mathematics

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The Emission Reduction Technology Decision of the Port Supply Chain

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Abstract: The technology options for sustainable development are explored with customer low-carbon preference in a port supply chain consisting of one ship and one port. Port supply chains can opt for either shower power or low-sulfur fuel oil to cut down emissions. We set game models considering three power structures: the port dominant (port-led Stackelberg game), the ship dominant (ship-led Stackelberg game), and the port and ship on the same footing (Nash game). We compare the performances of different technologies. It is shown that, when customer low-carbon preference and carbon tax are both low, LSFO is the appropriate choice from the supply chain's profit perspective, SP is preferred from the emission control perspective, and LSFO is preferred from the social welfare perspective. However, when customers' low-carbon preferences, carbon tax, and environmental concerns are all low or all high, LSFO should be adopted from the view of social welfare. The profits and carbon emissions of the supply chain in the Nash game are higher than those in the Stackelberg game. While the environmental concern is low, the social welfare of the supply chain in the Nash game is greater than that in the Stackelberg game. Otherwise, it is less than that in the Stackelberg game. The obtained results can help governments formulate policies and ships make emission reduction technology decisions according to their own interests.

Keywords: port supply chain; customers' low-carbon preference; emission reduction technologies

MSC: 91-10

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Citation: Zhou, Y.; Zhou, H. The Emission Reduction Technology Decision of the Port Supply Chain. *Mathematics* **2024**, *12*, 848. https://doi.org/10.3390/math12060848

Academic Editor: Ripon Kumar Chakrabortty

Received: 15 February 2024
Revised: 10 March 2024
Accepted: 11 March 2024
Published: 14 March 2024

1. Introduction

The port industry is an important link to the modern logistics supply chain. However, the port is also a large carbon emitter [1] because it relies on the consumption of petrochemical energy. Statistics show that the carbon emissions emitted by the ports and ships yearly are more than 2.7% of total global emissions. Without appropriate steps, the proportion will more than double by 2050 [2]. A 2018 study by the International Transport Forum emphasizes the crucial role of ports in decreasing the carbon emissions of worldwide marine transport. Implementing low-carbon initiatives at ports may greatly enhance the process of lowering carbon emissions in maritime transport [3]. Ships are usually powered by diesel auxiliary engines when berthing at the ports, and the diesel auxiliary engines emit large amounts of pollutants such as CO, NOx, and SOx into the air during operation, which account for 55.0–77.0% of port emissions [4]. The 70th session of the IMO in October 2016 introduced amendments, guidelines, and circulars of the International Convention for the Prevention of Pollution from Ships. The focus was on amending Annex VI "Rules for the Prevention of Air Pollution from Ships" and establishing a global mandate effective from 1 January 2020, limiting the sulfur content of marine fuels to 0.50%.

In recent years, China's port development has achieved remarkable results, and world-class port clusters such as the Yangtze River Delta, the Bohai Sea Rim, Guangdong, Hong Kong, and Macao have been gradually built. The port's cargo throughput and container throughput have ranked first in the world for many consecutive years. Among the top

10 ports in terms of cargo throughput and container throughput, China accounts for eight and seven seats, respectively. To promote the emission reduction of air pollutants from ships, the Chinese government has implemented a series of measures. For example, in December 2015, the Ministry of Transport of China established a domestic emission control area (ECA) in the waters of the Pearl River Delta, the Yangtze River Delta, and the Bohai Rim (Beijing, Tianjin, and Hebei). At the end of 2018, the scope of the ECA in China was expanded to include coastal areas and major inland waters. In September 2021, the "Measures for the Administration of Shore Power for Ports and Ships" stipulated that ships (except liquid cargo ships) with shore power (SP) facilities should use SP when berthing at a berth with SP supply capacity in a coastal port for more than 3 h, or at a berth with SP supply capacity in an inland port for more than 2 h, if the ships do not adopt effective alternative emission reduction measures [5].

SP and low-sulfur oil (LSFO) are frequently used as emission reduction technologies for ships when berthing at berths. SP serves as a land-to-ship electricity connection, enabling ships to switch off onboard diesel-powered engines when they are docked. In order to use shore power, ships have to install facilities to receive power, while ports build facilities on the shore to transmit power. Both ports and ships have to afford a significant initial investment to construct SP facilities, but SP can cut down carbon emissions effectively. Hall [6] proposed that SP could reduce all carbon emissions of ships at ports by 48–70%. LSFO is a clean energy source with less than 0.1% sulfur content. Adopting LSFO without retrofitting and upgrading means no initial investment. Nevertheless, LSFO is expensive and emits a greater amount of carbon emissions compared to SP.

Enterprises make emission reduction decisions based on their own factors and the supply chain's external factors which include government regulation policy and consumers' green preferences. The carbon trading system and carbon tax are two common regulation policies. A carbon tax is a tax on carbon emissions from the burning of fossil fuels. The carbon tax policy is more flexible, fairer, and broader in coverage, and it can effectively achieve the sustainable development of the economy and environment. Under the carbon tax policy, to avoid high taxes, ports and shipping companies have to take measures to reduce carbon emissions, and reducing emissions inevitably requires investment, such as upgrading and improving technology, replacing with cleaner fuels, and limiting speed. At present, there are many countries implementing carbon tax policies, such as Sweden, the Netherlands, Norway, and Finland [7]. To help government regulators formulate more reasonable carbon tax schemes, many scholars have studied the carbon tax policies in port areas [8–10].

On the other hand, consumers are becoming more inclined to protect the environment and are more likely to opt for low-carbon products when making purchases. They are prepared to shell out more money for low-carbon products. Wang and Zhao [11] investigated how manufacturers and retailers reduce their carbon emissions when customers have a preference for low-carbon products and concluded that consumers' preference for low-carbon products is a key factor in enterprise decision making. Therefore, under the carbon tax, considering the low-carbon preferences of customers, how do port and shipping enterprises make emission reduction technology decisions?

Based on this, we evaluate the two technologies from a port supply chain point of view considering the customers' low carbon preference. The port supply chain consists of one port and one ship. The port is an upstream member and is responsible for providing the service of loading/unloading to the ship, while the ship offers a range of services to customers. Furthermore, the regulators impose appropriate carbon taxes on the carbon emissions of a port to maximize social welfare [12]. The port supply chain chooses suitable emission reduction technologies with profit maximization considering the customers' low-carbon preference. We set models by the game method in three scenarios (port-led Stackelberg (PS) [13], ship-led Stackelberg (SS) [14], and Nash (NS) game). A comparison of profits, carbon emissions, and sustainability between the two technologies is conducted.

We offer the following three primary contributions. (1) We investigate the selection of technologies from a port supply chain point of view, a topic that has not been widely explored in the current research. (2) We compare SP and LSFO under carbon tax from the perspective of social benefits. (3) We consider the customers' low-carbon preference, which is rarely discussed in the field of port and shipping. The acquired outcomes assist the port and ship in selecting suitable technologies and offer valuable perspectives on government policy.

The remainder of this paper continues with some related literature. We then introduce the necessary notation and assumptions, which are followed by the models and solutions. We compare the equilibrium results and engage in a comprehensive discussion, subsequently proceeding with numerical experiments. Finally, the conclusions are given.

2. Literature Review

This research has a strong correlation with three areas of the literature: low-carbon technology choice in supply chains, marine transport logistics and green ports, and customers' low-carbon preference.

2.1. Low-Carbon Technology Choice in Supply Chains

In the background of the growing influence of environmental regulations, constructing low-carbon supply chains is an inevitable choice for enterprises' development. The adoption of low-carbon technology is very important in supply chains. Liu et al. [15] evaluated multi-stage low-carbon technology investment strategies by constructing an evolution model that consists of a manufacturer investing in low-carbon technology and a supplier providing low-carbon technology. Cao et al. [16] examined mode selection strategies of energy performance contracts considering carbon tax policy. Jiang et al. [17] constructed a differential game model based on social welfare maximization and discussed how the technology spillover effect and incremental cost of carbon transfer influence carbon quota allocation. Liu et al. [18] investigated how GT's investment strategy in a manufacturer–supplier supply chain affected investment and sustainable production decisions, as well as the most advantageous government subsidy incentive. Yu et al. [19] put forward a framework for investing in energy-efficient technologies to address the decision-making challenges faced by companies striving to achieve a harmonious equilibrium between profits and investments. Song et al. [20] considered subsidies, consumers' low-carbon preferences, and the low-carbon information trust to analyze the optimal operation decisions of two manufacturers in a green supply chain. Yang et al. [21] investigated the port emission reduction decision-making problem within a carbon trading mechanism. They compared the SP and LFSO from the view of sustainable development, but they did not consider the impact of customers' green preferences.

