

Article

# Green Procurement Decisions with Carbon Leakage by Global Suppliers and Order Quantities under Different Carbon Tax

### Rena Kondo, Yuki Kinoshita and Tetsuo Yamada \*

Department of Informatics, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan

\* Correspondence: tyamada@uec.ac.jp; Tel.: +81(42)-443-5269

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Abstract: Manufactures have been pressed to reduce greenhouse gas (GHG) emissions by environmental regulations and policies. Towards to reduction of GHG emissions, a carbon tax has been already introduced in 40 countries. Owing to different carbon prices among countries, there are potential risks of carbon leakage, where manufacturers transfer production operations to the countries with lower taxes to pursue lower costs. Moreover, procurement costs and GHG emissions vary by country because of economic conditions and electric energy mixes. Therefore, total GHG emissions could be globally reduced if manufactures relocate their production bases or switch suppliers in the country with lower GHG emission levels. This study proposes a green procurement decision for the supplier selection and the order quantity for minimizing GHG emission and costs considering the different carbon taxes in different countries. First, a bill of materials for each part is constructed through the life cycle inventory database with the Asian international input/output tables for a case study. Second, a green procurement decision considering the different carbon prices is formulated using integer programming. Finally, the results, including carbon leakage, are analyzed from the viewpoint of manufacturers, governments, and global perspectives.

**Keywords:** global warming; global supply chain; carbon trading; circular economy; carbon leakage; negative externalities; sustainable development goals; environmental governance; environmental fiscal efficiency; low carbon economy

### 1. Introduction

The Circular Economy Action Plan published in 2015 in EU enhances shifting from linear traditional economic model "take-make-consume-disposal" or "extract-produce-use-dump material and energy flow" [1] to "closing the loop" of product lifecycles for sustainable manufacturing [2]. This circular economy is also expected to achieve the goals of the Paris Agreement in terms of reducing greenhouse gas (GHG) emissions by minimizing usage of resources such as materials and energy [3]. The Paris Agreement signed at the 21st Conference of Parties (COP 21) in 2015 encouraged the 188 emerging and developed countries to adopt a sustainable low-carbon future [4]. In Asia, for instance, the CO<sub>2</sub> volume released into the air accounted for more than 40% of the total emissions worldwide in 2013, especially in China, which emitted 28.7% of the total emission recorded [5]. It has been suggested that, if the circular economy is expanded to Asia, the competition rule managing resource circulation will change [6]. Although, the circular economy will bring lower GHG emission production, it is not easy to challenge transition to the circular economy business model since companies need to be profitable in addition to improving their environmental performance under highly competitive business environments [1].



With respect to another trend about manufacturing, Industry 4.0 has been developed and provided immense opportunities for realizing sustainable manufacturing using the ubiquitous information and communication technology infrastructure [7]. Then, Industry 4.0 era enables easily to collect and share product information such as procurement cost and GHG emissions for virgin material production between suppliers and factories in global supply chain. Under Industry 4.0, GHG emissions and procurement cost could be also estimated automatically by using the 3D-CAD and life cycle inventory (LCI) database. This LCI provides a representative unit's process data collected at the national or regional level, covering a wide range of industries [8]. These technologies would be helpful and useful in constructing low carbon supply chain globally against global warming in not only developed and but also emerging countries. Hence, the manufacturers can design the supply chain and products while reducing GHG emissions, and the circular economy in Industry 4.0 can contribute to reducing GHG emissions while manufacturing products efficiently with lower cost.

In forward supply chains consisting of parts/materials manufacturing, assembly manufacturing, and logistics stages, the CO<sub>2</sub> emissions sometimes account for more than 90% of the CO<sub>2</sub> emissions for electric products and home appliances, such as copiers, cell phones, refrigerators, air conditioners, and TVs [9]. Therefore, the material procurement stage in the supply chain is important for reducing GHG emissions. According to the LCI database [10], the material-based GHG emissions depend on the country of manufactured from. One reason for this is that the energy mix for electric power from coal, natural gas, and nuclear resources varies by country. In general, materials manufactured in developed countries have lower GHG emissions but higher procurement costs. On the other hand, those manufactured in emerging countries have higher GHG emissions, the most appropriate suppliers and order quantity should be considered simultaneously. The supplier selection is the process of selecting appropriate suppliers for specific components, especially to ensure lower procurement cost of parts [11] and material-based GHG emissions. The order quantity refers to the number of products and parts, which determines replenishment in a single order [12] and is important in decision-making for reducing the procurement costs [13].

On the other hand, a carbon tax system has been introduced in several countries, particularly those in Europe and Asia to strengthen the campaign on CO<sub>2</sub> emissions globally [14]. The carbon tax is an environmental levied tax, where the penalty cost is decided by the level of the CO<sub>2</sub> emissions produced by an economic activity [15]. Consequently, carbon taxes are expected to give economic incentives to manufacturers to reduce GHG emissions during manufacturing processes even in countries that do not have other environmental policies related to global warming [15].

However, the carbon price differs by country; for example, the carbon price is 126 \$/t in Sweden, 8 \$/t in China [16], and 2.89 \$/t in Japan [17]. Moreover, the prices are expected to increase in the future, along with the number of countries that would impose the carbon tax system [14]. In France, the carbon price was 27 \$/t in 2016, but it will reach 68 \$/t by 2020 and 121 \$/t by 2030 [17]. Given the differences in carbon prices among countries, the Carbon Market Watch has highlighted the potential risk of carbon leakage wherein companies in countries that use the carbon tax system may transfer operations to countries with less ambitious climate measures, like "carbon tax havens," in an effort to minimize costs related to complying with stringent climate policies [6]. This can mislead to an increase in the total GHG emissions globally [6]. The World Bank Group also suggests that carbon leakage and its consequences increase the GHG emissions in the country that has less ambitious climate measures [18]. Shaharudin et al. [19] surveyed 12,479 publications and pointed out the needs of future studies to integrate energy policy into the low carbon supply chain model in order to understand how policy makers can encourage industry to comply with low carbon emission and energy management practices. Therefore, there is a need to study appropriate carbon prices among countries that are involved and investigate how to reduce the GHG emissions not only in each country but also across the borders in designing global supply chain and procurement process.

