Research Article

How Government Subsidy Impacts on the Supply Chain Decision for LNG-Fuelled Ships

Yan Li [ID][1] **and Jiao Yang**[2]

[1]*Department of Logistics and Information Management, Jianghan University, Wuhan430056, Hubei, China*
[2]*Department of Business Administration, Moutai Institute, Renhuai, Guizhou 564507, China*

Correspondence should be addressed to Yan Li; yldesign@jhun.edu.cn

LNG-fuelled ships help fight environmental pollution induced by fossil fuel. Chinese government has also considered encouraging the shipbuilder's initiative of producing or introducing LNG-fuelled ships through subsidies. However, rare scholars have concerned the impact of government subsidy on the supply chain decision of LNG-fuelled ships in the existing studies. This study takes green degree and government subsidy into account in the LNG-fuelled ship supply chain of a manufacturer and an owner and studies the pricing, market demand, and supply chain benefits. Our main contributions are considering the correlation between the green degree of LNG ships and government subsidy factors and exploring the influence of government subsidy on supply chain decision-making under decentralized and centralized decision-making by ship manufacturers and owners. The results show that government subsidies are conducive to promoting the whole profit and the market demand in the ship supply chain. Centralized decision generates higher profits than decentralized decisions. In the centralized decision model, government subsidies and the green degree of LNG-fuelled ship are positively correlated with the market demand. In the decentralized decision model, the price of an LNG-fuelled ship charged by shipbuilder when providing subsidies for owners is greater than that when providing subsidies for shipbuilder. Manufacturers and owners should pay attention to the greenness of ships, and the government should adopt appropriate subsidy policies to encourage the production and application of LNG ships.

1. Introduction

In recent years, China's shipping industry has experienced a rapid growth. According to the data revealed by Ministry of Transport of the People's Republic of China (MTPRC) (https://xxgk.mot.gov.cn/2020/jigou/zhghs/202006/t20200630_3321335.html), the total freight transport volume increased from 6.136 billion tons in 2015 to 7.472 billion tons in 2019, with an annual growth rate of 4%. Specifically, the freight volume through inland waterway transport accounts for 52.4% of the total volumes. However, the rapid development of shipping industry is also accompanied by large amounts of air pollutant emissions, which mainly originate from the combustion of traditional diesel fuel in ships [1]. To reduce the energy consumption and pollutant emissions induced by shipping development, the Commission on

Marine Environment (CME) of the International Maritime Organization (IMO) stipulated that global ships should use fuels with sulfur content of no more than 0.5% outside the Emission Control Area (ECA) since 2020 [2]. The stringent regulations have prompted shipbuilders and owners to shift their interests on developing greener ships from oil-fuelled ships to LNG-fuelled ships. The liquefied natural gas (LNG) is considered as the most appropriate fuel to replace oil fuel to date, as the utilization of LNG is conducive to reducing particulate (PM), sulfur (SOx), nitrogen (NOx), and carbon dioxide (CO_2) emissions to a large extent [3, 4]. Given these advantages, LNG-fuelled ships have been widely concerned by an increasing number of shipping companies.

With China's important role in global economic development, China has contributed tremendously to the shipping business. Especially, the inland waterway transport

system in China, based around the Yangtze, Pearl, and Heilongjiang rivers and the Beijing-Hangzhou Canal, is increasingly flourishing. MTPRC has released that the total number of China's inland waterway transport ships in 2019 reaches to 119.5 thousand, whereas the number of coastal water transport ship and ocean transport ship is 10.4 thousand and 1.7 thousand, respectively. Thus, the inland waterway transport systems should be responsible for considerable pollution and have stronger motivations to develop "clean energy" models. Since 2009, Chinese government has begun to encourage shipbuilders and owners to utilize LNG-fuelled ships. Several related official documents were issued by the State Council and MTPRC. Even more, MTPRC announced two pilot demonstration projects of LNG-fuelled waterway transport in September 2014 and October 2016, respectively. However, the results of these actions aiming at promoting shipbuilders and owners to switch to LNG-fuelled ships are far from the governments' expectations. The main reason for this dilemma may be the huge cost of transforming the ship's power system [5]. Due to a lack of funds, shipbuilders and owners may be reluctant to proactively switch to LNG-fuelled ships. To mitigate this problem, governments are inclined to utilize subsidies to encourage them to invest in LNG-fuelled ships, and this approach often produces positive effects [6].

The governments often utilize subsidies to stimulate the power transformation in the shipping industry. However, it is noteworthy that different subsidy objects and ways exert different policy effects [7]. For governments, they concern more on choosing appropriate decision-making modes that can promote shipping companies to adopt LNG-fuelled ships to a large extent. For shipping companies, they would consider the behaviors of upstream and downstream companies in a supply chain when making their own decisions. In previous studies, the importance of supply chain decision-making modes has been widely recognized. Most research studies have investigated the pricing, supply chain coordination, and the influences of decision-making modes on the supply chain performance [8, 9]. Some scholars also focused on the role of government subsidy in the supply chain coordination mechanism [10–13], [14]. However, there has been very limited research on the impact of government subsidy on the supply chain performance under different decision-making modes in LNG-fuelled ship supply chain.

Therefore, this study explores the influence of government subsidy on the supply chain profit and market demand in the ship supply chain decision, which refers to shipbuilders and owners' decisions that jointly transform to LNG-fuelled ships. Through the comparison of centralized decisions and decentralized decisions, we can help the shipbuilders and owners to choose the optimum decision scheme. Specifically, this study examined how to arrange the decision modes of supply chain members in the case of different government subsidies.

(1) Considering green degree, we built the decision models for one shipbuilder and one owner's ship supply chain targeting at studying the supply chain decisions of LNG-fuelled ships

(2) We investigated the impacts of government subsidies on the supply chain profit and market demands of LNG-fuelled ships under the centralized decision model and decentralized decision model, respectively.

(3) We also analyzed the influences of different government subsidy objects including shipbuilders and shipowners on the supply chain profit and market demands under the decentralized decision model

The remainder of this study is organized as follows. Section 2 reviews the existing studies closely related to our research. Section 3 describes the model assumptions, notations, and demands. The model construction and solutions are proposed in Section 4. In Section 5, we compare the influences of government subsidies on the price of LNG-fuelled ships and the supply chain profit with the numerical example analysis. Finally, the study concludes with findings and future research suggestions in Section 6.

2. Literature Reviews

In this section, we mainly review the literature related to two streams of research: the development status and prospects of LNG-fuelled ships and green supply chain research for different government subsidies.