The above research mainly investigates the emission reduction investment strategy and technology selection in the production supply chain under government regulation policies, such as carbon trading systems, carbon tax, and subsidies. However, in the port and shipping supply chain, relevant research on emission reduction investment strategies and technology decision making is still lacking. In fact, the emission reduction decision-making process between the port supply chain and the general production supply chain is completely different. Taking shore power as an example, the use of SP not only requires facilities investment from ports but also requires ships to transform SP facilities, and the initial investment of both sides is huge. Ports can incentivize ships to use SP through measures such as granting priority berthing rights to ships and preferential SP service fees. Considering the characteristics of emission reduction technologies in the port industry, the study compares the two technologies from the supply chain perspective, which could enrich the current study.

2.2. Marine Transport Logistics and Green Ports

The emergence of international trade has made shipping a major means of transporting goods across the globe. The port has shifted its role from being a mere loading and unloading hub to becoming the hub of worldwide logistic services, making it a critical element of maritime transportation. Consequently, the port area is likely to generate more pollutants, which has piqued the interest of researchers in the development of eco-friendly harbors.

Ding et al. [22] examined the economic viability of the Northern Sea Route in comparison to the Suez Canal Route through the implementation of two proposed carbon tax schemes (fixed vs. progressive). Cariou et al. [23] analyzed the consequences of using a maritime bunker levy on the financial benefits, commercial activities, and ship owners' emissions. Gao et al. [24] investigated the architecture of a container ocean shipping system under a carbon tax. Song et al. [25] examined the effects of the carbon tax on the green shipping supply chain in the context of port competition. Xin et al. [26] developed a programming model based on integers to facilitate the green scheduling of shuttle tanker fleets.

Scholars also explored the impact of environmental regulation policies on port operations. Zhao et al. [27] established a carbon emission calculation model for container port operations based on energy consumption, using ships and containers as measurement units, aiming to enable port enterprises to develop reasonable carbon peaking plans. The support vector regression model considering outlier is used to predict the container throughput, then the time series of carbon emissions is obtained through the calculation model, and the judgment standard of carbon peak time based on the Mann–Kendall trend test method is designed to determine the carbon peak time. Li et al. [28] built a two-tiered maritime supply chain comprising a solitary port and shipping company to tackle the problem of collaborative emission reduction between ports and shipping companies while ensuring pollution control. They established four decision-making models of ports and ships: port-led Stackelberg game, vertical integration model, Nash bargaining of port and ship cooperation, and green port and ship cooperation. They also analyzed changes in port prices, emission reduction levels, freight volume of shipping companies, and profits. Chen et al. [29] studied the influence of ECA on international shipping and proposed that a great deal of collaboration and coordination should be implemented on a global scale to decrease ship emissions. Hu et al. [30] investigated the shipping container subsidy in the context of multimodal transportation that includes waterways within the regional transportation network. Liu et al. [31] examined the impact of dividing three distinct ECAs on the quality of port air in the Pearl River Delta region.

At present, in terms of green ports, traditional green shipping management issues have been combined with emission reduction requirements, and some green port technologies and their emission reduction effects have been studied in depth. Ports have various resources such as berths, shore bridges, and yard bridges. Most of the current research uses cost-oriented objectives to optimize the allocation or scheduling of these resources, and when the emission minimization or energy-saving maximization goals are taken into account, the decision model and solution algorithm need to be redefined and designed. This study systematically analyzes and compares port emission reduction technologies, taking into account not only their costs but also their emissions, as well as overall social welfare.

2.3. Customers' Low-Carbon Preference

With the gradual emphasis on ecosystems and the widespread dissemination of the low-carbon consumption concept, consumers' low-carbon preference is gradually increasing. Studies indicate that products with lower carbon emissions are more marketable, and consumers are inclined to spend more on them [32,33]. The customers' preference in the port and navigation field contributes positively to the reduction in port emissions, although research on this subject is scarce. Scholars have extensively debated the low-carbon preference of consumers in the past few years. This study primarily focuses on three aspects: verifying whether consumers have such preferences, identifying key elements influencing their low-carbon preferences, and examining how low-carbon preferences affect decisions in low-carbon supply chains.

In terms of how low-carbon preferences affect the operational decisions in supply chains, Yu and Hou [34] established a differential game model based on cost sharing and coordination to study how consumers' low-carbon preferences affected market demand in the product supply chain. Xu et al. [35] proposed that the manufacturers' emission reduction efforts and the dealers' low-carbon promotion efforts were affected by the cost coefficient related to the promotion of low-carbon products by dealers, the low-carbon reputation sensitivity coefficient of consumers, and the impact coefficient of the emission reduction efforts of manufacturers on the low-carbon reputation. Gao et al. [36] studied the incentive strategy of the low-carbon supply chain through modeling and optimization methods based on the information update of low-carbon preferences. The results show that profit-driven cooperation among supply chain members could improve both their own profits and the carbon reduction efficiency of the entire supply chain. Effective information updates are more efficient at reducing carbon emissions than promotional allowances. Ding et al. [37] investigated manufacturers' decisions on encroachment and carbon emissions reduction, taking into account the carbon trading system and consumers' preferences for low-carbon production. The findings indicated that manufacturers invariably benefited from encroachment decisions if the government opted against cap-and-trade regulations, leading to consistent profit losses for retailers. Sun et al. [38] established a manufacturer-led Stackelberg game model considering the low-carbon preferences of consumers and the lag of emission reduction technologies. They proposed that the low-carbon preferences of consumers and the lag time of emission reduction technologies have a positive effect on the carbon emission transfer level of manufacturers but have no effect on the commitment level of suppliers. Only when the lag time of emission reduction technologies is kept within an appropriate range would the increase in consumers' low-carbon preference increase the supply chain profits. Zhu [39] concluded that in the case of low R&D difficulty, high consumer trust or R&D difficulty, high consumers' low-carbon preferences, and brand recognition, advantageous brand enterprises could improve CER levels and profits by using blockchain.

At present, the research on low-carbon preference mainly focuses on the field of low-carbon supply chain operation and management, including supply chain production decision making, emission reduction investment strategy, and cooperation among supply chain members. But, there are relatively few studies on the influence of customers' low-carbon preferences on emission reduction decision making within the port supply chain. This study compares port emission reduction technologies, considering the impact of customers' low-carbon preferences.

3. Notation and Assumptions

The port emission reduction game model considering customers' low-carbon preferences under carbon tax is composed of a port, a ship, and port customers, as shown in Figure 1. SP and LSFO could be chosen to cut down carbon emissions. There is a lack of correlation between demand and competition among vessels. The simple supply chain consisting of one port and one ship is put forward to expound the problem in the literature [21,23,40]. Of course, in future studies, we could also extend to numerous ports and ships.

3.1. Notation

The parameters and variables are expressed in Table 1. i ($i = E, L$) represents the emission reduction technologies, where E describes SP and L denotes LSFO. The subscript j ($j = S, P, N$) denotes the types of game (SS, PS, and NS). The supply chain adopts technology i ($i = E, L$) in j game, denoted by the subscript $i - j$. Port, ship, and supply chain are denoted by superscripts k ($k = p, s, sc$). p represents the total service price and satisfies $p = m + w$.

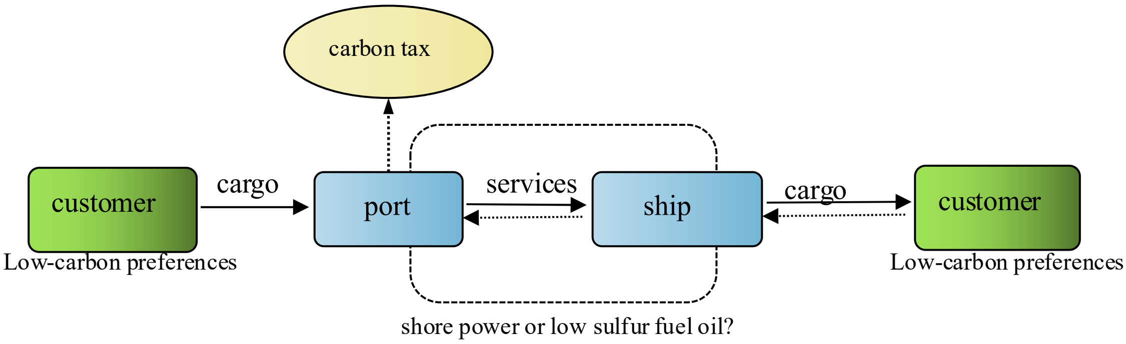

Figure 1. The process of emission reduction decision making in the port supply chain.

