IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received May 18, 2020, accepted June 17, 2020, date of publication June 22, 2020, date of current version July 2, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3004183

Using System Dynamics and Game Model to Estimate Optimal Subsidy in Shore Power Technology

XIAODONG LI[1,2], HAIBO KUANG[1], AND YAN HU[1]
[1]Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian 116026, China
[2]College of Transportation Engineering, Dalian Maritime University, Dalian 116026, China

Corresponding author: Haibo Kuang (khb@dlmu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 71831002 and Grant 71672016, in part by the Program for Innovative Research Team in University of Ministry of Education of China under Grant IRT_17R13, and in part by the Innovation Project of Double First-Class Construction Program under Grant BSCXXM020.

ABSTRACT To cope with severe environmental problems, the government has implemented strict emission control policies, and promoted the use of technology such as shore power (SP) in the form of subsidies. The SP providers of the shipping lines like the ports provide better SP services to shipping lines by improving its reliability, such as safety and standardization. This paper examines a two-echelon maritime supply chain consisting of a port and a shipping line under government green subsidy and explores the subsidy mechanism and its impact. The optimal government subsidy intensity and subsidy reduction point are confirmed using game theory. The system dynamics (SD) method is used to analyze the influence and evolution of practical problems such as government subsidy efficiency, information asymmetry, and inconsistent decision-making periods under multiple games utilizing the optimal response function. The paper shows that both shipper SP preference and decision period affect the SP reliability. When the shipper's preference is high, the actual shipper's subsidies and government subsidies are inefficient. Information asymmetry borne by ports and shipping line causes considerable fluctuations in the game and does not affect the actual subsidies received by shippers. Also, shipping line downstream of the supply chain are more affected by it. This paper offers insight for the government to formulate subsidy policies in the maritime supply chain.

INDEX TERMS Subsidy policy, emission control, game theory, system dynamics, shore power.

I. INTRODUCTION

Maritime shipping logistics is an efficient and sustainable mode of transportation. It is the lifeline of the global economy and undertakes 90% of global trade [1]. However, the maritime industry has caused high water and air pollution scare both in the ocean and in the inland waterways. International shipping accounted for 2.2% of the global anthropogenic CO2 emissions in 2012, and according to the current development prospects of maritime transport, in 2050, maritime emissions will increase by 50% - 250% [2]. The harmful pollutants generated by shipping include CO2, sulfur dioxide (SO_2), and nitrogen oxides (NO_x), and the latter account for 15% and 13% of global emissions, respectively [3], [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Justin Zhang.

Additionally, particulate matter (PM) emissions from shipping in coastlines and ports have shown to cause breathing-related deaths, particularly in Europe and China, where thousands of vessels and ten million tons of containers are handled in a year. The EU Commission and IMO (International Maritime Organization) have proposed a series of policies to reduce shipping pollution, including Emission Control Areas (ECAs), shipping speed limits, and bunker levy [5]–[7]. SO_2 has made significant improvements in the reduction of emissions. According to Zis and Psaraftis [8], in 2015, SO2 emissions from all forms of transportation accounted for 3.5%, compared to road, which accounted for 0.48%. SO2 emissions from maritime transport have significantly reduced since 2005. To reduce emissions at berths, the EU set a 0.1% SO2 emission limit for ships at berth or sailing on inland rivers [9]. In 2018, the Chinese Ministry of Transport announced ECAs containing China's coastline and inland rivers, 0.5% SO_2 emission limit for a ship at berth and its adjacent sea areas, and 0.1 % for sailing on inland rivers [10]. Shipping lines with their ships are forced to use clean equipment technology or Low Sulphur Fuel Oil (LSFO) to reduce emissions and comply with emission control regulations.

Generally, when the ship is docked, it needs to keep the continuous operation of the fuel engine to ensure the safety of ship's high-power pump and support system. Consequently, Ships docking emissions are the main source of air pollution, particularly in Europe and China. Shore power (SP, also known as cold ironing) means that when a ship is docked at a port, it is connected to the land-side power equipment to supply the ship's pumps, communications, lighting and other power needs from the shore side, thereby turning off the auxiliary engine to reduce the ship's exhaust emissions. Since SP could significantly reduce ship pollution emissions, it is widely used in port areas to improve air quality.