However, material-based GHG emissions and carbon leakage have not been treated simultaneously in the global procurement process even though these differ by country. Thus, it is necessary to reduce not only the GHG emissions for each country but also the total GHG emission globally across all countries.

This study proposes green procurement decisions of global suppliers and order quantity by introducing the different carbon price among Asian countries, and investigates the effect of carbon leakage. The main focus of this study is to analyze the impacts of the different carbon price in each country on the global supply chain with consideration of economic levels and GHG emissions among countries by using Asian LCI database. Moreover, GHG emissions at the logistic stage for a home appliance is less than 10% in the forward supply chain consisted of parts/materials manufacturing, assembly manufacturing, and logistics stages [9]. Therefore, this study addresses the procurement cost, carbon tax, and GHG emissions at the material production phase, and assumes that the transportation cost and GHG emissions for transportation from the supplier to a factory are not considered.

The outline of this paper is as follows: Section 2 reviews the literature on carbon tax and carbon leakage. Section 3 models the green procurement of supplier selection and order quantity by introducing the different carbon price among countries. In there, the order quantity and supplier selection are formulated by using integer programming to achieve reduction in both GHG emissions and total costs simultaneously. Section 4 prepares a product example and scenarios of supplier selection. A bill of materials (BOM) for each Asian country including the GHG emissions and the procurement costs for each part is constructed through the LCI database with the Asian international I/O tables. Section 5 discusses the results including that for the carbon leakage. Finally, Section 6 gives the conclusions of this study and proposes future works.

#### 2. Literature

There are many studies on low-carbon economies and supply chains as shown in Table 1. Villar Rubio, Quesada Rubio, Molina Moreno [20] used GDP, environmental tax revenue, population as evaluation indices to analyze convergence in environmental fiscal effort. Ruiz-Guerra et al. [21] treated air pollution by cruise tourism at port of Barcelona. Jensen et al. [22] and Jovanovic' et al. [23] focused on GHG emissions in agriculture and analyzed the relationships between agricultural economies and GHG emissions. Sun et al. [24] investigated effects of GDP, trade amount, and energy consumption on immediate and long-term CO<sub>2</sub> emissions the trade within Belt and Road regions.

Ghani et al. [4] provided optimized GHG reduction policy plans by focusing on tracing GHG emissions in supply chain of the residential, commercial, and industrial building construction industries. Kuo and Lee [25] investigated a bi-objective optimization problem with the Pareto frontier under the trade-offs between cost and carbon footprint. Urata et al. [26] proposed a model for an Asian global supply chain network that balanced both the procurement/transportation cost and the material-based  $CO_2$  emissions, and conducted a sensitivity analysis of the emissions cost with carbon trading, in which the cost is applied based on the amount of  $CO_2$  emissions beyond the target reduction ratio for  $CO_2$  emissions and is added to the total costs [26]. Kuo et al. [27,28] investigated a bi-objective optimization problem of supply chain network design for solving the trade-off problem, in which carbon footprints were decreased while cost effectiveness was ensured. Kondo et al. [29] applied a low-carbon and economic supplier selection method to a cell phone and compared the results of two types of products, a cell phone and a vacuum cleaner. In these studies, the authors disregarded carbon tax in selecting suppliers though the suppliers may be changed because of the costs that are affected by carbon tax.

Literature	<b>Evaluation Indices</b>			Carbon Tax	Carbon Leakage	Supply Chain Decision		Subject
Cost/Profit Environment		Consideration of Carbon Price	Different Carbon Price among Multiple Countries	Effect of Carbon Leakage	Supplier Selection	Order Quantity	Countries/Regions	
Villar Rubio, Quesada Rubio, Molina Moreno (2017) [20]	GDP, Environmental tax revenue	-	-	-	-	-	-	15 EU countries
Ruiz-Guerra et al. (2019) [21]	-	Air pollution such as NO, NO <sub>2</sub> , and O <sub>3</sub>	-	-	-	-	-	Barcelona
Jensen et al. (2019) [22]	Х	Non-CO <sub>2</sub> GHG emissions	Х	-	-	-	-	82 individual countries
Jovanovi´c et al. (2015) [23]	GDP per capita	GHG emissions per capita, CO <sub>2</sub> emissions per capita	-	-	-	-	-	18 developed countries and 11 developing countries in Europe
Sun et al. (2019) [24]	GDP per capita, trade amount	CO <sub>2</sub> emissions, Energy consumption	-	-	-	-	-	49 high-emission countries in Belt and Road regions
Ghani et al. (2018) [4]	Х	GHG emissions	-	-	-	-	-	USA
Kuo and Lee (2019) [25]	Х	Carbon footprint	-	-	-	Х	Х	Taiwan
Urata et al. (2017) [26]	Х	CO <sub>2</sub> emissions	-	-	-	Х	Х	Japan, China and Malaysia
Kuo et al. (2014) [27]	Х	GHG emissions	-	-	-	Х	Х	Taiwan
Kuo et al. (2017) [28]	Х	GHG emissions	-	-	-	Х	Х	Taiwan
Kondo et al. (2019a) [29]	Х	GHG emissions	-	-	-	Х	Х	Japan and China
Almutairi and Elhedhli (2014) [30]	Х	CO <sub>2</sub> emissions	Х	-	-	-	-	Canada
Kuo et al. (2016) [31]	Х	CO <sub>2</sub> emissions	Х	-	-	-	-	Taiwan
Fahimnia et al. (2015) [32]	Х	CO <sub>2</sub> emissions	Х	-	-	Х	Х	Australia
Zakeri et al. (2015) [33]	Х	CO <sub>2</sub> emissions	Х	-	-	Х	Х	Australia
Kondo et al. (2019b) [34]	Х	GHG emissions	Х	-	-	Х	Х	Japan and China
Wang et al. (2018) [35]	Trade intensity	Carbon intensity	Х	-	Х	-	-	China
Santos et al. (2018) [36]	Trade share	Emissions intensity	Х	-	Х	-	-	Brazil
								Belgium, France,
Martin et al. (2014) [37]	Trade intensity	Carbon intensity	Х	-	Х	-	-	Germany, Hungary, Poland and the UK
		VBE (value-added						
Liu and Fan (2017) [38]	GDP	based accounting of CO <sub>2</sub> emissions)	-	-	Х	-	-	77 economies
Barker et al. (2007) [39]	GDP	$CO_2$ emissions	-	-	Х	-	-	25 EU countries
This study	Х	GHG emissions	Х	Х	Х	Х	Х	Japan, China and Malaysia