Table 1. Variables.

Notation	Description
Variables	
a	Market size, $a > 0$
b	Sensitivity coefficient of market demand to the price $(b > 0)$
q	Demand for cargo
c_t	The unit navigation transportation cost of ship
c_s	The unit service cost of ship when SP is implemented
c_L	The unit service cost of ship when LSFO is implemented
c_E	The unit service cost of port when SP is implemented
γ	Low-carbon preference of customers
θ	Carbon tax
e_i	Technology i's unit carbon emissions
p_c	Environmental concern
U_{i-j}^k	The profit of k in j game with adoption technology i
T_{i-j}	The carbon emissions in j game with adoption technology i
sw_{i-j}	The social welfare in j game with adoption technology i
Decision variables	
w_{i-j}	The ship's service price when adopting technology i in j game
m_{i-j}	The port's service price when adopting technology i in j game

3.2. Basic Assumptions

To make it easier to model and analyze, the following two assumptions are given.

Assumption 1. $c_L < c_E + c_s, e_L > e_E$.

In practice, the construction investment of shore power is huge; taking the power supply of 10,000 TEU container ships as an example, the construction cost for the port to transmit power is about CNY 6–10 million, and the cost for the ship to install facilities to receive power is about CNY 3–6 million. Especially under the premise that the current utilization rate of shore power is low in China, the total cost of using SP for ships is greater than the cost of using LSFO, which is about CNY 1 more per KWH [41].

Therefore, it is assumed that the costs of SP are higher, i.e., $c_L < c_E + c_s$. Moreover, SP produces fewer carbon emissions compared with LSFO [42], i.e., $e_E < e_L$.

Assumption 2. *The function of demand is* $q = a - b(m + w) + \gamma(e - e_i), i = E, L; a, b > 0$. m *denotes the port's service price, while* w *indicates the ship's service price.* $w + m$ *denotes the service price faced by the customer, and* $\gamma(e - e_i)$ *represents the effect of low-carbon preferences on demand. In the research on port supply chains, the linear demand function is widely used, referring to the literature* [43,44].

4. Modeling and Solving

4.1. The Adoption of SP

Formulas (1)–(5) are used to calculate the profits, carbon emissions, and social welfare when SP is employed.

$$U^p = mq - c_E q - e_E \theta q \tag{1}$$

$$U^s = wq - c_t q - c_s q = (w - c_t - c_s)(a - b(m + w) + \gamma(e - e_E)) \tag{2}$$

$$U^{sc} = U^s + U^p \tag{3}$$

$$T = qe_i, i = E, L \tag{4}$$

$$sw = U^s + U^p - p_c T^2 \tag{5}$$

Equation (1) represents the earnings of the port, mq represents the revenues from shipping companies, $c_E q$ describes the cost to use SP, and $qe_L\theta$ describes the expenses of releasing carbon dioxide. In Equation (2), wq represents the ship's profits from customers, $c_t q$ describes the cost of transportation, and $c_L q$ is the expense associated with using SP. Equations (3) and (4) represent the total profits and the total carbon emissions, respectively. According to Krass [12], $p_c T^2$ refers to the negative disutility of carbon emissions in Equation (5), and the social welfare (sw) includes the ship's profits and the port's profits minus the negative disutility of emissions.

The results are given in Table 2 by standard backward induction, and the solution process is given in Appendix A.

Table 2. Results with adoption SP.

Cases	m_{E-j}	w_{E-j}	T_{E-j}
$j = N$	$\frac{a+\gamma e-\gamma e_E-bc_E+2bc_s-bc_t+2be_E\theta}{3b}$	$\frac{a+\gamma e-\gamma e_E+2bc_E-bc_s+2bc_t-be_E\theta}{3b}$	$\frac{e_E A}{3}$
$j = S$	$\frac{a+\gamma e-\gamma e_E-bc_E+3bc_s-bc_t+3be_E\theta}{4b}$	$\frac{a+\gamma e-\gamma e_E+bc_E-bc_s+bc_t-be_E\theta}{2b}$	$\frac{e_E A}{4}$
$j = P$	$\frac{a+\gamma e-\gamma e_E-bc_E+bc_s-bc_t+be_E\theta}{2b}$	$\frac{a+\gamma e-\gamma e_E+3bc_E-bc_s+3bc_t-be_E\theta}{4b}$	$\frac{e_E A}{4}$
Cases	U^p_{E-j}	U^s_{E-j}	U^{sc}_{E-j}
$j = N$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{9b}$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{9b}$	$\frac{2A^2}{9b}$
$j = S$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{16b}$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{8b}$	$\frac{3A^2}{16b}$
$j = P$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{8b}$	$\frac{(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{16b}$	$\frac{3A^2}{16b}$
Cases		$sw_{E\text{-}j}$	
$j = N$		$\frac{\left(2-be_E^2 p_c\right)(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{9b}$	
$j = S$		$\frac{\left(3-be_E^2 p_c\right)(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{16b}$	
$j = P$		$\frac{\left(3-be_E^2 p_c\right)(a+\gamma e-\gamma e_E-bc_E-bc_s-bc_t-be_E\theta)^2}{16b}$	

Here, A = $a + \gamma e - \gamma e_E - bc_E - bc_s - bc_t - be_E\theta$.

4.2. Implementation of LSFO

Formulas (6) and (7) are used to calculate the profits when LSFO is employed.

$$U^p = mq - e_L \theta q \tag{6}$$

$$U^s = wq - c_t q - c_L q = (w - c_t - c_L)(a - b(m + w) + \gamma(e - e_L)) \tag{7}$$

Equation (1) represents the earnings of the port, mq represents the revenues from shipping companies, and $qe_L\theta$ describes the expenses of releasing carbon dioxide. Equation (2) represents the profits of the ship, wq represents the ship's profits, $c_t q$ describes the cost of transportation, and $c_L q$ is the expense associated with using LSFO.

By standard backward induction again, the results are given in Table 3. The solution process is shown in Appendix A.

Table 3. Results with adoption of LSFO.

Cases	m_{L-j}	w_{L-j}	T_{L-j}
$j = N$	$\frac{a+\gamma e+2bc_L+2be_L\theta-\gamma e_L-bc_t}{3b}$	$\frac{a+\gamma e+2bc_t-\gamma e_L-bc_L-be_L\theta}{3b}$	$\frac{e_L B}{3}$
$j = S$	$\frac{a+\gamma e+3bc_L+3be_L\theta-\gamma e_L-bc_t}{4b}$	$\frac{a+\gamma e+bc_t-\gamma e_L-bc_L-be_L\theta}{2b}$	$\frac{e_L B}{4}$
$j = P$	$\frac{a+\gamma e+bc_L+be_L\theta-\gamma e_L-bc_t}{2b}$	$\frac{a+\gamma e+3bc_t-\gamma e_L-bc_L-be_L\theta}{4b}$	$\frac{e_L B}{4}$
Cases	U^p_{L-j}	U^s_{L-j}	U^{sc}_{L-j}
$j = N$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{9b}$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{9b}$	$\frac{2B^2}{9b}$
$j = S$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{16b}$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{8b}$	$\frac{3B^2}{16b}$
$j = P$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{8b}$	$\frac{(a-bc_L-be_L\theta-bc_t+\gamma e-\gamma e_L)^2}{16b}$	$\frac{3B^2}{16b}$
Cases		$sw_{L\text{-}j}$	
$j = N$		$\frac{\left(2-be_L^2 p_c\right)(a+\gamma e-bc_t-bc_L-be_L\theta-\gamma e_L)^2}{9b}$	
$j = S$		$\frac{\left(3-be_L^2 p_c\right)(a+\gamma e-\gamma e_L-bc_L-bc_t-be_L\theta)^2}{16b}$	
$j = P$		$\frac{\left(3-be_L^2 p_c\right)(a+\gamma e-bc_t-bc_L-be_L\theta-\gamma e_L)^2}{16b}$	

Here, B = $a + \gamma e - \gamma e_L - bc_L - bc_t - be_L\theta$.

5. Analysis and Discussion

This section evaluates the impact of various variables on profits, emissions, and social welfare, which can help shipping companies decide on appropriate technologies and provide decision-making advice for governments to formulate corresponding policies.

For detailed proofs of lemmas and propositions, we refer the reader to Appendix A.

5.1. Profit Analysis

In this section, we investigate how profits are affected by the parameters and carbon tax in the port supply chain.