Since using SP can drastically reduce CO_2, SO_x, NO_x, and black carbon (BC) [11], port authorities promote the use of SP for ships at berth. In China, the Shanghai port and Shenzhen port have put in place policies on SP subsidies [12]. However, although most ports have built SP facilities and new ships have SP equipment, the SP utilization rate is low due to inefficiency and technical standard. The SP technical standards are inconsistent in different countries, while carriers use SP technology with unified standards and high safety [13]. Concurrently, there are information asymmetry problems and inconsistent decision-making periods in the port and shipping line process. Additionally, the government faces long-term subsidy policy stability problems and the problem of a decrease of the subsidy under the financial pressure in the future.

This paper constructs a two-level green maritime supply chain that includes ports and shipping lines to address the information asymmetry problem, inconsistent decision-making periods and subsidy stability. The main contributions of this paper are as follows:

1) Use game theory to build a decision model for a port and a shipping line, and analyze the government subsidy mechanism to establish the optimal subsidy intensity.
2) Combine game theory with system dynamics (SD), and construct a Dynamic Maritime Green Subsidy Model (DMGSM) using game theory's response function to solve the problem of equilibrium for repeated games.
3) Solve the information asymmetry problem in the decision-making process of port and shipping line through random function and condition function of SD.

The rest of this paper is presented as follows. Section II summarizes the literature on green ports, maritime subsidy mechanisms, and the application of game theory and SD in ports. Section III introduces the game theory model and analysis; Section IV builds the DMGSM; calculation results and discussions are addressed in Section V, while a brief conclusion is made in Section VI.

II. LITERATURE REVIEW

This paper relates to the literature on three streams, green ports, maritime subsidy mechanism, and application of game theory and SD in ports.

A. GREEN PORTS

Green ports and maritime logistics are relatively new with rapid growth since 2006 [14]. Although most researches on green ports focus on ECAs policy and its impact [15]–[18], there is limited research on the sustainable port technologies [19], [20]. Tseng and Pilcher [21] studied the challenges of introducing SP in Kaohsiung port using qualitative and quantitative methods with stakeholders. Although the introduction of SP is needed in the long run, its most significant obstacle is the short-term high construction cost. Zis [20] outlined a method for comprehensively assessing whether ports and shipowners should invest in SP, which pointed out that the lack of technical coverage in ports was the main obstacle in implementing SP. Additionally, for the ships with SP capability, port authorities will need to invest further to improve SP standards and regulation. Chen *et al.* [22] examined the interaction mechanism of the demonstration and promotion of SP in China using the fuzzy DEMATEL model. The model highlighted three factors that affect the SP as policies, support systems, and SP construction standards. Although most researches have analyzed the promotion and restrictions of SP as one of the green port technologies, none examined the game relationship between ports and shipping lines after SP construction. The researches have also not pointed out the investment impact of ports after application of SP.

B. MARITIME SUBSIDY MECHANISM

This paper contributes to the literature focus on government subsidy mechanisms in the maritime supply chain, a crucial policy in shipping [23], [24]. Traditionally, ports are purely commercial enterprises, and the government subsidy increases the contribution of ports to the national economy [24]. However, the severe environmental problems force governments to examine the environmental subsidies, such as moving freights from high carbon intensity to low carbon intensity modes [25]. Medda and Trujillo [26] analyzed short sea transport in Europe and pointed out that subsidy policy promotes water transport when road congestion is not severe. Qu *et al.* [27] proposed a performance-based system model that analyzed the liner shipping pricing and port subsidy problems. They established that direct subsidies to shippers would directly change their behavior and significantly stimulate demand. Generally, different subsidy targets in port and shipping line decisions have different effects. Nevertheless, there is limited research on port sustainability investment, government subsidy, and other stakeholders like shipping lines.

C. APPLICATION OF GAME THEORY AND SD IN PORTS

Our research examines the application of game theory and SD in ports, which has been used by many researchers in the last few decades. Most work focuses on port competition [28], [29] and economics of ports [30], [31]. There is limited literature on the application of these methods in green ports, although it has been widely developed in the port industry. Cui and Notteboom [32] examined the competition between the private port and landlord port under government emission control tax, and they highlighted that the government has to input on environmental protection, maximize social welfare, and promote individual motivations. Park *et al.* [33] pointed out that the optimal emission level is affected by maximum reservation price, capacity, and environmental damage costs of ports. SD is used in analyzing the impact of port environmental policies on port efficiency. Based on this purpose, Woo *et al.* [34] introduced a simulation to examine the Busan port using historical data. Additionally, green technologies such as LSFO, SP, and scrubbers plays a crucial role in green ports. Sheng *et al.* [35] developed a game model to analyze the competitive relationship between ports and shipping companies under emission control, and simulate different control methods, but they didn't think about government green subsidies. Yang *et al.* [36] conducted a two-level maritime supply chain of ports and shipping lines and compared two emission reduction technologies with the different power structures of the supply chain. Lai *et al.* [37] examined sustainable technology in shipping lines and proposed a two-period game-theoretical model under market uncertainty. However, according to [20], for ports, it is crucial to invest in improving the SP standards and regulations. Most researches do not have effective game results due to information asymmetry.

