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Modeling Individual Carbon Cap-and-Trade Systems Across Nations to Design Global Supply Chain Networks

Miyu Kotegawa
Department of Informatics
The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo, Japan
K2330045@edu.cc.uec.ac.jp

Yuki Kinoshita
Department of Informatics, Faculty of Engineering
Kindai University
1 Takaya Umenobe, Higashi-Hiroshima, Hiroshima, Japan
kinoshita@hiro.kindai.ac.jp

Tetsuo Yamada
Department of Informatics
The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo, Japan
tyamada@uec.ac.jp

Abstract

Carbon cap-and-trade is installed in many countries to give economic incentives for Greenhouse Gas (GHG) reduction. Each country or region introduced an individual carbon market so that GHG emission allowance and carbon price differ in countries. However, since a supply chain network is constructed globally, different GHG emission allowances and carbon prices among countries need to be considered simultaneously for GHG reduction with an affordable cost using a carbon cap-and-trade system. Moreover, customs duty, FTAs, GHG emissions, and procurement costs are also different among countries due to different energy mix and economic situations. This study models a global supply chain network with custom duty, FTAs, and carbon cap-and-trade under different GHG emission allowances, and carbon prices among countries using integer programming. Sensitivity analysis of carbon price is conducted to analyze impacts on total costs, GHG emissions, and supply chain configuration. It was found cases in the numerical experiments that required carbon prices in 2030 and 2050 to reduce GHG emissions such as 215 and 670 [USD/t-CO2eq] were effective for GHG and cost reductions under carbon cap-and-trade.

Keywords
Carbon cap-and-trade, Global supply chain network, Carbon neutrality, Free Trade Agreement (FTA), and Custom Duty.

Introduction

Assembly products such as smartphones and vacuum cleaners are delivered through global supply chain networks. A global supply chain network means links between procurement, production, transportation, and sales across countries. To overcome global warming, Greenhouse Gases (GHG) in whole supply chains is required to be reduced. Carbon neutrality by 2050 is set as a world common target (European Parliament 2023). As one of the incentives of GHG reduction in supply chains, many countries and regions introduced a carbon cap-and-trade system. Carbon cap-and-trade is a mechanism that buys and sells emissions allowance based on actual GHG emissions (Fareeduddin et al. 2015). Emissions allowances are allocated to each company in advance, and the difference between them and actual emissions can be bought and sold (Xing et al. 2017). The amount of traded GHG emissions allowance and carbon price depend on the carbon market in each country or region. Although the supply chain network is connected globally, each country or region has introduced its own markets.

Therefore, GHG emission allowance and carbon price in carbon cap-and-trade differ among countries. For example, Sweden and South Korea's carbon prices in carbon cap-and-trade are 137[USD/t-CO2eq] and 16 [USD/ t-CO2eq], respectively (World Bank 2021). In a Japanese case, it was declared in 2023 that carbon cap-and-trade will be introduced from 2026 in the "Basic Policy for the Realization of GX". Although many countries already installed carbon cap-and-trade, a report of the High-Level Commission on Carbon Prices said that it is necessary to reach at least 50 [USD/t-CO2eq] to 100 [USD/ t-CO2eq] in 2017 USD by 2030 (Word Bank 2023) to achieve carbon neutrality. Moreover, according to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global warming of 1.5℃, it is required to rise to 135 to 6050 [USD/t-CO2eq] in order to limit the global average temperature rise to 1.5 ℃. Regarding Japan, the carbon prices will be required to be risen as 215 [USD/t-CO2eq] and 670 [USD/t-CO2eq], respectively, to achieve the 2030 GHG reduction target (by 45%), which is 46% reduction compared to 2013 level and carbon neutrality by 2050 (Suk et al. 2022).

As well as GHG emission allowance and carbon price in carbon cap-and-trade, the GHG emissions and procurement costs are different among countries due to energy mix and economic situations. In other words, even if the same parts are manufactured using the same process. GHG emissions for the parts are different among countries. Especially, according to research by SHARP, GHG emissions from materials is much larger in supply chain network compared to manufacturing, logistics, and disposal (SHARP 2023). Material-based GHG emissions of each part can be estimated by using the Life Cycle Inventory (LCI) database. Generally, developed countries have higher procurement costs but lower GHG emissions, whereas developing countries tend to have lower procurement costs but higher GHG emissions. Therefore, GHG emissions in supply chains can be reduced economically by switching suppliers composing suppliers in developed and developing countries. Different customs duties and FTA also need to be considered to construct global supply chain network. Therefore, to design a global low-carbon supply chain network, it is required to address GHG emissions, tariffs, FTAs, GHG emission allowance and carbon price in carbon cap-and-trade depending on countries simultaneously. Also, to achieve carbon neutrality, although each country and region has its own carbon market, carbon price would be higher and GHG emission allowance would be lower in each carbon market. Thus, the following research questions (RQs) are come up with:

RQ1: Will GHG emissions really fall by raising carbon prices?
RQ2: What impacts are caused on the supply chain network by raising carbon prices?

