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RESEARCH ARTICLE

Global Supply Chain Network Design Under Cap-and-Trade System and Analysis of Carbon Price and Emission Allowance

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Abstract: Carbon cap-and-trade has been introduced to reduce greenhouse gas (GHG). Carbon cap-and-trade is expected to incentivize reducing GHG emissions because it enables the receipt of refunds based on the gap between actual GHG emissions and the predetermined allowance. Moreover, GHG emissions, procurement costs and custom duties depend on the country, its economic conditions, the electric energy mix, and Free Trade Agreements (FTAs). To reduce GHG emissions with an affordable cost in a global supply chain, it is important to select suppliers and factory locations considering these factors. Furthermore, since carbon price and GHG emission allowance could be changed, manufacturers should also be paid attention to cost fluctuations due to carbon cap-and-trade. This study develops a mathematical model for a global supply chain with a carbon cap-and-trade system, analyzes GHG emissions and costs under different carbon prices and GHG emission allowances. First, procurement cost and GHG emissions for each part are estimated using the Life Cycle Inventory (LCI) database, and a bill of materials (BOM), listing the estimated cost and GHG emissions for each procured country, is created. Second, a global supply chain with a carbon cap-and-trade is formulated using mathematical programming. Third, numerical experiments are conducted to illustrate a design example. Finally, the results are discussed and analyzed from the viewpoints of reducing costs, GHG emissions, cost-effectiveness, and switching suppliers. It is found cases that the carbon cap-and-trade system can be effective in constructing a global low-carbon supply chain considering customs duties and FTAs and that carbon price has a greater impact on the reduction of GHG emissions instead of GHG emissions allowance in the numerical experiments.

Keywords: carbon neutral, supplier selection, mathematical programming, material based GHG emissions, free trade agreement (FTA), custom duty, life cycle inventory (LCI) database

1. Introduction

Global supply chains follow chains of events across countries, ranging from the procurement of materials for a product to its manufacturing in factories, sales, and consumption. To economically decarbonize the global supply chain, the greenhouse gas (GHG) emissions and costs should be considered by each country.

For carbon neutrality, each country should set GHG reduction targets. For example, in 2020, the Japanese government declared that it would achieve carbon neutrality by 2050. Moreover, Japan has worked toward reducing GHG emissions to achieve 46% reduction in GHG emissions from 2013 level by 2030 (Ministry of the Environment, 2022). Canada aims for a 40-50% reduction target for CO2 emissions by 2030, compared to its GHG emissions in 2005 (Government of Canada, 2024). At a

climate summit, the U.S. has declared that it aims for a 50-52% reduction target for its GHG emissions by 2030 compared to GHG emissions in 2005 (United States of America, 2021). Due to global warming, disaster risks such as flood have increased (Zeng et al., 2023). Carbon pricing would also help governments cover expenditures for flood risks (Zeng et al., 2023), in addition to economic incentive to reduce GHG emissions. To achieve their carbon emission reduction goals, many countries have installed carbon cap-and-trade systems. The carbon cap-and-trade system is expected to be more cost-effective because it reduces GHG emissions and allows the purchase of emission allowances (Fareeduddin et al., 2017). This mechanism involves buying and selling emission credits (Xing et al., 2017). The emissions allowance is set in advance for each company, and emission credits are traded between companies that exceed the specified amount and those that do not (Marufuzzaman et al., 2014). To achieve carbon neutral, carbon price would become higher and GHG emission allowance become lower. As other methods to reduce GHG emissions, there are different 3 carbon policies; carbon tax, carbon offset, and carbon cap-and-trade. Carbon cap is a method to enforce reduction of GHG emissions by determining upper limits for GHG emissions. This mechanism can reduce GHG emissions certainly. Carbon tax is a financial penalty for GHG emissions. Carbon offset is a mechanism purchase additional carbon credit if necessary. However, they cannot sell the allowance if it is not necessary (Marufuzzaman et al., 2014).

Addition to different carbon policies and carbon prices in each country, GHG emissions are different due to different power generation methods. As a result, the production of same parts may lead to different GHG emissions (Rebitzer et al., 2004). According to research by SHARP, GHG emissions from materials is much larger in forward supply chain including material production, manufacturing and distribution (SHARP, 2023). GHG emissions for every step in the process for each country can be estimated by using the Life Cycle Inventory (LCI) database. The LCI database lists GHG emission intensities (Rebitzer et al., 2004). By referring an adequate GHG emission intensity, GHG emissions for each step can be estimated (Rebitzer et al., 2004). Generally, developed countries tend to have higher procurement costs and lower GHG emissions, whereas developing countries tend to have lower procurement costs and higher GHG emissions. Therefore, GHG emissions in a global supply chain can be reduced with an affordable cost by encompassing developed and developing countries.

To build a global low-carbon supply chain, different custom duty and Free Trade Agreements (FTAs) (Xing et al., 2017) are also important factors since utilization of FTAs can promote to switch suppliers in developed countries with higher procurement cost but lower GHG emissions by saving tariffs (Kinoshita et al., 2023). An FTA is an agreement between two or more countries or regions to eliminate or reduce tariffs (Nagao et al., 2022). Even though manufactures can eliminate tariff owing to FTAs, increment of carbon prices in selected location of suppliers and factories can lead to an additional cost. Indeed, according to World Bank (2023), adjusting inflation, carbon prices would need to reach 61 to 122 USD by 2030 in 2023 USD. Furthermore, GHG emission allowance in carbon cap-and-trade would also decrease for carbon neutrality. For manufactures, it is beneficial to grasp impacts of carbon price fluctuation on GHG emissions and total cost so that they can construct a global low-carbon supply chain to achieve cost-effectiveness of GHG reduction and to moderate cost increment. For governments, it will be required to set suitable carbon price and GHG emission allowance not to disturb manufacturers' activities.

Thus, the following research questions (RQs) are posed:

RQ1: What impacts are brought in a global low-carbon supply chain by changing a carbon price and a GHG emission allowance in carbon cap-and-trade?

RQ2: How should manufacturers build a global low-carbon supply chain to save additional cost by increasing a carbon price and decreasing GHG emission allowance?

RQ3: How much carbon price and GHG emission allowance are suitable to achieve higher a cost-effectiveness of GHG reduction in a global low-carbon supply chain?

Therefore, this paper considers different procurement cost, GHG emissions, tariffs, and FTAs among countries, simultaneously to build a global low-carbon supply chain with an affordable cost. Moreover, this paper analyzes the impacts of carbon price and emission allowance on a global low-carbon supply chain.

The proposed model determines factory location, suppliers, and quantity of production and transportation. On the other hand, there are 3 layers of decision makings of supply chain, namely, strategic, tactical, and operational decision makings. Factory location selection and supplier selection are a strategic decision, while decision of quantity of production and transportation is strategic or operational decision (Ravindran & Warsing, 2013). Although factory location and supplier selections are different types of decisions, Meixell and Gargeya (2005) pointed out the importance of integration of these decisions. Moreover, this study also considers the carbon cap-and-trade, which involves emission allowance and carbon price depending on a country. The volumes of material-based GHG emissions determined by the number of procuring parts and locations of suppliers can cause higher economic loads in the supply chain due to GHG emission allowance and carbon price. Therefore, to design global low-carbon supply chain with an affordable cost, this study determines the locations of factories and suppliers, and the number of procuring products simultaneously.

