Modeling Carbon Border Tax for Material-Based GHG Emission and Costs in Global Supply Chain Network

Takaki Nagao[1], Hiromasa Ijuin[1], Keisuke Nagasawa[2], and Tetsuo Yamada[1](✉)

[1] Department of Informatics, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu 182-8585, Tokyo, Japan
{n2130089,i2040014}@edu.cc.uec.ac.jp, tyamada@uec.ac.jp
[2] Graduate School of Advanced Science and Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan
nagasa-kei@hiroshima-u.ac.jp

Abstract. One of the problems in an environmental policy is carbon leakage, which is increasing GreenHouse Gas (GHG) emissions as an adverse effect due to the production shift from countries with strict climate change policies to those with careless ones. In this situation, Carbon Boarder Adjustment (CBA) is considered as a countermeasure for mitigating GHG emission and carbon leakage globally, with European Union (EU) agreeing to introduce the CBA in 2026. CBA is expected to have huge impact upon a global supply chain network. The reasons of it are that total cost and GHG emissions on a global supply chain network have been influenced by the different procurement cost, customs duty and GHG level from each country by the price level, the governmental policy, and the energy mix. However, it is not revealed how much effect CBA has for the cost, and GHG emission on a global supply chain network. Thus, this study models a global supply chain network with CBA as the intersection of environment and economy. First, a global supply chain network with CBA is modeled and formulated for minimizing the total cost using integer programming. Second, a problem example is prepared with bill of materials for the procurement cost and the GHG emission using life cycle assessment. After that, under the market in the U.S., a numerical experiment is conducted to validate the proposed model. Finally, the effect of CBA is discussed.

Keywords: Carbon Border Adjustment Mechanism · Carbon Leakage · Trans Pacific Partnership · Integer Programming · Life Cycle Assessment

1 Introduction

Recently, Carbon Boarder Adjustment (CBA) has been agreed upon to be introduced by European Union (EU) council as an economical and environmental scheme for avoiding carbon leakage [1]. Carbon leakage is the adverse effect of environmental policies, due to the production shifts form a country with strong policy to the other country with careless

H. Kohl et al. (Eds.): GCSM 2022, LNME, pp. 328–336, 2023.
https://doi.org/10.1007/978-3-031-28839-5_37

policy [2]. CBA is one of the countermeasure policies for carbon leakage. Under the CBA, an additional cost as importing tax is imposed based on the difference of climate policy [3].

This CBA has large impact on a global supply chain network [4]. This is because total cost and GreenHouse Gas (GHG) emissions on a global supply chain network have been influenced by the different procurement cost, customs duty and GHG level from each country by the price level and the energy mix [5].

Regarding the literature on CBA and a supply chain, Lim et al. [4] studied EU's CBA in terms of an economic scheme. Resultantly, they concluded that the CBA mechanism was not in line with international trade rules. In addition, it was too costly for the global economy while the goal of preventing climate change was agreeable. According to Martin et al. [6], industrial fields with carbon leakages did not apply to Emission Trade Systems (ETS), which were the regional cap-and-trade for GHG. Kondo et al. [7] analyzed the supplier selections considering GHG emission, and quantitatively showed whether there is a carbon leakage on global supply chain through numerical experiments. Nagao et al. [8] analyzed the impact of disruption for costs on a global supply chain network. However, the CBA based on GHG emission is not considered through modelling of the global supply chain network.

This study models a global supply chain network with CBA as the intersection of environment and economy. It specifically aims to estimate the effect of CBA based on an analysis for a global supply chain network by numerical experiments. The contribution of this paper is a new quantitative evaluation for CBA on the industrial field.

In this study, the Research Questions (RQs) are developed as follows.

RQ1: What is the effect of the cost and the GHG emission on a global supply chain by CBA?
RQ2: What is the CBA rate required to prevent carbon leakage?

2 Model and Formulation

In this section, in order to analyze CBA on a global supply chain network, the model and the formulation for numerical experiments are described. Section 2.1 develops the global supply chain model with CBA based on the previous study [8]. In Sect. 2.2, the model is formulated for minimizing total cost and the formulation of CBA based on GHG emission is given.