This research paper difiers from the other researches because it focuses on both the government subsidy of the shipper and the information asymmetry and equilibrium solution. Additionally, the paper considers the SP reliability preference of the shipper, which significantly impact port and shipping line decisions [20], [22]. This research attempts to complement and expand the existing literature on sustainability investment and government subsidy in ports and shipping lines.

III. GAME ANALYSIS UNDER GOVERNMENT SUBSIDY

A. GAME DESIGN AND NOTATIONS

This paper analyzes a two-echelon maritime supply chain that includes a port and a shipping line with its ships. The port is an upstream service provider of the shipping line. In this model, governments set an emission control area, which includes the port and two different technologies (SP or LSFO). The port provides SP terminal services and charges berthing fees. Additionally, the port continually strives to improve the SP's technology safety and standardization, known as SP reliability. The shipping line is a green freight carrier, and the ships have installed SP equipment. The service price paid by the customer to the carrier includes the freight charges, the port fee, and the additional cost of SP or LSFO. With the improvement of SP reliability, customers will use the SP terminals with safety standards.

TABLE 1. Meaning of the notations in the game model.

Parameters	Description	Dimensions
a	Potential market demand	TEU
b	Price-sensitive parameter	/
θ	Coefficient of SP reliability	/
q	Total demand	TEU
k	Coefficient of SP reliability cost	/
f	Unit extra service cost adopting SP	CNY
λ	Government subsidy intensity	CNY
π_P	Port's total profit	CNY
π_S	Shipping line's total profit	CNY
Decision variables:	**Description**	**Dimensions**
p	Shipping line' freight rate	CNY
w	Port's service fee	CNY
e	Port's SP reliability	/

At the same time, in order to improve the utilization of SP terminal, the governments will subsidize local shippers using the SP terminal. On the one hand, the subsidy improves the utilization rate of SP terminals and induces the preference of shippers. On the other hand, it promotes the improvement of SP standards and the safety of ports.

The relevant notations in this paper are shown in Table 1.

For the convenience of subsequent modeling and analysis, the following assumptions are made.

1) We consider the scenario where local shippers choose ports and shipping companies for export business. That is because the government subsidy, which is given to foreign ships, causes leakages of the government's welfare from the subsidized port. Also, according to the Chinese government's green port subsidy rules, the subsidies must be local Chinese companies[12].
2) We normalize the base cost of the port and shipping line to zero. The shipping line' extra cost that adopts LSFO is also zero. This analysis is done when the ship docks at the port. Normalizing the cost to zero does not affect the game results. We use LSFO since its cheaper than SP. However, since adopting SP is cleaner than LSFO, the governments use subsidies to increase SP usage. Due to this, we normalize the extra cost of LSFO to zero for simplicity, which does not affect the results.
3) The potential market demand is a linear function of freight fee, and the port's SP reliability affects it. $q = a - b(p - \lambda e) + \theta e$, $b > \theta > 0$. The linear demand function is hugely adopted in the maritime supply chain field [37]–[40]. In this research, the government directly subsidizes shippers based on port SP reliability; so shipper's actual freight charges are $p - \lambda e$. Additionally, the port SP reliability has a positive effect on total demand.

B. GAME ANALYSIS

We assume that both of the port and the shipping line strategize based on the principle of maximizing profits. The game decision sequence includes: the port firstly decides its service fee w and SP reliability level e, while the shipping line decides its freight rate p. The profit functions are expressed as:

$$\max_{w,e} \pi_P = wq - \frac{1}{2}ke^2 \tag{1}$$

$$\max_{p} \pi_S = (p - w - f)\, q \tag{2}$$

In (1), the second term represents the port's cost of upgrading the SP reliability, which is quadratic in e. Additionally, we assume that the coeficient k is a large number ($k > (\theta + b\lambda)^2/4b$), which means SP upgrading cost is relatively high. This avoids impossible situations, in which the port can upgrade SP at a lower cost to obtain a larger profit.