2.1. Development Status and Prospects of LNG-Fuelled Ships. In response to the IMO's clean energy regulations, an increasing number of studies have targeted at LNG-fuelled ships and other environment friendly ships. Utilizing the method of life cycle assessment (LCA), Bengtsson et al. [15] assessed the environmental performance of marine clean fuels. The results showed that LNG and other alternative fuels conforming to the SECA 2015 and Tier III NOx requirements could reduce the potential of acidification and eutrophication by 78–90% over a life cycle. Given LNG fuels' potential in the shipping industry, many countries like Norway, Holland, Denmark, and Italy have ordered a large number of LNG-fuelled ships. Calderón et al. [16] analyzed the application of LNG fuels in the maritime industry and then explored the potential of LNG fuels' future growth. They argued that ships powered by LNG fuels, especially those with smaller ship sizes and shorter distances, are growing. The growth speed of LNG-fuelled ships mainly depends on its future price and capital cost, as well as the cost of ship conversion [17].

Due to the increasing importance of LNG-fuelled ships, some scholars have extended their research to the utilization of LNG-fuelled ships from the perspective of supply chain. Jokinen et al. [18] presented a model to promote the supply chain design decisions by minimizing the total costs associated with LNG fuel procurement. Similarly, Bittante et al. [19] established a mathematical model that considers the LNG distribution by a heterogeneous fleet of ships and applies mixed integer linear programming to find the ship supply chain structure. These studies have concerned the importance of LNG-fuelled ships in a supply chain; nevertheless, what is noteworthy is that the prior studies rarely investigate the relevance of decision-making among upward

and downward partners in an LNG-fuelled ships supply chain.

2.2. Green Supply Chain Research for Different Government Subsidies.

With the enhancement of people's awareness of environmental protection, there are more and more research studies on green supply chain [20, 21]. The government also subsidizes green supply chain members. The existing literature focuses on the influence of government subsidies on green supply chain. Based on the data from 1998 to 2011, Grigolon et al. [22] studied the subsidy issue of scrapped cars in Europe during the financial crisis and then analyzed the automobile subsidy and sales of eight European countries or regions. Guo et al. [23] concerned a green supply chain system that consists of three members, namely, supplier, manufacturer, and government and then explored the influences of government subsidies on social welfare and the profits of supply chain members. Madani and Rasti-Barzoki [24] presented a competitive mathematical model that considers government as the leader and two competitive green and nongreen supply chains as the followers. They further argued that the influence of increasing the government subsidy rate is significantly beyond that of the raising tax rate, as the government subsidy can lead to a higher profit growth of supply chain and a more enduring product sustainability. Lou et al. [25] studied the issues considering government's green subsidies and optimal decisions of a manufacturer and dual-channel retailers in a two-echelon dual-channel supply chain. They found that a product's green degree of the centralized supply chain is always higher than that of the decentralized supply chain. Shib [26] conducted a comparison between green and nongreen marketing which included subsidies and taxes implementation by government. Meng et al. [27] discussed the decision-making impact on dual-channel green supply chains with and without government subsidies. Rong and Xu [28] evaluated the impact of manufacturer altruistic preferences and government subsidies on the multinational green supply chain under dynamic tariff.

This literature review reveals that previous studies, which have highlighted the role of government subsidy in a green supply chain, mainly focused on the methods and effects of government subsidies, without considering a horizontal comparison between government subsidies for manufacturers and those for retailers, not to mention the comparison in an LNG-fuelled ship supply chain. In other words, although the existing studies have investigated the development status and prospects of LNG-fuelled ships and highlighted the role of government subsidy in a green supply chain, they did not unite them in a coordinating framework. To the best of our knowledge, little research has examined government funding's effect through subsidies on the supply chain profit and market demand of LNG-fuelled ships under different decision-making modes. Give that, we need to look from the perspective of the government to discuss how different government subsidies impact the members' decision-making under the circumstance of LNG-fuelled ships supply chain.

3. Problem Definition and Assumptions

3.1. Problem Definition.

In this study, we focus on the optimal decision-making scheme for the production and sale of LNG-fuelled ships under the premise that production and utilization will be promoted by government subsidies. For simplicity, we describe a supply chain model that consists of a singer shipbuilder and a singer owner. Shipbuilders produce or transform LNG-fuelled ships and owners operate them. The government can maximize social welfare by providing subsidies to the ship supply chain. The size of the market demand depends on the price and the green degree of the LNG-fuelled ship. This problem can be solved under two different plans: centralized decision and decentralized decision. We further compared the two schemes to reveal the most profitable one for the shipbuilder and the owner.

3.2. Assumptions and Notations.

We defined the following main assumptions:

Assumption 1. All information in the decision-making process of government, shipbuilder, and owner are completely symmetrical. These three actors are all rational and they pursue the benefit maximation of their own.

Assumption 2. We focus on a ship supply chain system that consists of a single shipbuilder and a singer owner. We mainly consider one important factor involving LNG-fuelled ships called green degree (β), without considering the roles of other factors such as ship specification, carrying capacity, appearance, comfort level, and manufacturing quality.

Assumption 3. There is no shortage for shipbuilders' products. We do not consider the ship return or wastage in shipbuilders' transaction with owners. At the same time, the owners could make profits after purchasing the LNG-fuelled ships.

Assumption 4. Whether the government provides subsidies to the shipbuilders or owners, the total subsidy for an LNG-fuelled ship (S) is fixed. The subsidy policies from both central government and local government are the same.

Assumption 5. The earnings of an LNG-fuelled ship charged by the owner (P) are fixed under different circumstances of operating LNG-fuelled ships by themselves and renting them out to others.

Assumption 6. The supply chain members could obtain the government subsidies only when the green degree of LNG-fuelled ship is above the lowest standard stipulated by the state (β_0).

Given the fact that the manufacturing technology of an LNG-fuelled ship in China is still in a development stage, manufacturers must increase their R&D investment when manufacturing LNG-fuelled ships. Following previous studies [29] that have revealed the function relations between the manufacturer's R&D cost and the green degree of

LNG-fuelled ship, we also assume that the cost function for R&D of an LNG-fuelled ship is $C(\beta) = 1/2\alpha\beta^2$, where α is the R&D ratio of an LNG-fuelled ship based on green degree. The R&D cost of the LNG-fuelled ship is a fixed input cost, which is independent with the production cost of an LNG-fuelled ship. We assume that γ represents the subsidy adjustment ratio of an LNG-fuelled ship based on green degree. The total government subsidies for an LNG-fuelled ship are $S = \gamma(\beta - \beta_0)$.

The demand function of the LNG-fuelled ship is related to the price and green degree of the LNG-fuelled ship charged by owners. We assume that D is the potential demand size of the LNG-fuelled ship. Thus, the demand function of the LNG-fuelled ship in the market is $Q = D - kP + \sigma\beta$, where σ represents the marginal effect of the LNG-fuelled ship's green degree on the quantity demand in the market, reflecting the environmental awareness of stakeholders. The increase of green degree of LNG-fuelled ships will give rise to the stakeholders' increasing willingness to utilize LNG-fuelled ships, thus promoting the market demand for LNG-fuelled ships.