These discissions are called as network optimization and solved by optimization model. (Ravindran & Warsing, 2013) Hence, this study proposes a global low-carbon supply chain network under carbon cap-and-trade as a network optimization model.

Regarding to parameters, to obtain a global low-carbon supply chain network by solving the optimization problem, GHG emissions parameters and cost such as logistics costs, procurement cost, and manufacturing cost are considered.

Originality of this research is to propose a mathematical model to determine the number of parts/products and locations of suppliers/factories simultaneously for a global low-carbon supply chain network with carbon cap-and-trade, tariffs and FTAs.

Contribution of this paper is to support decision makers by providing construction of a global low-carbon supply chain including GHG emissions and total cost, and with risks of cost increment due to change of carbon price and GHG emission allowance under carbon cap-and-trade by conducting sensitivity analysis.

The remainder of this study is organized as follows. In Section 2, literature review is conducted from viewpoint of global supply chain management and carbon policies. Section 3 formulates a global supply chain network that considers carbon cap-and-trade, custom duties, and FTAs.

Section 4 explains the problem example and clarifies the assumptions for a global supply chain, carbon cap-and-trade, and input data of the parts involved in a product's supply chain. Section 5 presents a sensitivity analysis on the carbon price and GHG emission allowance. Section 6 examines preferred carbon price and GHG emission allowance to achieve a higher cost-effectiveness of GHG reduction. Finally, Section 7 concludes the study and suggests ways to conduct further studies.

2. Literature Review

This section reviews the literature on supply chains in the context of carbon policy. **Table 1** shows the literature on supply chains in terms of the global supply chain management and carbon policy. Zeng et al. (2022) focused on financial indicators and corporate's ESG performance to evaluate green supply chain performance. They suggested an evaluation method by adapting the entropy weight method, and analyzed 200 companies. Xia et al. (2022) explored the impact of fiscal decentralization reform on CO2 emissions in China. They reviewed the impact of fiscal imbalance, fiscal transfer, and industrial structure on carbon emissions. Zhao et al. (2020) investigated the carbon policy effectiveness on carbon emissions and economics by comparing a policy mix and a single policy. They examined the differences among carbon tax only, carbon cap-and-trade only, and mix of carbon tax and cap-and-trade. Although these studies analyzed GHG emissions and costs, they did not decide supply chain network.

Liu et al. (2021) have proposed a cost-sharing model between manufacturer and retailer. They evaluated the impact of carbon emission reduction cost-sharing with consumer preferences and carbon cap-and-trade. Wu et al. (2022) have also focused on manufacturer and retailer to analyze the impact of a carbon tax, low-carbon subsidy, mixed carbon tax, and low-carbon subsidy on carbon emissions and income. Choudhary et al. (2015) have proposed a logistic optimization model including production/recovery centers, distribution/collection centers, markets, and disposal centers. The proposed model addressed carbon tax, carbon cap, carbon cap-and-trade to derive the optimal network configuration, minimizing both the cost and total carbon footprint of the network. Marufuzzaman et al. (2014) have presented mathematical models to identify locations and production plants with carbon policies, namely, carbon cap, carbon tax, carbon cap-and-trade, and carbon offset. They compared costs and CO2 emissions among these 4 carbon policies.

Sherafati et al. (2020) proposed an optimization model to determine production quantities at factories and the number of transported products to customers under a carbon policy. Their model considered 4 carbon policies, and one policy could be adopted by changing some constraints. Fareeduddin et al. (2015) have modeled a closed-loop supply chain design with carbon policies, such as carbon tax, carbon cap, and carbon cap-and-trade. Their model included factories, distribution centers, markets, collection centers, recycling centers, and disposal centers. They also considered difference of technology at a factory determining GHG emissions. Those 6 previous studies investigated cost and

Table 1. Literature on supply chain and carbon policy

Literature	Global Supply Chain Management					Cost/Profit	Carbon Policy			
	Supplier	Factory Location	Market	Custom Duty	FTAs		Carbon tax	Carbon cap	Carbon cap-and-trade	Carobn offset
Zeng et al. (2022)						✓				
Xia et al. (2022)						✓				
Zhao et al. (2020)						✓	✓		✓	
Liu et al. (2021)		✓	✓			✓			✓	
Wu et al. (2022)		✓	✓			✓	✓			
Choudhary et al. (2015)		✓	✓			✓	✓	✓	✓	
Marufuzzaman et al. (2014)		✓	✓			✓	✓	✓	✓	✓
Sherafati et al. (2020)		✓	✓			✓	✓	✓	✓	✓
Fareeduddin et al. (2015)		✓	✓			✓	✓	✓	✓	
Majumdar et al. (2023)	✓	✓	✓			✓			✓	
Fareeduddin et al.(2017)	✓	✓	✓			✓	✓	✓	✓	✓
Xu et al. (2017)	✓	✓	✓			✓	✓	✓	✓	
Nagao et al. (2022)	✓	✓	✓	✓	✓	✓		✓		
Kinoshita et al. (2023)	✓	✓	✓	✓	✓	✓	✓			
This paper	✓	✓	✓	✓	✓	✓		✓	✓	

GHG emissions with carbon policies between factories and markets only, even though material-based CO2 emissions for assembly products can occupy larger percent against forward supply chain including material, manufacturing and distribution (SHARP, 2023).

Regarding previous studies addressing suppliers, Majumdar et al. (2023) have treated a supply chain network including suppliers, factories, distribution centers, and markets under carbon cap-and-trade. They compared an independent model solving separate upstream and downstream of a supply chain network with an integrated model solving a whole supply chain network. Fareeduddin et al. (2017) have investigated the impact of carbon cap, carbon tax, cap-and-trade, and carbon offsets on a multi-product closed-loop supply chain. Their model also determined technologies at factories and transportation mode. Xu et al. (2017) have presented dedicated and hybrid a closed-loop supply chain network with carbon policies. They investigated impacts of demand, carbon price, and return rate on both models in terms of both carbon emissions and costs. These 3 papers focused on supply chain network with carbon policies. However, they did not take into account of custom duty and FTAs even though supply chin network is constructed globally.

Regarding global supply chain networks with GHG emissions, custom duty and FTAs, Nagao et al. (2022) models a global supply chain with carbon cap and distribution scenarios. Kinoshita et al. (2023) focused on carbon tax and analyzed impacts of carbon prices on global supply chain network with custom duty and FTAs. However, these studies have not considered carbon cap-and-trade. Therefore, this study adopts carbon cap-and-trade to a global low-carbon supply chain network with custom duty and FTAs.

3. Mathematical Model

3.1. Problem Statement

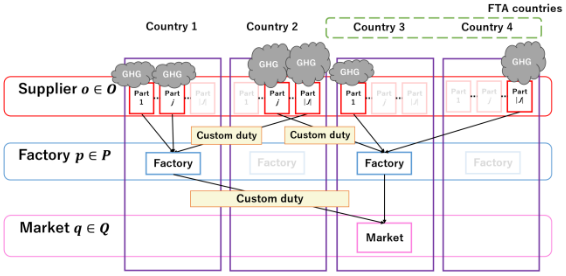
This section models a global supply chain network that incorporates carbon cap-and-trade using integer programming based on the global supply chain model of Nagao et al. (2022). The aim is to minimize the total cost and reduce material-based GHG emissions.

