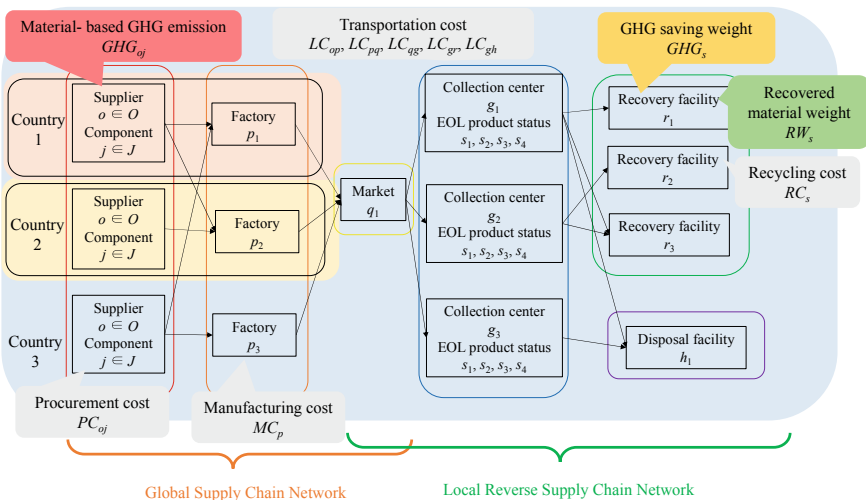

Fig. 1 Global closed-loop supply chain network model: Case of 3 countries

When the EOL product is transported to recovery facility, it is recycled based on EOL product status *s*. On the other hand, when the EOL product is transported to disposal facility, it is disposed.

In this study, material-based GHG emission by each material GHG_{oj} for component *j* is different based on procured country from supplier *o*. Moreover, recycling cost RC_s, recovered material weight RW_s, and GHG saving weight GHG_s and by recycling EOL product is dependent on the status *s*. The recycling cost RC_s includes disassembly, processing and disposal costs. The disassembly cost is based on disassembly time by Recyclability Evaluation Method (REM) [13]. The processing cost relates to shredding and so on. The disposal cost is the sum of final processing cost such as landfill and sale of recycling material. The recovered material weight RW_s means the recovered material weight by recycling EOL product.

The notations used in this study are as follows:

Sets:

O   Set of suppliers, $o \in O$
J   Set of components, $j \in J$
P   Set of factories, $p \in P$
Q   Set of markets, $q \in Q$
G   Set of collection centers, $g \in G$
R   Set of recovery facilities, $r \in R$
H   Set of disposal facilities, $h \in H$
S   Set of statues of EOL product, $s \in S$

Variables:

v_{opj} Amount of components *j* transported from supplier *o* to factory *p*
v_{pq} Amount of products transported from factory *p* to market *q*
v_{qg} Amount of EOL products transported from market *q* to collection center *g*
v_{grs} Amount of EOL products with status *s* transported from collection center *g* to recovery facility *r*
v_{ghs} Amount of EOL products with status *s* transported from collection center *g* to disposal facility *h*
u_p 1 if the fixed opening cost at factory *p* is opened, and 0 otherwise
u_r 1 if the fixed opening cost at recovery facility *r* is opened, and 0 otherwise
TC   Total cost [US$]
TGC   Total cost of global supply chain network [US$]
TRC   Total cost of local reverse supply chain network [US$]
RR   Entire recycling rate of local reverse supply chain network [%]
ε_{RR} Epsilon rate of entire recycling rate [%]
TGHG   Total GHG emission on global GCLSC [g-CO$_2$eq]
GHG_{oj} GHG emission weight for component *j* procured from supplier *o* [g-CO$_2$eq]
GHG_s GHG saving weight by recycling EOL product with status *s* [g-CO$_2$eq]

Parameters:

LC_{op} Transportation cost of a component from supplier o to factory p [US\$]
LC_{pq} Transportation cost of a product from factory p to market q [US\$]
LC_{qg} Transportation cost of a EOL product from market q to collection center g [US\$]
LC_{gr} Transportation cost of a EOL product collection center g to recovery facility r [US\$]
LC_{gh} Transportation cost of a EOL product collection center g to disposal facility h [US\$]
PC_{oj} Procurement cost of component j by supplier o [US\$]
MC_{op} Manufacturing cost per product at factory p [US\$]
RC_s Recycling cost per EOL product with status s [US\$]
FC_p Fixed cost for opening factory p [US\$]
FC_r Fixed cost for opening recovery facility r [US\$]
RW_s Recovered material weight of EOL product with status s [g]
PW Total weight of a EOL product [g]