In the rest of the study, the notations defined in Table 1 are used.

4. Model Construction and Solutions

4.1. Centralized Decision Model. In a centralized decision-making mode, the shipbuilder and owner of an LNG-fuelled ship are regarded as a whole of cooperation. Under this circumstance, whether the government provides subsidies to shipbuilder or owner, the total subsidies for an LNG-fuelled ship are fixed. The whole supply chain targets at the maximum profit for both shipbuilder and owner and thereby maximizing the overall profit of the supply chain. In the model, costs include manufacturing costs and green research and development costs, while benefits include product sales benefits and government subsidies. Profit is equal to revenue minus cost. Therefore, the overall profit function of LNG-fuelled ship supply chain is as follows:

$$\Pi = [P - C + \gamma(\beta - \beta_0)](D - kP + \sigma\beta) - \frac{1}{2}\alpha\beta^2. \quad (1)$$

Proposition 1. *In a centralized decision-making mode, the overall profit function of LNG-fuelled ship supply chain is a concave function concerning P. There is a unique optimal solution P^* to the function, which maximizes the value of function Π.*

Proof. The first and second derivatives related to P for the function of equation (1) are obtained as follows, respectively.

$$\frac{\partial \Pi}{\partial P} = (D - kP + \sigma\beta) - k[P - C + \gamma(\beta - \beta_0)],$$

$$\frac{\partial^2 \Pi}{(\partial P)^2} = -2k < 0. \quad (2)$$

The function Π is a concave function concerning P. We then set $\partial\Pi/\partial P = 0$ as follows:

$$P^* = \frac{D + \sigma\beta}{2k} + \frac{C - \gamma(\beta - \beta_0)}{2} \quad (3)$$

If we substitute (3) into the function Π, we obtain the following equation:

$$\max \Pi = \frac{[D + \sigma\beta - kC + \gamma k(\beta - \beta_0)]^2 - 2k\alpha\beta^2}{4k}. \quad (4)$$
□

Corollary 1. *In a centralized decision-making mode, the price P of LNG-fuelled ships charged by owners is a strictly decreasing function of the subsidy adjustment ratio γ. In other words, the price of LNG-fuelled ships charged by owners decreases with the increase of subsidy adjustment ratio.*

Proof. The first derivative with respect to γ for the function of equation (3) is obtained as follows:

$$\frac{\partial P}{\partial \gamma} = \frac{\beta_0 - \beta}{2}. \quad (5)$$

As $\beta > \beta_0$, we get $\partial P/\partial\gamma < 0$, so P is a decreasing function of γ.

In practice, as the subsidy adjustment ratio of an LNG-fuelled ship increases, the shipbuilder and owner in the LNG-fuelled ship supply chain will obtain more subsidy from government. Therefore, the price of the LNG-fuelled ship will subsequently decrease, indicating that the increasing subsidy adjustment ratio is beneficial to the ship operators. □

Proposition 2. *In a centralized decision-making mode, the quantity of the LNG-fuelled ship demanded in the market Q is a strictly increasing function of both the subsidy adjustment ratio γ and the green degree β, that is, the quantity of the LNG-fuelled ship demanded in the market increases with the increase of subsidy adjustment ratio and green degree.*

Proof. We substitute equation (3) into equation (1) and obtain the following equation:

$$Q = \frac{D + \sigma\beta - k[C - \gamma(\beta - \beta_0)]}{2}. \quad (6)$$

We then calculate the first derivative associated with γ and β for the function of (6) as follows:

$$\frac{\partial Q}{\partial \gamma} = \frac{k(\beta - \beta_0)}{2} > 0,$$

$$\frac{\partial Q}{\partial \beta} = \frac{\sigma + k\gamma}{2} > 0. \quad (7)$$

Thus, the quantity of the LNG-fuelled ship demanded in the market Q is a strictly increasing function of both the subsidy adjustment ratio γ and the green degree β. We can suggest that the government should increase subsidies for the LNG-fuelled ships supply chain and raise the green degree of LNG-fuelled ships to enhance their demand in the market. □

TABLE 1: Notations.

Parameter	Definition
β_0	The lowest standard of green degree of the LNG-fuelled ship stipulated by the state
β	Green degree of the LNG-fuelled ship
S	Government subsidy for an LNG-fuelled ship
γ	Subsidy adjustment ratio of an LNG-fuelled ship based on green degree
D	The potential demand size of the LNG-fuelled ship
α	R&D ratio of an LNG-fuelled ship based on green degree
W	Price of an LNG-fuelled ship charged by the shipbuilder
P	Earnings of an LNG-fuelled ship charged by the owner
Q	Quantity of the LNG-fuelled ship demanded in the market
Π_m^1, Π_r^1	Profit functions for the shipbuilder and owner in the mode of decentralized decision when government subsidy is provided for the shipbuilder, respectively.
Π_m^2, Π_r^2	Profit functions for the shipbuilder and owner in the mode of decentralized decision when government subsidy is provided for the owner, respectively.
Π	Profit function for the LNG-fuelled ship supply chain in the mode of centralized decision
$C(\beta)$	Cost function for R&D of an LNG-fuelled ship
C	Cost of manufacturing an LNG-fuelled ship
k	Elasticity coefficient of the price of the LNG-fuelled ship
σ	Marginal effect of LNG-fuelled ship's green degree on the quantity demand in the market, $0 < \sigma \leq 1$

Proposition 3. *When $2\sigma\gamma - \alpha < 0$ is satisfied, the function of green degree β^* for LNG-fuelled ship is as follows:*

$$\beta^* = \frac{(\sigma + k\gamma)(Ck - D + \beta_0 k\gamma)}{(\sigma + k\gamma)^2 - 2\alpha k}. \qquad (8)$$

Proof. The first and second derivatives related to β for the function of equation (2) are obtained as follows, respectively.

$$\frac{\partial\Pi}{\partial\beta} = \sigma(P - C + 2\gamma\beta - \gamma\beta_0) - \alpha\beta + \gamma(D - kP). \qquad (9)$$

$$\frac{\partial^2\Pi}{(\partial\beta)^2} = 2\sigma\gamma - \alpha. \qquad (10)$$

Hence, when $2\sigma\gamma - \alpha < 0$ is satisfied, the whole profit in the LNG-fuelled ship supply chain is a concave function concerning β. There is a unique optimal solution for this function, which maximizes the value of function Π.