This study addresses a global low-carbon supply chain network under carbon cap-and-trade, especially focusing on different GHG emission allowances and carbon prices in each country. The optimization model is proposed to minimize cost and carbon cap-and-trade cost-determined GHG emissions and carbon prices in each country.
The remainder of this study is organized as follows. Section 2 reviews previous studies about the supply chain model with carbon policies. Section 3 models and formulates a global supply chain network under carbon cap-and-trade with consideration of different carbon prices and emission allowances depending on countries. Section 4 explains the problem examples and scenarios of this study. Section 5 discusses the results of the experiments. Finally, Section 6 concludes the study and suggests how future studies can be considered.

2. Literature Review

Zhao et al. (2020) focused on the analysis of macroeconomics in terms of the economy under exogenous shock. They adopt a dynamic stochastic general equilibrium model, and compared 3 situations which are a mix of carbon tax and carbon cap-and-trade, carbon tax only, and carbon cap-and-trade only. Liu et al. (2021) focused on cost-sharing between manufacturers and retailer to reduce carbon emissions in the production process under carbon cap-and-trade. Also, they asses consumer's preferences for low-carbon products. Sherafati et al. (2020) addressed supply chain design with carbon policies and development levels in factory. Their model optimizes the number of productions in factories and transported products to markets with consideration of 4 carbon policies: carbon cap, carbon tax, carbon cap-and-trade, and carbon offset. Although these 3 previous studies have considered carbon cap-and-trade, those models did not treat suppliers.

Regarding designing a supply chain network with suppliers, Eslamipoor et al. (2023) designed a supply chain network consisted of suppliers, factories, and markets with or without carbon policy using an optimization model. They compared four scenarios: without carbon policy, with carbon tax policy, with carbon cap-and-trade policy, and with carbon cap. Tsao et al. (2021) constructed a supply chain network consisting of suppliers, factories, distribution centers, and markets under cap-and-trade. Their model adopts minimum and maximum carbon CO2 traded in the carbon market. Even though material-based CO2 emissions for assembly products can constitute a larger percentage within the forward supply chain (SHARP, 2023), neither of them evaluate material-based GHG emissions. They addressed CO2 emissions regarding transportation and production in factories whose GHG emissions are lower than that of material production. Majumdar et al. (2023) evaluated GHG emissions of parts and designed a supply chain network including suppliers, factories, distribution centers, and markets. However, even though the supply chain network is constructed globally, custom duties and FTAs are not considered.

Regarding global supply chain network with GHG emissions, custom duties and FTAs, Nagao et al. (2022) built a model for a global supply chain with carbon caps and distribution scenarios. Kotegawa et al. (2024) constructed a global supply chain with custom duty and FTAs considering mix policy consisted of carbon tax and carbon cap-and-trade simultaneously. Kinoshita et al. (2023) developed a global supply chain network model to evaluate different carbon tax in each country with custom duty and FTAs. Since each country installed its own carbon market, GHG emission allowance and carbon price in carbon cap-and-trade differ. However, previous studies did not evaluate different GHG emission allowance and carbon price with custom duty and tariffs, even though supply chain network are consisted globally and different carbon markets exist. To fill in this gap, this study addressed different GHG emission allowance and carbon price in carbon cap-and-trade, custom duty and FTAs simultaneously. Also, this study proposes a mathematical model to determine suppliers, factory locations, and the number of transported parts and products.

3. Model and Formulation

3.1 Model

The proposed model considers a global supply chain network with custom duty, FTAs, and carbon cap-and-trade under different GHG emission allowance and carbon price depending on the countries. The model is based on the global supply chain model of Kinoshita et al. (2023). Figure 1 describes the proposed model of global supply chain with carbon cap-and-trade under different GHG emission allowance and carbon price depending on countries. Supplier $\boldsymbol{o}$ provides parts to factory $\boldsymbol{p}$ with different material-based GHG emissions and procurement cost. GHG emission allowance in country of supplier $\boldsymbol{o}$ are predetermined. If the amount of GHG emissions from supplier $\boldsymbol{o}$ in a country exceeds the GHG emission allowance, additional cost needs based on the exceeded amount and carbon price. Meanwhile, if the amount of GHG emissions in a country is less than emission allowance, profit can be earned by selling the rest of emission allowance with carbon price. Products are manufactured in each factory. After that, the products are transported to the market $\boldsymbol{q}$. Custom duty and FTAs exist in the model. Then, custom duty is levied to transport parts and products between different countries, where there are not any FTAs between.