2.1 Model

Figure 1 shows CBA cost by material-based GHG emission in the proposed model of this study. When the GHG emission of goods manufactured in non-CBA countries is higher than one domestically produced in the country with CBA, it is assumed that the CBA is imposed. The CBA cost is calculated by multiplying the excess amount of GHG emission for importing products by a given CBA rate. To estimate quantitatively the CBA cost, material-based GHG emissions using Life Cycle Inventory (LCI) database [5] is used by Life Cycle Assessment (LCA) [9].

The global supply chain model is developed based on Nagao et al. [8] with a global supply chain model with customs duty and Trans Pacific Partnership (TPP), which is a comprehensive Free Trade Agreement (FTA). In the model, the product consists of N_j type parts. Part j is procured from supplier o to factory p, where the product is assembled at factory p. Then, assembled products are transported to market q. Meanwhile, the customs duties C_{pq}^{TS} are imposed when importing goods.

Set of suppliers in countries forming the TPP is defined as group G, which is a set of supplier cities. Among TPP member countries, the customs duty C_{op}^{TS} is not imposed. In other cases, importers need to pay customs duty when importing goods. Then, the developed element of the proposed model is CBA scheme. It can be applied when importing parts or products across the border of a country, similar to customs duties.

It is noted that this proposed model is assumed for the strategic planning stage of CBA scheme, where a just-in-time environment is applied similar to Nagao et al. [8], which represents fewer inventory operations [10]. Thus, inventory control with lead time is out of scope in this study.

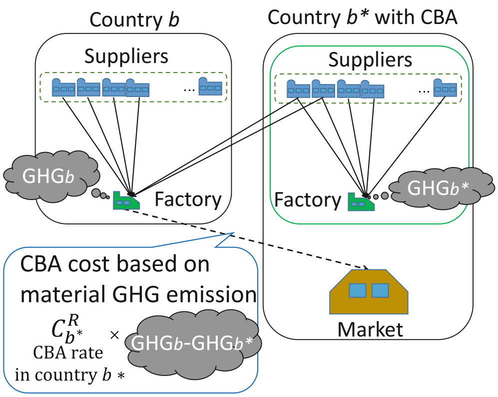

Fig. 1. CBA cost by material-based GHG emission in the proposed model of this study.

The notations used in this study are as follows:

Sets:
O: Set of suppliers, $o \in O$.
G: Set of suppliers in countries forming the TPP, $g \in G$, $G \subset O$.
B: Set of country, $b \in B$.
J: Set of parts, $j \in J$.
P: Set of factories, $p \in P$.
Q: Set of markets, $q \in Q$.

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 at factory p.
z_{pq}: 1 if the route between factory p and market q is opened, and 0 otherwise.
u_p: 1 if factory p is opened, and 0 otherwise.

Evaluation:
TC: Total cost [USD].
TG: Total GHG emission [t-CO2eq].

Cost parameters:
C_{op}^{LC}, C_{pq}^{LC}: Logistics cost per unit part and product for transportation.
C_{oj}^{PC}: Procurement cost of procuring per unit part j by 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 cost for opening route from factory p to market q, and opening factory p.

Production parameters:
N_j: Total number of parts j, consisting of one product.
N_q: Demand for products in market q.
M: : Very large number (Big M).
F_p: Production capacity at factory p.
S_{oj}: 1 if part j is supplied by supplier o, and 0 otherwise.

GHG parameters:
C_{b*}^{R}: CBA cost per ton of GHG emission at country b*[USD/t-CO2eq].
$E_p^{b^*}$: Non-negative value: The amount of GHG emission produced at factory p which is higher than one in country b* with CBA, and 0 otherwise.
H^{b^*} : Unit GHG emission per one product produced in country b* with CBA.
X_p: The amount of GHG emission produced at factory p.

2.2 Formulation

The objective functions are formulated to minimize total cost TC based on Nagao et al. [8]. TC is comprised from total manufacturing cost TMC, total transportation cost TTC, total customs duty cost $TCDC$, and total CBA cost $TCBA$ as shown in Eq. (1).