Lemma 1. *U^{sc}_{i-j} is a concave of c_i, c_t, γ, θ, and e_i. Furthermore, U^{sc}_{E-j} is also concave with respect to c_s.*

When the customers' low-carbon preferences are certain, as carbon taxes, emissions, and operational costs increase, the total profits of the port supply chain initially suffer as a result of higher costs. When operating costs and carbon taxes reach an exorbitant level, the supply chain may not be able to provide services, resulting in a complete cessation of profits. When the carbon tax is certain, with the low-carbon preference increasing, the market demand also increases; thus, the profits of the supply chain rise. However, when the consumers' low-carbon preference and carbon tax increase at the same time, although consumers' low-carbon preference leads to more market demand, the whole supply chain's profits still decline with the increase in carbon tax and production costs.

Proposition 1. *The port supply chain's profits satisfy*

$$U^p_{i-P} \geq U^p_{i-N} \geq U^p_{i-S}; U^s_{i-P} \leq U^s_{i-N} \leq U^s_{i-S}; U^{sc}_{i-N} \geq U^{sc}_{i-P} = U^{sc}_{i-S}$$

Proposition 1 shows that being a leader always earns more profit than acting as a follower. In the Nash game, the supply chain's profit is the highest; thus, equality of relationships should be encouraged, with the regulators' concern being the whole profits of the supply chain.

Proposition 2. *The port supply chain's total profits of different technologies satisfy the following: if* $\theta - \frac{\gamma}{b} < \frac{c_s + c_E - c_L}{e_L - e_E}$, *then*

$$U^p_{E-j} < U^p_{L-j}, U^s_{E-j} < U^s_{L-j} \text{ and } U^{sc}_{E-j} < U^{sc}_{L-j}$$

Proposition 2 indicates, given a certain customer's low-carbon preference, that LSFO is the most suitable option for a low carbon tax ($\theta < \frac{c_s + c_E - c_L}{e_L - e_E} + \frac{\gamma}{b}$) in terms of the supply chain's profitability. Otherwise, SP is the preferable option. It should be noted, however, that an exceptionally high carbon tax would lead to a lack of demand in the market. Consequently, regardless of the technology implemented, the gains from the supply chain are nearly negligible.

In the situation that the carbon tax is certain, LSFO is the most suitable option for a high customer low-carbon preference $\left(\gamma > b\theta - b\frac{(c_s + c_E - c_L)}{e_L - e_E}\right)$, in terms of the supply chain's profitability. Otherwise, SP is the preferable option.

5.2. Carbon Emissions Analysis

In this section, we investigate how carbon emissions are affected by operational costs and carbon taxes in the port supply chain.

Lemma 2. T_{E-j} *decreases in* $c_E, c_t,\ c_s; \theta$, *increases in* γ; T_{L-j} *decreases in* $c_t, c_{\ L}$; *and* θ *increases in* γ.

As costs and carbon taxes increase, so does the cost of services of the supply chain, leading to a reduction in market demand and total carbon emissions.

Proposition 3. *The port supply chain's carbon emissions satisfy*

$$T_{i-N} \geq T_{i-S} = T_{i-P}$$

Proposition 3 implies that when the port and shipping company are on an equal footing, they are likely to provide lower prices to draw in more customers and broaden the market, thus leading to an increase in emissions. The leader in a Stackelberg game always limits the motivation of the other to offer services, which in turn induces carbon emission reduction. Proposition 1 suggests that the Nash game yields the highest total supply chain profits. Nevertheless, when regulators aim for carbon emission reduction, the Stackelberg approach is favored.

Proposition 4. *The total carbon emissions of the supply chain with the adoption of different technologies satisfy*

If $\theta - \gamma\frac{(e + e_{\ E} + e_L)}{b(e_{\ E} + e_L)} < \frac{ae_E - bc_E e_E - bc_s e_E - bc_t e_E - ae_L + bc_L e_L + bc_t e_L}{be_E{}^2 - be_L{}^2}$, *then* $T_{E-j} < T_{L-j}$ *otherwise,* $T_{E-j} \geq T_{L-j}$.

In the situation that the customer's low-carbon preference is certain, in the port supply chain, if the carbon tax is minimal and the optimal profits are almost unaffected by carbon emissions, then LSFO is the more desirable option. In this situation, the low cost of services has caused a surge in demand, coupled with the higher unit carbon emissions, and the utilization of LSFO yields a greater amount of carbon emissions compared to the use of SP. As the carbon tax rises, Proposition 2 suggests that SP is the more cost-effective option due to its overall cost advantage. Even though using SP has lower carbon emissions per unit, if the carbon tax is increased to a certain level, the total carbon emissions from using SP could surpass those of using LSFO due to the availability of more services in the supply chain. Importantly, though, there exists a maximum limit on the carbon tax, guaranteeing favorable market demand. The upper limit may be surpassed by the threshold in Proposition 4, leading to $T_{E-j} < T_{L-j}$ under all possible values of θ and γ. Yet even then, the gap between emissions of the two technologies is still decreasing in θ.

In the case that the carbon tax is certain, if the customers' low-carbon preferences are high, the market demand for greener SP increases, and the carbon emissions of implementing SP would exceed those of using LSFO.

In the situation of low carbon tax and low consumers' low-carbon preference, the supply chain's optimal profit is basically not affected by the two factors. From the perspective of overall cost, LSFO becomes the first choice. But LSFO with higher unit carbon emissions produces more carbon emissions than SP. As carbon tax increases, the advantage of using SP in terms of cost becomes more and more obvious. If the carbon tax and the customers' low-carbon preference attain certain conditions, the overall emissions of adopting SP may exceed those of using LSFO due to the fact that the port and ship may tend to provide more services. It should be noted that the value of the carbon tax cannot exceed a threshold to guarantee positive demand. This finding provides valuable insights to develop effective carbon tax policies and emission reduction management measures.

5.3. The Analysis of Social Welfare

We examine how channel power structures, operational costs, and carbon taxes affect social welfare in this section.

Proposition 5. *In different power structures, the supply chain's social benefits satisfy*

$$\begin{gathered} If\, p_c < \frac{5}{7be_i{}^2}, then\ sw_{i-P} = sw_{i-S} < sw_{i-N}, \\ otherwise\ sw_{i-P} = sw_{i-S} \geq sw_{i-N} \end{gathered}$$

Propositions 1 and 3 indicate that the Nash game yields the highest profits and produces the most carbon emissions. When the environmental concern is kept low, the detrimental consequences of emissions on social welfare are minimal. Consequently, there is the greatest level of social welfare in the Nash game. As the environmental concern rises, the detrimental consequences of emissions on social welfare become more pronounced. When environmental concerns rise to a threshold, the social benefits of the Stackelberg game exceed those of the Nash game. This suggests that regulators should incentivize certain channel power structures to maximize social welfare.

Proposition 6. *The social welfare under various technologies satisfies*

$$\begin{aligned} & If\ p_c < \frac{2\rho}{\omega}, thensw_{E-j} < sw_{L-j} (j = P, S, N), \\ & If\ \frac{2\rho}{\omega} < p_c < \frac{3\rho}{\omega}, thensw_{E-N} > sw_{L-N}, sw_{E-j} < sw_{L-j} (j = P, S), \\ & If\ p_c > \frac{3\rho}{\omega}, thensw_{E-j} > sw_{L-j}. \end{aligned}$$

where

$$\begin{gathered} \rho = 2b\gamma\theta c_L e_e + 2b\gamma\theta c_t e_e - 2b\gamma\theta e_L^2 + \gamma^2\theta^2 e_e^2 + 2a\gamma e_L - 2b\gamma c_t e_L + 2e\gamma^2 e_L \\ +2b\gamma\theta^2 e_e e_L - 2a\gamma\theta e_e - 2e\gamma^2\theta e_e - 2b\gamma c_L e_L - \gamma^2 e_L^2 \end{gathered}$$

$$\begin{aligned} \omega = 2abc_L e_e^2 \quad & +2abc_t e_e^2 + 2be\gamma\theta e_e^2 e_L - a^2 e_e^2 - 2ae\gamma e_e^2 + 2be\gamma c_L e_e^2 - e^2\gamma^2 e_e^2 \\ & -b^2 c_L^2 e_e^2 + 2ab\theta e_e^2 e_L - 2b^2 c_L c_t e_e^2 - b^2 c_t^2 e_e^2 + 2be\gamma c_t e_e^2 + 2a\gamma\theta e_e^3 \\ & +2e\gamma^2\theta e_e^3 - 2b\gamma\theta c_L e_e^3 - 2b\gamma\theta c_t e_e^3 - \gamma^2\theta^2 e_e^4 - 2b^2\theta c_L e_e^2 e_L \\ & -2b^2\theta c_t e_e^2 e_L - 2b\gamma\theta^2 e_e^3 e_L + a^2 e_L^2 + 2ae\gamma e_L^2 + e^2\gamma^2 e_L^2 - 2abc_L e_L^2 \\ & -2be\gamma c_L e_L^2 + b^2 c_L^2 e_L^2 - 2abc_t e_L^2 - 2be\gamma c_t e_L^2 + 2b^2 c_L c_t e_L^2 + b^2 c_t^2 e_L^2 \\ & -b^2\theta^2 e_e^2 e_L^2 - 2a\gamma e_L^3 - 2e\gamma^2 e_L^3 - 2ab\theta e_L^3 - 2be\gamma\theta e_L^3 + 2b\gamma c_L e_L^3 \\ & +2b^2\theta c_L e_L^3 + 2b\gamma c_t e_L^3 + 2b^2\theta c_t e_L^3 + \gamma^2 e_L^4 + 2b\gamma\theta e_L^4 + b^2\theta^2 e_L^4 \end{aligned}$$

Proposition 6 examines the impact of two distinct technologies on social benefits. The findings indicate that when the carbon emission cost is reduced, the social benefits associated with SP are greater than those of LSFO. Nevertheless, due to the complexity of the threshold expression, we will illustrate this situation with a numerical example.

