

Game Research of Port and Ship Emission Reduction under Carbon Quota

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Abstract

This study explores emission reduction of a port supply chain that consists of one port and one ship operator under a cap-and-trade scheme. In order to reduce financial burden of the government, make full use of market factors to promote emission reduction. This paper discusses whether government can guide port to participate in emission reduction of ship operator by setting up a carbon trading market, promote the construction of green port, alleviate financial pressure, and reduce the green service cost of ship operator. At the same time, it also discusses impact of consumers' low-carbon preference on port and shipping emission reduction. Specifically, three different game models, centralized channel case, decentralized channel case and cost sharing contract, are constructed to explore this issue. The results show that in real life, government should take reasonable measures to encourage port to participate in the reduction of ship operator. At the same time, it should increase the publicity of carbon emission reduction and improve consumers' attention to low carbon environmental protection. In addition, government should also reasonably regulate the carbon unit price in carbon trading market according to actual situation.

Keywords

Emission control; Cap-and-trade; Game theory; Port supply chain; Low-carbon preference.

1. Introduction

The port industry, being more prosperous because of increasing volume of global trade, also create a huge amount of pollutants such as NO_x, SO₂, CO, particulate matter (PM), and main greenhouse gas, CO₂, which endanger coastal residents' health seriously. According to International Maritime Organization (2014), "for the year 2012, total shipping emissions were approximately 938 million tonnes CO₂ and 961 million tonnes CO₂e (CO₂equivalent) for GHGs combining CO₂, CH₄ and N₂O. International shipping emissions for 2012 are estimated to be 796 million tonnes CO₂ and 816 million tonnes CO₂e. International shipping accounts for approximately 2.2% and 2.1% of global CO₂ and GHG emissions on a CO₂e basis, respectively [1]. When ships are in ports, auxiliary diesel engines are usually used to generate electricity to support ship production and daily life. During this period, diesel combustion produces many greenhouse gases (GHG), sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM) and other harmful pollutants, which are harmful to health of residents and ports in offshore areas and have a significant impact on sustainable development. The International Maritime Organization (IMO) has implemented the IMO 2020 sulfur cap that requires all ships to decrease sulfur in fuel oil from 3.5% to 0.5% m/m [2]. The IMO 2020 states that ship operators can continue to use sulfur-rich fuels but install exhaust gas cleaning systems (scrubbers). The function of a scrubber is to use seawater to wash out sulfur in the exhaust gas. Alternatively,

ship operators can switch from high-sulfur fuel (HSF) to low-sulfur fuel (LSF) directly or use liquefied natural gas (LNG) [3,4]. Hence, in general, there are three abatement options available for ship operators to comply with the IMO 2020 sulfur cap: installing SOx scrubbers, switching to LSF, and running on LNG [5]. However, in medium and long term, regardless of the measures taken by ship operators to reduce carbon emissions, they will have to bear considerable operating costs, because compared to the previous use of HSF, they are relatively expensive. Although ship operators to adopt green technology make level of pollutants in port area decreased, the environmental quality has been significantly improved. But the ship operators pay a lot of operating costs, increasing economic burden. Many experts and scholars suggest that government should provide appropriate subsidies for use of emission reduction ships to reduce their economic burden. Indeed, there are instances where subsidies are offered to ship operators to encourage switching to LSF even before the implementation of the IMO 2020. For instance, the Taiwanese government, through the Ministry of Transportation and Communications, had announced that it would offer subsidy (US\$ 172) to all ships that use LSF when calling at the Taiwanese ports [6]. The study found that government subsidies can encourage more ship operators to adopt low-carbon technology, which is beneficial to reduce carbon emissions. However, some experts and scholars also pointed out that current research has some limitations. The existing research does not consider budget constraint as government will always encounter financial constraints to implement a policy [7]. It can be seen that construction of green port only government and ship participation is not enough. The construction and development of green ports require joint participation of all sectors of society, and their responsibilities and obligations require each subject to assume their respective roles. As a participant of green port construction, it is responsibility of port to attach importance to green development, and its role cannot be ignored.

The stress on emission control prompted governments to implement low-carbon policies, including cap-and-trade scheme, carbon inflexible cap, carbon tax and carbon offset, which are designed to curb greenhouse gases emissions such as CO₂ and sulfur oxides. Under a cap-and-trade scheme, firms allocated with a carbon emission quota can sell extra quota to or buy it from a carbon trading market with certain carbon price. This practice has been accepted widely due to an elasticity of regulation. As to today's consumers, they are willing to pay more for environmental-friendly products in presence of social responsibility [8]. This research is also based on these two factors.

Therefore, purpose of this study is to reduce carbon emissions by government's implementation of carbon trading policies. The government guides port to participate in emission reduction of ship by setting up a carbon trading market. At the same time, it considers influence of consumers' low carbon preference on emission reduction, finds most effective coordination scheme, promotes construction of green port, alleviates financial pressure of government, and reduces green service cost of ship operator.

The contribution of this study lies in following aspects: (1) at present, there is little research on government guiding port to participate in construction of ship green service in literature of port and shipping supply chain emission reduction. This study sets up a carbon trading market to guide port to participate in construction of ship green service, and promotes construction of green port, which fills gap in this research. (2) The method proposed in this study not only reduces economic burden of ship operator, but also has important practical significance for promotion and use of green technologies such as low sulfur fuel. (3) Both port and ship operator are in a supply chain, and development of two is a game process. The two influence each other, and shipping operator is emission reduction, port and ship operator benefit at the same time, in this process prone to "free rider" behavior, thereby reducing enthusiasm of emission reduction. The scheme proposed in this study can effectively solve this problem, and reference for similar cases.

The rest of the paper is organized as follows. In Section 2, related literature is reviewed. Section 3 presents notation and assumptions. The optimal decisions and performances of supply chain under different decision models are derived and discussed in Section 4. Section 5 compares results of various cases. Section 6 gives numerical experiments to provide managerial insights, and Section 7 concludes this study.

2. Literature Review

This study is closely related to three streams of literature, green ports and ocean transport logistics, cap-and-trade, and supply chain coordination strategy.