2.2 Formulation

This GCLSC model has a bi-objective problem for minimizing total cost *TC* and for maximizing the entire recycling rate *RR*. Regarding the total cost *TC* on GCLSC network, Eq. (1) minimizes of total cost of global supply chain network *TGC* and local reverse supply chain network *TRC*. Equation (2) maximizes the entire recycling rate *RR* on GCLSC network which is the ratio of total recovered material weight of recycling EOL product at recovery facilities against the total collected material weight of collecting EOL product at collection centers. Equation (3) means the total cost of global supply chain *TGC* including the procurement cost PC_{oj} for component j from supplier o, the manufacturing cost MC_p of product in factory p, the opening factory cost FC_p for assembly factory p, and the transportation cost LC_{op} and LC_{pq} transported from supplier o to factory p and from factory p to market q. Equation (4) represents the total cost of local reverse supply chain network *TRC* including the recycling cost *RCs* for recycling EOL product with status s, the opening facility cost FC_r for recovery facility r, and the transportation cost LC_{qg}, LC_{gr}, and LC_{gh} transported from market q to collection center g and from collection center g to recovery facility r or disposal facility h. Equation (5) is epsilon constraint of entire recycling rate *RR* for GCLSC network. Equation (6) shows the total GHG emission *TGHG* which is the difference between the sum of GHG emission weight GHG_{oj} for procured component j minus the sum of GHG saving weight GHG_s for recycled EOL product with status *s*.

Objective functions and GHG evaluation:

$$TC = TGC + TRC \rightarrow \min \qquad (1)$$

$$RR = \frac{\sum_{g\in G}^{G} \sum_{r\in R}^{R} \sum_{s\in S}^{S} RW_s v_{grs}}{\sum_{q\in Q}^{Q} \sum_{g\in G}^{G} TW v_{pq}} \to \max \tag{2}$$

$$TGC = \sum_{o\in O}^{O} \sum_{p\in P}^{P} \sum_{j\in J}^{J} (PC_{oj} + LC_{op}) v_{opj} + \sum_{p\in P}^{P} \sum_{q\in Q}^{Q} (LC_{pq} + MC_p) v_{pq}$$
$$+ \sum_{p\in P}^{P} FC_p u_p \tag{3}$$

$$TRC = \sum_{q\in Q}^{Q} \sum_{g\in G}^{G} LC_{qg} v_{qh} + \sum_{g\in G}^{G} \sum_{r\in R}^{R} \sum_{s\in S}^{S} (RC_s + LC_{gr}) v_{grs}$$
$$+ \sum_{g\in G}^{G} \sum_{h\in H}^{H} \sum_{s\in S}^{S} LC_{gr} v_{grh} + \sum_{r}^{R} FC_r u_r \tag{4}$$

$$RR \geqq \varepsilon_{RR} \tag{5}$$

$$TGHG = \sum_{o\in O}^{O} \sum_{p\in P}^{P} \sum_{j\in J}^{J} GHG_{oj} v_{opj} - \sum_{g\in G}^{G} \sum_{r\in R}^{R} \sum_{s\in S}^{S} GHG_s v_{grs} \tag{6}$$

3 Problem Example

To design the GCLSC network, a problem example is prepared to integrate a global supply chain and local reverse supply chain. A vacuum cleaner with 23 types of components is used as examples of assembled and EOL product as well as Hayashi et al. [14], Ijuin et al. [7], and Ishii et al. [15]. It is assumed that a motor in vacuum cleaner is excluded because the procurement cost of the motor is about 95% of the sum of procured components for all the components. The details of GCLSC example are prepared in this study as follows.

- As suppliers, 52 cities are set from 4 country for China, Malaysia, the United States, and Japan, in other word, each country has 13 suppliers.
- As candidate factories' location, 4 cities for Shanghai, Kuala Lumpur, Seattle, and Tokyo, are selected. The production capacity of each factory is 6,000 units, and the market demand set at Tokyo, the Japan, is 12,000 units.
- As collection centers, 3 sites in Itabashi, Koto, and Ota where are in Japan, are prepared.

- As recovery facilities for recycling EOL product, 3 sites in Ota, Chiba, and Chofu where are in Japan, are selected. They have recyclable capability based on status *s* of EOL product.
- As disposal facility, Koto site where is in Japan, is prepared.

The statuses of EOL products in the case of vacuum cleaner are also prepared based on disassembly scenarios [13]. From disassembly scenarios, the recycling cost RC_s and recovered material weight RW_s, and GHG saving weight GHG_s are divided 4 statuses. For example, the EOL product with status number #4 has 1.53 [US$] for recycling cost, 952.79 [g] recovered material weight, and 1276.94 [g-CO$_2$eq] GHG saving weight by recycled components in EOL product and it is recycled in recovery facility in Chiba or Ota.