5.4. Managerial Insights and Practical Implications

In this section, some management insights and practical inspiration are proposed based on the above results to provide some countermeasures and suggestions to relevant stakeholders.

5.4.1. The Emission Reduction Technology Decision Making for the Port and Ship

According to Proposition 1, as to the market relationship between port and ship, the profit obtained by one part acting as a leader is more than that obtained being a follower in the game model. Meanwhile, the total profit of the port supply chain in the Nash game is greater than that in the Stackelberg game. Therefore, ports or ships either strive to be in a dominant position or strive to be in an equal position in the game. In practice, due to the characteristics of port resources, ports are often in the leading position, so shipping companies tend to carry out alliances. For example, the world's three largest alliances (THE Alliance, 2M, and Ocean Alliance) began operations in April 2017, and all eight of the world's largest container shipping companies are included. These three alliances carry about 80% of the total container trade and about 95% of the cargo on east–west trade routes [45]. Such alliances greatly increase market share and improve coordination with regional transportation departments and ports.

The choice of technologies depended on the carbon tax policy and the low-carbon preferences of customers. According to Proposition 2, if the carbon tax is low, using LSFO for the ship would be preferred. Under the high carbon taxes, ports and ships should choose to use SP when customers' low-carbon preferences are low. With the growth of customers' low-carbon preferences, the advantages of using SP do not exist, and more profits can be obtained by choosing to use LSFO.

5.4.2. The Policies and Management Measures for Government

At present, the Chinese government is vigorously promoting shore power. According to Proposition 2, levying a higher carbon tax is conducive to the promotion of shore power. When the carbon tax is high, the port and ship will be more active in using shore power, but the carbon tax has a ceiling; beyond this ceiling, port and shipping enterprises will not be willing to offer services, because there is no profit at this time. The customers' low-carbon preferences may lead to the expansion of market demand, which may lead to more carbon taxes. Therefore, a higher preference of customers for low carbon is not necessarily conducive to the promotion of shore power. However, according to Proposition 4, under a high carbon tax, although the unit carbon emission of SP is relatively low, the total emissions from the use of SP may exceed the total emissions from the use of LSFO, because the port and shipping enterprises may provide more services at this time. Therefore, in order to reduce the total emissions, the carbon tax should be in the appropriate middle range. At this time, enterprises will choose SP, and the total emissions of using SP will also be lower than those of using LSFO.

In terms of market competition relations, if the government aims to maximize the profits of enterprises, according to Propositions 1 and 3, then the government administration should support the Nash game that encourages ports and ships to be on an equal footing. If regulators are concerned about emissions control, then the Stackelberg game in which one party is in a dominant position should be encouraged. If the government focuses on the maximization of social welfare, then when the social attention is large, the Stackelberg game should be better, and the Nash game should be supported when the social attention is small.

6. Numerical Example Analysis

A few numerical illustrations are presented in this section to provide a more comprehensive explanation of the quotes and propositions obtained above. The parameters are [31] $a = 200, b = 3.5, c_E = 2.8, c_t = 3.6, c_s = 0.6, e_E = 4.2,\ e_L = 4.9,\ e = 5.4, c_L = 1.6$.

6.1. Influence of θ and γ on Profits

The profits of the port and ship are shown in Figures 2 and 3, respectively. In line with Proposition 1, being a leader always achieves more profits than acting as a follower, while the Nash game has the greatest overall earnings compared to the Stackelberg game, as depicted in Figure 4.

The comparison of profits between the two technologies is complicated. In cases where carbon taxes and customers' low-carbon preferences are minimal, the emission penalties are negligible, and using LSFO is the suitable option. As the carbon tax increases, SP is expected to become the preferred option. As the carbon tax rises to a certain level, the supply chain will be unable to generate any additional revenue due to the stringent emission penalties, resulting in the supply chain's financial loss.

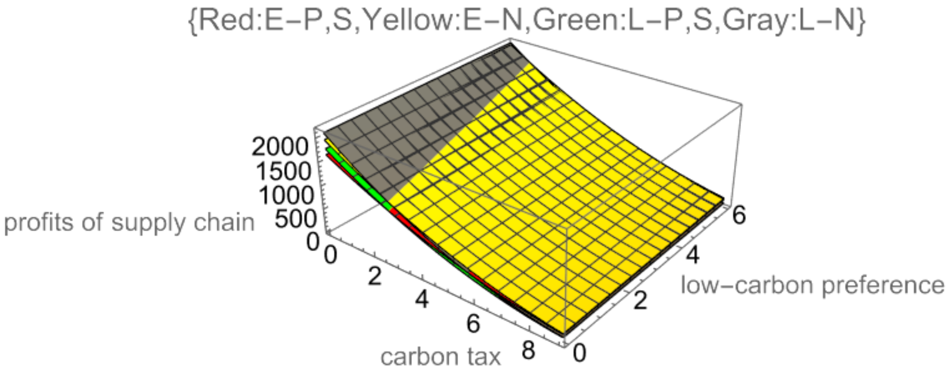

Figure 2. The port supply chain's total profits.

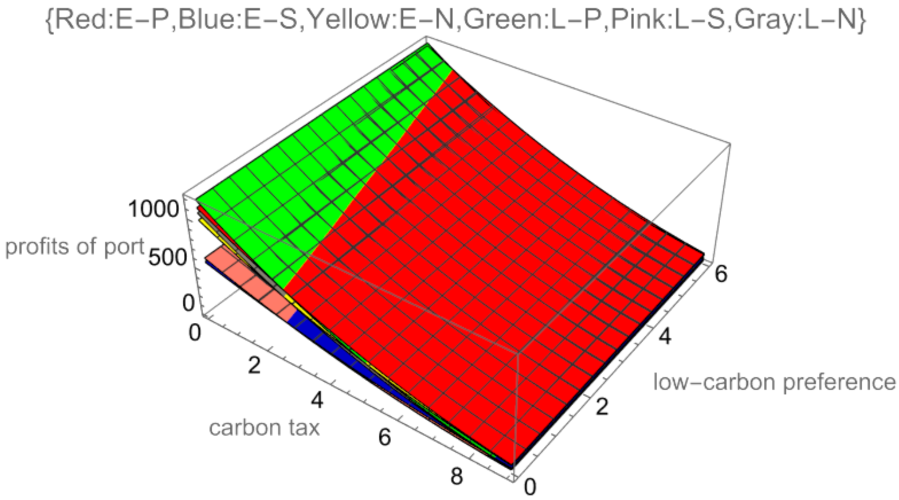

Figure 3. The profits of the port.

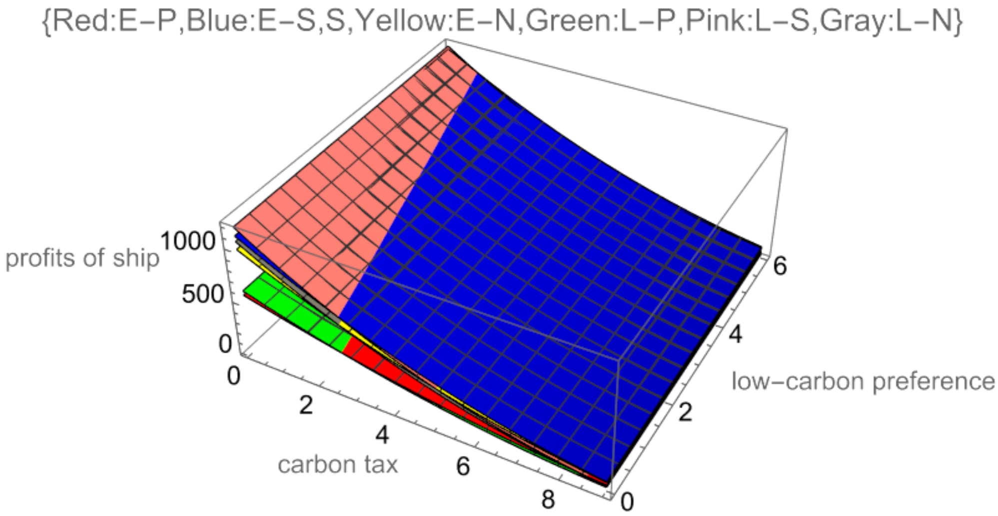

Figure 4. The ship's profits.