2.1. Green Ports and Ocean Transport Logistics

With the development of trade globalization, shipping has become an important way of global cargo transportation. As a key node of maritime transportation, ports transform their functions from traditional loading and unloading to connection centers of global logistics service supply chain, which draws researchers' attention to construction of green ports. Yang et al. [9] constructed a carbon emissions calculation model consisting of service centers of logistics, information and business. They suggested use of SP or LSFO to reduce carbon emissions in port areas. Chen et al. [10] investigated how Emission Control Area (ECA) influenced global shipping and suggested extensive coordination at international level to reduce ship emissions. Rene et al. [11] described high voltage of shoreside power (SP) in Croatia with their pros and cons to determine optimal solution for Croatian ports. Lu and Wu [12] recommended green port standards in green port construction for Chinese government to develop and set up an environmental port logistics system. Their research emphasized importance of port-integrated logistics, and they encouraged ports to provide multifunctional logistics services. Based on real annual data, Linda Styhre et al. [13] quantified t Gothenburg, Long Beach, Osaka, and Sydney, and discusses potential of greenhouse gas emission reduction after implementation of four important measures (Channel deceleration; Land power supply; Reduce berth turnover time; Alternative fuels). The above research shows that people are more and more interested in reducing carbon emissions in port areas. However, the existing literature is very difficult to discuss carbon emissions from perspective of game theory. This study uses game theory to study this problem.

2.2. Cap-and-trade

The public prefers cap-and-trade scheme due to its elasticity. Xu et al. [14] studied supply chain coordination with a green technology under cap-and-trade scheme, they found firms could cooperate to reduce carbon emissions without decreasing their profits. Yang et al. [15] studied two competitive supply chains under cap-and-trade scheme. Their results showed that vertical cooperation leads to a higher carbon emissions reduction rate and lower retail prices. Drake et al. [16] studied impact of emissions tax and emissions cap-and-trade regulation on a firm's technology choice and capacity decisions. Chai et al. [17] considered impact of carbon trading on remanufacturing industry, and concluded that carbon trading is beneficial to both normal market competition and green market competition of remanufactured products, which means that carbon trading is conducive to promoting development of remanufacturing industry. Several emerging industries benefit from carbon trading mechanism. For example, Fang et al. [18] studied impact of carbon trading on new energy industry in China and pointed out that mature carbon trading market could facilitate development of new energy. It is obvious that carbon trading is acting as an effective way to reduce carbon emission and will affect more industries. However, the existing literature rarely applies carbon cap policy to port and shipping emission reduction. This paper applies carbon quota policy to field of port and shipping emission reduction, and explores its impact on port and shipping emission reduction.

2.3. Supply Chain Coordination Strategy

Many scholars have proposed a series of strategies and methods for study of supply chain coordination. These strategies and methods enable supply chain members to allocate costs in products or services to improve supply chain performance. Notably, latest research has focused on sustainable supply chains. For example, Ghosh and Shah [19] explored impact of cost-sharing contract on decision-making of supply chain members undertaking green initiatives. Arda [20] studied profit/cost implications of collaboration between supply chain members for upstream eco-efficient innovation by comparing cost-sharing and revenue-sharing contracts. Yang and Chen [21] discussed effect of cost-sharing and revenue-sharing contracts on manufacturers' carbon emission abatement efforts, among others. Yanju Zhou [22] studies on a low-carbon supply chain channel consisting of a manufacturer and a retailer to optimize low-carbon supply chain management decisions and improve supply chain performance through contract design. Mohammadreza Sinayi et al. [23] point out that cooperation between manufacturers and retailers always leads to production of greener products, increases profits of whole supply chain and increases surplus of consumers. The present study considers cost sharing contract and compares it with centralized control model and decentralized control model to explore whether it can coordinate supply chain.

3. Notation and Assumptions

Under the background of cap-and-trade scheme, a supply chain with one port and one ship operator is proposed in this study. When ship is parked in port for loading and unloading, green technologies such as low-sulfur fuel are used to reduce carbon emissions. Government set up a carbon trading market to guide port to share some costs of ship operator. Specifically, government allocates a certain amount of carbon quota to port. When carbon emission of port area is less than carbon quota, port can sell excess carbon quotas in carbon trading market, and vice versa. The higher the green service level of ship operator, the higher the income of port in the carbon trading market, which can share part of the cost for ship operator to achieve a win-win effect. The relationship between port, ship operator, government and customer is explained below (refer Figure 1).

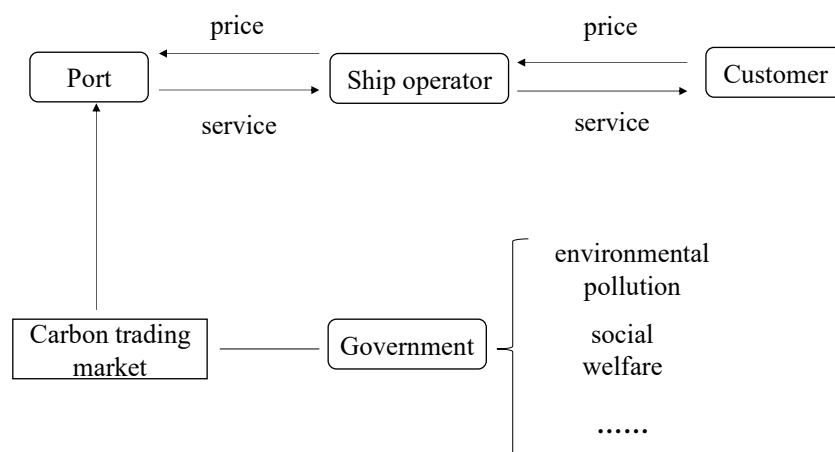


Figure 1. Supply chain structure considered

3.1. Notation

Relevant parameters and decision variables are summarized in Table 1.

Table 1. Notation for parameters and decision variables.

Notation	Meaning
e	Initial unit carbon emissions before ship emission reduction
t	Unit carbon price in the carbon trading market
n	Environmental concern
U	The negative disutility of total emitted pollutant
T	Total carbon emissions
k	Carbon emission quota for the port
π^s	Profit of the ship operator
π^p	Profit of the port
π^{sc}	Profit of the supply chain
Decision variables	
w	Service price of the port
p	Service price of the supply chain
$g(0 < g < 1)$	Share proportion of port
θ	Emission reduction level of ship operators

3.2. Basic Assumptions

Assumption 1. In order to facilitate study, referring to research method of Yang[1], carbon emissions in this study only include emissions when the ship is parked in port, excluding emissions of other periods of ship.