We then set (9) equal to zero as follows:

$$\beta = \frac{(\sigma + k\gamma)(Ck - D + \beta_0 k\gamma)}{(\sigma + k\gamma)^2 - 2\alpha k}. \qquad (11)$$

According to the parameter relationship related to green degree, the shipbuilder can set an optimal standard of green degree for LNG-fuelled ships, so as to optimize the decision-making process of the overall LNG-fuelled supply chain. □

4.2. Decentralized Decision Model

4.2.1. The Model That Governments Provide Subsidies for Shipbuilders. When governments provide subsidies for shipbuilders, the subsidies mainly exert effects through reducing the manufacturing cost and thus improving the overall profit of LNG-fuelled ship supply chain. In this case, the profit functions of shipbuilder and owner are as follows:

$$\Pi_m^1 = [W - C + \gamma(\beta - \beta_0)](D - kP + \sigma\beta) - \frac{1}{2}\alpha\beta^2, \qquad (12)$$

where

$$S = \begin{cases} 0, & \text{subsidies for owners} \\ \gamma(\beta - \beta_0), & \text{subsidies for shipbuilders} \end{cases} \qquad (13)$$

$$\Pi_r = (P - W + S)(D - kP + \sigma\beta). \qquad (14)$$

where

$$S = \begin{cases} \gamma(\beta - \beta_0), & \text{subsidies for owners} \\ 0, & \text{subsidies for shipbuilders} \end{cases} \qquad (15)$$

Proposition 4. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for shipbuilders, if $\beta > \beta_0$ and $2k(2\alpha - \sigma\gamma) > \sigma^2 - k^2\gamma^2$ are satisfied, there is a unique optimal solution for the price of a LNG-fuelled ship (W) and profit charged by the shipbuilder (Π_m^1), as well as a unique optimal earning of an LNG-fuelled ship (P) and profit charged by the owner (Π_r^1).*

Proof. The solution for this Stackelberg game model is obtained by backward induction. First, we take the first and second derivatives related to P for the function of equation (14) as follows:

$$\frac{\partial\Pi_r^1}{\partial P} = D + \sigma\beta - k(2P - W). \qquad (16)$$

We can see that Π_r^1 is a strictly concave function, where there is a unique optimal solution for P enabling owners to obtain the maximum profit.

We then set $\partial\Pi_r^1/\partial P = 0$ and obtain $P' = D + \sigma\beta + kW/2k$. By substituting P' into (12), Π_m^1 is given as follows:

$$\prod_{m}^{1} = \frac{(D + \sigma\beta - kW)[W - C + \gamma(\beta - \beta_0)] - \alpha\beta^2}{2}. \quad (17)$$

If we calculate the second partial derivatives with regard to W and β for the function of (17), we get the following: $\partial^2 \Pi_m^1 / (\partial W)^2 = -k$, $\partial^2 \Pi_m^1 / \partial\beta \, \partial W = \sigma - k\gamma/2$ and $\partial^2 \Pi_m^1 / (\partial\beta)^2 = \sigma\gamma - \alpha$. Thus, the Hessian matrix of Π_m^1 is

$$H = \begin{pmatrix} -k & \dfrac{\sigma - k\gamma}{2} \\ \dfrac{\sigma - k\gamma}{2} & \sigma\gamma - \alpha \end{pmatrix}. \quad (18)$$

If it satisfies the condition $|H_1| = -k < 0$, such that $2k(2\alpha - \sigma\gamma) > \sigma^2 - k^2\gamma^2$, then the Hessian matrix of function Π_m^1 is negative definite, which implies that Π_m^1 is a strictly concave function related to the parameters of (W, β). There is a unique optimal solution (W^*, β^*) enabling the function Π_m^1 to get the maximum value.

We then calculate the maximum value of concave function Π_m^1 based on the condition of $\beta > \beta_0$. Given the constraint conditions are linear, we can treat the programmatic issue as a convex optimization, where the Kuhn–Tucker condition is a necessary and sufficient condition for finding the extremum. We utilize the Lagrangian multiplier method to solve this problem. If the Lagrangian multiplier is assumed to be $\lambda(\lambda \geq 0)$, the corresponding Lagrangian function is constructed as follows:

$$F_m(W, \beta, \lambda)$$

$$= \frac{(D + \sigma\beta - kW)[W - C + \gamma(\beta - \beta_0)] - \alpha\beta^2}{2} + \lambda(\beta - \beta_0). \quad (19)$$

The first derivatives with regard to W, β, λ for the function of $F_m(W, \beta, \lambda)$ are as follows:

$$\frac{\partial F_m}{\partial W} = \frac{D + \sigma\beta - k[2W - C + \gamma(\beta - \beta_0)]}{2} = 0,$$

$$\frac{\partial F_m}{\partial \beta} = 1 - \alpha\beta + \frac{D - kW + \sigma[W - C + \beta + \gamma(\beta - \beta_0)]}{2} = 0,$$

$$\lambda(\beta - \beta_0) = 0, \quad \lambda \geq 0. \quad (20)$$

If $\lambda > 0$ and $\beta - \beta_0 = 0$ are satisfied, we can obtain

$$W' = \frac{D + \sigma\beta + kC}{2k},$$

$$\lambda = \frac{\sigma[D - (\sigma + k\gamma)\beta] + k(4\alpha\beta + \sigma C - \gamma D + k\gamma C)}{4k}. \quad (21)$$

If $\lambda = 0$ and $\beta - \beta_0 > 0$ are satisfied, we can obtain

$$W^{'*} = \frac{D + \sigma\beta + k[C - \gamma(\beta - \beta_0)]}{2k}. \quad (22)$$

By substituting (22) into $P' = D + \sigma\beta + kW/2k$ and (17), the earnings of an LNG-fuelled ship charged by the owner is obtained as follows:

$$P'^* = \frac{3D + 3\sigma\beta + k[C - \gamma(\beta - \beta_0)]}{4k}. \quad (23)$$

The optimal profit that the shipbuilder obtains is as follows:

$$\prod_{m}^{1} = \frac{[D + \sigma\beta + k\gamma(\beta - \beta_0) - kC]^2}{8k} - \frac{\alpha\beta^2}{2}. \quad (24)$$

By substituting (22) and (23) into (14), we calculate the optimal profit that the owner obtains as follows:

$$\prod_{r}^{1} = \frac{[D + \sigma\beta - kC + k\gamma(\beta - \beta_0)]^2}{16k}. \quad (25)$$

$\square$

Corollary 2. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for shipbuilders, both the optimal price W of an LNG-fuelled ship charged by shipbuilder and the optimal earning P that owner obtains are a strictly decreasing function of the subsidy adjustment ratio γ.*

Proof. Based on $\beta > \beta_0$, the first derivatives with respect to γ for the function of equations (22) and (23) are obtained as follows:

$$\frac{\partial W'}{\partial \gamma} = -\frac{\beta - \beta_0}{2} < 0; \cdot$$

$$\frac{\partial P'}{\partial \gamma} = -\frac{\beta - \beta_0}{4} < 0. \quad (26)$$