6.2. Influence of θ and γ on Carbon Emissions

As illustrated in Figure 5, the Nash game has the most carbon emissions as described in Proposition 4. When θ and γ are minimal, the total carbon emissions with the adoption of LSFO is more than those of using SP. With the carbon tax increasing, the total carbon emissions of SP are greater compared to LSFO. As the carbon tax rises to a considerable degree, the supply chain's services of all three power structures become significantly lower, and the emissions under different power structures also approach one another. Given the minimal carbon emission penalty associated with low carbon taxes, adopting LSFO can earn more profits due to its cost-effectiveness. Low service costs will lead to a surge in demand and, combined with high carbon emissions per unit, using LSFO produces more emissions compared to the adoption of SP.

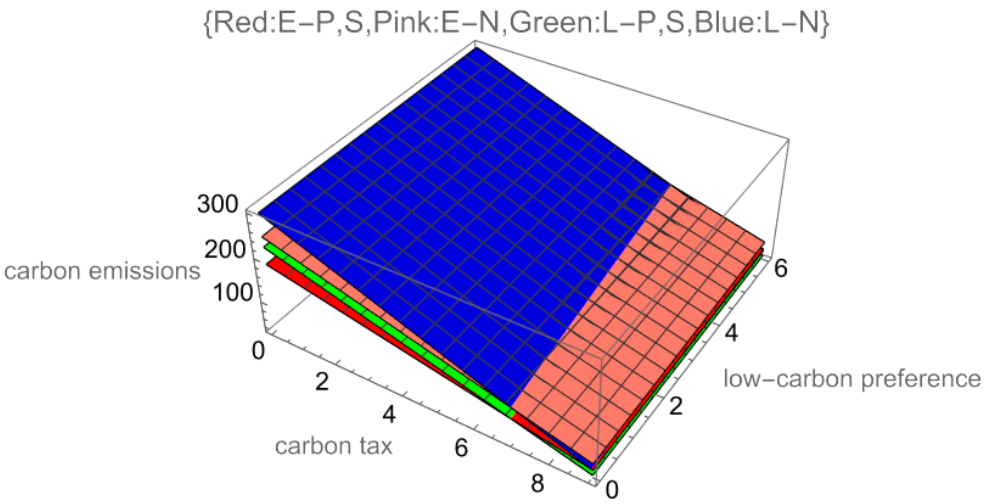

Figure 5. Total carbon emissions.

6.3. Influence of θ and γ on Social Welfare

Figure 6 illustrates how carbon tax, customers' low-carbon preferences, and environmental concerns impact social welfare. Given a certain technology, if environmental concern is low, the Nash game would be the most suitable option from a social welfare point of view. In any other cases, the Stackelberg games are expected to be superior, as indicated in Proposition 4.

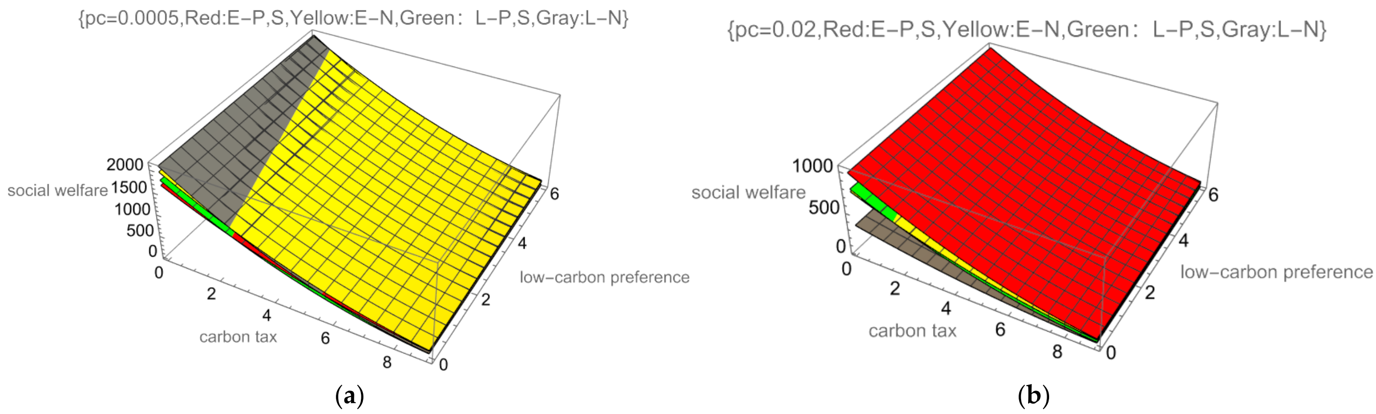

Figure 6. The social welfare.

Comparing the social welfare between the two technologies is a complex task, so the Nash game is regarded as a representative instance. Two different environmental concern cases are shown in Figure 6. The low-environmental consciousness situation (pc $= 0.0005$) is shown as Figure 6a, and Figure 6b describes the high-environmental consciousness situation (pc $= 0.02$). Proposition 2 suggests that when θ and γ are both low, the economic benefit of the supply chain implementing LSFO is greater than that of using SP. However, the total carbon emissions with the adoption of LSFO are more than that of SP according to Proposition 4. Under the low environmental concern, implementing LSFO is more suitable from the viewpoint of social welfare. As the environmental consciousness grows, the disutility of carbon emissions increases. With higher unit carbon emissions, the social welfare of the adoption of LSFO drops more significantly than that of SP. Consequently, SP with more social welfare is favored over LSFO when it comes to high environmental concerns.

7. Conclusions

This paper discusses the decision making of emission control technology (SP and LSFO) in the port supply chain. The model is constructed in three power structures using game theory. By analyzing the equilibrium results, some results are obtained.

Firstly, for maximizing the supply chain's profit, a balanced supply chain on both sides is better than the Stackelberg game. When the customers' low-carbon preferences and carbon tax are low, LSFO is the preferred option; otherwise, SP should be the more suitable choice.

Secondly, for controlling emissions, the Stackelberg game consistently produces fewer carbon emissions than the Nash game. When the customers' low-carbon preferences and carbon tax are low, LSFO is the better option than SP; otherwise, SP should be chosen.

Finally, from the point of social welfare, the Nash game has the highest social welfare when the environmental concern is low, whereas the Stackelberg games have more social welfare when the environmental concern is high. The technical comparison, however, is more complex. Generally speaking, when customers' low-carbon preferences, carbon tax, and environmental concerns are all low or high, LSFO is preferred. Otherwise, SP would be better.

Most of the existing studies on emission control in port areas focus on the emission reduction efforts and emission reduction investment of port and shipping enterprises under government policies, such as subsidies, carbon tax, and carbon trading mechanisms. However, there is little literature on quantitative analysis and comparison of the two technologies (SP and LSFO). Yang et al. [21] compared SP and LSFO from the perspective of sustainable development under the carbon trading mechanism, but they did not take into account the influence of customers' low-carbon preferences. This study shows that under customers' low-carbon preferences, a higher carbon tax may not necessarily make the supply chain choose the cleaner technology SP, because the expansion of market demand led by customers' low-carbon preferences may promote the supply chain to use general clean technology (LSFO) to obtain more profits, which will inevitably lead to more carbon emissions. Also, in terms of social welfare, when customers' low-carbon preferences, carbon tax, and environmental concerns are all low or high, the social welfare of using LSFO is greater than that of using SP. Otherwise, the social benefits of using SP are more substantial. The results obtained can further enrich the existing research. Meanwhile, these can give ports and ships valuable information to select suitable emission reduction technologies, and it is also very useful for regulars to formulate appropriate policies from the view of their own interests.