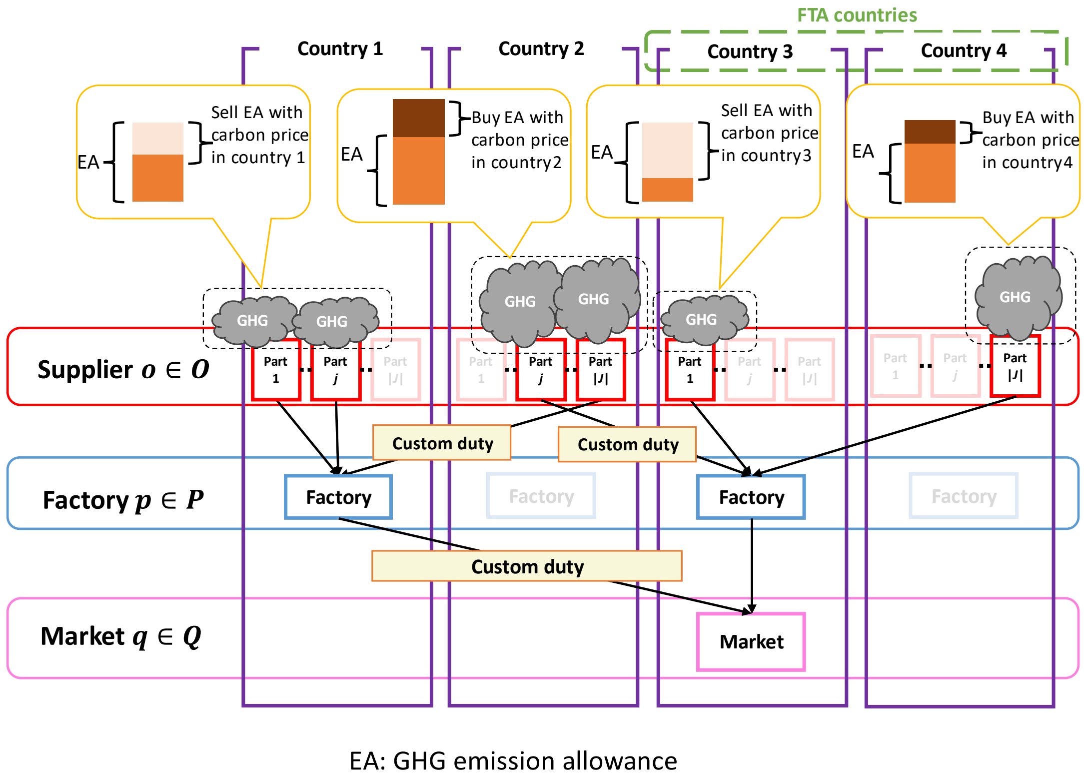

Figure 1. The model of global supply chain with carbon cap-and-trade under different carbon price depending on countries

3.2 Formulation

The notations used in the mathematical model for a global supply chain network with carbon cap-and-trade under different carbon cap-and-trade price depending on countries are as follows:

(1) Sets

T: Set of tariff partnerships, $t \in T$.
N: Set of countries, $m, n \in N$.
N_t: Set of countries agreed tariff partnership t, $N_t \subset N$
O: Set of suppliers, $o \in O$.
P: Set of factories, $p \in P$.
Q: Set of markets, $q \in Q$.
J: Set of parts, $j \in J$.

(2) Decision variables

v_{opj}: Number of parts j transported from supplier o to factory p.
v_{pq}: Number of products transported from factory p to market q.
k_p: Number of products manufactured in factory p.
z_{pq}: 1 if the route between factory p and market q is open, and 0 otherwise.
u_p: 1 if factory p is opened, and 0 otherwise.
l_{oj}: Number of parts j transported from supplier o.
E_n: GHG emissions amount in country n.

(3) Parameters

PC_{oj}: Procurement cost per unit of part j from supplier o.
GHG_{oj}: Material-based GHG emissions per unit of part j from supplier o.
TC_{op}: Transportation cost from supplier o to factory p.
TC_{pq}: Transportation cost from factory p to market q.
MC_p: Manufacturing cost per unit of product at factory p.
ORC_{pq}: Cost of opening route between factory p and market q.
OFC_p: Cost of opening factory p.
CAP_p^{PROD}: Production capacity at factory p.
$\delta(h)$: Country of facility h, $h \in O \cup P \cup Q$.
NP_j: Number of parts j composing product.
D_q: Number of product units demanded at market q.
S_{oj}: 1, when supplier o can supply part j
0, otherwise
CD_{opj}^{PART}: Custom duty of the importation of part j from supplier o to factory p.
CD_{pq}^{PROD}: Custom duty of the importation of product from factory p to market q.
α_{mnj}: Custom duty rate on the importation a part j between country m and n.
β_{mnj}: Custom duty rate on the importation a product between country m and n.
CP_m^{TRADE}: Carbon cap-and-trade price in country m.
EA_m: Emission allowance in country m.