Therefore, both the optimal price of an LNG-fuelled ship charged by shipbuilder and the optimal earning that owner obtains decrease with the increase of subsidy adjustment ratio. $\square$

Proposition 5. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for shipbuilders, the quantity of the LNG-fuelled ship demanded in the market Q is a strictly increasing function of both the subsidy adjustment ratio γ and the green degree β.*

Proof. We substitute equation (23) into $Q = D - kP + \sigma\beta$ and obtain

$$Q' = \frac{D + \sigma\beta - kC + k\gamma(\beta - \beta_0)}{4}. \quad (27)$$

Based on $\beta > \beta_0$, we then calculate the first derivatives related to γ and β and obtain

$$\frac{\partial Q'}{\partial \gamma} = \frac{k(\beta - \beta_0)}{4} > 0,$$

$$\frac{\partial Q'}{\partial \beta} = \frac{\sigma + \gamma k}{4} > 0. \tag{28}$$

Hence, the quantity of the LNG-fuelled ship demanded in the market increases with the increase of subsidy adjustment ratio γ and green degree β. □

4.2.2. The Model That Government Provides Subsidies for Owners. When governments provide subsidies for owners, the subsidies mainly exert effects through reducing the purchasing cost when owners purchase LNG-fuelled ships from shipbuilders. In this case, the profit functions of shipbuilder and owner are as follows:

$$\prod_m^2 = (W - C)(D - kP + \sigma\beta) - \frac{1}{2}\alpha\beta^2. \tag{29}$$

$$\prod_r^2 = [P - W + \gamma(\beta - \beta_0)](D - kP + \sigma\beta). \tag{30}$$

Proposition 6. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for owners, if $\beta - \beta_0 > 0$ is satisfied, there is a unique optimal solution for the price of an LNG-fuelled ship (W) and profit charged by the shipbuilder (Π_m^1), as well as a unique optimal earning of an LNG-fuelled ship (P) and profit charged by the owner (Π_r^1).*

Proof. As mentioned before, the solution for this Stackelberg game model is obtained by backward induction. First, we take the first and second derivatives related to P for the function of equation (30) as follows:

$$\frac{\partial \Pi_r^2}{\partial P} = D + \sigma\beta - k[2P - W + \gamma(\beta - \beta_0)],$$

$$\frac{\partial^2 \Pi_r^2}{(\partial P)^2} = -2k < 0. \tag{31}$$

Since the second derivative is less than zero, we can deem that Π_r^2 is a concave function concerning P. There is a unique optimal solution enabling the first derivative to be equal to zero. We then obtain $P'^* = D + \sigma\beta + k[W - \gamma(\beta - \beta_0)]/2k$ and substitute it into (30) as follows:

$$\prod_m^2 = (W - C)\frac{D + \sigma\beta - k[W - \gamma(\beta - \beta_0)]}{2} - \frac{\alpha\beta^2}{2}. \tag{32}$$

We then calculate the first and second derivatives related to W for the function of (32) and obtain $\partial^2 \Pi_m^2/(\partial W)^2 = -k < 0$ and $\partial \Pi_m^2/\partial W = D + \sigma\beta - k[2W - C - \gamma(\beta - \beta_0)]/2$.

It can be seen that there is a unique optimal solution for Π_m^2 enabling the first derivative to be equal to zero as follows:

$$W''^* = \frac{D + \sigma\beta + k[C + \gamma(\beta - \beta_0)]}{2k}. \tag{33}$$

By substituting (33) into $P'' = D + \sigma\beta + k[W - \gamma(\beta - \beta_0)]/2k$, we obtain

$$P''^* = \frac{3D + 3\sigma\beta + kC - k\gamma(\beta - \beta_0)}{4k} \tag{34}$$

By substituting (33) and (34) into (29) and (30), respectively, we obtain

$$\prod_m^2 = \frac{[D + \sigma\beta - kC + k(\beta - \beta_0)]^2}{8k} - \frac{\alpha\beta^2}{2},$$

$$\prod_r^2 = \frac{[D + \sigma\beta - kC + k\gamma(\beta - \beta_0)]^2}{16k}. \tag{35}$$

□

Corollary 3. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for owners, the optimal price W of an LNG-fuelled ship charged by shipbuilder is a strictly increasing function of the subsidy adjustment ratio, whereas the optimal earning P that owner obtains is a strictly decreasing function of the subsidy adjustment ratio γ.*

Proof. By calculating the first derivative related to γ for the function of equation (33), we obtain that the first derivative is bigger than zero, so it can be concluded that the optimal price of an LNG-fuelled ship increases with the increase of subsidy adjustment ratio. In a similar vein, by calculating the first derivative related to γ for the function of equation (34), we obtain that the first derivative is smaller than zero, so it can be concluded that the optimal earning that owner obtains decreases with the increase of subsidy adjustment ratio. □

Proposition 7. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for owners, the quantity of LNG-fuelled ship demanded in the market Q is a strictly increasing function of both the subsidy adjustment ratio γ and the green degree β.*

Proof. We substitute equation (23) into $Q = D - kP + \sigma\beta$ and obtain

$$Q' = \frac{D + \sigma\beta - kC + k\gamma(\beta - \beta_0)}{4}. \tag{36}$$

Based on $\beta > \beta_0$, we calculate the first derivatives with regard to γ and β for the function of (36) and obtain that the first derivatives are bigger than zero. Therefore, the quantity of the LNG-fuelled ship demanded in the market increases with the increase of subsidy adjustment ratio γ and green degree β. □

4.3. Further Result Analysis

4.3.1. Comparison of Results for Centralized Decision and Decentralized Decision. By comparing P and Q under two different circumstances of centralized decision and decentralized decision, we can obtain some conclusions.

Proposition 8. *The price of an LNG-fuelled ship charged by the owner is smaller in a centralized decision model than that in a decentralized decision model, that is, $P^* < P'^*$. The quantity of the LNG-fuelled ship demanded in the market is bigger in a centralized decision model than that in a decentralized decision model, that is, $Q > Q'$.*

Proof. We subtract equation (3) from (23) and subtract equation (6) from (27) as follows:

$$
\begin{aligned}
P'^* - P^* &= \frac{D + \sigma\beta - kC + k\gamma(\beta - \beta_0)}{4k} > 0, \\
Q - Q' &= \frac{D + \sigma\beta - kC + k\gamma(\beta - \beta_0)}{4} > 0.
\end{aligned}
\tag{37}
$$

Thus, we obtain $P^* < P'^*$ and $Q > Q'$.   □

Proposition 9. *The whole profit for the LNG-fuelled ship supply chain in a centralized decision model is bigger than the sum of profits of both the shipbuilder and owner in a decentralized decision model, that is, $\Pi > \Pi_m^1 + \Pi_r^1$.*

Proof. We subtract equations (24) and (25) from (4) as follows:

$$
\prod - \left(\Pi_m^1 + \Pi_r^1\right) = \frac{\left[D + \sigma\beta - kC + k\gamma(\beta - \beta_0)\right]^2}{16k} > 0.
\tag{38}
$$

Therefore, we obtain $\Pi > \Pi_m^1 + \Pi_r^1$.   □

4.3.2. Comparison of Results That Governments Provide Subsidies for Shipbuilders and Owners. By comparing W, P, Π_m, and Π_r under two different circumstances that governments provide subsidies for shipbuilders and owners, we can obtain some further conclusions.