A backward induction method was used to solve the problems. For the shipping line, because $\partial^2\pi_S/\partial p^2 = -2b < 0$, π_S is a concave function with p for a given w and e. By solving $\partial\pi_S/\partial p = 0$, we get the optimal best response function of p:

$$p(w, e) = \frac{a + e(b\lambda + \theta) + b(w + f)}{2b} \tag{3}$$

Then we substitute (4) to (1), we get the Hessian matrix of $\pi_P(w, e)$ below:

$$H = \begin{bmatrix} \dfrac{\partial^2\pi_P}{\partial w^2} & \dfrac{\partial^2\pi_P}{\partial w\partial e} \\ \dfrac{\partial^2\pi_P}{\partial e\partial w} & \dfrac{\partial^2\pi_P}{\partial e^2} \end{bmatrix} = \begin{bmatrix} -b & \dfrac{\theta + \lambda b}{2} \\ \dfrac{\theta + \lambda b}{2} & -k \end{bmatrix} \tag{4}$$

Since $H_1 = -b < 0\, |H| = bk - (\theta + \lambda b)^2/4b > 0$, $\pi_P(w, e)$ is a concave function with w and e. By solving $\partial\pi_P/\partial w = 0$, $\partial\pi_P/\partial e = 0$ we get the optimal best response function of w and e:

$$w(e, p) = \frac{2[a + e(b\lambda + \theta) - bp]}{b}; \quad e(w) = \frac{w(b\lambda + \theta)}{k} \tag{5}$$

Solving (4) and (6), we get the optimal results of the port and shipping line.

$$w^* = \frac{2k(a - bf)}{4bk - (b\lambda + \theta)^2}; \quad e^* = \frac{(a - bf)(b\lambda + \theta)}{4bk - (b\lambda + \theta)^2} \tag{6}$$

$$p^* = \frac{3ak - f\left[(b\lambda + \theta)^2 - bk\right]}{4bk - (b\lambda + \theta)^2} \tag{7}$$

Then we substitute (7)-(8) into the port and shipping line's profit function, the equilibrium demand and profits are as below:

$$q^* = \frac{bk(a - bf)}{4bk - (b\lambda + \theta)^2}; \quad \pi_P^* = \frac{k(a - bf)^2}{8bk - 2(b\lambda + \theta)^2} \tag{8}$$

$$\pi_S^* = \frac{bk^2(a - bf)^2}{\left[4bk - (b\lambda + \theta)^2\right]^2} \tag{9}$$

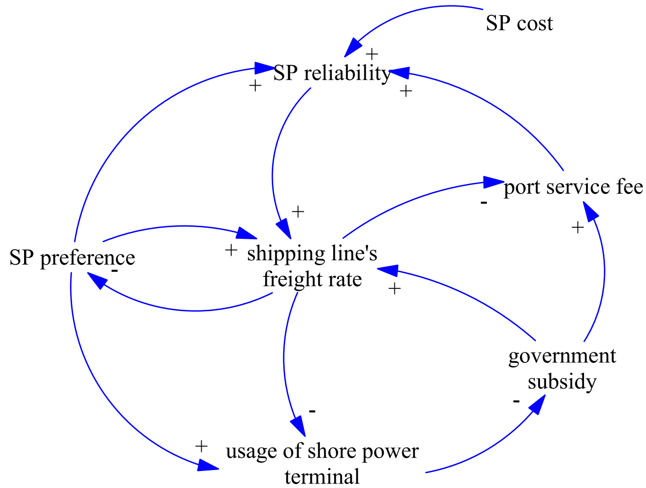

FIGURE 1. Casual loop diagram of SD model.

To analyze the situation before and after government subsidies, we set $\lambda = 0$, then we get the optimal freight rate before subsidy. $p^0 = \left(3ak - f\left(\theta^2 - bk\right)\right)\left(4bk - \theta^2\right)$.

By observing p^0 and p^* we find that $\Delta p = p^* - p^0 = \frac{3bk\lambda(b\lambda+2\theta)(a-bf)}{\left[4bk-(b\lambda+\theta)^2\right](4bk-\theta^2)} > 0$. This means that after the government subsidizes the shipper, the shipping line increases the freight rate, which is a disguised price.