The proposed model determines suppliers, factory locations, and the transported number of parts and products under carbon cap-and-trade with different GHG emission allowances and carbon prices in each country. The objective function is the minimization of the total costs TC consisted of procurement costs, transportation costs, manufacturing costs, custom duty costs, fixed costs of opening the factory and route, and carbon cap-and-trade costs.
Objective:

$$\sum_{o\in Ob}\sum_{p\in P}\sum_{j\in J}\left(PC_{oj}+TC_{op}^{PART}+CD_{opj}^{PART}\right)v_{opj}+\sum_{p\in P}\sum_{q\in Q}\left(MC_p+TC_{pq}^{PROD}+CD_{pq}^{PROD}\right)v_{pq} + \sum_{p\in P}\sum_{q\in Q}ORC_{pq}z_{pq}+\sum_{p\in P}OFC_p u_p + CPC \rightarrow min \quad (1)$$

Equation (2) expresses carbon cap-and-trade cost. Carbon cap-and-trade cost CPC is calculated by multiplying the difference between the emission allowance set in advance for each country EA_n and the actual GHG emissions E_n by the carbon price in the country CP_n^{TRADE}. Total GHG emissions in the country n is represented as shown in Equation (3). Equation (4) - (7) defines a constraint of the number of transported parts and products. Stocks in suppliers and factories are not considered. Equation (8) represents only opened route is used for the transportation of products. Equation (9) expresses the production capacity in each factory. Equations (10) and (11) define the custom duty for each part and product. Equation (12) and (13) represents the custom duty rate for each part and product. If FTAs exist between countries m and m, custom duty is eliminated by setting α_{mnj} or β_{mn} as 0. The number of transported parts and products are not negative as shown in equation (13).
constraints:

$$CPC=\sum_{n\in N}(E_n - EA_n)\times CP_n^{TRADE} \quad (2)$$

$$E_n=\sum_{o\in O|\delta(o)=n}\sum_{j\in J}GHG_{oj}\, l_{oj} \quad \forall n\in N \quad (3)$$

$$\sum_{p\in P}v_{opj}=l_{oj} \quad \forall o\in O, \forall j\in J \quad (4)$$

$$\sum_{o\in O}S_{oj}v_{opj}=NP_j k_p \quad \forall o\in O, \forall p\in P \quad (5)$$

$$\sum_{q\in Q}v_{pq}=k_p \quad \forall p\in P \quad (6)$$

$$\sum_{p\in P}v_{pq}=D_q \quad \forall q\in Q \quad (7)$$

$$v_{pq}\le M z_{pq} \quad \forall p\in P, \forall q\in Q \quad (8)$$

$$k_p\le CAP_p^{PROD}u_p \quad \forall p\in P \quad (9)$$

$$CD_{opj}^{PART}=PC_{oj}\alpha_{\delta(o)\delta(p)j} \quad \forall o\in O, \forall p\in P, \forall j\in J \quad (10)$$

$$CD_{pq}^{PROD}=MC_p\beta_{\delta(p)\delta(q)} \quad \forall p\in P, \forall q\in Q \quad (11)$$

$$\alpha_{mnj}=\begin{cases}0, & if\,\exists t\in T\ s.t.\ m,n\in N_t\\ any\ given\ value, & otherwise\end{cases} \quad \forall m,n\in N, \forall j\in J \quad (12)$$

$$\beta_{mn}=\begin{cases}0, & if\,\exists t\in T\ s.t.\ m,n\in N_t\\ any\ given\ value, & otherwise\end{cases} \quad \forall m,n\in N \quad (12)$$

$$v_{opj}, v_{pq}\ge 0 \quad \forall o\in O, \forall p\in P, \forall j\in J, \forall q\in Q \quad (13)$$

4. Design Example

A vacuum cleaner consisting of 23 parts is used to illustrate design example of the proposed global supply chain with custom duty and FTAs and carbon cap-and-trade. Assumption of input data are as follows.

- Suppliers are in 4 countries: the U.S., Malaysia, China, and Japan. Each country has 13 suppliers. There are four candidates for factory; Shanghai, Kuala Lumpur, Seattle, and Tokyo. The demand is set as 6,000 units in Tokyo. Each factory can produce 3000 units;
- TPP Agreement is considered in this study, so that, the custom duty between Japan and Malaysia is eliminated;
- The motor (#19) in the vacuum cleaner is excluded from this experiment as well as Nagao et al. (2022) because it accounted for extremely higher of GHG emissions by 95% against total GHG emissions.