The decisions made by ports and ships regarding emission reduction are influenced by various factors, including the ports' natural resources, ship characteristics, the competitive dynamics among ports, the vessels' competitive relationship, and market unpredictability. So the process is more intricate. Consequently, exploring a more realistic port and shipping supply chain that includes multiple ports and ships is the future research direction. In addition, the game-theoretical models could be expanded to include subsidies or additional strategic interactions, and the artificial neural network [46] could also be used as an optimization method in the next study.

Author Contributions: Conceptualization, H.Z.; methodology, H.Z.; software, Y.Z.; validation, H.Z.; formal analysis, H.Z. and Y.Z.; investigation, Y.Z.; resources, H.Z.; writing—original draft preparation, Y.Z.; writing—review and editing, Y.Z.; funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The research is supported by the Natural Science Foundation of Guangdong Province of China, grant number 2021A1515110213, and the Key Construction Discipline Scientific Research Ability Enhancement Project of Guangdong Province, grant number 2022ZDJS094.

Data Availability Statement: All data generated or analyzed during this study are included in this article.

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

Appendix A

1. Solutions with adoption of SP

(1) In ship-leading Stackelberg, the port's profit is $U^p = (m - c_E)q - qe_E\theta$

Solving $\frac{\partial U^p}{\partial m} = 0$, $m^* = \frac{a+bc_s-bw+\gamma(e-e_E)+be_E\theta}{2b}$, substituting m* into U^s, and solving $\frac{\partial U^s}{\partial w} = 0, w_{E-S} = \frac{a+\gamma(e-e_E)+b(c_E-c_s+c_t-e_E\theta)}{2b}$; thus,

$$m_{E-S} = \frac{a+\gamma(e-e_E)-b(c_E-3c_s+c_t-3e_E\theta)}{4b},$$

$$U^p_{E-S} = \frac{[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{16b}, U^s_{E-S} = \frac{[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{8b}$$

$$U^{sc}_{E-S} = \frac{3[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{16b},$$

$$T_{E-S} = \frac{e_E(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))}{4}$$

$$sw_{E-S} = \frac{(3-b{e_E}^2p_c)(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{16b}$$

(2) In the Nash game, the ship's profit is $U^s = (w - c_t - c_s)[a - b(m+w)] - qe_E\theta$. Solving $\frac{\partial U^s}{\partial w} = 0, w^* = \frac{a+bc_E+bc_t-bm+\gamma e-\gamma e_E}{2b}$, the port's profit is $U^p = (m - c_E)q - qe_E\theta$. Solving $\frac{\partial U^p}{\partial m} = 0, m^* = \frac{a+bc_s-bw+\gamma(e-e_E)+be_E\theta}{2b}$

Now, solving above two equations simultaneously,

$$m_{E-N} = \frac{a+\gamma(e-e_E)-b(c_E-2c_s+c_t-2e_E\theta)}{3b}, w_{E-N} = \frac{a+\gamma(e-e_E)+b(2c_E-c_s+2c_t-e_E\theta)}{3b},$$

Thus,

$$U^p_{E-N} = \frac{(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{9b},$$

$$U^s_{E-N} = \frac{(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{9b}$$

$$U^{sc}_{E-N} = \frac{2(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{9b},$$

$$T_{E-N} = \frac{e_E(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))}{9},$$

$$sw_{E-N} = \frac{(2-be_E{}^2p_c)(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{9b}.$$

(3) In the port-leader game, the ship's profit is $U^s = (w-c_t-c_s)[a-b(m+w)] - qe_E\theta$. Solving $\frac{\partial U^s}{\partial w} = 0, w^* = \frac{a+bc_E+bc_t-bm+\gamma e-\gamma e_E}{2b}$, substituting w^* into U^p, and solving $\frac{\partial U^p}{\partial m} = 0, m_{E-P} = \frac{a+\gamma(e-e_E)+b(c_E-c_s+c_t-e_E\theta)}{2b}$; thus,

$$w_{E-P} = \frac{a+\gamma(e-e_E)+b(3c_E-c_s+3c_t-e_E\theta)}{4b}$$

$$U^p_{E-P} = \frac{[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{8b}, U^s_{E-P} = \frac{[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{16b}$$

$$U^{sc}_{E-P} = \frac{3[a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta)]^2}{16b}, T_{E-P} = \frac{e_E(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))}{4}$$

$$sw_{E-P} = \frac{(3-be_E{}^2p_c)(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{16b}.$$

2. Solutions with adoption of LSFO

When LSFO is implemented, the results can be easily obtained by the same method used in the situation of adoption of SP. In order to avoid repetition, the solving process is omitted.

3. Proofs

Proof of Lemma 1.

(1) when $j = P$: $\frac{\partial^2 U^{sc}_{i-P}}{\partial^2 c_i} = \frac{\partial^2 U^{sc}_{i-P}}{\partial^2 c_t} = \frac{3b}{8} > 0, \frac{\partial^2 U^{sc}_{E-P}}{\partial^2 c_s} = \frac{3b}{8} > 0, \frac{\partial^2 U^{sc}_{i-P}}{\partial^2 \gamma} = \frac{3(e_i-e)^2}{8b} > 0, and\ \frac{\partial^2 U^{sc}_{i-P}}{\partial^2 e_i} = \frac{3(b+\theta)^2}{8} > 0.$

(2) when $j = S$: $\frac{\partial^2 U^{sc}_{i-S}}{\partial^2 c_i} = \frac{\partial^2 U^{sc}_{i-S}}{\partial^2 c_t} = \frac{3b}{8} > 0, \frac{\partial^2 U^{sc}_{E-S}}{\partial^2 c_s} = \frac{3b}{8} > 0, \frac{\partial^2 U^{sc}_{i-S}}{\partial^2 \gamma} = \frac{3(e_i-e)^2}{8b} > 0, and\ \frac{\partial^2 U^{sc}_{i-S}}{\partial^2 e_i} = \frac{3(b+\theta)^2}{8} > 0.$

(3) when $j = N$: $\frac{\partial^2 U^{sc}_{i-N}}{\partial^2 c_i} = \frac{\partial^2 U^{sc}_{i-N}}{\partial^2 c_t} = \frac{4b}{9} > 0, \frac{\partial^2 U^{sc}_{E-N}}{\partial^2 c_s} = \frac{4b}{9} > 0, \frac{\partial^2 U^{sc}_{i-N}}{\partial^2 \gamma} = \frac{4(e_i-e)^2}{9} > 0, and\ \frac{\partial^2 U^{sc}_{i-N}}{\partial^2 e_i} = \frac{4(b+\theta)^2}{9} > 0.$

□

Proof of Proposition 1. For the port,

$$U^p_{E-P}-U^p_{E-S}=\frac{A^2}{16b}\geq 0, U^p_{E-P}-U^p_{E-N}=\frac{A^2}{72b}\geq 0, U^p_{E-S}-U^p_{E-N}=-\frac{7A^2}{144b}\leq 0$$

$$U^p_{L-P}-U^p_{L-S}=\frac{B^2}{16b}\geq 0, U^p_{L-P}-U^p_{L-N}=\frac{B^2}{72b}\geq 0, U^p_{L-S}-U^p_{L-N}=-\frac{7B^2}{144b}\leq 0$$

Therefore, $U^p_{i-P}\geq U^p_{i-N}\geq U^p_{i-S}$.
For the ship,

$$U^s_{E-P}-U^s_{E-S}=-\frac{A^2}{16b}\leq 0, U^s_{E-P}-U^s_{E-N}=-\frac{7A^2}{144b}\leq 0, U^s_{E-S}-U^s_{E-N}=\frac{A^2}{72b}\geq 0$$

$$U^s_{L-P}-U^s_{L-S}=-\frac{B^2}{16b}\leq 0, U^s_{L-P}-U^s_{L-N}=-\frac{7B^2}{144b}\leq 0, U^s_{L-S}-U^s_{L-N}=\frac{B^2}{72b}\geq 0$$

Therefore, $U^s_{i-P}\leq U^s_{i-N}\leq U^s_{i-S}$.
For the supply chain,

$$U^{sc}_{E-P}-U^{sc}_{E-S}=0, U^{sc}_{E-P}-U^{sc}_{E-N}=\frac{5(a+\gamma(e-e_E)-b(c_E+c_s+c_t+e_E\theta))^2}{144b}\geq 0$$

$$U^{sc}_{L-P}-U^{sc}_{L-S}=0, U^{sc}_{L-P}-U^{sc}_{L-N}=\frac{5(a+\gamma(e-e_L)-b(c_L+c_t+e_L\theta))^2}{144b}\geq 0$$

Therefore, $U^{sc}_{i-N}\geq U^{sc}_{i-P}=U^{sc}_{i-S}$. □

Proof of Proposition 2.

$$U^s_{E-j}-U^s_{L-j}=\beta(2a-2\gamma e+\gamma(e_E+e_L)-b(c_E+c_L+c_s+2c_t+e_L\theta+ e_E\theta))(\gamma(e_E-e_L)+c_L-c_E-c_s+\theta e_L-\theta e_E)$$

$$U^p_{E-j}-U^p_{L-j}=\mu(2a-2\gamma e+\gamma(e_E+e_L)-b(c_E+c_L+c_s+2c_t+e_L\theta +e_E\theta))(\gamma(e_E-e_L)+c_L-c_E-c_s+\theta e_L-\theta e_E)$$

$$U^{sc}_{E-j}-U^{sc}_{L-j}=\varphi(2a-2\gamma e+\gamma(e_E+e_L)-b(c_E+c_L+c_s+2c_t+e_L\theta+e_E\theta))(\gamma(e_E -e_L)+c_L-c_E-c_s+\theta e_L-\theta e_E)$$

where β,μ,φ are constants.