Disguised price reveals shippers' incomplete access to gov-ernment subsidies; we set ξ as the shipper's actual subsidy, where $\xi = \lambda e^* - \Delta p = \frac{\lambda(a-bf)\left[bk(b\lambda-2\theta)-\theta^2(b\lambda+\theta)\right]}{\left[4bk-(b\lambda+\theta)^2\right](4bk-\theta^2)}$. To ensure the shipper gets a positive subsidy, governments need to make $\xi \geq 0$, and we get $\lambda \geq \frac{(2bk+\theta^2)\theta}{(bk-\theta^2)b}$.

To reflect the effect of government subsidies, we set E to represent the efficiency of government subsidies:

$$E = \frac{\Delta q}{\lambda e^* q^*} = \frac{b(b\lambda + 2\theta)\left[4bk - (b\lambda + \theta)^2\right]}{(b\lambda + \theta)(a - bf)\left(4bk - \theta^2\right)} \tag{10}$$

Due to financial pressure, the government will not always subsidize. So, we set I to represent the upper bound of total subsidy under financial pressure. The government subsidy int-ensity λ needs to satisfy the subsidy interval $0 \leq \lambda e^* q^* \leq I \Rightarrow 0 \leq \lambda \leq I/e^* q^*$, so the highest subsidy inte-nsity $\lambda_M = I/e^* q^*$.

Because $\lambda \geq \left(2bk + \theta^2\right)\theta / \left(bk - \theta^2\right)b$ we find a critical point θ_C, which satisfies $\left(2bk + \theta_C^2\right)\theta_C / \left(bk - \theta_C^2\right)b = \lambda_M = I/e^* q^*$; this means that due to the existence of an upper bound total subsidy after SP reliability and market maturity, the government must reduce or cancel subsidies. Furthermore, θ_C is the critical point for the government to reduce subsidies.

We set r to represent the subsidy reduction rate to get $\Delta\lambda = r\lambda$. When θ increases to $\theta + \Delta\theta$, the λ reduces to $\lambda - \Delta\lambda$. The reliability of SP after subsidy reduction should not be lower than SP reliability before subsidy reduction, whi-ch means $e^*|_{\theta+\Delta\theta,\lambda-\Delta\lambda} \geq e^*|_{\theta,\lambda}$ then we get $0 \leq r \leq \Delta\theta/b\lambda$.

Government subsidies help to determine the SP market ma-turity, and also promote the progress of SP technology