Figure 1 describes the proposed model of a global supply chain that reduces GHG emissions and total costs by applying carbon cap-and-trade and FTAs. Part j is procured and delivered from supplier o and transported to factory p. A product is manufactured by assembling N_j parts that have been brought to factory p. The finished product is then transported to market q.

Material-based GHG emissions are calculated based on the LCI database of the Asian Input-Output Table. Considering that power generation methods differ depending on the country, even for the same parts, GHG emissions based on materials differ from country to country. Developed countries, which generally use a high proportion of clean energy, have low GHG emissions and high costs, whereas emerging countries tend to use energy with high GHG emissions and low costs.

Each country has different tariffs and FTAs, which are considered in this model. In trade between countries with FTAs, tariffs are eliminated or reduced. For example, FTAs exist between Countries 3 and 4, as shown in **Figure 1**. Therefore, the parts and products transported between Countries 3 and 4 can save custom duties. On the other hand, parts transported from Country 2 to Country 1 and products transported from Country 1 to Country 3 are levied as tariffs based on custom duty rate as shown in **Figure 1**.

Figure 1: Proposed global supply chain with carbon cap-and-trade



3.2. Formulation

The notations used in this study for the global supply chain network model with carbon cap-and-trade are as follows:

(1) Sets

O: Set of suppliers, $o \in O$.

J: Set of parts, $j \in J$.

P: Set of factories, $p \in P$.

Q: Set of markets, $q \in Q$.

(2) Decision variables

v_{opj}: Transported number of parts j from supplier o to factory p.

v_{pq}: Transported number of products from factory p to market q.

k_p: Produced number of products 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.

(3) Parameters

C_{op}^{LC}, C_{pq}^{LC}: Logistics costs per unit of a part and product for transportation.

C_{oj}^{PC}: Procurement cost of part j from supplier o.

C_{op}^{TS}, C_{pq}^{TS}: Customs duty per unit part and product on transportation.

C_p^{MF}: Manufacturing cost per product at factory p.

C_{pq}^{RT}, C_p^{FC}: Fixed opening cost of the route from factory p to market q, and opening factory p.

N_j: Total number of parts j comprising one product.

$N_q^{product}$: Amount of demand for products in market q.

F_p: Production capacity of factory p.

GHG_{oj}: GHG emissions per part j from supplier o.

E^{cap}: GHG emission allowance.
CP^{trade}: Carbon price in cap-and-trade.
M: Very large number.

(4) Cost evaluation
TC: Total cost [USD].
TMC: Total manufacturing cost [USD].
$CATC$: Total carbon cap-and-trade cost [USD].

(5) GHG evaluation
E: GHG emissions amount.

This study aims to minimize the total cost in Equation (1). The total cost TC includes total manufacturing cost TMC and cost for carbon cap-and-trade cost $CATC$. The GHG emissions amount E at the material manufacturing stage is the sum of the GHG emissions amount per part for each country GHG_{oj} multiplied by the number of parts j supplied by supplier o l_{oj}, as shown in Equation (2). Equations (3) represents TMC. $CATC$ is represented in Equation (4). Equations (5)–(12) are constraints that require the parts and products to be transported. Equation (5) ensures that the supplied number of parts j by supplier o l_{oj} meets the transported number of parts j from supplier o to factory p. The required number of parts j at factory p is procured from adequate suppliers as shown in Equation (6). All produced products at factory p are transported to markets as shown in Equation (7). Equation (8) enforces demands in all markets to be satisfied. Equations (9) and (10) ensure that only opened factories and routes can be used. Equation (11) indicates decision variables z_{pq} and $u_p$are binary valuables. The transported number of parts and products are non-negative as shown in Equation (12).

Objectives:

$$TC = TMC + CATC \rightarrow min \tag{1}$$

s.t.

$$E = \sum_{o\in O}\sum_{j\in J} GHG_{oj} l_{oj} \tag{2}$$

$$\begin{aligned} TMC = {} & \sum_{o\in O}\sum_{j\in J} C^{PC}_{oj} l_{oj} \\ & + \sum_{p\in P} C^{MF}_{p} k_p \\ & + \sum_{p\in P}\sum_{q\in Q} C^{RT}_{pq} z_{pq} + \sum_{p\in P} C^{FC}_{p} u_p \\ & + \sum_{o\in O}\sum_{p\in P}\sum_{j\in J} C^{LC}_{op} v_{opj} \\ & + \sum_{p\in P}\sum_{q\in Q} C^{LC}_{pq} v_{pq} \\ & + \sum_{o\in O}\sum_{p\in P}\sum_{j\in J} C^{PC}_{oj} C^{TS}_{op} v_{opj} \\ & + \sum_{p\in P}\sum_{q\in Q} C^{MF}_{p} C^{TS}_{pq} v_{pq} \end{aligned} \tag{3}$$

$$CATC = (E - E^{cap}) \times CP^{trade} \tag{4}$$

$$\sum_{p\in P} v_{opj} = l_{oj} \quad \forall o \in O, \forall j \in J \tag{5}$$

$$\sum_{p\in P} S_{oj} v_{opj} = N_j k_p \quad \forall p \in P, \forall j \in J \tag{6}$$

$$\sum_{q\in Q} v_{pq} = k_p \quad \forall p \in P \tag{7}$$

$$\sum_{p\in P} v_{pq} = N^{product}_{q} \quad \forall q \in Q \tag{8}$$

$$\sum_{q\in Q} v_{pq} \leq F_p u_p \quad \forall p \in P \tag{9}$$

$$v_{pq} \leq M z_{pq} \quad \forall p \in P, \forall q \in Q \tag{10}$$

$$z_{pq,} u_p = \{1,0\} \quad \forall p \in P, \forall q \in Q \tag{11}$$

$$v_{opj,} v_{pq} \geq 0 \quad o \in O, \forall p \in P, \forall j \in J, \forall q \in Q \tag{12}$$

4. Problem Example

4.1. Assumptions of product and supply chain network

Numerical experiments are conducted based on Nagao et al. (2022) to analyze the effects of cap-and-trade on a global supply chain with taxes and FTAs. A design example is illustrated using 3D-CAD model and LCI database. The used data is not real data but has certain degree of reliability since they are estimated using statistics and database. As an example of data estimation, first, data such as weight and type of materials for each part are obtained from 3D-CAD model. Second, part unit cost is calculated based on material unit cost from statistic data. Third, procurement cost for each country is calculated based on price level of the country. Finally, material-based GHG emissions for each part is estimated using on the LCI database from Asian International Input and Output tables (Horiguchi et al., 2012). **Table 2** shows BOM of the parts and procurement cost (Nagao et al., 2022). The assumptions of a product and supply chain network are listed as follows:

1) It is used that a vacuum cleaner consisting of 23 parts is used as a product example.
2) The supply chain consists of the following four countries: China, Malaysia, the U.S., and Japan. The TPP are only considered as the FTAs; that is, customs duty between Malaysia and Japan is 0 [USD].
3) Parts and products are the same quality although different supplies and factories are selected. Additionally, only cost and GHG are difference.
4) Each country has 13 suppliers. The factories are selected from the following four candidate locations: Tokyo, Seattle, Shanghai, and Kuala Lumpur. The demand for the product is assumed to be 6,000 pieces in Tokyo.
5) Part #19 (motor) is excluded from numerical experiments as well as Nagao et al. (2022) because it accounts for over half of the GHG emissions.