Table 1.	Literature on lo	ow-carbon supply	v chains that	consider	carbon	tax and	carbon	leakage
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Studies on carbon tax are shown in Table 1. Almutairi and Elhedhli [30] and Kuo et al. [31] examined impacts of a carbon tax on enterprise strategies, by solving the problem of minimizing costs with a carbon tax. However, both studies did not consider the supply chain decisions including supplier selection and order quantity. Fahimnia et al. [32] and Zakeri et al. [33] modeled the supply chain planning throughout manufacturing plant, warehouse, and customer for minimizing the total cost with the carbon tax. Kondo et al. [34] proposed a low-carbon and economic supplier selection method by introducing the carbon tax. In general, the carbon price differs by country because it is decided by the government in each country. As a result, the risk of carbon leakage is great. However, their study did not consider the different carbon prices in other countries and did not discuss carbon leakage.

With regard to carbon leakage, Wang et al. [35] expanded the analysis of carbon leakage from the view point of emissions trading system (ETS) sectors to that of non-ETS sectors, and investigated the interaction between the ETS and other policies. Santos et al. [36] evaluated the impacts of carbon pricing instruments on the industry in Brazil and found the carbon leakage could occur as an expected outcome. Martin et al. [37] analyzed the current scheme in order to address the carbon leakage implemented in the EU ETS. Liu and Fan [38] estimated the value-added based accounting of CO<sub>2</sub> Emissions (VBE), which was also named accumulated CO<sub>2</sub> emissions behind economic increase. They also found that emission importers would be helpful for emission exporters to reduce carbon leakage in six examples of ETRs in Europe by measuring the carbon leakage. However, these studies did not consider carbon leakage when the supplier and order quantity are selected and determined under carbon tax conditions. To reduce GHG emissions, it is required to reduce GHG emissions not only for each country but also globally.

Therefore, this study proposes green procurement decisions of supplier selection and order quantity by introducing different carbon prices among countries in Asia, and investigates the effect of carbon leakage in the entire supply chain. This study mainly focusses on modeling and discussions in terms of GHG emissions and carbon tax/procurement cost to investigate risk of the carbon leakage in the global supply chain by introducing different carbon prices in each country. This is because supply chain decisions with carbon leakage has been ignored though the literatures treat the other dimensions as shown in Table 1. Additionally, it may bring not to identify which factors have direct or large impacts of the carbon leakage in the global supply chain, even if the other dimensions could be all considered. By considering both the different carbon prices among countries and the risk of carbon leakage, manufacturers and governments could reduce GHG emissions and costs, thus resolving the global warming beyond their countries.

#### 3. Procedure

### 3.1. Overview

This section outlines the green procurement decisions for order quantity and supplier selection given different carbon prices among countries based on Kondo et al. [34]. Figure 1 shows the procedure of the low-carbon and economic supplier selection method with order quantity for different carbon taxes among countries. The procedure consists of six steps. In step 1, a bill of materials (BOM) is constructed through the LCI database with Asian international I/O tables to identify the types of materials and department names [40]. In step 2, the procurement cost for each part is estimated based on a census of manufactures [40] and economic conditions in each country [41]. Then, in step 3, the GHG emissions are estimated by using the LCI database with the Asian international I/O tables. In step 4, green procurement decisions for order quantity and supplier selection with different carbon prices in different countries are formulated by employing integer programming. In step 5, the order quantity and the supplier are determined using a mathematical programming package with a numerical optimizer [42]. Finally, in step 6, the decisions of order quantity and supplier selection are analyzed.



**Figure 1.** Procedure of low-carbon and economic supplier selection method with order quantity for different carbon taxes among countries.

# 3.2. Steps 1–3: Construction of the Bill of Materials and Estimation of the Procurement Costs and the GHG Emissions

The procurement costs and the GHG emissions are estimated based on Yoshizaki et al. [11] and Kondo et al. [29,34]. The system boundary, which means the range and limit of an investigation object [43,44], is set as the raw material production and logistics in this study. A BOM is constructed to identify the types of materials and department names in the LCI database with the Asian international I/O tables. Then, the Japanese procurement costs for each part are estimated using the Japanese census of manufacturers [40] as the 3D-CAD model does not provide this cost information. The procurement costs for the parts manufactured in other Asian countries are then estimated using a price level determined by the economic conditions for each country. For example, the procurement costs in China and Malaysia may be 0.517 and 0.552 times lower than those in Japan, respectively [41].