Assumption 2. This study assumes that carbon emissions of ship berthing in port are all attributed to carbon emissions generated in process of port operation, and port is responsible for them.

Assumption 3. In actual market, according to characteristics of service industry, main factors affecting customer purchase service are service unit price and service level. Referring to market demand function of JAFARI et al. [24], we assume that market demand function is $q = a - bp + r\theta$. In this equation, a is total market potential, b is price sensitivity of consumer demand, r is consumer sensitivity to emission reduction level.

Assumption 4. Ship operator needs cost investment to achieve carbon emission reduction. Based on green development cost function of Ma [25], cost of ship operator is a quadratic function of green service level, is $\frac{1}{2}i\theta^2$. In this equation, i is greening investment parameter, $i > 0$.

Assumption 5. Under cap-and-trade scheme, government set a reasonable carbon emission quota for port and pursue two goals, to maximize port supply chain's profit, and to minimize carbon emissions. Following Krass et al.[26], these two goals are necessarily conflicting such that this study introduces a weighted objective for government, namely social welfare function, consisting of sum of economic profits and total emissions multiplied by an "environmental concern" parameter. This parameter converts emissions into monetary economic profit, measuring degree of society's environmental concerns with respect to pollutant emitted by supply chain, is $SW = \pi^{sc} - U$, in this equation, U denotes negative disutility of total emitted pollutant, $U = nT^2$.

Assumption 6. a , b , i , n , r are all greater than 0.

Assumption 7. Port and ship operator have complete information, both are rational game players.

Assumption 8. It is assumed that only port and ship operator share profits of whole supply chain.

Assumption 9. For ease of calculation, $s = p - w$, s is unit service charge actually charged by ship operator.

In summary, profit functions of the port, the ship operator, and the supply chain can be obtained as follows,

$$\begin{aligned}\pi^p &= wq - [q(1 - \theta)e - k]t \\ \pi^s &= (p - w)q - \frac{1}{2}i\theta^2 \\ \pi^{sc} &= \pi^p + \pi^s \\ T &= q(1 - \theta)e \\ U &= nT^2 \\ SW &= \pi^{sc} - U\end{aligned}\quad (1)$$

This study is divided into two parts. The first part studies game analysis of port and ship operators' emission reduction without considering consumers' low-carbon preference under carbon quota policy. The second part studies game analysis of port and ship operator' emission reduction with considering consumers' low-carbon preference under carbon quota policy. In this study, the Stackelberg game method is used, with port as leader and solution order as backward induction. The coordination effect of cost sharing contract is studied and compared with centralized channel case and decentralized channel case, respectively.

4. Game Models

4.1. Game Model Without Considering Consumers' Low Carbon Preference Under Carbon Quota Policy.

1. Centralized channel case (N-C)

Port and ship operator are in a state of complete trust, and both sides take profit optimization of supply chain as goal to make emission reduction decisions. Decision model is as follows,

$$\begin{aligned}q &= a - bp \\ \pi^{sc} &= pq - [q(1 - \theta)e - k]t - \frac{1}{2}i\theta^2 \\ T &= q(1 - \theta)e \\ U &= nT^2 \\ SW &= \pi^{sc} - U\end{aligned}\quad (2)$$

the first order condition

$$\begin{aligned}\frac{\partial \pi^{sc}}{\partial p} &= a - 2bp + bet(1 - \theta) \\ \frac{\partial \pi^{sc}}{\partial \theta} &= e(a - bp)t - i\theta\end{aligned}\quad (3)$$

the second order condition

$$\frac{\partial^2 \pi^{sc}}{\partial^2 p} = -2b$$

$$\begin{aligned}
\frac{\partial^2 \pi^{sc}}{\partial^2 \theta} &= -i \\
\frac{\partial^2 \pi^{sc}}{\partial p \partial \theta} &= -bet \\
\frac{\partial^2 \pi^{sc}}{\partial \theta \partial p} &= -bet
\end{aligned} \tag{4}$$

the Hessian matrix is

$$\begin{bmatrix} -2b & -bet \\ -bet & -i \end{bmatrix}$$

for $bi - b^2 e^2 t^2 > 0$, the Hessian matrix is negative definite. Equating the first order conditions to 0 we get,

$$\begin{aligned}
p_c &= -\frac{ai + beit - abe^2 t^2}{b(-2i + be^2 t^2)} \\
\theta_c &= -\frac{et(a - bet)}{-2i + be^2 t^2}
\end{aligned} \tag{5}$$

substituting the above value into (2) and we get

$$\begin{aligned}
q_c &= \frac{-ai + beit}{-2i + be^2 t^2} \\
\pi_c^{sc} &= kt - \frac{i(a - bet)^2}{2b(-2i + be^2 t^2)} \\
T_c &= \frac{ei(-2i + aet)(-a + bet)}{(-2i + be^2 t^2)^2} \\
U_c &= \frac{e^2 i^2 n(-2i + aet)^2 (a - bet)^2}{(-2i + be^2 t^2)^4} \\
SW_c &= kt - \frac{1}{2b(-2i + be^2 t^2)^4} i(a - bet)^2 (8i^3(-1 + be^2 n) + b^3 e^6 t^6 + 4be^2 i^2 t(-2aen + 3t) + 2be^4 i t^2 (a^2 n - 3bt^2))
\end{aligned} \tag{6}$$

2. Decentralized channel case (N-D)

In case of Stackelberg game dominated by port, port and ship operator conduct non-cooperative two-stage game. In the first stage, port determines the unit service price. In the second stage, the ship operator determines its unit service price and emission reduction intensity. The decision model is shown in equation (1).

$$\begin{aligned}
q &= a - bp \\
\pi^s &= sq - \frac{1}{2} i \theta^2
\end{aligned} \tag{7}$$