4.2. Scenarios of carbon price and GHG emission allowance

Two GHG emission allowance are established to validate the effects of cap-and-trade on a global supply chain. Japanese reduction target under the Paris Agreement was 26% compared to its GHG emission amount in 2013. USA reduction target at the Climate Summit was 50%. For the aforementioned reasons, emission allowance is set at 74% or 50% of the total GHG emissions from constructed supply chain without carbon cap-and-trade. Carbon price is changed as 0, 5, 50, 100, 150, 200, 250, 300, 400, 500 [USD/t-CO2eq]. To analyze impacts of carbon cap-and-trade, baseline is set. Baseline refers to the constructed supply chain without the carbon cap-and-trade system. Thus, the baseline is designed to minimize the total cost only.

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

5. Results: Impact of cap-and-trade

Two scenarios, namely 74% and 50% GHG emission allowance, are examined in terms of GHG emissions and total costs.

5.1 Emission allowance: 74%

Figure 2 illustrates GHG emission and total cost with a 74% emission allowance. The blue line represents the total cost corresponding to the left vertical axis, whereas the orange line represents the GHG emissions corresponding to the right vertical axis. The horizontal axis indicates the carbon price. As the carbon price became higher, GHG emissions decreased. However, the total cost increased compared to that of the baseline when the carbon price is set at 50 [USD/t-CO2eq]. The total costs decreased as the increment in the refund increased by selling surplus emission allowance. Focusing on GHG emissions, when the carbon price is five [USD/t-CO2eq], the GHG emissions did not change. When it is 50 [USD/t-CO2eq], GHG emissions reduced by 32% compared to those at the baseline, while the total cost increased by 1% only. At a carbon price of 50 [USD/t-CO2eq], refunds were obtained because the actual GHG emissions were less than 74% of the emission allowance.

As shown in **Figure 2**, in the case of 74% GHG emission allowance, the GHG emissions can be reduced over 30% within 1% cost increment by setting carbon price equal to or over 50 [USD/t-CO2eq]. In this experiment, the cost is maximum when the carbon price is 50 [USD/t-CO2eq]. Setting the carbon price above 50 [USD/t-CO2eq] could reduce both GHG emissions and total costs at the same time. The results show that it is better to set the carbon price to more than 50 [USD/t-CO2eq].

In terms of a constructed supply chain network, when the carbon price increased from five [USD/t-CO2eq] to 50 [USD/t-CO2eq], the suppliers of the five parts were changed. The changed parts included #9, #10, #12, #14, and #16. The numbers with "#" indicate the part number as shown in **Table 2**. For example, #1 means part number of "wheel of nozzle". Additionally, when the carbon price increased from 300 [USD/t-CO2eq] to 400 [USD/t-CO2eq], suppliers for #12 and #16 were changed. As shown in **Figure 2**, GHG emissions at carbon price 400 [USD/t-CO2eq] become much lower that of carbon price 300 [USD/t-CO2eq].

The mesh filter (#12) and upper filter (#16) showed higher GHG emissions as shown in **Table 2**. Thus, GHG emissions can be reduced with fewer supplier changes by changing suppliers at parts that have higher GHG emissions per part compared to other parts.

Figure 2: Trend of total cost and GHG emission with the 74% emission allowance as increment of carbon price

Table 2. BOM of the parts and procurement cost.

Part No.	Part name	Material name	Required number for a product	Weight [g]	Procurement cost [USD]				GHG emissions [g-CO2eq]			
					China	Malaysia	the U.S.	Japan	China	Malaysia	the U.S.	Japan
1	Wheel of nozzle	Polypropylene	2	7.07	0.0056	0.0051	0.0062	0.0098	39.82	17.16	7.48	7.51
2	Wheel stopper	Polypropylene	2	1.71	0.0014	0.0012	0.0015	0.0024	9.63	4.15	1.81	1.82
3	Upper nozzle	Polypropylene	1	50.35	0.0401	0.0365	0.0444	0.0698	283.59	122.20	53.25	53.51
4	Lower nozzle	Polypropylene	1	41.25	0.0328	0.0299	0.0364	0.0572	232.33	100.11	43.62	43.84
5	Nozzle	Polypropylene	1	34.50	0.0275	0.0250	0.0305	0.0478	194.31	83.73	36.49	36.67
6	Right handle	Polypropylene	1	47.93	0.0390	0.0355	0.0432	0.0678	275.59	118.75	51.75	52.00
7	Switch	Polyvinyl chloride	1	4.65	0.0033	0.0030	0.0037	0.0058	23.65	10.19	4.44	4.46
8	Left handle	Polypropylene	1	51.70	0.0412	0.0375	0.0456	0.0716	291.19	125.47	54.67	54.95
9	Left body	Polypropylene	1	187.27	0.1491	0.1359	0.1653	0.2595	1054.76	454.50	198.05	199.02
10	Rgiht body	Polypropylene	1	179.88	0.1432	0.1305	0.1588	0.2493	1013.13	436.56	190.23	191.17
11	Dust case cover	Methacrylate resin	1	36.57	0.0554	0.0505	0.0614	0.0964	391.89	168.87	73.58	73.95
12	Mesh filter	Carbon fiber	1	18.45	0.3441	0.3136	0.3816	0.5990	2967.54	1211.26	557.95	438.22
13	Connection pipe	Aluminum alloy	1	47.17	0.0581	0.0530	0.0644	0.1012	409.95	72.76	63.58	47.03
14	Dust case	Methacrylate resin	1	175.69	0.2661	0.2425	0.2951	0.4632	1882.72	811.27	353.51	355.25
15	Exhaust tube	Methacrylate resin	1	32.04	0.0230	0.0210	0.0255	0.0401	162.99	70.23	30.60	30.76
16	Upper filter	Carbon fiber	1	17.74	0.3309	0.3015	0.3669	0.5759	2853.34	1164.65	536.47	421.36
17	Lower filter	Polypropylene	1	29.33	0.0234	0.0213	0.0259	0.0406	165.19	71.18	31.02	31.17
18	Protection cap	Polystyrene (ABS)	1	22.29	0.0251	0.0229	0.0278	0.0437	177.60	76.53	33.35	33.51
20	Rubber of outer flame of fan	Synthetic rubber	1	22.85	0.0319	0.0291	0.0354	0.0556	332.83	125.15	65.88	55.96
21	Outer flame of fan	Polypropylene	1	55.11	0.0679	0.0619	0.0753	0.1182	478.96	85.01	74.29	54.94
22	Lower fan	Polypropylene	1	15.08	0.0120	0.0109	0.0133	0.0209	84.93	36.60	15.95	16.03
23	Fan	Aluminum alloy	1	62.10	0.0765	0.0697	0.0848	0.1332	539.71	95.79	83.71	61.91