Afterwards, the GHG emissions for each country are estimated based on the procurement costs and the LCI database with the Asian international I/O tables. The Asian LCI database includes the GHG emission levels in Japan, China, Malaysia, Indonesia, the Philippines, Singapore, Thailand, Korea, Taiwan, and the USA [45]. Therefore, the global supply chain in these countries can be evaluated in terms of procurement costs and GHG emissions.

To calculate the material-based GHG emissions and procurement cost in each country based on Yoshizaki et al. [11]. The data came from 4 different databases: 3D-CAD model [46], price level in each country [41], Census of Manufacturing [40], and LCI database with Asian International I/O tables [45]. The weight and type of material for each part were referred from 3D-CAD model [46]. Then, the weight and material type for each part can have higher accuracy [47]. The procurement cost in each country was calculated based on part weight, unit material price, and the price level in each country [41]. The material unit price was obtained from census of manufacturing [40]. Then, the obtained material price means representative and average data [47].

The GHG emission of each part procured in each country was calculated by using the procurement cost and GHG emissions intensity in LCI database with Asian International I/O tables [45]. According to Horiguchi et al. [45], the calculated GHG emissions with LCI database with Asian International I/O tables differs within 10% from the statics values for all countries except of Singapore. Therefore,

the calculated GHG emissions and procurement cost are enough to repeatability as far as the databases are used.

# 3.3. Steps 4–5: Formulation and Determination of Order Quantity and Supplier Selection with Different Carbon Prices

A formula to determine the order quantity and supplier selection with a different carbon price in different countries is needed to minimize the procurement costs/carbon tax and the GHG emissions. The main motivation of this study is not to solve an actual industrial and complex case, but to support green procurement decisions for not only large companies but also small and medium sized enterprises by analyzing the impacts of the different carbon tax on the constructing global supply chain with and without the carbon leakage. This is because global warming is a worldwide serious issues and needs to be dealt with in developed and emerging countries together. Therefore, company in emerging country or small and medium sized enterprises in developed countries may not have engineers with enough technical skills, but the green procurement decisions are required for sustainability. Then, the simple but standard models are also helpful and universal for not only large manufactures with operations research (OR) specialist but also smaller ones with an undergraduate student and starters of OR, who can formulate and solve it without any difficulty, to support green procurement decision with the carbon tax. The notations and formulations are explained in detail below.

(i) Sets

*J*: Set of parts,  $j \in J$ *L*: Set of suppliers,  $l \in L$ 

(ii) Decision variables

 $f_{li}$ : Quantity of procured part *j* from supplier *l* 

(iii) Parameters

 $PC_{lj}$ : Procurement cost of part *j* from supplier *l*   $e_{lj}$ : GHG emissions for part *j* at supplier *l*   $n_j$ : Quantity of part *j* needed for a product  $N_{product}$ : Quantity of product demands  $Q_{min, lj}$ : Minimum order quantity from supplier *l* for part *j*  $CTAX_l$ : Unit cost of carbon price per ton at supplier *l* 

To minimize the cost within the constraints of the GHG emissions using the LCI database with the Asian international I/O tables, Equation (1) is the objective function needed to minimize the total procurement costs for each part in the BOM [11] and carbon tax. The GHG emissions in this study is calculated based on LCI database with Asian international I/O tables [45]. According to the LCI database with Asian international I/O tables, GHG includes N<sub>2</sub>O (nitrous oxide), HFCs (hydrofluorocarbon), PFCs (perfluorocarbon) and SF<sub>6</sub> (sulfur hexafluoride). Since they are represented as [g-CO<sub>2</sub> eq.] unit, non-CO<sub>2</sub> GHG volumes are also converted as CO<sub>2</sub> volumes. Therefore, unit cost of carbon price  $CTAX_{lj}$  is multiplied by GHG emission  $e_{lj}$  to calculate carbon tax.

Equation (2) ensures that the quantity of procured parts from the suppliers meets the number of parts required by the product demand for each part *j*. The required number of each part *j* for one product is denoted as  $n_j$ . The value of  $n_j$  is delivered from the BOM. On the other hand, quantity of product demands is expressed as  $N_{product}$ . Thus, the total required number of each part *j* to satisfy the product demand is obtained by multiplying  $n_j$  by  $N_{product}$  as shown in the right side of equation (2). The constraint equation (3) ensures that the quantity of transported parts  $f_{lj}$  from supplier *l* is equal to or higher than the minimum order quantity  $Q_{min,lj}$ . A mathematical programming package named as Numerical Optimizer developed by NTT DATA Mathematical Systems Inc. are used in calculating for this model [42].

$$TPC = \sum_{j \in J} \sum_{l \in L} \left( PC_{lj} + e_{lj} CTAX_l \right) f_{lj} \to Min$$
<sup>(1)</sup>

Subject to

$$\sum_{l \in L} f_{lj} = n_j N_{product} \forall j \in J$$
<sup>(2)</sup>

$$f_{lj} \ge Q_{min,lj} \forall l \in L, \forall j \in J$$
(3)

#### 3.4. Step 6: Analysis for the Effect of Carbon Leakage

The bi-criteria for lower GHG emission and costs, including different carbon taxes among multiple countries, are examined by determining the order quantity and supplier selection. Using an Asian case study in which Japan, China, and Malaysia are considered, the sensitivity analyses are conducted by setting the different Chinese and Malaysian carbon prices. The results of order quantity and supplier selection are discussed, including the effect of carbon leakage.