4 Result

To solve the bi-objective problem for minimizing total cost and maximizing the entire recycling rate, the entire recycling rates *RR* between from 0 [%] (minimum) to 60 [%] (maximum) are changed by epsilon constraint ε_{RR}. Figure 2 shows the total cost and the total material-based GHG emission of GCLSC network with the entire recycling rate *RR*. The sum of manufacturing cost and procurement cost was the highest, accounting for over 90% of the total cost. Even if any target recycling rate were set, the total transportation cost on global supply chain, the total procurement cost, the total manufacturing cost, and total opening facility cost for assembly factories were not changed in the all cases. Because of that, the entire recycling rate can not impact on the global supply chain in the example. On the other hand, the total transportation cost on the local reverse supply chain, the total recycling cost and the total opening facility cost were increased. One of the reasons was that lager amount of EOL products was recycled in attempting to increase the entire recycling rate.

From Fig. 2, when the entire recycling rate was increased by 20 [%], the total GHG emission was decreased by 6,000 [kg-CO$_2$eq]. This is because weight of recovered materials was less GHG emission than procuring virgin one. Therefore, it is found that GHG emissions could be lower at the same time as increasing the recycling rate.

Figure 3 shows the GCLSC network in the case with the maximal entire recycling rate (60 [%]). In the case, Chinese and Malaysian suppliers were selected. Additionally, from Fig. 2, 92% of the total cost was occupied by total manufacturing cost and total procurement cost. Therefore, candidate locations with lower procurement and manufacturing cost, such as suppliers and factories in China and Malaysia, were selected.

On the other hand, Chiba's recovery facility in Japan whose opening cost was the highest in the candidate locations is opened. One of the reasons is that was the recovery facilities in Ota and Chofu can not recycle the EOL products with statuses 1 (All components disassembled) and 2 (Recycling rate maximum) assumed as in this
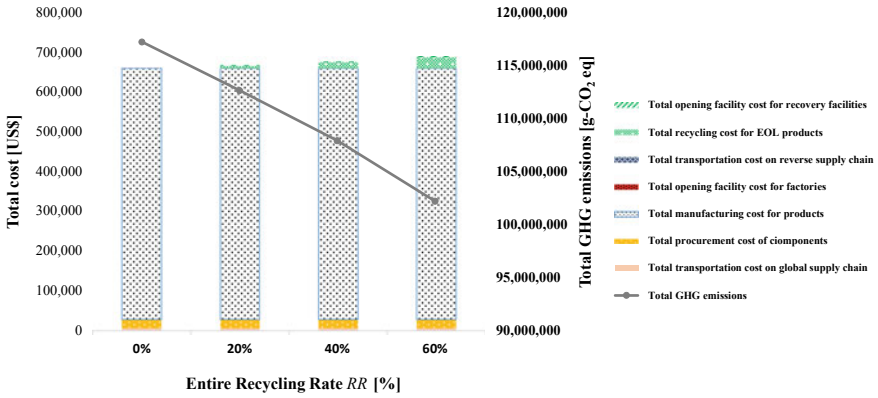
Fig. 2 Total cost and total GHG emission of GCLSC with entire recycling rate
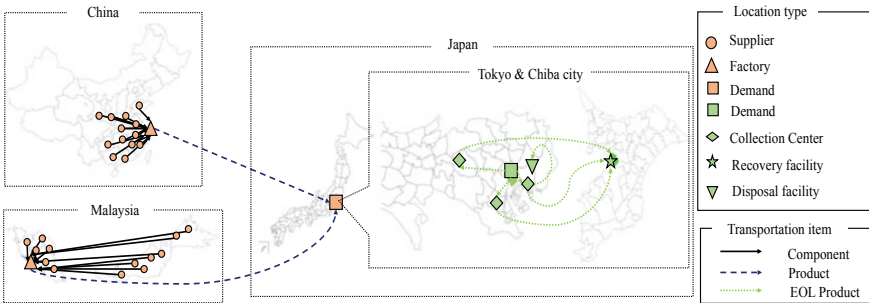

Fig. 3 GCLSC network flow of component, product, and EOL products with the maximal entire recycling rate (60 [%]) (Map source: https://www.freemap.jp/)

study. In order to increase the entire recycling rate, all EOL products were transported and recycled in Chiba's recovery facility in the case.

5 Conclusion

This study designed the GCLSC network and observed changes of the costs, entire recycling rate, total GHG emission, and network flow for component, product and EOL product.

In the GCLSC network, costs in global forward supply chain such as component procurement and manufacturing product was by 9 times higher than ones in the local reverse supply chain. Thus, total GHG emission was decreased because larger amount of EOL products were recycled when the entire recycling rate is increased. In the global supply chain flow, suppliers and factory were selected in China and

Malaysia for saving procurement cost and manufacturing cost. On the other hand, as a local reverse supply chain flow, Chiba's recovery facility which had the highest opening was opened in order to increase the entire recycling rate.

Further studies should consider a multi-objective model to minimizing cost, to maximize recycling rate, and to minimize GHG emission simultaneously.

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