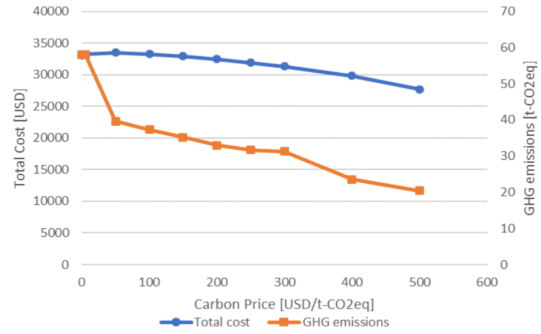


Figure 3: Cost and GHG emissions with the 74% emission allowance

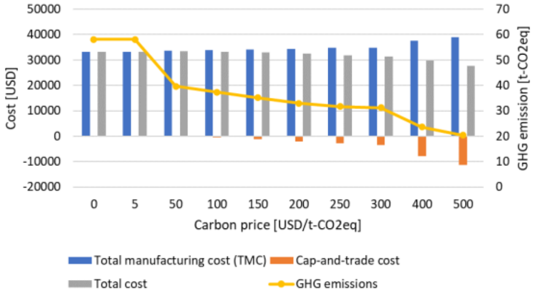


Figure 3 illustrates the total manufacturing cost (*TMC*), total carbon cap-and-trade cost (*CATC*), total cost, and GHG emissions with a 74% emission allowance. *CATC* can be negative because of refunds. Thus, the total cost, which is the sum of *TMC* and *CATC* is lower than the *TMC*. The *TMC* increased; however, the total cost decreased with increasing refunds. This is because Chinese factory procured many parts from the Chinese suppliers with higher GHG emissions, and then the suppliers were switched to Japanese or Malaysian for attaining lower GHG emissions but higher procurement costs. Consequently, the transportation costs of parts and customs duty costs increased to transported parts from Malaysian and Japanese suppliers. Moreover, when the carbon price increased, the GHG emissions could be reduced, and refund amount for reduced GHG emissions could increase. Consequently, the total costs were reduced.

5.2. Emission allowance: 50%

Figure 4 shows GHG emissions and total cost for 50% emission allowance. Similar to 74%, when the carbon cost is five [USD/t-CO2eq], GHG emissions did not decrease at all. When it was 50 [USD/t-CO2eq], the total cost increases by 1% and GHG emissions reduce by 32%. Comparing **Figures 2** and **4**, GHG emissions with 50% emission allowance showed the same trends as those with 74% GHG emission allowance, but the total costs showed different trends. The total cost kept increasing with a carbon price of 300 [USD/t-CO2eq] and then decreased when the carbon prices were set equal to or greater than 400 [USD/t-CO2eq] because of refunds. Although the carbon price increased from 50 [USD/t-CO2eq] to 300 [USD/t-CO2eq], the GHG reduction was 31% to 46% as shown in **Figure 4** compared that of baseline. That is, additional reduction of GHG emissions was relative smaller of carbon price from 100 to 300 [USD/t-CO2eq] by considering carbon price becoming 6 times larger. However, when the carbon price was set at 400 [USD/t-CO2eq], GHG emissions reduced by 59% with the refund compared that of baseline. Consequently, it may be better to set the carbon price at 50 or greater than 400 [USD/t-CO2eq] in terms of cost-effectiveness for GHG emission reduction.

Furthermore, carbon prices of 400 and 500 [USD/t-CO2eq] could reduce GHG emissions over 59% with refunds, as shown in **Figure 5**. The structures of supply chains of carbon price 400 and 500 [USD/t-CO2eq] were the same as that of the 74% emission allowance at carbon price 400 and 500 [USD/t-CO2eq], respectively.

Figure 4: Trend of total cost and GHG emission with the 50% emission allowance as increment of carbon price

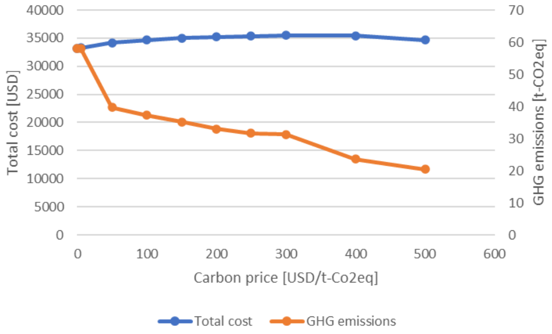


Figure 5: Cost and GHG emissions with the 50% emission allowance

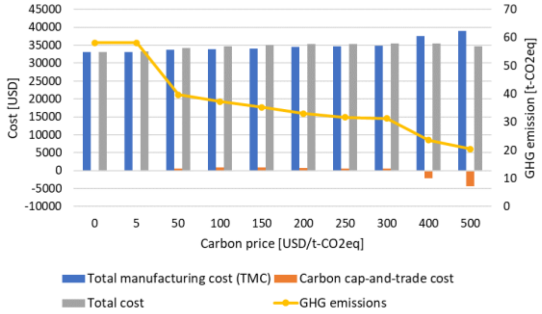


Table 3: The additional costs when the allowance is changed from 74% to 50% and carbon price is raised

		Eission allowance: 50%									
		0	5	50	100	150	200	250	300	400	500
Emission allowance: 74%	0	0	145.2278	1452.278	2904.555	4356.833	5809.11	7261.388	8713.665	11618.22	14522.78
	5		145.2278	1452.278	2904.555	4356.833	5809.11	7261.388	8713.665	11618.22	14522.78
	50			531.7025	1063.405	1595.108	2126.81	2658.513	3190.215	4253.62	5317.025
	100				824.675	1237.013	1649.35	2061.688	2474.025	3298.7	4123.375
	150					921.7575	1229.01	1536.263	1843.515	2458.02	3072.525
	200						788.45	985.5625	1182.675	1576.9	1971.125
	250							651.8625	782.235	1042.98	1303.725
	300								660.345	880.46	1100.575
	400									-2195.1	-2743.88
	500										-4324.18

Table 4: Sourcing parts at each carbon price

Factory		China				Malaysia			
Supplier		China	Malaysia	Japan	the U.S.	China	Malaysia	Japan	the U.S.
Carbon price [USD/t-CO2eq]	50	1,3,4,5,6,8,11,13,15,17,18,20,21,22	**9**,**10**,**12**,**14**,**16**,23	2,7			1,2,3,4,5,6,7,8,**9**,**10**,11,**12**,13,**14**,15,**16**,17,18,20,21,22,23		
	200	3,18,22	6,8,**9**,**10**,11,**12**,13,**14**,**16**,21,23	1,2,4,5,7,15,17,20			1,2,3,4,5,6,7,8,**9**,**10**,11,**12**,13,**14**,15,**16**,17,18,20,21,22,23		
	400		**9**,**10**,11,13,**14**,21,23	1,2,3,4,5,6,7,8,15,17,18,20,22	**12**,**16**		1,2,3,4,5,6,7,8,**9**,**10**,11,13,**14**,15,17,18,20,21,22,23		**12**,**16**

5.3. Comparing different emission allowance

Comparing the results when GHG emission allowance is set at 50% and 74%, factories and supplier selections of 50% and that of 70% are the same at each carbon price set, respectively. However, the total cost differs owing to the amount of refund. For carbon neutrality, the carbon price would be higher and GHG emission allowance would be lower. However, it can be difficult for manufacturers to quickly reconstruct their global supply chain to respond to the changed carbon price or GHG emission allowance. Therefore, this subsection analyzes the effects of changing the carbon price and the GHG emission allowance on the constructed global supply chain.