#### 4. Problems

#### 4.1. Assumptions

This section explains the assumptions employed for the input data of GHG emission, supplier selection, and carbon leakage scenarios treated. In this study, the proposed method is applied to a cell phone case study [29,34], and some assumptions are based on Kondo et al. [34]. Table A1 in Appendix A shows the BOM of each part of the cell phone [29,34], including the procurement cost and the GHG emission in each country. Regarding the GHG emission and cost, it is noted that there is a trade-off between the procurement cost and GHG emission among these three countries. This is because the energy mix for electric power from coal, natural gas, and nuclear resources differs among these countries according to the LCI database with the Asian international input-output (I/O) tables [45]. For example, from Table A1, the GHG emission for a part such as the #9 junction in China is 6.4 and is 3.1 times higher than those in Japan and Malaysia. On the other hand, the procurement cost for the same part in Japan is 1.9 and 1.8 times higher than that in China and Malaysia, respectively.

Enumerated below are the assumptions used for supplier selection for the example problem in this study:

- There are three suppliers that can supply the needed part. One is in Japan, a developed country, and the other two are in China and Malaysia, both emerging countries. China is selected as it the largest importer and second largest exporter of Japanese products [48]. The Malaysian economy is also considered as it has shown remarkable economic growth since 2010 [26].
- There is only one supplier per part per country.
- One manufacturer in Japan can satisfy 1000 Japanese product demands. The product demand quantity is a fixed parameter and not a decision variable.
- The minimum order quantity per supplier is assumed to be 1.
- The Japanese supplier is always chosen for the part #11 LCD made of glass because the percentages of weights for the part #11 LCD is lower such as 0.49%.

#### 4.2. Scenarios of Different Carbon Prices among Multiple Countries

To examine whether the target ratio of GHG reduction in the Paris agreement can be achieved in the supply chain with and without carbon leakage, green procurement scenarios with different carbon prices among the selected countries are prepared. Many countries are expected to introduce a carbon tax system to reduce GHG emissions. In general, the carbon prices may increase in the future [14]. Thus, sensitivity analyses for the carbon prices are conducted to investigate the effect of the tax increase among multiple countries.

According to the Paris Agreement, the Japanese government set a target of reducing 2013 GHG emissions by 26% by 2030 [49]. Then, an initial supply chain configuration is constructed to achieve a 26% reduction in GHG emissions. The assumptions for the different carbon prices in this study are as follows:

- The carbon price in Japan is set as 2.89 \$/t, which is current price in Japan [17].
- This study investigates the effects of Chinese and Malaysian carbon prices changes.
- The sensitivity analysis for the carbon price is conducted up to 289 \$/t. This is because the carbon price that needs to be imposed in Japan should be 10 times to more than 100 times higher than the current price of 2.89 \$/t for Japan to realize its goal according to Weekly Economist [50].

### 5. Results: Effect of Difference Carbon Prices in Countries

This section investigates the impact of carbon leakage on the total GHG emissions in the entire supply chain. Carbon leakage refers to the situation where the strict climate policy of one country with GHG emission reduction results in an increase in emissions in another country. Then, the increase in the GHG emissions is normally larger than the reduction in the first country. Hence, although a manufacturer in the supply chain can reduce its total costs, including the carbon tax payment, the reduction may cause higher GHG emissions globally [6].

On the other hand, countries have different GHG emission intensities owing to their electric energy mix based on the LCI database [10,45]. Therefore, there might be a case where the total GHG emissions in the entire supply chain are reduced despite the occurrence of carbon leakage. This is because carbon leakage depends on both the carbon prices and GHG emission intensities in various countries. For instance, if a manufacture relocates to a country with a lower carbon price and lower GHG emissions intensity from a country with a higher carbon price and higher GHG emissions intensity, the total GHG emissions in the entire supply chain would be reduced even if carbon leakage occurs. Here, three research questions can be posed:

- RQ1: Do different carbon prices among countries always cause carbon leakage? Does carbon leakage always increase the total GHG emissions in the entire supply chain?
- RQ2: What different costs and GHG breakdowns can be observed in cases with increments and decrements in the total GHG emissions in the entire supply chain?
- RQ3: How much should the carbon price in each country be set to avoid carbon leakage and to reduce GHG emissions throughout the entire supply chain?

# 5.1. RQ1: Do Different Carbon Prices among Countries always Cause Carbon Leakage? Does Carbon Leakage always Increase the Total GHG Emissions in the Entire Supply Chain?

Sensitivity analyses of Chinese and Malaysian carbon prices are conducted in this subsection to identify the relationships between the occurrence of carbon leakage and different carbon prices. Figure 2 compares the GHG emission ratios to that in the initial supply chain configuration. The following Chinese carbon prices were used: 8.00 \$/t, 28.90 \$/t, 57.80 \$/t, and 86.70 \$/t. The following Malaysian carbon prices were used: 2.89 \$/t, 28.90 \$/t, 57.80 \$/t, ..., 289.00 \$/t, as shown in Figure 2. Collectively, there were a total of 44 cases with different Chinese and Malaysian carbon prices. Each bar shows the increment/decrement in GHG emission ratios with the initial supply chain configuration as the baseline. In there, the supply chain was constructed to have GHG emissions that were 26% lower than those in the supply chain constructed to minimize costs. The blue and orange bars indicate that, owing to carbon leakage, the GHG emissions increased by over 30% and within 15%, respectively. On the other hand, the grey and yellow bars indicate that, despite the occurrence of carbon leakage, GHG emissions decreased by 40% and over 50%, respectively.