Proposition 10. *Under the circumstances of a decentralized decision-making mode and governments' subsidies for shipbuilders and owners, respectively, the associations of W, P, Π_m, and Π_r are as follows:*

$$
\begin{aligned}
W'' &> W', \\
P' &= P'', \\
\Pi_m^1 &= \Pi_m^2, \\
\Pi_r^1 &= \Pi_r^2.
\end{aligned}
\tag{39}
$$

It can be seen that whether governments provide subsidizes for shipbuilders or owners, the optimal profit of shipbuilders and owners in the LNG-fuelled ship supply chain is consistent. However, the price of an LNG-fuelled ship charged by shipbuilder increases when governments choose to provide subsidies for owners.

In summary, in a decentralized decision model, both the shipbuilder and owner pursue the benefit maximization of their own. Although the owner can obtain higher earnings in a decentralized decision model, the quantity of the LNG-fuelled ship demanded in the market is thus lower. At the same time, considering $\Pi > \Pi_m^1 + \Pi_r^1$, choosing the centralized decision is more appropriate in the LNG-fuelled ship supply chain.

5. Results and Insights

5.1. Numerical Example Analysis. In the following, we will put the influencing mechanism into practice by an example and analyze how this mechanism is impacted by other factors.

Suppose $D = 40$, $C = 6.5$, $\sigma = 1.5$, $r = 2$, $\alpha = 2.5$, $k = 2$, $\beta_0 = 0.2$, and $\beta = 0.6$, which will be used in this section. We obtain the numerical results as given in Table 2.

As given in Table 2, the profit of supply chain in the centralized decision model is greater than that in the decentralized decision model. Both the price of an LNG-fuelled ship charged by shipbuilder and the earning that owner obtains in the decentralized decision model are bigger than those in the centralized decision model. The possible reasons may be that in the decentralized decision model, the shipbuilders and owners will pay their great efforts in benefit maximation of their own and thus increase the price of the LNG-fuelled ship, ultimately leading to a smaller quantity demanded in the decentralized decision model. Therefore, the size of market demand of LNG-fuelled ships in the centralized decision model is bigger than that in the decentralized decision model. From the perspective of subsidy object, no matter in the centralized decision model or in the decentralized decision model, the price of an LNG-fuelled ship charged by shipbuilder when giving subsidies for owners is bigger than that when giving subsidies for shipbuilders. The numerical results of the example are consistent with the abovementioned corresponding propositions.

5.2. Influence of Government Subsidies on the Supply Chain Profit of LNG-Fuelled Ships. To reflect the influences of subsidy adjustment ratio γ and green degree β on the supply chain profit under different circumstances, we take the centralized decision model as an example and set different parameters to obtain the results. Figure 1 shows the results.

Figure 1 shows that in a centralized decision model, when the green degree of the LNG-fuelled ship is above the lowest standard that governments provide subsidies, the increase of subsidy adjustment ratio and green degree will increase the whole profit of supply chain. The possible reasons may be that the increase of subsidy adjustment ratio can lead to a decrease of the price of the LNG-fuelled ship, as well as improving the quantity of the LNG-fuelled ship demanded in the market, thus giving rise to an increase of the whole profit of supply chain.

In a similar vein, to illustrate the influences of subsidy adjustment ratio γ and green degree β on shipbuilders and

TABLE 2: The numerical results in the centralized and decentralized decision models.

Decision model	Subsidy object	P	W	Q	Π	Π_m	Π_r
Centralized decision	Shipbuilder	13.075	10.309	14.750	108.331	67.538	40.793
	Owner	13.075	11.109	14.750	108.331	67.538	40.793
Decentralized decision	Shipbuilder	16.763	13.075	7.375	—	53.941	27.195
	Owner	16.763	13.875	7.375	—	53.941	27.195
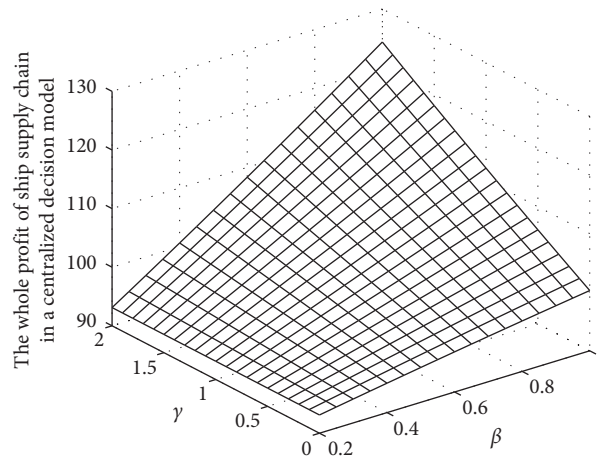
FIGURE 1: The impact of γ and β on supply chain profit in a centralized decision model.

Subsidies for shipbuilders
Subsidies for owners

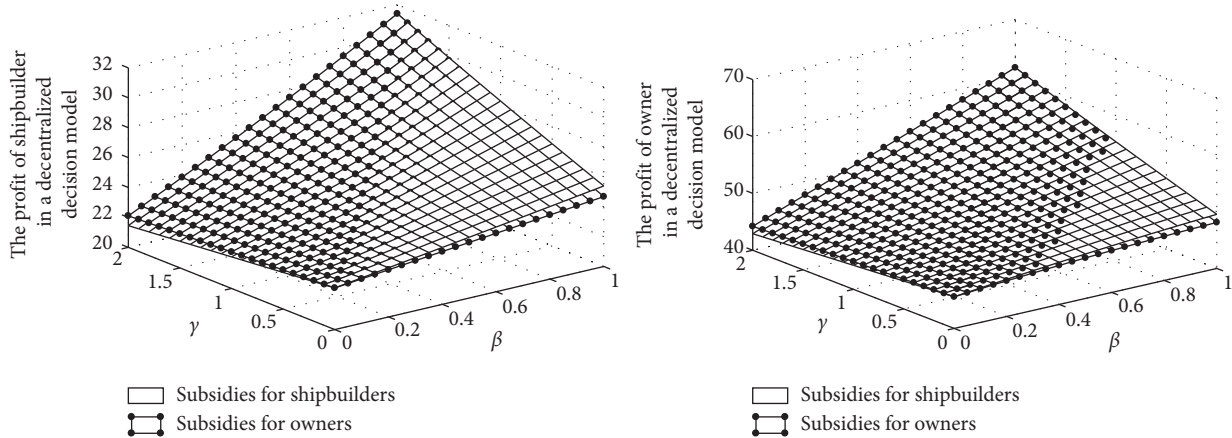Subsidies for shipbuilders
Subsidies for owners

FIGURE 2: The impact of γ and β on the profit of the shipbuilder and owner in a decentralized decision model.

owners, we take the decentralized decision model as an example and set different parameters to obtain the results. Figure 2 shows the results.