Table 1 shows a part of bill of materials for the procurement cost and GHG emissions of Left handle in vacuum cleaner.

In Climate Summit, USA declared that GHG reduction target was set as 50~52% by 2030 compared to 2005 level (The White House, 2021). Also, Japan set 46% reduction target of GHG emissions by 2030 compared to 2013 level. To achieve the targets, GHG emission allowance would be reduced. Therefore, the emission allowance in this study is set as 50% of the total GHG emissions in supply chain network without carbon policy. Carbon price is set as shown in Table 2 These carbon prices in Table 2 are based on current and required carbon price for carbon neutrality. Case1 represents current carbon cap-and-trade price. In Japan, Tokyo and Saitama are introduced the carbon cap-and-trade system with carbon price 5 [USD/t-CO2eq]. Some of regions in China also use carbon cap-and-trade system with 1 to 6 [USD/t-CO2eq]. California and Massachusetts in the U.S. are introduced carbon cap-and-trade, respectively. In California, the carbon price is set as 18 [USD/ t-CO2eq] (World Bank 2021). Therefore, case1 referred to current carbon prices in China, Malaysia, the U.S., and Japan are set as 6, 0, 18, and 5 [USD/t-CO2eq], respectively.
On the other hand, Suk et al. (2022) reported Japan have to raise carbon price as 215 and 670 by 2030 and 2050, respectively to achieve Japanese reduction target. Based on these carbon prices, 9 combinations of carbon prices are set as shown in Table 2. Furthermore, 2 scenarios are prepared to raise carbon price from current price to 670 [USD/t-CO2eq]. One scenario means that Japan will raise the carbon price earlier than other countries. The other one indicates that other countries will raise their carbon price earlier than Japan, the relationships these 2 scenarios and cases in Table 2 are shown in Figure 2. Both scenarios have 2 pathways to reach 670 [USD/t-CO2eq] of carbon price in all countries as shown in Figure 2.

One pathway in the scenario "Japanese carbon price rises later" is from case 1 via cases 2, 4, and 5 to case 6.

Table 1. A part of bill of materials for the procurement cost and GHG emissions of left handle (#8)

Part name	Weight [g]	Procurement cost [USD]				GHG emissions [g-CO2eq]			
		China	Malaysia	the U.S.	Japan	China	Malaysia	the U.S.	Japan
Left handle	51.70	0.0412	0.0375	0.0456	0.0716	291.19	125.47	54.67	54.95

Table 2. Carbon cap-and-trade price in each country

	baseline	case1	case2	case3	case4	case5	case6	case7	case8	case9
Carbon cap-and-trade price in China [USD/t-CO2eq]	0	6	215	670	215	670	670	6	6	215
Carbon cap-and-trade price in Malaysia [USD/t-CO2eq]	0	0	215	670	215	670	670	0	0	215
Carbon cap-and-trade price in the U.S. [USD/t-CO2eq]	0	18	215	670	215	670	670	18	18	215
Carbon cap-and-trade price in Japan [USD/t-CO2eq]	0	5	5	5	215	215	670	215	670	670