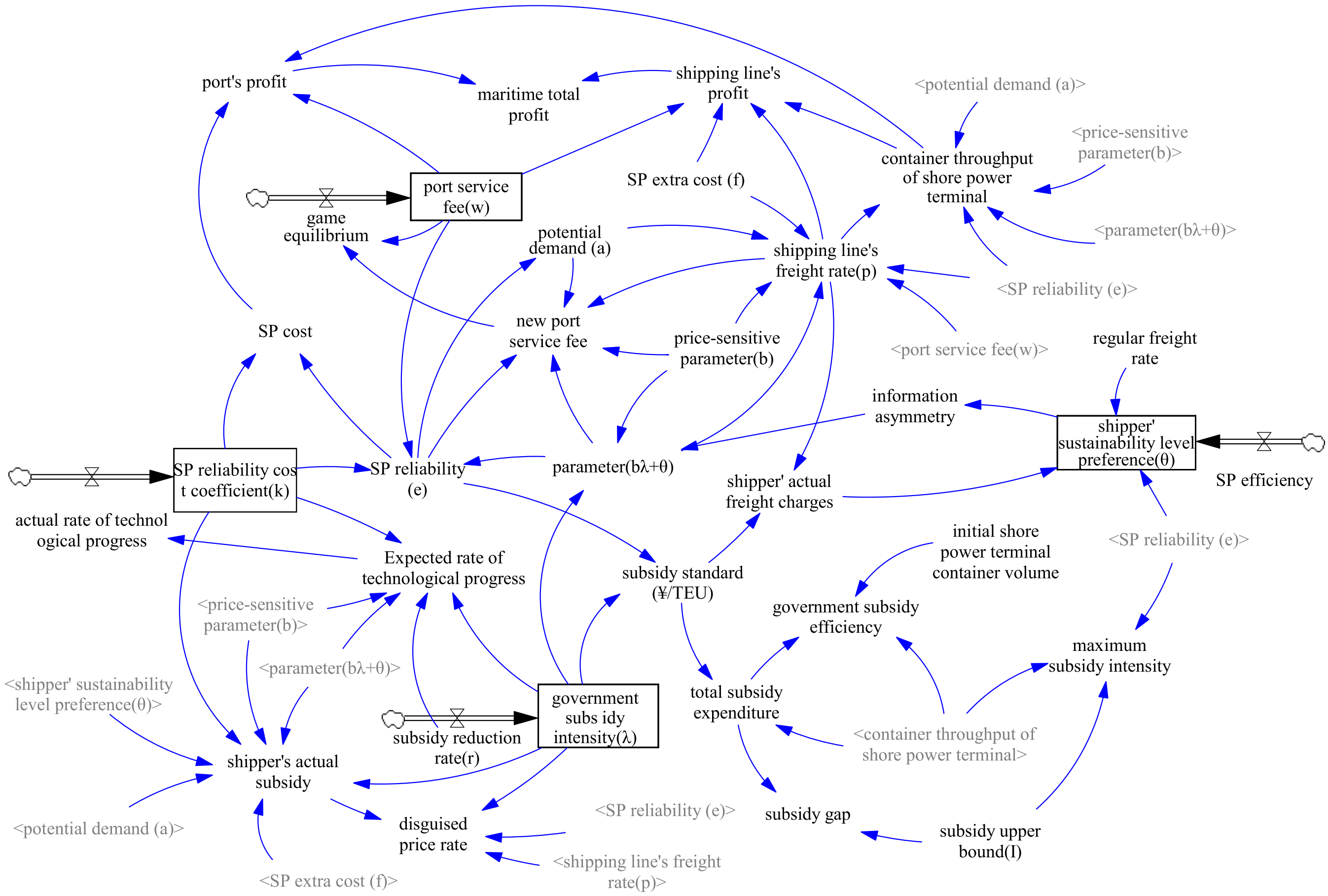

FIGURE 2. Casual loop diagram of SD model.

to a c-ertain extent, thereby reducing the reliability cost of SP. Her-e we set $\eta = \Delta k/k$ to represent the progress rate of SP tech-nology. After technological advances, the coe-ficient k is $k_{new} = k(1-\eta)$. Similarly r, the reliability of SP after techn-ology progress cannot be lower than that before, which mean-s $e^*|_{k-\Delta k,\lambda-\Delta\lambda} \geq e^*|_{k,\lambda}$, then, we get $\eta \geq r\lambda\left[(b\lambda+\theta)^2 + rb\lambda(b\lambda+\theta) - 4bk\right]/4k(b\lambda+\theta)$. Beca-use of the SP technology progress, the government can also g-uarantee the SP reliability under the condition of the subsidy reduction mechanism.

IV. DYNAMIC GAME SIMULATION BASED ON SD

From the game model, we analyze the equilibrium results under traditional static games. However, practically, information asymmetry and differences in decision periods have often encountered that lead to dynamic changes in in-game equilibrium. An SD approach was applied to improve the above game model.

A. CONCEPT OF THE SD MODEL

The game system includes government subsidies, SP reliability investment, and market preference. The casual loop diagram is shown in Fig.1.

Firstly, the governments formulate support policies for port SP technology. Secondly, the port sets an optimal SP reliability and service fee under the government subsidy. Under this situation, the shipping line sets the optimal freight rate and form negative feedback with market preference. With the increase of market preferences driven by government subsidies, the government has to adopt a subsidy reduction mechanism in the face of fiscal pressure. The system repeats the game for a limited time until it approaches the game equilibrium and the steady system state.

B. SD MODEL CONSTRUCTION

Based on the above casual loop diagram, we constructed a dynamic maritime green subsidy model (DMGSM) using *Vensim PLE 7.3.5* software, a widely used SD simulation tool. The system flow graph of DMGSM consists of the subsystem, as shown in Fig. 2 Concurrently, it also includes the relevant changes in SP efficiency and regular freight rate. Additionally, we use functions such as 'DELAY' and 'RANDOM' to reflect the inconsistency and randomness of DMGSM.