Objective function:

$$TC = TMC + TTC + TCDC + TCBA \rightarrow min \tag{1}$$

Consisting items of *TC* are set as follows.

$$TMC = \sum_{o\in O}\sum_{p\in P}\sum_{j\in J} C_{oj}^{PC} v_{opj} + \sum_{p\in P}\sum_{q\in Q} C_{p}^{MF} v_{pq} + \sum_{p\in P}\sum_{q\in Q} C_{pq}^{RT} z_{pq} + \sum_{p\in P} C_{p}^{FC} u_{p} \tag{2}$$

$$TTC = \sum_{o\in O}\sum_{p\in P}\sum_{j\in J} C_{op}^{LC} v_{opj} + \sum_{p\in P}\sum_{q\in Q} C_{pq}^{LC} v_{pq} \tag{3}$$

$$TCDC = \sum_{o\in O}\sum_{p\in P}\sum_{j\in J} C_{oj}^{PC} C_{op}^{TS} v_{opj} + \sum_{p\in P}\sum_{q\in Q} C_{p}^{MF} C_{pq}^{TS} v_{pq} \tag{4}$$

$$TCBA = \sum_{p\in P} E_{p}^{b^*} C_{b^*}^{\mathrm{R}} \tag{5}$$

$$E_{p}^{b^*} = \begin{cases} 0, & X_p - k_p H^{b^*} < 0 \\ X_p - k_p H^{b^*}, & X_p - k_p H^{b^*} \geq 0 \end{cases} \tag{6}$$

$$X_p = \sum_{p\in P}\sum_{o\in O}\sum_{j\in J} v_{opj} H_{oj} \tag{7}$$

TMC in Eq. (2) is the sum of the procurement cost of parts, manufacturing cost of products, route opening cost, and factory opening cost. *TTC* in Eq. (3) is the sum of transportation cost of parts from suppliers to factories and products from factories to markets. *TCDC* in Eq. (4) is the sum of the customs duty cost of parts and products. *TCBA* in Eq. (5) is calculated by the rate of CBA in the applied country timed the difference between total GHG emission at factory p and the expected emission produced only in a CBA country.

Equation (6) calculates $E_p^{b^*}$ as the difference of GHG emission at factory p by the expected emission of domestic local supply chain in the country $b*$ applied CBA. This Equation means the CBA cost is imposed by using the difference of GHG emission when material-based GHG emission of products produced at factory p is higher than one produced only in the CBA country $b*$. In Eq. (7), the sum of material-based GHG emission at factory p is calculated by multiplying the number of transportation parts and the parts GHG emission in supplier o.

The other constraints are set similar to Nagao et al. [8] for the number of products, parts, transportation volume, demand, opening route/factory, and production capacity at factories, and decision variables for binary and non-negative.

3 Problem Example

For conducting numerical experiments, problem examples about product, supply chain, cost and GHG emission of parts, and CBA assumption are given in this section.

To analyze the effect of CBA for a global supply chain network, problem examples are prepared based on Nagao et al. [8] as follows:

- Supply chain network example

  13 suppliers are located across countries such as the U.S., China, Malaysia, and Japan. As a candidate location of a factory, four cities are set at Seattle, Shanghai, Kuala Lumpur, and Tokyo, where the products are manufactured using transported parts from suppliers. The manufacturing cost for the product is different from countries. 3,000 manufacturing products units applies as the production capacity for each factory. Seattle in the U.S. is set as a market location, and the demand is 6,000 units.
- Customs duty and TPP example

  The customs duty rate for importing parts and products between the U.S. and China is 25%, and that between a TPP country and a non-TPP one is 10%. Between TPP countries, i.e., Malaysia and Japan, customs duty is 0%.
- GHG and cost example

  The material-based GHG emission and the procurement cost are vary with parts and countries. Average GHG emissions and average procurement costs of parts in each country are shown in Table 1 [11]. Moreover, so as to illustrate an application of the proposed model to a supply chain design example, the product example and assumptions are same as Urata et al. [12]. In their study, it is assumed that #19 motor is always supplied from Japan. This is because the GHG emission including CO2 emissions of the motor (#19) is so high that it is about 95% of the total emissions.