Obtaining Hessian matrix by solving first and second order condition,

$$\begin{bmatrix} -2b & 0 \\ 0 & -i \end{bmatrix}$$

the Hessian H is negative definite. Equating the first order conditions to 0 we get,

$$\begin{aligned}s &= \frac{a - bw}{2b} \\ \theta &= 0\end{aligned}\quad (8)$$

the optimal solution is substituted into the port profit function and we solve first order condition, is

$$w = \frac{a + bet}{2b}$$

substituting the value of w into equation (8), we get

$$\begin{aligned}s &= \frac{a - bet}{4b} \\ \theta &= 0\end{aligned}\quad (9)$$

substituting the above value into (1) and we get

$$\begin{aligned}s_d &= \frac{a - bet}{4b} \\ \theta_d &= 0 \\ w_d &= \frac{a + bet}{2b} \\ p_d &= \frac{1}{4} \left(\frac{3a}{b} + et \right) \\ q_d &= \frac{1}{4} (a - bet) \\ \pi_d^s &= \frac{(a - bet)^2}{16b} \\ \pi_d^p &= \frac{1}{4} \left(\frac{3a}{b} + et \right) \\ \pi_d^{sc} &= \frac{1}{8} \left(\frac{a^2}{b} - 2aet + t(8k + be^2t) \right) \\ T_d &= \frac{1}{4} e(a - bet) \\ U_d &= \frac{1}{16} e^2 n (a - bet)^2 \\ SW_d &= \frac{a^2(3 - be^2n) + 2abe(-3 + be^2n)t + bt(16k + be^2(3 - be^2n)t)}{16b}\end{aligned}\quad (10)$$

3. Cost sharing contract (N-S)

The port offers to share g ($0 < g < 1$) proportion of the total cost of greening.

In the first stage, the port determines the unit service price and allocation proportion; in the second stage, ship operator determines the unit service price and emission reduction intensity. The decision model is as follows.

$$\begin{aligned}
q &= a - bp \\
\pi^p &= wq - [q(1 - \theta)e - k]t - \frac{1}{2}gi\theta^2 \\
\pi^s &= sq - \frac{1}{2}(1 - g)i\theta^2 \\
\pi^{sc} &= \pi^p + \pi^s \\
T &= q(1 - \theta)e \\
U &= nT^2 \\
SW &= \pi^{sc} - U
\end{aligned} \tag{11}$$

Firstly, the decision variables of ship operator are solved. Obtaining Hessian matrix by solving first and second order condition,

$$\begin{bmatrix} -2b & 0 \\ 0 & (-1 + g)i \end{bmatrix}$$

for $2bi - 2bgi > 0$, equating the first order conditions to 0 we get,

$$\begin{aligned}
s &= \frac{a - bw}{2b} \\
\theta &= 0
\end{aligned} \tag{12}$$

the optimal solution is substituted into the port profit function and we solve first and second order condition, is

$$\begin{aligned}
\frac{\partial \pi^p}{\partial w} &= \frac{1}{2}(a + bet - 2bw) \\
\frac{\partial \pi^p}{\partial g} &= 0 \\
\frac{\partial^2 \pi^p}{\partial w^2} &= -b \\
\frac{\partial^2 \pi^p}{\partial g^2} &= 0 \\
\frac{\partial^2 \pi^p}{\partial w \partial g} &= 0 \\
\frac{\partial^2 \pi^p}{\partial g \partial w} &= 0
\end{aligned} \tag{13}$$

From the above calculation, it can be seen that the sharing ratio g does not exist. Equating the first order condition of w to 0 we get,

$$w_s = \frac{a + bet}{2b} \tag{14}$$

Substituting the value of w_s into the value of θ and s we get

$$\begin{aligned} s_s &= \frac{a - bet}{4b} \\ \theta_s &= 0 \end{aligned} \quad (15)$$

From the above results, it can be seen that the unit service cost of the ship operator, the intensity of emission reduction, and the service cost of the port are consistent with the decentralized channel case. Combined with the actual situation, although the port is very willing to share a part of the cost for the ship operators, the ship operators are still unwilling to reduce emissions for their own interests, and only $g_s = 0$. That is to say, cost allocation can not coordinate the supply chain without considering consumers' low-carbon preference. Therefore, the equilibrium values obtained is consistent with the decentralized channel case, which will not be discussed here.

4.2. Game Model Considering Consumers' Low Carbon Preference Under Carbon Quota Policy

1. Centralized channel case (G-C)

The decision model is as follows,

$$\begin{aligned} q &= a - bp + r\theta \\ \pi^{sc} &= pq - [q(1 - \theta)e - k]t - \frac{1}{2}i\theta^2 \\ T &= q(1 - \theta)e \\ U &= nT^2 \\ SW &= \pi^{sc} - U \end{aligned} \quad (16)$$

the solution steps are consistent with the N-C and no longer repeat. For $2bi - r^2 - 2bert - b^2e^2t^2 > 0$, there is an optimal equilibrium value:

$$\begin{aligned} q_c^G &= \frac{bi(-a + bet)}{r^2 + b(-2i + et(2r + bet))} \\ \pi_c^{sc-G} &= kt - \frac{i(a - bet)^2}{2(r^2 + b(-2i + et(2r + bet)))} \\ T_c^G &= \frac{bei(-a + bet)(-2bi + r(a + r) + be(a + r)t)}{(r^2 + b(-2i + et(2r + bet)))^2} \\ U_c^G &= \frac{b^2e^2i^2n(a - bet)^2(-2bi + r(a + r) + be(a + r)t)^2}{(r^2 + b(-2i + et(2r + bet)))^4} \\ SW_c^G &= kt - \frac{i(a - bet)^2}{2(r^2 + b(-2i + et(2r + bet)))} - \frac{b^2e^2i^2n(a - bet)^2(-2bi + r(a + r) + be(a + r)t)^2}{(r^2 + b(-2i + et(2r + bet)))^4} \end{aligned} \quad (17)$$

2. Decentralized channel case (G-D)

The decision model is as follows,

$$\begin{aligned} q &= a - bp + r\theta \\ \pi^p &= wq - [q(1 - \theta)e - k]t \\ \pi^s &= sq - \frac{1}{2}i\theta^2 \end{aligned}$$

$$\begin{aligned}
\pi^{sc} &= \pi^p + \pi^s \\
T &= q(1 - \theta)e \\
U &= nT^2 \\
SW &= \pi^{sc} - U
\end{aligned} \tag{18}$$

the solution steps are consistent with the N-D and no longer repeat. For $2bi - r^2 > 0$, there is an optimal equilibrium value:

$$\begin{aligned}
s_d^G &= -\frac{i(a - bet)}{2(-2bi + r^2 + bert)} \\
\theta &= \\
w_d^G &= -\frac{r(a - bet)}{2(-2bi + r^2 + bert)} \\
p_d^G &= -\frac{a(3bi - r^2) + be(bi - r(2a + r))t}{2b(-2bi + r^2 + bert)} \\
q_d^G &= \frac{bi(-a + bet)}{2(-2bi + r^2 + bert)} \\
\pi_d^{s-G} &= \frac{i(2bi - r^2)(a - bet)^2}{8(-2bi + r^2 + bert)^2} \\
\pi_d^{p-G} &= -\frac{a^2i - 2abeit + t(8bik - 4kr^2 + be(bei - 4kr)t)}{4(-2bi + r^2 + bert)} \\
\pi_d^{sc-G} &= \frac{1}{(8(-2bi + r^2 + bert)^2)} (a^2i(6bi - 3r^2 - 2bert) + 2abeit(-6bi + 3r^2 + 2bert) \\
&\quad + t(8k(-2bi + r^2)^2 + be(3bei - 16kr)(2bi - r^2)t - 2b^2e^2r(bei - 4kr)t^2)) \\
T_d^G &= \frac{bei(-a + bet)(r(a + 2r) + b(-4i + ert))}{4(-2bi + r^2 + bert)^2} \\
U_d^G &= \frac{b^2e^2i^2n(a - bet)^2(r(a + 2r) + b(-4i + ert))^2}{16(-2bi + r^2 + bert)^4} \\
SW_d^G &= \frac{1}{8} (8kt - \frac{1}{(2(-2bi + r^2 + bert)^4)} (i(a - bet)^2(6r^6 + b^4e^2in(-4i + ert)^2 + 4br^4(-9i \\
&\quad + 4ert) + 2b^3(-24i^3 - 4ei^2r(en(a + 2r) - 8t) + e^2ir^2(en(a + 2r) - 14t)t \\
&\quad + 2e^3r^3t^3) + b^2r^2(72i^2 + 14e^2r^2t^2 + ei(en(a + 2r)^2 - 64rt))))))
\end{aligned} \tag{19}$$

3. Cost sharing contract (G-S)

The decision model is as follows.

$$\begin{aligned}
q &= a - bp + r\theta \\
\pi^p &= wq - [q(1 - \theta)e - k]t - \frac{1}{2}gi\theta^2 \\
\pi^s &= sq - \frac{1}{2}(1 - g)i\theta^2 \\
\pi^{sc} &= \pi^p + \pi^s \\
T &= q(1 - \theta)e \\
U &= nT^2
\end{aligned}$$

$$SW = \pi^{sc} - U \quad (20)$$

The solution steps are consistent with the G-S and no longer repeat. Let $A = \frac{b^2 i((2-3g)r^2 - 2b(-1+g)(2(-1+g)i + ert))}{(2b(-1+g)i + r^2)^2}$, $B = -\frac{1}{(2b(-1+g)i + r^2)^4} 4bi^2 r(a - bw)(-ber(2b(-1+g)i + r^2)t + a(b(2+g)ir - r^3 + 2be(b(-1+g)i - r^2)t) + b(b(-4+g)ir + 2r^3 + 2be(b(i - gi) + r^2)t)w)$, $C = \frac{1}{(2b(-1+g)i + r^2)^3} bir(2a(r^3 - 2b^2e(-1+g)it + br(-2i + ert)) + b(r^3(et - 3w) + 4b^2e(-1+g)itw - 2br((-3+g)iw + et(i - gi + rw))))$. For $2bi - 2bgi - r^2 > 0$, $A < 0$ and $AB - C^2 > 0$, there is an optimal equilibrium value:

$$\begin{aligned} s_s^G &= \frac{4i(a - bet)}{-9r^2 - 4b(-4i + et(3r + bet))} \\ \theta_s^G &= -\frac{2(a - bet)(3r + 2bet)}{9r^2 + 4b(-4i + et(3r + bet))} \\ w_s^G &= \frac{a(-8bi + 3r^2) + 2be(-4bi + r(4a + 3r))t + 4b^2e^2(a + r)t^2}{b(9r^2 + 4b(-4i + et(3r + bet)))} \\ p_s^G &= \frac{3a(-4bi + r^2) + 2be(-2bi + r(4a + 3r))t + 4b^2e^2(a + r)t^2}{b(9r^2 + 4b(-4i + et(3r + bet)))} \\ q_s^G &= \frac{4bi(-a + bet)}{9r^2 + 4b(-4i + et(3r + bet))} \\ g_s^G &= 1 - \frac{2r}{3r + 2bet} \\ \pi_s^{S-G} &= \frac{4i(a - bet)^2(4bi - 3r^2 - 2bert)}{(9r^2 + 4b(-4i + et(3r + bet)))^2} \\ \pi_s^{p-G} &= kt - \frac{2i(a - bet)^2}{9r^2 + 4b(-4i + et(3r + bet))} \\ \pi_s^{sc-G} &= \frac{4i(a - bet)^2(4bi - 3r^2 - 2bert)}{(9r^2 + 4b(-4i + et(3r + bet)))^2} + kt - \frac{2i(a - bet)^2}{9r^2 + 4b(-4i + et(3r + bet))} \\ T_s^G &= \frac{4bei(-a + bet)(-16bi + 6ar + 9r^2 + 4abet + 6bert)}{(9r^2 + 4b(-4i + et(3r + bet)))^2} \\ U_s^G &= \frac{16b^2e^2i^2n(a - bet)^2(-16bi + 6ar + 9r^2 + 4abet + 6bert)^2}{(9r^2 + 4b(-4i + et(3r + bet)))^4} \\ SW_s^G &= \frac{4i(a - bet)^2(4bi - 3r^2 - 2bert)}{(9r^2 + 4b(-4i + et(3r + bet)))^2} + kt - \frac{2i(a - bet)^2}{9r^2 + 4b(-4i + et(3r + bet))} \\ &\quad - \frac{16b^2e^2i^2n(a - bet)^2(-16bi + 6ar + 9r^2 + 4abet + 6bert)^2}{(9r^2 + 4b(-4i + et(3r + bet)))^4} \end{aligned} \quad (21)$$

5. Results and discussion

In this section, based on the equilibrium results obtained in Section 4, sensitivity analysis is carried out to obtain the impact of different parameters on the optimal pricing, the resulting emissions, profits and social welfare. The equilibrium results of three decision models are compared. These results can provide a reference for regulatory agencies to formulate emission reduction strategies of port supply chain.