**Figure 2.** Greenhouse gas (GHG) emissions ratios for different Chinese and Malaysian carbon prices compared to initial supply chain configuration: The initial supply chain is constructed with lower GHG emissions by 26% than that for cost minimum.

All the cases had carbon leakage caused by the different carbon prices, as the total GHG emissions in all cases were different from those in the initial supply chain configuration. By switching the supplier in a certain county to another country, it is unavoidable to increase the GHG emissions in the latter county. Therefore, carbon leakage occurred in the all cases. However, we found, in 18 out of the 44 cases, total GHG emissions were reduced in the entire supply chain with carbon leakage.

Three observations can be found from the numerical experiments as shown in Figure 2. One is that the total GHG emission increased when the Chinese carbon price was set as 8.00 \$/t. This was because the Chinese carbon price was too low to encourage manufacturers to reduce GHG emissions based on the carbon tax at the examined ranges in the numerical experiments. The second observation is that the Malaysian carbon prices should be equal to or less than 231.20 \$/t. This is because the total GHG emissions was decreased with carbon leakage when the Malaysian carbon price was equal to or less than 231.20 \$/t. The last observation is that cases of reductions for the total GHG emission in the entire supply chain increased as the Chinese carbon prices increased.

From these findings, it seems that the Chinese carbon prices should be higher than 8.00 \$/t, while the Malaysian one should be lower than 231.20 \$/t. Although it is generally believed that higher carbon prices are preferable for all countries to reduce GHG emissions within the country, higher Chinese but lower Malaysian carbon prices can bring reduction in total GHG emissions globally owing to the differences in the procurement cost and the GHG emission intensity in the numerical experiments.

To examine the paradox and the relationships between carbon prices and the total GHG emission reduction, the cost and GHG emission breakdowns in the cases with increments and decrements in the total GHG emissions are discussed in the next subsection.

# 5.2. RQ2: What Different Costs and GHG Breakdowns can be Observed in Cases with Increments and Decrements in the Total GHG Emissions in the Entire Supply Chain?

This subsection analyzes the cost and GHG breakdowns in two cases to determine the difference in the total GHG emission with carbon leakage. Cases A and B as shown in Figure 2 are analyzed. As stated in Section 5.1., even when carbon leakage occurs, the GHG emission throughout the supply chain could be reduced in some cases. To investigate the cost and GHG emission for each country,

this section compares the relationship between the GHG emission and the carbon leakage in the two cases follows:

- In cases A and B, the Malaysian carbon price was set as 231.20 \$/t and 260.10 \$/t, respectively.
- The Chinese carbon price for both cases was set as 86.70 \$/t.

Figure 3 shows the breakdown of the total cost and the total GHG emissions in the two cases. Furthermore, Table 2 shows the results of supplier selection in the initial supply chain configuration and cases A and B. From Figure 3, the total GHG emissions in case B were 90% higher than those in case A, even though the carbon tax in case B was 13% higher than that in case A. Consequently, the total cost in case B with a higher Malaysian carbon price was by 2.1% higher than that in case A with a lower Malaysian tax. To investigate the reasons for the differences in the total GHG emissions between cases A and B, we focused on the breakdown of GHG emissions. In case A, the Malaysian GHG emissions were 16 times lower than those of China. Therefore, the Malaysian government could reduce Malaysia's GHG emissions by raising its carbon price by 28.9 \$/t only. However, this would result in 90% higher GHG emissions in the entire supply chain.



Figure 3. Breakdown of total costs and total GHG emissions: Cases A and B, and the baseline.

The findings suggest that, although a higher carbon price could be effective in reducing the GHG emissions within a country, it could lead to an increase in the total GHG emission in the entire supply chain. Additionally, countries with lower GHG emission intensities should set lower carbon prices to reduce the total GHG emissions in the entire supply chain.

Part Number	Part Name	Material Name	Case A: Malaysia Carbon Tax Price is 231.20 (\$/t), Which is about Twice that of China			Case B: Mal (\$/t), Whic	aysian Carbon h is More thar of China	n Tax is 260.10 n Twice that	Initial Supply Chain Configuration that is Meant to Reduce GHG Emissions by 26%			
			Japan 2.89 \$/t	China 86.70 \$/t	Malaysia 231.20 \$/t	Japan 2.89 \$/t	China 86.70 \$/t	Malaysia 260.10 \$/t	Japan 0.00 \$/t	China 0.00 \$/t	Malaysia 0.00 \$/t	
1	Battery cover	Polycarbonate	0	1000	0	0	1000	0	0	1000	0	
2	Battery	Battery	0	0	1000	0	0	1000	0	1000		
3	Back case	Polycarbonate	0	1000	0	0	1000	0	0	1000	0	
4	Board	Circuit board	0	1000	0	0	1000	0	0	1000	0	
5	Microphone	SUS	0	0	1000	0	0	1000	0	0	1000	
6	Camera	ZINC alloy	0	0	1000	0	0	1000	0	0	1000	
7	Main button	Polycarbonate	0	1000	0	0	1000	0	0	998	2	
8	Number button	Polycarbonate	0	1000	0	0	1000	0	0	1000	0	
9	Junction	SUS	0	0	1000	0	1000	0	0	436	564	
10	Front case	Polycarbonate	0	1000	0	0	1000	0	0	1000	0	
11	LCD	Glass	1000	0	0	1000	0	0	1000	0	0	
12	Speaker	SUS	0	0	1000	0	0	1000	0	0	1000	
Total cost [\$]				209.83			214.23			144.49		
Total GHG emission [g-CO <sub>2</sub> eq]				379280		720760				633785		
Carbon tax [\$]			61.63				69.73		0.00			