Table 1. Average GHG emissions and procurement costs of parts in each country [11]

	Average Parts GHG emission [g-CO2eq]	Average Parts Procurement cost [USD]
The U.S	117	0.095
Malaysia	249	0.078
China	633	0.086
Japan	103	0.143

- CBA example

  It is assumed that the U.S. is applied with CBA in this study. It is imposed when material-based GHG emission for produced products is higher than ones manufactured domestically in the U.S only. The cost is calculated by multiplying the rate $C^{\mathrm{R}}_{\mathrm{TheU.S.}}$ by the excess amount of GHG emission $E_p^{\mathrm{TheU.S.}}$. Three CBA rate are respectively examined as 1, 10, and 100 [USD/t-CO2eq] in the experiments.

4 Result

In this section, the results of numerical experiments by using the formulation and the problem examples in Sects. 2 and 3 are shown and discussed in terms of the CBA rate, the costs, and the GHG emission related to carbon leakages.

Figure 2 shows the results of total cost *TC* and total GHG emission *TG* with a global supply chain as the baseline without CBA, the baseline with CBA by 100 [USD/t-CO2eq], and after redesign. It is noted that the CBA was not applied in the only case of baseline without CBA. From Fig. 2, the total cost *TC* was increased by 11% in the case with CBA before redesign, but increased only 5% from the baseline without CBA in the case with CBA after redesign.

After redesigned comparison to the baseline without CBA, the total transportation cost *TTC* was decreased by 74%, and total procurement cost *TPC* was increased by 18%. While the total CBA cost *TCBA* accounts for 10% of the total cost *TC*, that after redesign was only 2% of the total cost. Therefore, it is verified that this model can propose a supply chain reconfiguration to suppress the increment of total cost under CBA. On the other hand, the total GHG emission was decreased by 58% in the case after redesign with CBA. Thus, it is found that CBA rate of 100 [USD/t-CO2eq] has influence on the total cost and total GHG emission on the global supply chain network. Furthermore, it is noted that carbon leakages were not observed in this case. In the other numerical experiments, the results for the GHG emission and costs without CBA are not changed with the CBA rate of 1 and 10 [USD/t-CO2eq].

Therefore, it is found that CBA by material-based GHG emission has prevented carbon leakages when the CBA is applied to a low GHG country, the U.S. in this study.

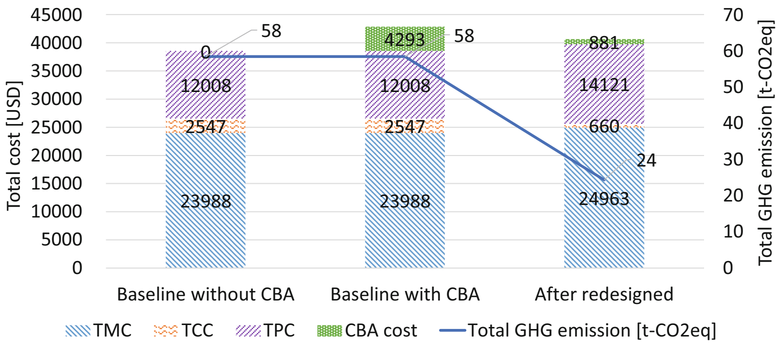

Fig. 2. The results of total cost *TC* and total GHG emission *TG* with a global supply chain as the baseline without CBA, the baseline with CBA by 100 [USD/t-CO2eq], and after redesign

5 Conclusion

This study modeled a global supply chain network with CBA as the intersection of environment and economy. It specifically aimed to estimate the effect of CBA based on an analysis for a global supply chain network by the numerical experiments. The contribution of this study was to model a global supply chain network for analyzing the CBA effect quantitatively using LCA. Answers of RQs developed in Sect. 1 are as follows:

- Answer of RQ1: What is the effect of the cost and the GHG emission on a global supply chain by CBA?