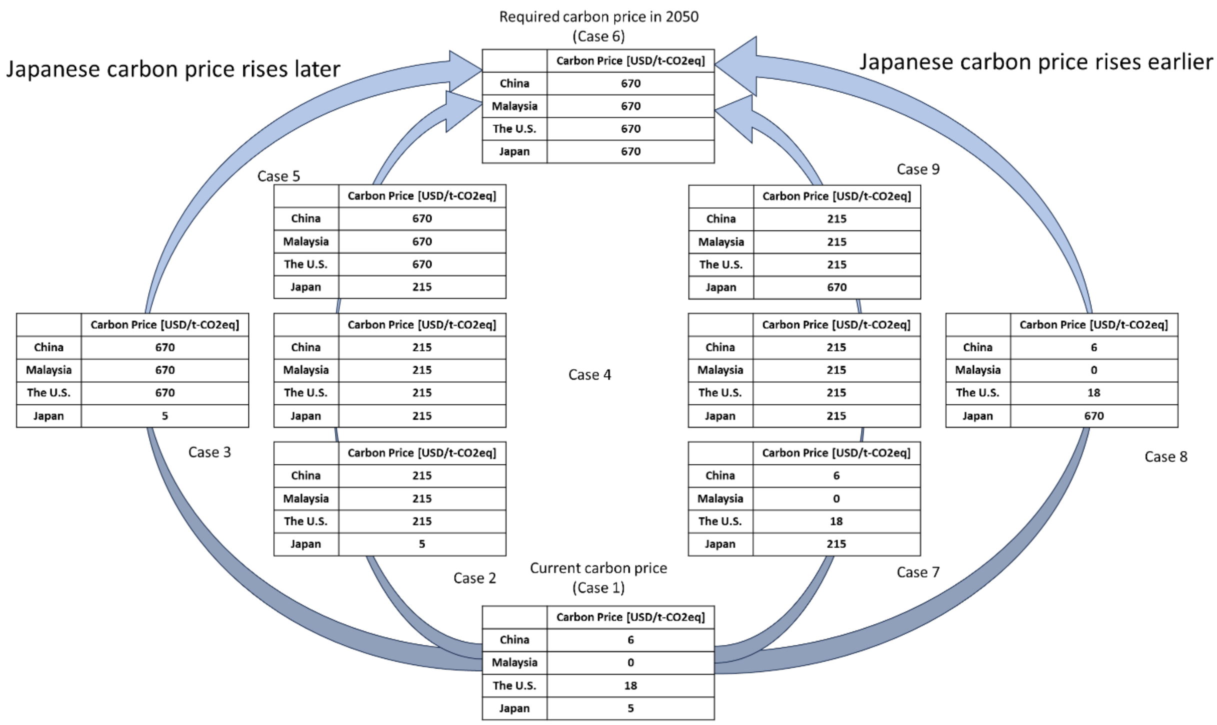

Figure 2. The relationships 2 scenarios and cases in Table 2 for pathway of raising carbon prices to 670 [USD/t-CO2eq]

The mathematical programming solver, namely, Nuorium Optimizer (NTT DATA Mathematical System Inc., 2022), is used for all experiments on an Intel(R) Core(TM) i5-4300U CPU @ 1.90 GHz 2.50 GHz PC with Windows 10 Pro installed.)

5. Results and Discussion

Three comparisons are examined in terms of GHG emissions and total costs. Baseline refers to constructed supply chain without carbon cap-and-trade. First, baseline, current carbon price (case 1), and required carbon price in 2050 (case 6) are analyzed. Next, the 2 scenarios are examined in terms of carbon price, GHG emissions, and total cost.

5.1 Comparison of Current Carbon price and Required carbon price in 2050

Figure 3 shows GHG emissions and total cost of 3 cases. The left bars represent costs corresponding to the left vertical axis and the right bars represent GHG emissions corresponding to the right vertical axis.In a case of current carbon price, total GHG emissions did not changed at all compared to that of the baseline. In addition, total cost was increased because of increment of carbon cap-and-trade cost. Hence, current carbon price in carbon cap-and-trade would not effective for GHG emissions reduction in the numerical experiments. On the other hand, when required carbon price in 2050 was applied, both total costs and GHG emissions were reduced by 2% and by 69% compared to those at the baseline. In the cases of baseline and current carbon price, the Chinese suppliers were selected for 20 parts excluding #2 and #7, which are cheaper because of their lighter weight, to provide parts to the factory in Shanghai. Then, Chinese GHG emissions in baseline accounted for 72% against total GHG emissions as shown in Figure 3. In the case of required carbon price in 2050, the procurement cost increased by 2,993 [USD] compared to the baseline because the all Chinese suppliers were switched to ones in other three countries. However, the total costs decreased because of 7,721 [USD] refunds by carbon cap-and-trade.

Comparing baseline and case of required carbon price in 2050, the same factories, namely Chinse and Malaysian factories were selected. At the case of required carbon price in 2050, more Japanese and the U.S. suppliers were selected instead of Chinese and Malaysian suppliers as shown in Figure 3. Chinese factory procured all parts from international suppliers owing to save GHG emissions, even though Chinese suppliers had a cheaper procurement cost.

One remarkable finding was that the 3 parts of highest GHG emissions were supplied from the U.S. to both Chinese and Malaysian Factories.