1. Comparison of game results between port and ship operator without considering consumers' low carbon preference.

$$(1) p_d - p_c = \frac{1}{4} \left(\frac{3a}{b} + et \right) + \frac{ai+beit-abe^2t^2}{b(-2i+be^2t^2)} = \frac{(-a+bet)(2i+be^2t^2)}{4b(-2i+be^2t^2)}$$

Since $a - bet > 0$, $(2i + be^2t^2) > 0$, $4b > 0$, $(2i - be^2t^2) > 0$, therefore, $p_d > p_c$. Similarly, $\theta_d < \theta_c$, $q_d < q_c$, $\pi_d^{sc} < \pi_c^{sc}$.

Proposition 1. $p_d > p_c$, $\theta_d < \theta_c$, $q_d < q_c$, $\pi_d^{sc} < \pi_c^{sc}$.

Proposition 1 shows that, without considering consumers' low-carbon preference, the profit, emission reduction and demand of the port supply chain in centralized channel case are greater than those in decentralized channel case, but the unit service cost is lower than that in the decentralized channel case. This shows that centralized channel case is the most beneficial for the whole port supply chain and consumers. In this situation, the mutual cooperation between port and ship operator can optimize the profit of the entire port supply chain. In this case, the profit of port and ship operator is higher than that in decentralized channel case.

$$(2) \text{ Proposition 2. } \theta_d = 0, \theta_c = -\frac{et(a-bet)}{-2i+be^2t^2}$$

Proposition 2 shows that the intensity of emission reduction of ship operator under decentralized channel case is 0. This shows that in the absence of any incentive policies, the enthusiasm of ship operators for emission reduction is not high. Even if the government sets up a carbon trading market to guide the port to participate in emission reduction, the port does not give any incentive measures to ship operator, resulting in ship operator unwilling to take any measures to reduce emissions from their own interests.

$$(3) \theta_d = \theta_s, p_d = p_s, q_d = q_s, \pi_d^{sc} = \pi_s^{sc}, SW_d = SW_s, g = 0$$

Proposition 3. Without considering consumers' low-carbon preference, although the port is willing to share part of the emission reduction cost for the ship operator, the ship operator is not willing to reduce emissions from its own interests.

It can be seen from proposition 3 that considering the fixed carbon quota allocated by the government, port is willing to share part of the emission reduction cost for ship operator in order not to pay too much cost in the carbon trading market; However, for ship operator, even if the port is willing to share a part of the cost of emission reduction, the profit of ship operator will be reduced compared with that of non-emission reduction, because once the ship operator reduces emission, the unit service price will inevitably increase. At this time, due to the lack of low-carbon preference of consumers, the demand will be greatly reduced, which is unfavorable for ship operator.

2. Comparison of game results between port and ship operator with considering consumers' low carbon preference.

$$(1) q_d^G - q_c^G = \frac{1}{2} bi(-a + bet) \left(\frac{-2bi+r^2-b^2e^2t^2}{(2bi-r^2-bert)(-2bi+r^2+2bert+b^2e^2t^2)} \right)$$

$$q_s^G - q_d^G = \frac{1}{2} bi(-a + bet) \left(\frac{r^2 + 4bert + 4b^2e^2t^2}{(2bi - r^2 - bert)(-16bi + 9r^2 + 12bert + 4b^2e^2t^2)} \right)$$

$$q_c^G - q_s^G = bi(-a + bet) \frac{-8bi + 5r^2 + 4bert}{(-2bi + r^2 + 2bert + b^2e^2t^2)(-16bi + 9r^2 + 12bert + 4b^2e^2t^2)}$$

Since $a - bet > 0$, $2bi - r^2 > 0$, $2bi - r^2 - 2bert - b^2e^2t^2 > 0$, $4bi - 3r^2 - 2bert > 0$, and $16bi - 9r^2 - 12bert - 4b^2e^2t^2 > 0$, therefore, $-q_d^G < q_s^G < q_c^G$. Similarly, $\theta_d^G < \theta_s^G < \theta_c^G$, $p_d^G > p_s^G > p_c^G$.

$$(2) \quad \pi_s^{sc-G} - \pi_c^{sc-G} = \frac{4i(a-bet)^2(4bi-3r^2-2bert)}{(9r^2+4b(-4i+et(3r+bet)))^2} + kt - \frac{2i(a-bet)^2}{9r^2+4b(-4i+et(3r+bet))} - (kt - \frac{i(a-bet)^2}{2(r^2+b(-2i+et(2r+bet))))$$

Suppose $D = 9r^2 + 4b(-4i + et(3r + bet))$, $E = (a - bet)^2$, $F = r^2 + b(-2i + et(2r + bet))$, $\pi_s^{sc-G} - \pi_c^{sc-G} = \frac{4iE(4bi-3r^2-2bert)}{D^2} - \frac{2iDE}{D^2} + \frac{iE}{2F} = iE \frac{4F(-D+2iE(4bi-3r^2-2bert))+D^2}{2D^2F}$, since $D < 0, E > 0, F < 0, 4bi - 3r^2 - 2bert > 0$, therefore $\pi_s^{sc-G} < \pi_c^{sc-G}$. Similarly, $\pi_d^{sc-G} < \pi_c^{sc-G}$, $\pi_d^{sc-G} < \pi_s^{sc-G}$, that is $\pi_d^{sc-G} < \pi_s^{sc-G} < \pi_c^{sc-G}$

Similarly, $\theta_d^G < \theta_s^G < \theta_c^G$, $q_d^G < q_s^G < q_c^G$

Proposition 4. Proposition 4 shows that the profit, emission reduction and demand of the supply chain in the case of cost sharing contract are greater than those in the case of decentralized channel case. Although the cost-sharing contract cannot reach the level of centralized channel case, it largely coordinates the supply chain. This shows that port actively participates in the emission reduction of ship operator and share part of the cost of emission reduction, which not only promotes the emission reduction level of ship operator to a large extent, but also increases the demand and improves the profit of the supply chain.

3. Influence of consumers' low carbon preference on emission reduction and social welfare

$$\theta_c^G - \theta_c - \theta_c = -\frac{r(a-bet)(2i+et(r+bet))}{(2i-be^2t^2)(r^2+b(-2i+et(2r+bet)))} > 0$$

$\theta_c^G > \theta_c$. Similarly, $q_c^G > q_c$, $\pi_c^{sc-G} > \pi_c^{sc}$, $SW_c^G > SW_c$; $\theta_d^G > \theta_d$, $q_d^G > q_d$, $\pi_d^{sc-G} > \pi_d^{sc}$, $SW_d^G > SW_d$.