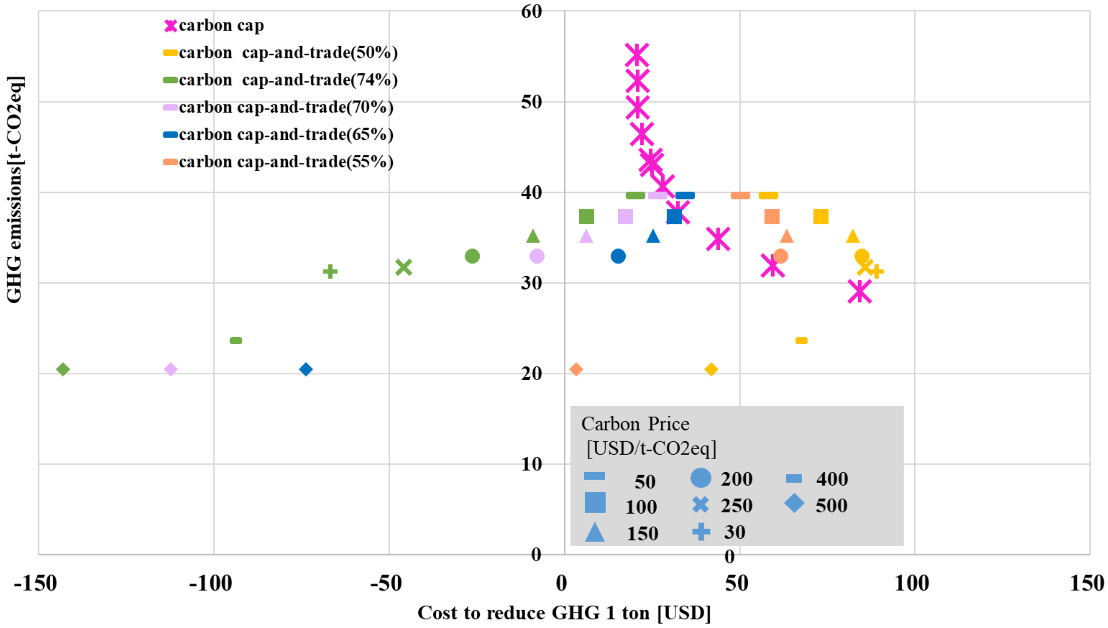
Table 3 shows the additional costs when the allowance is changed from 74% to 50% and carbon price is raised. The additional cost is calculated using the following formula:

$$Additional\ cost = \left(E_i^{74} - ECAP^{50}\right) \times CP_i^{trade}$$

E_i^{74} is GHG emissions when emission allowance is 74% and carbon price is i. $ECAP^{50}$ means emission allowance is set as 50%. For example, carbon price is set as 50 [USD/t-CO2eq], and the GHG emissions with 74% GHG emission allowance is 39.68 [t-CO2eq]. Then, the GHG emission allowance is changed to 50%. Hence, the excess GHG emissions of 10.63 [t-CO2eq] will be levied with 50 [USD/t-CO2eq]; therefore, the additional cost would become 531.70 (=10.63×50) [USD].

It is found that if the carbon price is set at 400 [USD/t-CO2eq] or more when the emission allowance decreased from 74% to 50%, it reduces costs as shown in **Table 3**. These results show that the total cost can be reduced when the GHG emissions allowance is changed from 74% to 50% by constructing a global supply chain with 400 or 500 carbon price [USD/t-CO2eq] in advance. To analyze the differences in the constructed global supply chain, three cases are discussed in detail. The three cases are supply chains constructed with 50, 200, 400 carbon prices [USD/t-CO2eq] under 74% GHG emission allowance. Especially, suppliers of parts #**9**, #**10**, #**12**, #**14**, and #**16** are focused.

Figure 6: GHG emissions and cost of reducing 1 ton of GHG emission



They are top three heaviest and first-and-second highest GHG emissions parts as shown in **Table 2**.

Table 4 shows sourcing parts at each carbon price. The numbers of **Table 4** indicate the part number as shown in **Table 2**. When the carbon price is 50 [USD/t-CO2eq]. Six parts (**#9**, **#10**, **#12**, **#14**, **#16** and #23) were procured from a Malaysian supplier and sent to a Chinese factory as shown in **Table 4**. Parts #2 and #7 were supplied by Japanese suppliers. All other 14 parts for Chinese factory were supplied by China.

When the carbon price is 200 [USD/t-CO2eq], eight parts (#1, #2, #4, #5, #7, #15, #17, and #20) were procured from Japanese suppliers for the Chinese factory. Chinese suppliers were chosen for only three parts, namely, #3 and #18 and #22. All other 11 parts including **#9**, **#10**, **#12**, **#14**, and **#16** were procured by Malaysian suppliers.

Comparing suppliers to Chinese factory, when carbon price was changed as 50, 200, and 400 [USD/t-CO2eq], the number of Chinese suppliers were changed as 14, 3, and 0 as carbon price increased. The number of Malaysian suppliers to Chinse factory were changed as 6, 11, and 7 as carbon price increased. That of Japanese suppliers were changed as 2, 8, and 13. The suppliers in the U.S. were selected when carbon price was 400 [USD/t-CO2eq] only.

Moreover, when the carbon price was 400 [USD/t-CO2eq], seven parts (**#9**, **#10**, #11, #13, **#14**, #21, and #23) were supplied by Malasia, and two parts (**#12** and **#16**) by the U.S. All other the 13 parts were supplied by Japanese suppliers, that is, even though the Chinese factory was selected, all parts to the Chinese factory were selected by Malaysian, Japanese, the U.S. suppliers.

Therefore, Chinese suppliers switched to Malaysian, Japanese, and the U.S. suppliers as carbon prices increased as shown in **Table 4**. The top three heaviest parts, namely the left body (**#9**), right body (**#10**), and dust case (**#14**), and the first- and second-highest GHG emission parts, namely the mesh filter (**#12**) and upper filter (**#16**), were prioritized to change suppliers for reductions in GHG emissions and total cost. This is because all of them were procured by Malaysian supplier when carbon price was 50 and 200 [USD/t-CO2eq], and only **#12** and **#16** were switched to the U.S. supplier when carbon price 400[USD/t-CO2eq]. Furthermore, these five parts have higher procurement cost among parts as shown in **Table 2**. When the carbon price was 200 [USD/t-CO2eq], they were procured from Malaysian supplier to minimize total cost. This supply chain construction can lead to higher additional cost by decreasing GHG emission allowance as 50% as shown in **Table 3**. The suppliers of these five parts should be selected Japanese or the U.S. one when carbon price was 200 [USD/t-CO2eq] to save additional cost by decreasing GHG emission allowance. Indeed, suppliers of **#12** and **#16** were selected the U.S. one when carbon price was 400 [USD/t-CO2eq] as shown in **Table 4**. This supply chain could save cost because of refund by decreasing GHG emission allowance as shown in **Table 3**.

6. Comparing Carbon Cap-and-Trade vs. Carbon Cap

In this section, to validate whether the same trends of GHG emissions and total costs are observed, additional experiments are conducted by changing the GHG emission allowance to 70%, 65%, 60%, and 55% with carbon price 50, 100, 150 and 200 [USD/t-CO2eq]. **Figure 6** shows the GHG emissions and the cost of reducing one ton of GHG emissions. To strengthen the cost-effectiveness of the GHG reduction, the results for the carbon cap are illustrated in **Figure 6**. The results of carbon cap are obtained by setting a constraint to enforce the GHG emission as shown in Equation (2) lower than a certain reduction target ε .