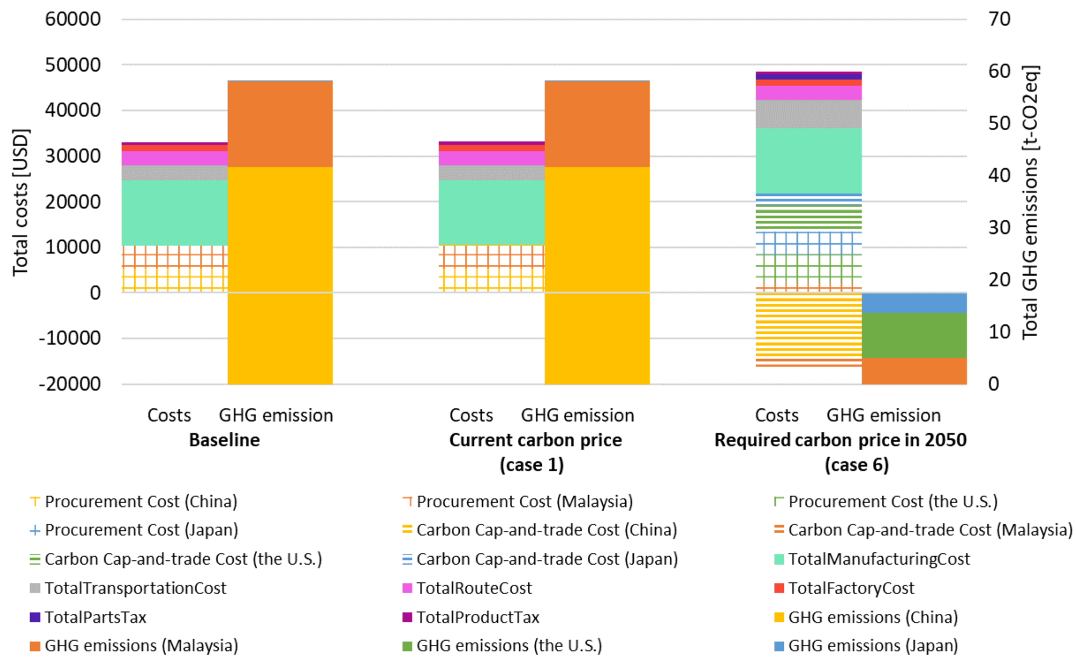

Figure 3. GHG emissions and total cost of 3 cases

5.2 Results when Japan raised carbon price later than other countries

Table 3 shows the results when Japan raised carbon price later than other countries. When carbon prices were raised in China, Malaysia, and the U.S. to 215 [USD/t-CO2eq] in cases 2 and 4, total costs increased over 5%, however total GHG emissions reduced over 45%. Moreover, when the carbon prices in except of Japan were raised to 670 [USD/t-CO2eq], both GHG emissions and total costs decreased as shown cases 3 and 5. These cases could reduce GHG emissions by about 70% compared that of baseline as shown in Table 3. However, it is noted that costs increased if Japanese carbon price rises as 670 [USD/t-CO2eq] as shown in case 6 in Table 3. The case 3 had lowest GHG emissions and total costs among 7 cases as shown in Table 3. In this case, Chinese factory procured all parts from Japanese suppliers. Malaysian factory procured 8 parts (#8, #9, #10, #11, #12, #14, #16, #20) from Japanese suppliers. All other 15 parts were procured from Malaysian suppliers. That is, Japanese suppliers provided the 3 heaviest parts (#9, #10, and #14), and the 3 highest GHG emissions parts (#12, #14, and #16). This supplier selection led to over 70% GHG reduction. In the case 3, suppliers in the U.S. and China were not selected.

Table 3. The results when Japan raised price later than other countries

	baseline	current carbon price (case1)	case2	case3	required carbon price in 2030 (case4)	case5	required carbon price in 2050 (case6)
Total Costs [USD]	33115.7	33240.6	35053.0	25498.6	35290.9	28000.7	32493.4
Total GHG emissions [t-CO2eq]	58.1	58.1	31.2	15.1	31.9	15.4	17.5
Reduction Rate of Total Costs [%]	-	-0.4	-5.9	23.0	-6.6	15.4	1.9
Reduction Rate of GHG Emissions [%]	-	0.0	46.2	73.9	45.1	73.4	69.8
Carbon Price in China [USD/t-CO2eq]	0	6	215	670	215	670	670
Carbon Price in Malaysia [USD/t-CO2eq]	0	0	215	670	215	670	670
Carbon Price in the U.S. [USD/t-CO2eq]	0	18	215	670	215	670	670
Carbon Price in Japan [USD/t-CO2eq]	0	5	5	5	215	215	670

5.3 Results when Japan raised carbon price earlier than other countries

Table 4 shows total GHG emissions and total costs of each case in the scenario that Japan raised carbon price earlier than other countries. Reduction rates of total costs and GHG emissions refer to the reduction ratio compared to the baseline. Comparing cases 1,7, and 8, there was no effect on GHG emission reductions even if Japanese carbon price was higher than others. As a result, the total cost increased by increasing carbon cap-and-trade cost. Furthermore, in the case 8, both GHG emissions and total costs increased.