Proposition 5. $\theta_c^G > \theta_c$, $q_c^G > q_c$, $\pi_c^{sc-G} > \pi_c^{sc}$, $SW_c^G > SW_c$, $\theta_d^G > \theta_d$, $q_d^G > q_d$, $\pi_d^{sc-G} > \pi_d^{sc}$, $SW_d^G > SW_d$.

Proposition 5 shows that whether it is a centralized channel case or a decentralized channel case, the demand, supply chain emission reduction level and profit, and social welfare are higher than those without considering consumers' low-carbon preference factors. In other words, the sensitivity of consumers to green service level can promote emission reduction, increase the demand, and improve the profit and social welfare of supply chain.

4. Sensitivity analysis

(1) Port share g is inversely proportional to r , is proportional to g and is proportional to e .

$$\frac{\partial g}{\partial r} = -\frac{4bet}{(3r+2bet)^2} < 0, \frac{\partial g}{\partial b} = \frac{4ert}{(3r+2bet)^2} > 0, \frac{\partial g}{\partial t} = \frac{4bre}{(3r+2bet)^2} > 0$$

Proposition 6. The more sensitive consumers are to green services, the lower the proportion of port to ship operator. The more sensitive consumers are to service prices, the higher the proportion of port sharing for ship operator is. The higher the carbon price in the carbon trading market, the higher the proportion of port to ship operator.

Proposition 6 shows that the sensitivity of consumer to green service level will increase the demand, and ship operator will benefit directly, so the enthusiasm of ship operator will become higher, and the proportion of port sharing from its own interests will decrease. The more sensitive consumers are to price, the more reluctant they are to purchase the services of ship operator. Port is allocated to ship operator in order to reduce the cost of ship operator and reduce the service price of ship operator. The higher the carbon price in the carbon trading market, the higher the cost the port pays in the carbon trading market if the emission reduction

is not high enough. Therefore, the higher the carbon price is, the higher the proportion of port to ship operator will be.

(2) Green emission reduction level θ is inversely proportional to i and is proportional to r .

$$\begin{aligned}\frac{\partial \theta_c^G}{\partial i} &= -\frac{2b((r+bet)(a-bet))}{(-2bi+r^2+2bert+b^2e^2t^2)^2} < 0; \\ \frac{\partial \theta_c^G}{\partial r} &= -\frac{(-a+bet)(2bi+r^2+2bert+b^2e^2t^2)}{(-2bi+r^2+2bert+b^2e^2t^2)^2} > 0; \\ \frac{\partial \theta_d^G}{\partial i} &= -\frac{br(a-bet)}{(-2bi+r^2+bert)^2} < 0; \\ \frac{\partial \theta_d^G}{\partial r} &= \frac{(2bi+r^2)(a-bet)}{2(-2bi+r^2+bert)^2} > 0; \\ \frac{\partial \theta_s^G}{\partial i} &= -\frac{32b(a-bet)(3r+2bet)}{(9r^2+4b(-4i+et(3r+bet)))^2} < 0; \\ \frac{\partial \theta_s^G}{\partial r} &= \frac{6(a-bet)(9r^2+4b(4i+et(3r+bet)))}{(9r^2+4b(-4i+et(3r+bet)))^2} > 0; \\ \frac{\partial \theta_c}{\partial i} &= -\frac{2et(a-bet)}{(-2i+be^2t^2)^2} < 0.\end{aligned}$$

Proposition 7. Whether considering consumers' low carbon preference or not, the emission reduction level of ship operator always decrease with the increase of emission reduction investment parameters. Considering consumers' low carbon preference, the emission reduction level of ship operator always increase with the increase of consumers' green sensitivity.

Proposition 7 shows that the larger the emission reduction investment parameter is, the higher the emission reduction cost is, and the more reluctant the ship operator is to reduce emissions; When the consumers are more sensitive to the level of green service, the ship operator is more willing to increase emission reduction to meet the market demand.

6. Numerical Analysis

Set the relevant parameters as shown in Table 2, according to the parameters in Table 2 to solve the parameters of each part of the supply chain members under different decision models. The calculation results are shown in Table 3 (Because the ship operator in the N-S case is unwilling to reduce emissions, the equilibrium solution is consistent with that in the N-D case. Only the equilibrium solution in N-D case is calculated here). It can be seen from table 3 that the demand, emission reduction level and supply chain profit of centralized channel case are greater than those of decentralized channel case without considering consumers' low-carbon preference, which confirms the point of Proposition 1. Although the social welfare under the centralized channel case is less than that under the decentralized channel case situation, this is due to the higher demand under the centralized channel case, resulting in higher emissions.

Table 2. Relevant parameters

Parameters	a	b	k	e	t	r	i	n
Numerical value	50	0.5	100	2	1	2	200	0.8

Table 3. Optimal values in different cases

Cases	s	w	p	q	θ	T	U	π^S	π^P	π^{SC}	SW
N-C	-	-	50.75	24.62	0.25	37.12	1102.33	-	-	1036.53	204.20
N-D	24.5	51.00	75.50	12.25	0	24.5	480.2	300.13	700.25	1000.38	520.18
G-C	-	-	51.77	25.65	0.77	11.82	111.77	-	-	1357.07	1245.30
G-D	25.26	50.49	75.75	12.63	0.25	18.88	285.11	312.60	718.81	1031.41	746.30
G-S	25.52	51.00	76.52	12.76	0.51	12.49	124.89	312.63	725.26	1037.89	912.99

Considering consumers' low-carbon preference, we can see that the optimal emission reduction level, the largest supply chain profit and social welfare all appear in the centralized channel case followed by the cost sharing contract, and the decentralized channel case is the worst.

Proposition 8. In the cost sharing contract, the carbon emission level of the supply chain is higher than that of the centralized channel case but lower than that of the decentralized channel case, and the social welfare is lower than that of the centralized channel case but higher than that of the decentralized channel case. Compared with the decentralized channel case, the profit of ship operator and port under the cost sharing contract have been improved to a certain extent. Thus, the cost sharing contract greatly coordinates the supply chain and improves social welfare.