Therefore, the constraint is set to $E \leq (1-\varepsilon)E^{max}$ and replaced with cap-and-trade constraint in Equation (4) to obtain global supply chain with carbon cap. The E^{max} represents GHG emissions in supply chain configured to minimize only total cost without carbon policy. The reduction of GHG emission, and increment of total cost are obtained from a comparison with the baseline. The cost to reduce GHG 1 ton [USD] in **Figure 6** represents relative values to baseline. The baseline was constructed supply chain network without carbon policies. The total cost and GHG emissions of the baseline were 33,115.7 [USD] and 58.1 [t-CO2eq], respectively.

Thus, the cost to reduce GHG 1 ton is calculated as $\frac{GHG\ emissions - GHG\ emissions\ of\ baseline}{total\ cost - total\ cost\ of\ baseline}$.

When 50 % GHG allowance with 400 [USD/t-CO2eq] carbon price, the total cost was 35,417.9 [USD] and the GHG emissions was 23.6 [t-CO2eq]. Therefore, cost to reduce GHG 1 ton is calculated as follows:

$$\frac{35{,}417.9 - 33{,}115.7}{58.1 - 23.6} = \frac{2{,}302.2}{34.5}$$

$$= 66.7\ [\mathrm{USD/t - CO2eq}]$$

On the other hand, when 74% GHG allowance with 400 [USD/t-CO2eq] carbon price, the total cost was 29,841.2 [USD] and the GHG emissions was 23.6 [t-CO2eq]. Therefore, cost to reduce GHG 1 ton is calculated as follows:

$$\frac{29{,}841.2\text{-}\ 33{,}115.7}{58.1 - 23.6} = \frac{-3{,}274.5}{34.5}$$

$$= -94.8\ [\mathrm{USD/t - CO2eq}]$$

Owing to refunds by selling rest of GHG emission allowance, the total cost can be lower than that of baseline as shown in the case of 74 % GHG allowance with carbon price 400 [USD/t-CO2eq]. Then, cost to reduce GHG 1 ton in **Figure 6** can be negative value. Three findings are then identified.

First, it is found that carbon cap-and-trade is better than carbon caps in terms of both GHG emissions and costs. As shown in this figure, carbon cap-and-trade can reduce GHG emissions at a lower cost than carbon caps in many cases. If a carbon cap is introduced, GHG emissions will only be reduced by the targeted reduction amount. However, if a carbon cap-and-trade is introduced, large amounts of GHG emissions will be reduced because of the refunds. In many cases, the cost of reducing GHG emissions with cap-and-trade could be lower than that of a carbon cap, as shown in **Figure 6**. This tendency remains even when emission allowances are changed.

Second, changing the emissions allowance does not affect the amount of GHG emissions; however, changing the carbon price is more effective. In these experiments, GHG emissions were not changed even when the emission allowance was. These features are illustrated in **Figure 6**. However, GHG emissions could be reduced by increasing carbon prices among all GHG emission allowances, as shown in **Figure 6**. Thus, it is better to change the carbon price instead of the emissions allowance.

Third, there are cases in which reducing emission allowances is less cost-effective than using carbon caps. This is because reducing the emissions allowance makes it more difficult to receive refunds, and it is also costly to purchase an emissions allowance. For example, when emission allowance is 50% and the carbon price is 100 [USD/t-CO2eq], it costs 2.26 times more to reduce GHG by one [ton] than the carbon cap. Carbon cap-and-trade can be a heavier burden on manufacturers than carbon caps if it is not refunded.

7. Conclusion and future studies

This study addresses the global low-carbon supply chain by applying a carbon cap-and-trade with custom duties and FTAs. A mathematical model is proposed to minimize the total cost and GHG emissions, and the emission allowance and carbon prices are analyzed. The numerical experiments show that carbon cap-and-trade is cost-effective of GHG reduction for the global supply chain considering custom duties and FTAs. Changing the emission allowance had less impacts of the GHG reduction, whereas carbon price could have much impacts of that in the experiments.

Answers for RQs in Section 1 are as follows:

1) RQ1: What impacts are brought in a global low-carbon supply chain by changing a carbon price and a GHG emission allowance in carbon cap-and-trade?
Changing the emissions allowance did not affect the amount of GHG emissions; however, changing the carbon price was more effective in the numerical experiments. In these experiments, GHG emissions were not changed even when the different emission allowance was. However, GHG emissions could be reduced by increasing carbon prices among all GHG emission allowances. Thus, it would be better to change the carbon price instead of the emissions allowance.

2) RQ2: How should manufacturers build a global low-carbon supply chain to save additional cost by increasing a carbon price and decreasing GHG emission allowance?
The additional cost caused by decreasing GHG emission allowance will be accrued in many cases as shown in **Table 3**. To save additional cost by decreasing GHG emission allowance, it would be better that suppliers of heavier or higher GHG emissions parts are selected ones with lower GHG emissions but higher procurement cost in advance despite increasing cost.

3) RQ3: How much carbon price and GHG emission allowance are suitable to achieve higher a cost-effectiveness of GHG reduction in a global low-carbon supply chain?
In the experiments, at the case of 74% GHG emission allowance, the carbon price should be set as equal to or greater than 50 [USD/t-CO2eq]. In the case of 50% GHG emission allowance, it may be better to set the carbon price at 50 or greater than 400 [USD/t-CO2eq]. Moreover, the carbon price in carbon cap-and-trade should be higher as decreasing GHG emission allowance to achieve higher cost-effectiveness of GHG reduction compared to carbon cap as shown in **Figure 6**.

Practical implications are as follows:

1) By only using data such as costs and GHG emissions of each part, logistics, and fixed opened facility costs, GHG

emissions and total costs can be estimated throughout the supply chain.
2) A decision maker can grasp a global low-carbon supply chain network to achieve reduction targets of GHG emissions or minimize the impact of carbon price fluctuations by conducting sensitivity analysis of carbon price. As well as tariffs, carbon price of each country is an important factor to configure a global low-carbon supply chain network. World Bank (2023) pointed out the necessity to increase the carbon price for carbon neutrality. Therefore, it will be beneficial for manufactures to grasp impacts of carbon price fluctuation on their supply chain network.
3) In terms of political decision, it would utilize to determine suitable carbon price in carbon cap-and-trade for carbon neutral economically. Furthermore, governments could examine the effects of carbon price on the supply chain network. Although governments could determine carbon price in their country to reduce GHG emissions, they also should not disturb manufactures' activities.

However, limitations are as follows:
1) Only material-based GHG emissions is considered. However, to decarbonize supply chain, GHG emissions caused by other phases such as transportation and factory operation should be considered.
2) It is assumed that suppliers can be switched easily, and all alternative suppliers can provide parts with the same quality. This study assumed that only procurement cost and GHG emissions are different among suppliers. However, it will be difficult to switch suppliers in some cases of real situations. For example, parts manufactured by higher unique technology can be procured from a particular supplier.
3) Changes of carbon price and available GHG emissions are not considered. Under carbon cap-and-trade, carbon price and available GHG emission allowance depending on demand and supply in carbon market. This study assumed that the carbon price was a fixed value so that the manufacture could always buy or sell volumes of GHG emission allowance with fixed price.

Comparing results in the related paper, Nagao et al. (2022) treated only carbon cap although carbon cap-and-trade is installed in many countries. Both of them also model a global supply chain network including suppliers, factories, and markets with GHG emissions. It was found cases that carbon cap-and-trade was better than carbon cap as shown in Section 6 in terms of cost-effectiveness of GHG reduction in the numerical experiments. Furthermore, mix policy consisted of carbon tax and carbon cap-and-trade would be better policy than carbon tax only and carbon cap-and-trade only in order to neutralize the negative effect on economy. Thus, future study should consider mix policy and examine the effects on GHG emissions and total costs (Kotegawa et al., 2024).