Figure 2 shows that in a decentralized decision model, when the green degree of the LNG-fuelled ship is above the lowest standard that governments provide subsidies, the increase of subsidy adjustment ratio and green degree will increase the profit of both the shipbuilder and owner. At the same time, whether governments provide subsidies for the shipbuilder or owner, there is no change for the profit of the shipbuilder and owner. The results are consistent with the abovementioned Proposition 10.

5.3. Influence of Government Subsidies on the Price of LNG-Fuelled Ships. To reflect the influences of subsidy adjustment ratio γ and green degree β on the price of an LNG-fuelled ship charged by owner P, respectively, we take the centralized decision model as an example and set different parameters to obtain the results. Figure 3 shows the results.

As shown in Figure 3(a), when the green degree of the LNG-fuelled ship is above the minimum standard (greater than 0.2), assuming the green degree is fixed, the increase of subsidy adjustment ratio will reduce the earning of a LNG-fuelled ship charged by the owner. In this case, the government subsidy compensates the decreasing earning. As
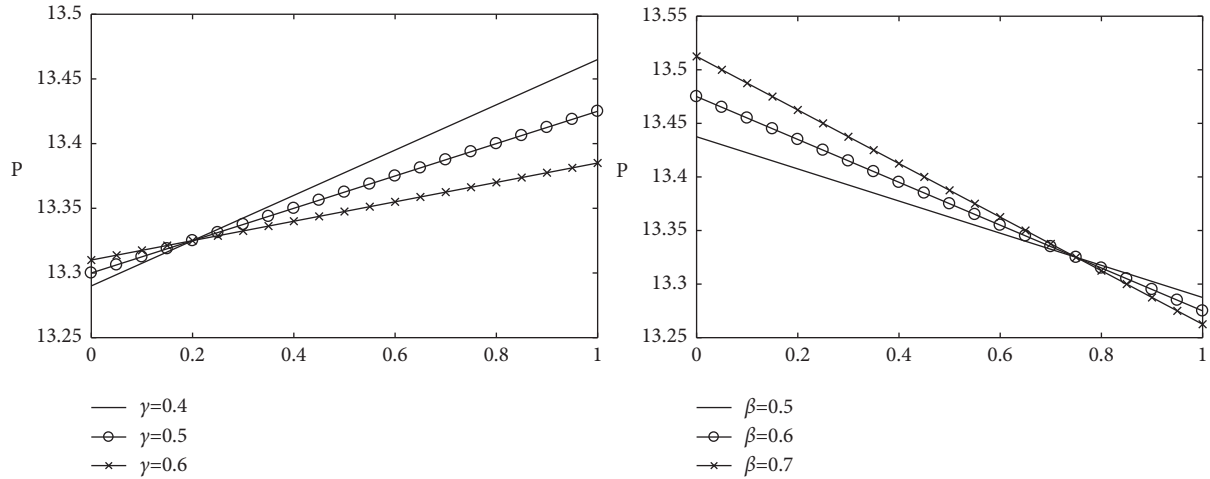
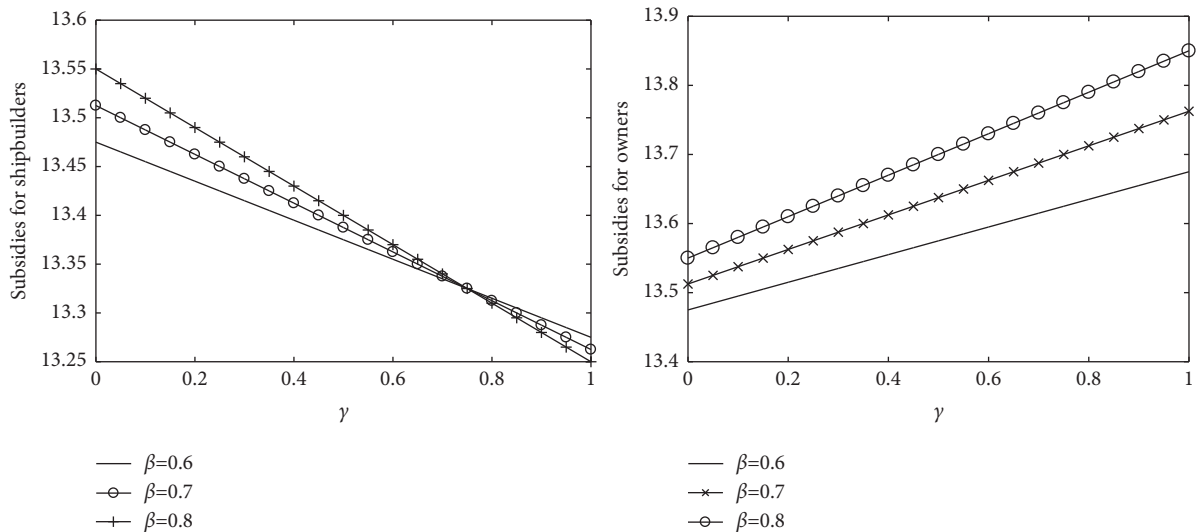Figure 3: The impact of γ and β on the price P in a centralized decision model.

Figure 4: The impact of γ on the price W in a decentralized decision model.

noted in Figure 3(b), when the green degree of the LNG-fuelled ship is less than a specific standard, the increase of green degree will increase the earning of a LNG-fuelled ship charged by the owner. In turn, the increase of green degree will give rise to a decrease of the earning. The potential reason may be that when governments provide higher subsidies, the enterprises may tend to produce LNG-fuelled ships with higher green degree, thus leading to a lower price of the LNG-fuelled ship and a higher size of market demand.

To exhibit the influences of subsidy adjustment ratio γ and green degree β on the price of a LNG-fuelled ship charged by shipbuilder W, respectively, as well as the impacts of different subsidy objects on the price W, we take the decentralized decision model as an example and set different parameters to obtain the results. Figures 4 and 5 show the results.