In addition, it can be seen from Table 3 that although the port shares part of the emission reduction cost for the ship operator, its profit is not lower, but higher than that when it does not share. Therefore, Proposition 9 can be obtained.

Proposition 9. Cost sharing contract is not only beneficial to the entire supply chain and ship operator, but also to improve the profits of port to achieve a win-win situation.

In addition, it can be seen from Table 3 that compared with the two centralized channel case, taking into account the consumer's low-carbon preference, the profit and social welfare of the supply chain have improved significantly, and the carbon emission reduction has decreased to a certain extent. The same is true of the comparison between the two decentralized channel case. This shows that consumers' low-carbon preference factors are beneficial to supply chain emission reduction and social welfare.

Table 4, table 5 and table 6 describe the impact of different carbon unit price t on supply chain profit, social welfare and emission reduction level. It can be seen from Table 4 that in addition to two decentralized channel case, in other game models, the emission reduction level of ship operator always increases with the increase of carbon unit price in the carbon trading market. In the two decentralized channel case, due to the independent decision-making of the port and the ship operator, the port does not give any incentive measures to the emission reduction of the ship operator, resulting in that the carbon unit price cannot affect the decision-making of the ship operator, and thus the emission reduction level of the ship operator is not affected. It can be seen that although the carbon trading market does not directly affect ship operator, it can indirectly drive ship operator to reduce emissions by affecting port. This suggests that in reality, the government should take measures to encourage port to participate in the reduction of emissions by ship operator.

Table 4. Impact of carbon unit price t on the emission reduction level of supply chain

	$t = 1$	$t = 1.1$	$t = 1.2$	$t = 1.3$	$t = 1.4$	$t = 1.5$	$t = 1.6$	$t = 1.7$	$t = 1.8$
θ_c	0.25	0.27	0.29	0.32	0.34	0.37	0.39	0.42	0.44
θ_d	0	0	0	0	0	0	0	0	0
θ_c^G	0.77	0.80	0.82	0.85	0.88	0.90	0.93	0.96	0.98
θ_d^G	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
θ_s^G	0.51	0.52	0.54	0.55	0.56	0.57	0.59	0.60	0.61

Table 5. Impact of carbon unit price t on supply chain profit

	$t = 1$	$t = 1.1$	$t = 1.2$	$t = 1.3$	$t = 1.4$	$t = 1.5$	$t = 1.6$	$t = 1.7$	$t = 1.8$
π_c^{SC}	1036.5	1312.88	1319.36	1325.95	1332.67	1339.51	1346.47	1353.55	1360.75
π_d^{SC}	1000.38	1006.7	1013.04	1019.38	1025.74	1032.09	1038.46	1044.83	1051.22
π_c^{SC-G}	1357.07	1365.95	1374.97	1384.13	1393.43	1402.86	1412.44	1422.16	1432.02
π_d^{SC-G}	1031.41	1038.89	1046.37	1053.86	1061.34	1068.82	1076.31	1083.79	1091.28
π_s^{SC-G}	1037.89	1046.37	1054.92	1063.54	1072.22	1080.97	1089.78	1098.66	1107.6

It can be seen from table 5 and table 6 that the higher the carbon unit price in the carbon trading market, the higher the profit of the supply chain; The higher the unit price of carbon in the carbon trading market, the higher the social welfare. This shows that the government can promote the emission reduction, improve the profits of the supply chain and improve the social welfare by appropriately increasing the carbon unit price in the carbon trading market.

Table 6. Impact of carbon unit price t on social welfare

	$t = 1$	$t = 1.1$	$t = 1.2$	$t = 1.3$	$t = 1.4$	$t = 1.5$	$t = 1.6$	$t = 1.7$	$t = 1.8$
SW_c	204.20	282.67	358.45	431.62	502.25	570.40	636.13	699.51	760.57
SW_d	520.18	528.46	536.75	545.05	553.34	561.64	569.95	578.26	586.57
SW_c^G	1245.30	1278.28	1308.62	1336.27	1361.17	1383.24	1402.40	1418.58	1431.65
SW_d^G	746.30	754.17	762.029	769.90	777.76	785.63	793.50	801.37	809.25
SW_s^G	912.99	927.91	942.72	957.43	972.05	986.56	1000.99	1015.31	1029.55

7. Conclusion and Future Research

Under the carbon quota policy, this paper discusses the influence of consumers' low-carbon preference factors on the emission reduction of port and ship supply chain. By building a game model of emission reduction between port and ship operator, this study discusses whether the port can share the cost of emission reduction of ship operators to promote supply chain emission reduction and improve social welfare. This study compares the emission reduction, profits, members' profits and social welfare of the supply chain under the centralized channel case, decentralized channel case and cost sharing case, and the results of the model are verified by numerical analysis.

The results show that, firstly, consumers' low-carbon preference is beneficial to improve the emission reduction level, profit and social welfare of the supply chain. Secondly, the cost sharing contract will not reduce the profits of the port, but can improve the profits of the port. At the same time, the cost sharing is also conducive to reducing the emission reduction costs of ship operator, improving the profits, reducing the carbon emissions of the supply chain, and overall social welfare. In addition, if the government increases the carbon unit price appropriately, it will help to improve the emission reduction, profits of the supply chain and social welfare. Finally, the higher the sensitivity of consumers to green service level, the greater the emission reduction of supply chain; the higher the investment parameters, the smaller the supply chain emission reduction. In summary, in real life, the government should take reasonable measures to encourage port to participate in the emission reduction of ship operator. At the same time, it should increase the publicity of carbon emission reduction and improve consumers' attention to low-carbon environmental protection. In addition, the government should also reasonably regulate the carbon unit price in the carbon trading market according to the actual situation.

There are also some deficiencies in this study, which can be further analyzed in the future. Firstly, this study only considers the game situation of port and ship operator' emission reduction under the background of carbon quota policy. Firstly, this study only considers the

game situation of port and ship operators in the context of carbon quota policy. In the future, we can study the situation of levying carbon tax on port areas with more carbon emissions and providing appropriate subsidies to port participants who actively reduce emissions. Secondly, the specific accounting of carbon emission reduction in port area is one of the research directions in the future, which is conducive to the implementation of low-carbon policy. Third, how to properly evaluate the carbon emission reduction results of ports and ship operators is also a big problem. Research in this direction can help government agencies to objectively and practically understand the impact of policies and regulations, and then judge the feasibility of relevant policies.

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