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Miyu Kotegawa: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing review editing, Visualization. **Yuki Kinoshita**: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing review editing, Visualization, Supervision, Project administration. **Tetsuo Yamada**: Conceptualization, Resources, Supervision, Project administration, Funding acquisition.

References

Choudhary, A., Sarkar, S., Settur, S. & Tiwari., M. K. (2015). A carbon market sensitive optimization model for integrated forward–reverse logistics. *Int. J. Production Economics*. 164, 433-444. http://dx.doi.org/10.1016/j.ijpe.2014.08.015

Fareeduddin, M., Hassan, A., Syed, M., & Selim, S. (2015). The Impact of Carbon Policies on Closed-loop Supply Chain Network Design. *Procedia CIRP*, 26, 335-340. https://doi.org/10.1016/j.procir.2014.07.042

Fareeduddin, M., Selim, S. Z. Hassan, A. & Syed, M. N. (2017). Multi-period planning of closed-loop supply chain with carbon policies under uncertainty. *Transportation Research Part D*. 52, 146-172. http://dx.doi.org/10.1016/j.trd.2016.10.033

Government of Canada. (2024). Net-zero emissions by 2050. Retrieved from. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html.

Horiguchi, K., Tsujimoto, M., Yamaguchi, H. & Itsubo, N. (2012). アジア国際産業連関表を用いた東アジア各国における温室効果ガス排出原単位データベースの開発 [Development of Greenhouse Gases Emission Intensity in Eastern Asia Using Asian International Input-Output Table]. In *Proceedings of the 7th Meeting of the Institute of Life Cycle Assessment*, 2012.236-239 https://doi.org/10.11539/ilcaj.2011.0.116.0.

Kinoshita, Y., Nagao, T., Ijuin, H., Nagasawa, K., Yamada, T. & Gupta, S. M. (2023). Utilization of Free Trade Agreements to Minimize Costs and Carbon Emissions in the Global Supply Chain for Sustainable Logistics. *Logistics*. 7(2), 32. https://doi.org/10.3390/logistics7020032

Kotegawa, M., Kinoshita, Y. & Yamada, T. (2024). Mix and Single Carbon Policy Evaluations for Cost-Effectiveness of GHG Reduction in Global Supply Chain Network. In: Chien, CF., Dou, R., Luo, L. (Eds.) Proceedings of Industrial Engineering and Management, Lecture Notes in Mechanical Engineering, Springer, Singapore. https://doi.org/10.1007/978-981-97-0194-0_66

Liu, M., Li, Z., Anwar, S. & Zhang, Y. (2021). Supply chain carbon emission reductions and coordination when consumers have a strong preference for low-carbon products. *Environmental Science and Pollution Research*. 28, 19969-19983. https://doi.org/10.1007/s11356-020-09608-0

Majumdar, A., Singh, S. P., Jessica., J and Agarwal, A. (2023). Network design for a decarbonized supply chain considering cap-and-trade policy of carbon emissions. *Annual of Operations Research*. https://doi.org/10.1007/s10479-023-05481-5

Marufuzzaman, M. and Duni, E. S. (2014). Environmentally Friendly Supply Chain Planning and Design for Biodiesel Production via Wastewater Sludge. *Transportation Science.* 48(4), 555-574. https://doi.org/10.1287/trsc.2013.0505

Meixell, M. J. & Gargeya, V. B. (2005). Global Supply Chian Design: A Literature Review and Critique. *Transportation Research Part E: Logistics and Transportation Review.* 41(6), 531-550. https://doi.org/10.1016/j.tre.2005.06.003

Ministry of the Environment. (2022). Annual Report on the Environment in Japan 2022. Retrieved from. https://www.env.go.jp/content/000176328.pdf.

Nagao, T., Ijuin, H., Nagasawa, K. & Yamada, T. (2022). Modelling of decarbonized global and local supply chain network for material-based greenhouse gas emission and costs with COVID-19 disruption and trans-Pacific partnership. *International Journal of Computational Intelligence Studies.* 11, 200–233. https://doi.org/10.1504/IJCISTUDIES.2022.129017

NTT DATA Mathematical System Inc. (2022). MSIISM. Retrieved from. https://www.msiism.jp/article/nuorium-optimizer-v24.html (accessed on December 29 2023).

Ravindran, A. R. & Warsing, D. P. (2013). Supply Chain Engineering: Models and Applications. USA: CRC Press.

Rebitzer, G., Ekvall, T., Frischknecht, R., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P. & Pennington, D.W. (2004). Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International.* 30, 701-720. https://doi.org/10.1016/j.envint.2003.11.005

SHARP. (2023). Sustainability Report 2023. Retrieved from. https://global.sharp/corporate/eco/report/pdf/ssr2023_e.pdf?v=2023.

Sherafati, M., Bashiri, M., Tavakkoli-Moghaddam, R. & Pishvaee, M.S. (2020). Achieving sustainable development of supply chain by incorporating various carbon regulatory mechanisms. *Transportation Research Part D.* 81, 102253. https://doi.org/10.1016/j.trd.2020.102253

United States of America. (2021). The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. Retrieved from. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf

World Bank. 2023. State and Trends of Carbon Pricing 2023. USA: World Bank. https://doi.org/10.1596/978-1-4648-2006-9.

Wu, H., Sun, Y., Su, Y., Chen, M., Zhao, H. & Li, Q. (2022). Which Is the Best Supply Chain Policy: Carbon Tax, or a Low-Carbon Subsidy? *Sustainability*. 14, 6312. https://doi.org/10.3390/su14106312

Xia, J., Li, R. Y. M., Zhan, X., Song, L. & Bai, W. (2022). A study on the impact of fiscal decentralization carbon emissions with U-shape and regulatory effect. Frontiers in Environmental Science. 10. https://doi.org/10.3389/fenvs.2022.964327

Xing, Z., Wang, J. & Zhang, J. (2017). CO2 Emission Performance, Mitigation Potential, and Marginal Abatement Cost of Industries Covered in China's Nationwide Emission Trading Scheme: A Meta-Frontier Analysis. *Sustainability*. 9, 932. https://doi.org/10.3390/su9060932

Xu, Z., Pokharel, S., Elomri, A. & Multu, F. (2017). Emission policies and their analysis for the design of hybrid and dedicated closed-loop supply chains. *Journal of Cleaner Production.* 142, 4152-4168. http://dx.doi.org/10.1016/j.jclepro.2016.09.192

Zeng, H., Li, R. Y. M. & Zeng, L. (2022). Evaluating green supply chain performance based on ESG and financial indicators. *Frontiers in Environmental Science.* 10. https://doi.org/10.3389/fenvs.2022.982828

Zeng, L., Li, R. Y. M., Zeng, H. & Song, L. (2023). Perception of sponge city for achieving circularity goal and hedge against climate change: a study on Weibo. *International Journal of Climate Change Strategies and Management.* 1756-8692. http://dx.doi.org/10.1108/IJCCSM-12-2022-0155

Zhao, L., Yang, C., Su, B. & Zeng, S. (2020). Research on a single policy or policy mix in carbon emissions reduction. Journal of Cleaner Production. 267, 122030. https://doi.org/10.1016/j.jclepro.2020.122030

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