  The cost breakdown was changed mainly for the decrease of transportation cost and the increase of total procurement cost when the applied CBA rate was 100 [USD/t-CO2eq]. Therefore, the total GHG emission was largely decreased.
- Answer of RQ2: What is the CBA rate required to prevent carbon leakage?

The rate of 1 to 100 [USD/t-CO2eq] did not bring carbon leakages. In terms of reducing GHG emission, the rate of 100 [USD/t-CO2eq] was appropriate. Moreover, it was found that application of CBA to low GHG level country was effective for preventing the carbon leakage in terms of material-based GHG emission and costs in the experiments.

In this study, CBA was treated as an environmental tax. Nevertheless, industrial production has been influenced by multiple environmental policies. Therefore, further study should consider the combination of the multi-environmental policy such as CBA and carbon tax.

Acknowledgement. This study was partially supported by the Japan Society for the Promotion of Science (JSPS), KAKENHI, Grant-in-Aid for Scientific Research (A), JP18H03824, from 2018 to 2023.

References

1. Council of the EU Press release, Council agrees on the Carbon Border Adjustment Mechanism (CBAM). https://www.consilium.europa.eu/en/press/press-releases/2022/03/15/carbon-border-adjustment-mechanism-cbam-council-agrees-its-negotiating-mandate/. Accessed 11 May 2022
2. Carbon Market Watch, Carbon Leakage. https://carbonmarketwatch.org/2014/08/29/carbon leakage/. Accessed 22 Jan 2019
3. Taxation and Customs Union, Carbon Border Adjustment Mechanism. https://ec.europa.eu/taxation_customs/green-taxation-0/carbon-border-adjustment-mechanism_en. Accessed 6 May 2022
4. Lim, B., Hong, K., Yoon, J., Chang, J. I., Cheong, I.: Pitfalls of the EU's carbon border adjustment mechanism. Energies. **14**, (2021). https://doi.org/10.3390/en14217303
5. Kokubu, K., Itsubo, N., Nakajima, M., Yamada, T.: Low Carbon Supply Chain Management. Chuokeizai-sha Inc, Tokyo, Japan (2015). (In Japanese)
6. Martin, R., Muûls, M., De Preux, L.B., Wagner, U.J.: On the empirical content of carbon leakage criteria in the EU emissions trading scheme. Ecol. Econ. **105**, 78–88 (2014). https://doi.org/10.1016/j.ecolecon.2014.05.010
7. Kondo, R., Kinoshita, Y., Yamada, T.: Green procurement decisions with carbon leakage by global suppliers and order quantities under different carbon tax. Sustainability. **11**(13), 3710, (2019). https://doi.org/10.3390/su11133710

8. Nagao, T., Ijuin, H., Yamada, T., Nagasawa, K., Zhou, L.: COVID-19 disruption strategy for redesigning global supply chain network across TPP countries. Logistics **6**(1), 2 (2022). https://doi.org/10.3390/logistics6010002
9. Sugiyama, H., Fukushima, Y., Hirao, M., Hellweg, S., Hungerbuhler, K.: Using standard statistics to consider uncertainty in industry-based life cycle inventory databases. Int. J. Life Cycle Assess **10**, 399–405 (2012)
10. Salvendy, G.: Handbook of Industrial Engineering Technology and Operations Management, 2nd edn. A Wiley-Interscience Publication, 605 Third Avenue, New York, USA (1992)
11. Hayashi, K., Matsumoto, R., Yamada, T., Nagasawa, K., Kinoshita, Y.: Designing a global supply chain network considering carbon tax and trans-pacific partnership agreement. In: Proceedings of the 2020 the Society of Plant Engineering Japan Spring Conference, pp. 97–100. The Society of Plant Engineering Japan, Tokyo, Japan (2020) (In Japanese)
12. Urata, T., Yamada, T., Itsubo, N., Inoue, M.: Global supply chain network design and Asian analysis with material-based carbon emissions and tax. Comput. Ind. Eng. **113**, 779–792 (2017). https://doi.org/10.1016/j.cie.2017.07.032