Since $q>0$, θ must satisfy $\theta<\frac{a+\gamma(e-e_E)-b(c_E+c_s+c_t)}{be_E}, \theta<\frac{a+\gamma(e-e_L)-b(c_L+c_t)}{be_L}$, if $0<\theta<\frac{c_s+c_E-c_L}{e_L-e_E}$, then

$$U^p_{E-j}<U^p_{L-j}, U^s_{E-j}<U^s_{L-j}\ and\ U^{sc}_{E-j}<U^{sc}_{L-j}$$

□

Proof of Lemma 2.

(1) when $j=P,S$: $\frac{\partial T_{i-j}}{\partial c_i}=\frac{\partial T_{i-j}}{\partial c_t}=-\frac{b}{4}e_i<0, \frac{\partial T_{E-j}}{\partial c_s}=-\frac{b}{4}e_E<0, \frac{\partial T_{i-j}}{\partial\theta}=-\frac{b}{4}e_i^2<0, \frac{\partial T_{i-j}}{\partial\gamma}=\frac{(e-e_i)e_i}{4}>0\ and\ \frac{\partial^2 T_{i-j}}{\partial^2 e_i}=-\frac{(\gamma+b\theta)}{2}<0$.

(2) when $j=N$: $\frac{\partial T_{i-N}}{\partial c_i}=\frac{\partial T_{i-N}}{\partial c_t}=-\frac{be_i}{3}<0, \frac{\partial T_{E-N}}{\partial c_s}=-\frac{be_E}{3}<0, \frac{\partial T_{i-N}}{\partial\theta}=-\frac{be_i^2}{3}<0, \frac{\partial T_{i-N}}{\partial\gamma}=\frac{(e-e_i)e_i}{3}>0\ and\ \frac{\partial^2 T_{i-N}}{\partial^2 e_i}=-\frac{2(\gamma+b\theta)}{3}<0$.

□

Proof of Proposition 3. Comparing the supply chain's carbon emissions under different power structures,

$$T_{i-P} - T_{i-S} = 0, \quad T_{L-P} - T_{L-N} = -\frac{e_L}{12}(a + \gamma(e - e_L) - b(c_L + c_t + e_L\theta))$$

$$T_{E-P} - T_{E-N} = -\frac{e_E}{12}(a + \gamma(e - e_E) - b(c_E + c_t + c_s + e_E\theta))$$

Since $q > 0$, θ must satisfy $\theta < \frac{a+\gamma(e-e_L)-b(c_L+c_t)}{be_L}$, $\theta < \frac{a+\gamma(e-e_E)-b(c_E+c_s+c_t)}{be_E}$; therefore, $T_{L-N} > T_{i-P} = T_{i-S}$. □

Proof of Proposition 4. Comparing carbon emissions of two technologies,

$$T_{E-j} - T_{L-j} = \frac{e_E(a + \gamma(e - e_E) - b(c_E + c_t + c_s + e_E\theta)) - e_L(a + \gamma(e - e_L) - b(c_L + c_t + e_L\theta))}{4}$$

If $0 < \theta < \frac{ae_E - bc_e e_E - bc_s e_E - bc_t e_E - ae_L + bc_L e_L + bc_t e_L}{be_E{}^2 - be_L{}^2}$, then $T_{E-j} < T_{L-j}$ otherwise, $T_{E-j} \geq T_{L-j}$. □

Proof of Proposition 5. The social welfare of the supply chain is compared as follows:

$$sw_{i-P} - sw_{i-S} = 0 sw_{i-P} - sw_{i-N} = \frac{\left(3 - be_i{}^2 p_c\right)(a - b(c_i + c_s + c_t + e_i\theta))^2}{16b} - \frac{\left(2 - be_i{}^2 p_c\right)(a - b(c_i + c_s + c_t + e_i\theta))^2}{9b}$$

Therefore, if $p_c < \frac{5}{7be_i{}^2}$, then $sw_{i-P} = sw_{i-S} \leq sw_{i-N}$; otherwise, $sw_{i-N} \leq sw_{i-P} = sw_{i-S}$. □

Proof of Proposition 6.

$$sw_{E-j} - sw_{L-j} = \frac{\left(3 - be_E{}^2\beta\right)(a + \gamma e - \gamma e_E - bc_E - bc_s - bc_t - be_E\theta)^2}{16b} - \frac{\left(3 - be_L{}^2\beta\right)(a + \gamma e - \gamma e_L - bc_L - bc_t - be_L\theta)^2}{16b} (j = P, S)$$

$$sw_{E-N} - sw_{L-N} = \frac{\left(2 - be_E{}^2\beta\right)(a + \gamma e - \gamma e_E - bc_E - bc_s - bc_t - be_E\theta)^2}{16b} - \frac{\left(2 - be_L{}^2\beta\right)(a + \gamma e - \gamma e_L - bc_L - bc_t - be_L\theta)^2}{16b}$$

Therefore,
If $p_c < \frac{2\rho}{\omega}$, then $sw_{E-j} < sw_{L-j} (j = P, S, N)$,
If $\frac{2\rho}{\omega} < p_c < \frac{3\rho}{\omega}$, then $sw_{E-N} > sw_{L-N}$, $sw_{E-j} < sw_{L-j} (j = P, S)$,
If $p_c > \frac{3\rho}{\omega}$, then $sw_{E-j} > sw_{L-j}$.

$$\rho = 2b\gamma\theta c_L e_e + 2b\gamma\theta c_t e_e - 2a\gamma\theta e_e + \gamma^2\theta^2 e_e^2 - 2e\gamma^2\theta e_e + 2a\gamma e_L + 2e\gamma^2 e_L - 2b\gamma c_L e_L - 2b\gamma c_t e_L + 2b\gamma\theta^2 e_e e_L - 2b\gamma\theta e_L^2 - \gamma^2 e_L^2$$

$$\begin{aligned}\omega = 2abc_L e_e^2 - a^2 e_e^2 &- e^2\gamma^2 e_e^2 + 2be\gamma c_L e_e^2 - b^2 c_L^2 e_e^2 - 2ae\gamma e_e^2 + 2abc_t e_e^2 + 2be\gamma c_t e_e^2 \\ &- 2b^2 c_L c_t e_e^2 - b^2 c_t^2 e_e^2 + 2a\gamma\theta e_e^3 + 2e\gamma^2\theta e_e^3 - 2b\gamma\theta c_L e_e^3 - 2b\gamma\theta c_t e_e^3 \\ &- \gamma^2\theta^2 e_e^4 + 2ab\theta e_e^2 e_L + 2be\gamma\theta e_e^2 e_L - 2b^2\theta c_L e_e^2 e_L - 2b^2\theta c_t e_e^2 e_L \\ &- 2b\gamma\theta^2 e_e^3 e_L + a^2 e_L^2 + 2ae\gamma e_L^2 + e^2\gamma^2 e_L^2 - 2abc_L e_L^2 - 2be\gamma c_L e_L^2 \\ &+ b^2 c_L^2 e_L^2 - 2abc_t e_L^2 - 2be\gamma c_t e_L^2 + 2b^2 c_L c_t e_L^2 + b^2 c_t^2 e_L^2 - b^2\theta^2 e_e^2 e_L^2 \\ &- 2a\gamma e_L^3 - 2e\gamma^2 e_L^3 - 2ab\theta e_L^3 - 2be\gamma\theta e_L^3 + 2b\gamma c_L e_L^3 + 2b^2\theta c_L e_L^3 \\ &+ 2b\gamma c_t e_L^3 + 2b^2\theta c_t e_L^3 + \gamma^2 e_L^4 + 2b\gamma\theta e_L^4 + b^2\theta^2 e_L^4\end{aligned}$$

□

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