**Table 2.** Supplier selection results for the initial supply chain configuration and cases A and B.

## 5.3. RQ3: How Much the Carbon Price in Each Country be to Set Avoid Carbon Leakage and to Reduce GHG *Emissions throughout the Entire Supply Chain?*

This subsection discusses how much carbon price is desirable for each country to reduce the total GHG emissions in the entire supply chain. From the discussions in Sections 5.1 and 5.2, there were two main findings. One finding was that, although different carbon prices in multiple countries would cause carbon leakage, there could be cases where the total GHG emission in the entire supply chain could decrease. The other finding was that countries with lower GHG emissions intensity should set lower carbon prices than countries with higher GHG emission intensity. Hence, this subsection tries to find an effective carbon price for total GHG emissions reduction in the entire supply chain.

From Figure 2, when the Chinese carbon price became equal to or higher than 28.90 \$/t, the GHG emissions decreased as the Malaysian carbon price decreased. For example, when the Malaysian carbon price was changed from 86.70 \$/t to 57.80 \$/t, the total GHG emissions in the entire supply chain decreased as shown in Figure 2. When the Chinese carbon price was 57.80 \$/t, the total GHG emissions decreased when the Malaysian carbon price became equal to or less than 144.50 \$/t. When the Chinese carbon price was 86.70 \$/t, the total GHG emission decreased when Malaysian carbon price became equal to or less than 144.50 \$/t. When the Chinese carbon price was 86.70 \$/t, the total GHG emission decreased when Malaysian carbon price was equal to or less than 231.20 \$/t in case A, as stated in Section 5.2 and as shown in Figure 3. Then, it was found that if Malaysian carbon tax become 3 times higher than that in China, the total GHG emissions in the entire supply chain increase.

Moreover, it can be observed from Figure 2 that the number of cases with an increment in the total GHG emission from the initial supply chain configuration decrease as the Chinese carbon price increases. For example, there were eight cases where the total GHG emissions increased when the Chinese carbon price was 28.90 \$/t. On the other hand, there were only two cases where the total GHG emissions increased when the Chinese carbon tax was 86.70 \$/t. Therefore, the Chinese carbon price should be set as 86.70 \$/t to reduce the risk that total GHG emissions may increase due to carbon leakage. Additionally, the Malaysian carbon price should be less than 3 times that of China to reduce the total GHG emissions by the carbon tax.

Even though the Japanese carbon price was the lowest (2.89 \$/t) among the countries in all cases, Japanese suppliers were not selected owing to their higher procurement cost in the numerical experiments while the average GHG emissions of Japanese parts are 44% lower than those of parts from Malaysia. Thus, it might be preferable to set a negative carbon price in developed countries such as Japan to reduce the GHG emissions in the entire supply chain.

The research limitation of the scope is that the proposed model focusses on the procurement cost, GHG emissions and carbon tax to analyze the carbon leakage with less difficulty of OR. The proposed model does not include all dimensions, which should be considered in constructing real-world supply chain, such as transportation, inventory, and workforce, etc.

However, there is another possible contribution of the research is that the proposed model can adopt to evaluation of suppliers in terms of the procurement cost, GHG emissions and carbon tax in the initial decision-making phase as an input of a more complex multi-criteria decision-making process. As a result, the model could be used to evaluate the potential for low-carbon supply chain with the affordable cost under the different carbon tax for the manufacturers in constructing real-world supply chain.

#### 6. Conclusions

This study proposed green procurement decisions for the supplier selection and order quantity with different carbon prices among the countries to minimize total costs and GHG emissions. The case conditions were applied through an investigation of different carbon prices in selected Asian countries. Additionally, the effects of carbon leakage were analyzed. The experimental procedure consisted of the following steps. First, BOM for a cell phone consisting of the GHG emissions and the procurement costs for each part in each country concerned was constructed by using the LCI database with the Asian international I/O tables. Secondly, a low-carbon and economic supplier selection method with

order quantity considering the different carbon prices among these countries was formulated. After that, the suppliers for each part were selected to achieve both GHG emissions and total costs reduction simultaneously. Finally, the supplier selections with different carbon prices among the countries were discussed along with their effect on carbon leakage. The findings of this study are as follows:

- Carbon leakage would always occur with different carbon prices among multiple countries in the case study. However, we found that there were some cases where the total GHG emissions were decreased in the entire supply chain. Therefore, carbon leakage does not always increase the total GHG reduction in the global supply chain.
- Higher carbon prices in each country can reduce the GHG emissions within the country; however, they could also lead to an increase in the total GHG emissions globally. Therefore, higher carbon prices may sometimes have a negative impact on the total GHG reduction globally, even though it seems to be preferable to set higher carbon prices in all countries for GHG reduction.
- Appropriate carbon prices were obtained for the different countries in the case studies. The Chinese carbon price should be set as 86.70 \$/t to reduce the risk that total GHG emissions will increase due to carbon leakage in the numerical experiments. On the other hand, the Malaysian carbon price should be less than 3 times that of China to reduce the total GHG emissions by the carbon tax. Similar findings are also suggested by Lu [51] that Southeast Asian nations including China and Malaysia governments must change their policy approaches in favor of supporting renewable or low-carbon energy use to meet rising energy demands, and adopt more environmentally-benign technology to produce and save energy.