Comparing cases 4, 6 and 9, raising carbon cap-and-trade price in all countries to 215 or 670 [USD/t-CO2eq], could reduce over 40% GHG emissions compared to that of baseline as shown in Table 4. Based on these results, raising Japanese carbon price earlier than other countries could not have effects on GHG reduction in the experiments. Moreover, raising carbon prices to 250 [USD/t-CO2eq] in all countries in effective of GHG reduction.

Table 4. The results when Japan raised prices earlier than other countries

	baseline	current carbon price (case1)	case7	case8	required carbon price in 2030 (case4)	case9	required carbon price in 2050 (case6)
Total Costs [USD]	33115.7	33240.6	33243.1	33247.5	35290.9	35405.9	32493.4
Total GHG emissions [t-CO2eq]	58.1	58.1	58.1	58.1	31.9	33.9	17.5
Reduction Rate of Total Costs [%]	-	-0.4	-0.4	-0.4	-6.6	-6.9	1.9
Reduction Rate of GHG Emissions [%]	-	0.0	0.0	-0.1	45.1	41.7	69.8
Carbon Price in China [USD/t-CO2eq]	0	6	6	6	215	215	670
Carbon Price in Malaysia [USD/t-CO2eq]	0	0	0	0	215	215	670
Carbon Price in the U.S. [USD/t-CO2eq]	0	18	18	18	215	215	670
Carbon Price in Japan [USD/t-CO2eq]	0	5	215	670	215	670	670

5.4 Comparing Two Scenarios to Change Carbon Price for carbon neutrality in 2050

2 scenarios that Japan raises its carbon price later or earlier than other countries were compared in this section. Comparing these scenarios, it would be better to raise Japanese carbon price later than other countries since the scenario of Japan raising earlier had cases that GHG emissions could not be reduced as shown in Table 4. Moreover, the scenario of Japan raising later could reduce much GHG emissions in 5 out of 7 cases as shown in Table 3.
Regarding factories, Shanghai and Kuala Lumpur were selected as factory locations in all cases. Comparing suppliers, if carbon price in Japan is raised earlier in Section 5.3, many Chinese suppliers were selected so that the amount of reduction of GHG emission was smaller. Additionally, parts were sourced from the U.S. only when carbon price in all countries reached 670 [USD/t-CO2eq]. On the other hand, in the case of raising Japanese carbon price later, many Japanese supplier were selected.

Based on these results, the 3 heaviest parts (#9, #10, and #14) and the 2 highest parts of GHG emissions (#12 and #16) should be supplied from Japan or the U.S. to reduce GHG emissions in carbon cap-and-trade. Also, all other parts would be better to be supplied from Malaysia to save procurement cost.
In addition, comparing reduction results and reduction targets, if carbon prices are set as 215 [USD/t-CO2eq], the target of 45% reduction will be achieved. Moreover, while this model cannot achieve carbon neutrality, when carbon prices were set as 670 [USD/t-CO2eq], GHG emissions reduced by about 70%. Therefore, the reported carbon price such as 215 and 670 [USD/t-CO2eq] would be effective in the numerical experiments.

6. Conclusion and Future Studies

This study models a global supply chain network with carbon cap-and-trade, custom duties, and FTAs. Different carbon price depending on countries are modeled base on Kinoshita et al. (2023). A mathematical model is proposed to determine suppliers, factory locations, and the number of transported parts/products. The design example was illustrated using a vacuum clear, and analyzed different carbon price in each country and different scenarios to reach 670 [USD/t-CO2eq] of carbon price in all countries. Results and discussions indicated that Japan would raise its carbon price in carbon cap-and-trade later to reduce GHG emissions in supply chain. Carbon prices of 215 and 670 [USD/t-CO2eq] reported by Suk et al. (2022) would be effective in the numerical experiments to achieve Japanese 46% reduction in 2030 compared to 2013 level, and carbon neutrality in 2050.
Future studies should consider implementing mix carbon policies consisted of carbon tax and carbon cap-and-trade with different carbon prices across countries.

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Biographies

Miyu Kotegawa is a master student in the Department of Informatics, The University of Electro-Communications, Japan. Her research activities include Global Supply Chains with Carbon Policies.

Yuki Kinoshita is an Assistant Professor, Department of Informatics, Faculty of Engineering, Kindai University, Hiroshima, Japan. His research interests are global low-carbon supply chain, environmentally friendly and economically material selection, disassembly production scheduling, information security risks and fraud issues in remanufacturing products.

Tetsuo Yamada is a Professor in in the Department of Informatics, The University of Electro-Communications, Japan. His research interests Closed-loop and Low-carbon Supply Chains, Enterprise Resource Planning (ERP), Management Information System, Product Lifecycle Management (PLM), Green Logistics, Information Sharing, e-Learning, Child Care and Household Chores, iku-men & women (parenting issues for both men and women), Healthcare, Work-Life Balance.