Figure 4(a) shows the results of providing subsidies for shipbuilders. We can see that if subsidy adjustment ratio is less than a specific standard, the increase of green degree will

increase the price of an LNG-fuelled ship charged by the shipbuilder. In turn, the increase of green degree will lead to a decrease of the price. Thus, it is very important to set the subsidy adjustment ratio. Figure 4(b) shows the results of providing subsidies for owners. We can see that the price of an LNG-fuelled ship charged by shipbuilder is positively associated with subsidy adjustment ratio. The increase of green degree will increase the price of an LNG-fuelled ship charged by the shipbuilder. The underlying reason may be that the increase of green degree will lead to an increase of green manufacturing cost, thus increasing the price.

Figure 5(a) shows the results of providing subsidies for shipbuilders. It can be seen that if green degree is above a specific standard, the price of an LNG-fuelled ship charged by the shipbuilder is negatively correlated to the subsidy adjustment ratio, that is, the size of market demand of LNG-fuelled ships is positively associated with the subsidy adjustment ratio. Figure 5(b) shows the results of providing subsidies for owners. We can see that if green degree is above
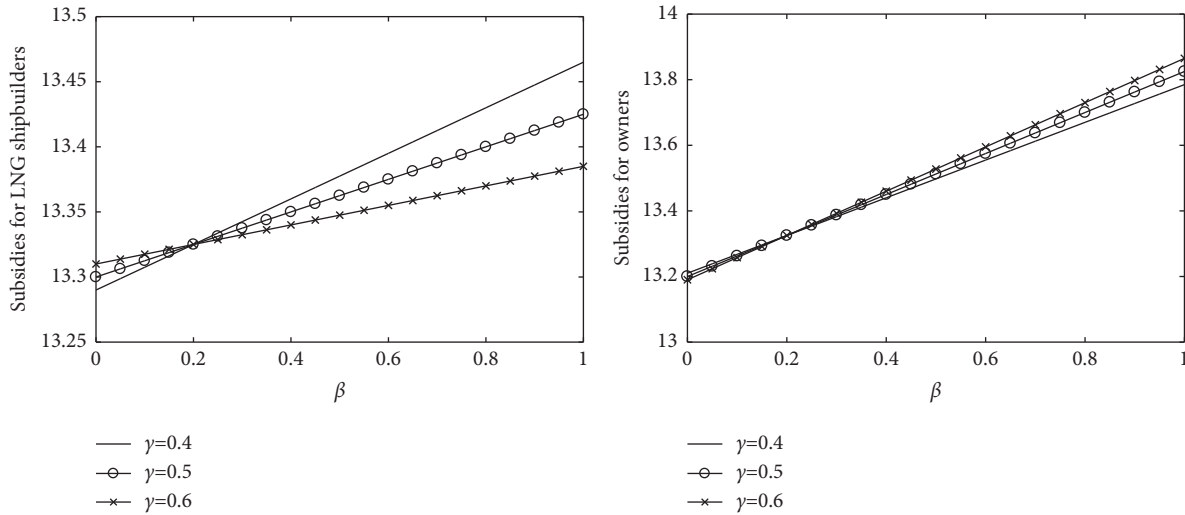
FIGURE 5: The impact of β on the price W in a decentralized decision model.

6. Conclusions and Suggestions for Future Research

In this study, a green supply chain of LNG-fuelled ships is studied which includes the following players: the government, shipbuilder, and owner. The government plays a significant role in promoting the utilization of LNG-fuelled ships through subsidies. In this circumstance, based on a supply chain model that consists of a singer shipbuilder and a singer owner, this work studies the supply chain decision issues under different decision models and subsidy objects. The results show that in a centralized decision model, the whole profit for the LNG-fuelled ship supply chain is bigger than the sum of profits of both the shipbuilder and owner in a decentralized decision model. In addition, the subsidy adjustment ratio is negatively related to the price of the LNG-fuelled ship, whereas both subsidy adjustment ratio and green degree are positively correlated with the quantity of LNG-fuelled ships demanded in the market. In a decentralized decision model, when governments provide subsidies for shipbuilders, the subsidy adjustment ratio is negatively related to the price of an LNG-fuelled ship charged by the shipbuilder. When governments provide subsidies for owners, the subsidy adjustment ratio is positively related to the price of an LNG-fuelled ship charged by the shipbuilder. However, no matter providing subsidies for shipbuilders or owners, the price of an LNG-fuelled ship charged by the owner is always negatively associated with the subsidy adjustment ratio. Furthermore, the price of an LNG-fuelled ship charged by the shipbuilder when providing

subsidies for owners is greater than that when providing subsidies for the shipbuilder.

There are some relevant practical implications based on above results. First, government subsidies are conducive to promoting research and development, production, and application of LNG-powered ships, so governments should adopt appropriate subsidy policies to subsidize different members of the supply chain. Second, the shipbuilders can increase the investment in LNG-fuelled ships and improve the green degree of LNG-fuelled ships, in an effort to increase the benefits of supply chain members. However, when the green degree exerts an adverse effect on the price of the LNG-fuelled ship, the supply chain members need to make the suitable pricing strategies according to the current cost situation and the development strategy of supply chain. Third, the shipowners should strengthen their awareness of green environmental protection, improve green preference, and discuss with ship manufacturers to choose appropriate centralized or decentralized decision-making mode, so as to increase income and promote environmental protection. Finally, the supply chain profit and the size of market demand are higher in centralized decision model than that in the decentralized decision model. The supply chain members of LNG-fuelled ships can adopt the coordination strategy to jointly utilize the LNG-fuelled ships, in order to maximize the benefit of the whole supply chain.

This study also has limitations that offer directions for future research. First of all, this study only considers a shipbuilder and an owner to form a two-echelon supply chain system and does not take into account many shipbuilding enterprises and a buyer competitive game problem; further research needs to consider government subsidy in this competitive environment, the different shipyard production green degree of LNG ship, and the same members of the decision-making problem. Second, this study only considers government subsidies in the supply chain of LNG-fuelled ships and does not consider taxes. If government subsidies and taxes are considered at the same time, supply

chain decision-making will be more complicated. Third, this research is theoretical research, and it is necessary to conduct practical research and obtain relevant actual data of the LNG-powered ship supply chain to verify the proposed theoretical model and the conclusions formed. Fourth, this work studies the impact of government subsidies on the decision-making of the LNG ship supply chain. In fact, there are still many non-LNG ships. The decision-making of the supply chain can be compared in the following cases: government subsidies and priority of way are given to LNG ships, while non-LNG ships had to pay environmental pollution tax and exercise normal right of way. This study mainly considers the subsidy adjustment ratio and green degree, without considering the governments' participation in the supply chain decision-making. Therefore, the introduction of three-level supply chain research of the decision model among government, shipbuilder, and owner may be one hot topic of future research.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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