Implications of this study are also listed as follows:

- The study evaluates and models how different carbon tax in each country effect on constructing an Asian low-carbon supply chain with lower cost throughout the numerical experiments.
- As carbon prices becomes higher, which is generally expected to enhance GHG reduction, a paradox bringing higher total GHG emissions by higher carbon prices was observed in the numerical experiments due to occurrences of carbon leakage in the global supply chain.
- The different carbon prices among multiple countries would not be always effective to reduce the total GHG emissions across the global supply chain because of the carbon leakages in the numerical experiments.
- The potential of this study contributes to decision support of constructing global low carbon supply chain with the different carbon tax. The carbon tax depends on technological challenges and political decisions reflected to the GHG emissions intensity and the carbon price, respectively. With regarding to the technological challenges, since the transition from coal towards oil, gas and renewable sources is slower in lower economic complexity suggested by Neagu and Teodoru [52], the GHG emissions in emerging countries would not be reduced in the short term. On the other hand, in terms of the political decisions, the carbon prices could be changed rapidly by each governor's decision for environmental policies because the carbon tax depends on the carbon price and the GHG emissions only in each country.

However, limitations of this study remain as follows:

- The cost and GHG emissions in the part transportation phase is not considered. Additionally, opening cost for new factories and switching cost for suppliers are not considered.
- By using LCI database with Asian I/O table, it cannot reflect efforts for obtaining lower GHG emission in each supplier, although difference cost and GHG emissions among Asian countries can be taken into account.
- Each supplier in different countries is assumed to be able to produce parts with the same qualities and functions. Then, manufacturers can maintain the qualities and functions of the same parts with different GHG emissions and procurement costs in switching suppliers.

- The material-based GHG emissions calculated by the proposed method in Yoshizaki et al. [11] assumes single material type by selecting the main materials used within a part. However, each part often includes different types of materials. Thus, the different GHG emissions based on different materials in the same part are not considered.
- The importing tax for parts are not addressed in the proposed model, although it is one of the essential factors to construct global supply chain. Since the different importing tax from each country would effect the total costs for manufacturing assembly products, the supplier selection for lower GHG emissions and cost could be reconfigured. Moreover, the free trade agreement (FTA) [53,54] such as Trans-Pacific Partnership (TPP), North American Free Trade Agreement (NAFTA), and the Regional Comprehensive Economic Partnership (RCEP) are not treated. By using the FTA with the carbon tax, the total GHG emissions in the whole supply chain could be reduced because the FTA can reduce the total cost of procurement parts from the developed countries, where the GHG emissions are lower but procurement cost is higher than one in emerging countries.

Further studies should apply this method to other types of products through 3D-CAD models and to other countries in the LCI databases with Asian I/O tables. They could also consider the lead time and different quantities of product demand for supplier selection and order quantity decisions. It would be helpful for industry 4.0 under a circular economy to discuss carbon leakage; however, this should be performed in a further study because it is a problem about the cost. Moreover, setting different target reduction ratios for GHG emission for each country is also a topic for future studies. Additionally, different carbon prices among grouped EU-15 countries should be analyzed based on environmental fiscal pressure [55]. Finally, this proposed method and analysis should apply to family business [56] and inter-organizational cooperation [57] since the global warming needs to be dealt with by worldwide and small and medium sized manufacturers.

**Author Contributions:** R.K., Y.K. and T.Y. conceptualized the goals and aims of this study and provided resources. R.K. and T.Y. designed the methodology. T.Y. acquired funds. R.K. generated metadata and formulated and operated the numerical experiments. Additionally, R.K. programmed and validated the formulation, visualized the results, and wrote the original draft. Y.K. and T.Y. managed this project and supervised the overall content, and reviewed this paper. Finally, Y.K. and T.Y. revised the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

### Appendix A

Part Part Number	Part Name	Material Name	Number	Weight [g]	Unit Price of Each Material [\$/g] <sup>–</sup>	Proc	curement Co	ost [\$]	GHG Emission [g-CO <sub>2</sub> eq]		
	I alt Ivallie		[piece]			Japan	China	Malaysia	Japan	China	Malaysia
1	Battery cover	Polycarbonate	1	1.00	0.0029	0.0029	0.0015	0.0016	2.24	10.69	5.40
2	Battery	Battery	1	58.10	0.0010	0.0581	0.0300	0.0321	19.33	137.92	32.29
3	Back case	Polycarbonate	1	1.00	0.0029	0.0029	0.0015	0.0016	2.24	10.69	5.40
4	Board	Circuit board	1	85.40	0.0010	0.0854	0.0442	0.0471	34.15	126.87	39.62
5	Microphone	SUS	1	0.50	0.0022	0.0011	0.0006	0.0006	0.82	5.25	1.65
6	Camera	ZINC alloy	1	5.30	0.0014	0.0077	0.0040	0.0042	3.57	27.99	5.82
7	Main button	Polycarbonate	1	1.00	0.0029	0.0029	0.0015	0.0016	2.24	10.69	5.40
8	Number button	Polycarbonate	1	1.00	0.0029	0.0029	0.0015	0.0016	2.24	10.69	5.40
9	Junction	SUS	1	47.50	0.0022	0.1067	0.0552	0.0589	77.64	498.69	157.21
10	Front case	Polycarbonate	1	1.00	0.0029	0.0029	0.0015	0.0016	2.24	10.69	5.40
11	LCD	Glass	1	1.00	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00
12	Speaker	SUS	1	0.60	0.0022	0.0013	0.0007	0.0007	0.98	6.30	1.99
	Average		1	16.95	0.0021	0.0229	0.0119	0.0126	12.31	71.37	22.13
	Total		12	203.40	0.0248	0.2748	0.1422	0.1518	147.69	856.47	265.58

Table A1. Bill of materials (BOM) of each part for the cell phone including the procurement cost and the GHG emission in each country [29,34].

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