The main objective of this paper's model is to simulate the impact of information asymmetry and inconsistency on the equilibrium of green port and shipping line from a dynamic game perspective. DMGSM was designed in consideration of

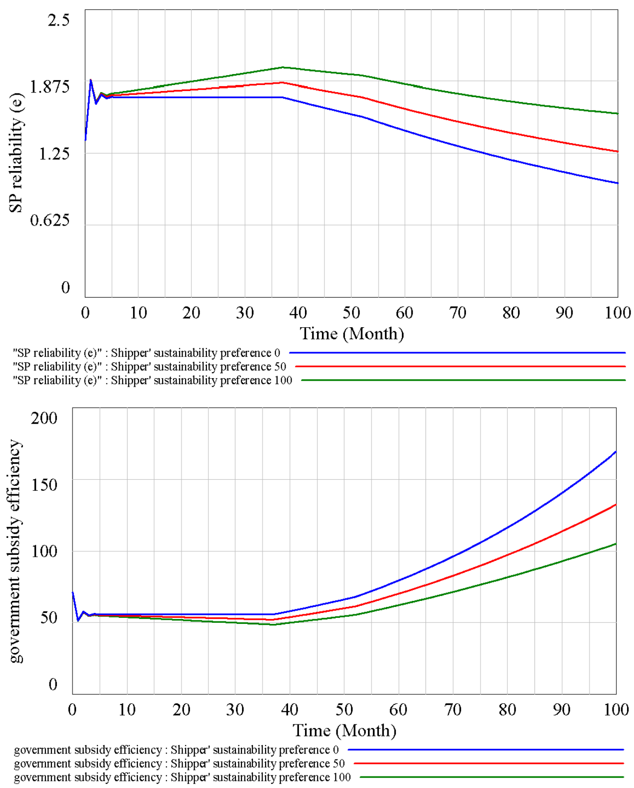

FIGURE 3. The impact of shipper preferences on SP reliability and government subsidies efficiency.

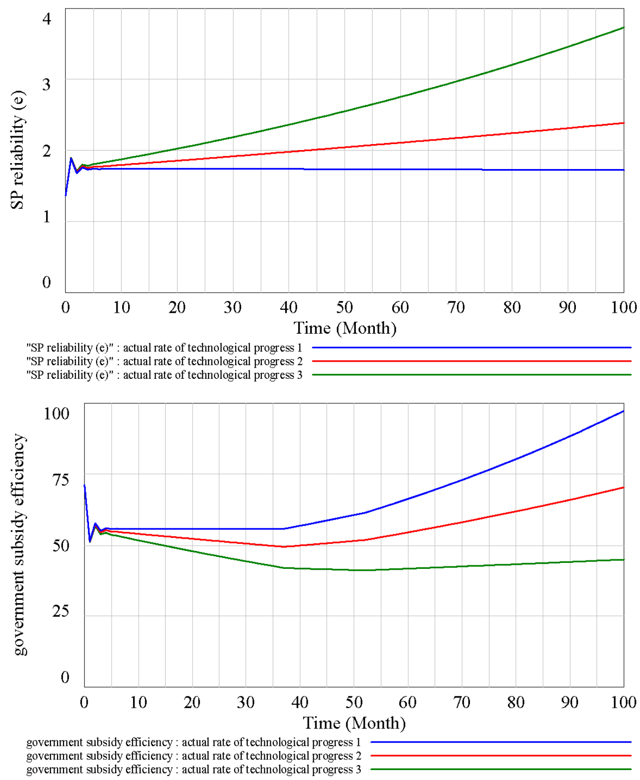

FIGURE 4. The impact of technological progress on SP reliability and government subsidies efficiency.

the analysis of the information asymmetry and inconsistency in the green shipping industry as the first experimental stage; the simulate data was collected based on the actual market.

The model setting is INITIAL TIME = 0, FINAL TIME = 100, Units for Time: Month. Relevant data were obtained from *China Port Yearbook* and actual survey interviews. From the optimal response function in Section III, the model equations can be seen in Appendix.

V. RESULTS AND DISCUSSION

A. SIMULATION RESULTS

Firstly, we used the DMGSM to simulate the common game scenario in Section III., and the results are shown in Tab.2.

The system we established that reached equilibrium after 17 rounds of games, the simulation results are consistent with the optimal solution of Section III, which means our DMGSM can represent the game process between the green port and the shipping line. In Tab.2, the optimal SP reliability is 1.7 when the shipper's green preference is 1000, and the optimal container throughput of SP terminal is 165497 TEU. Although the government subsidy standard is 173.7 CNY/TEU, the actual subsidy of the shipper is only 27.3 CNY/TEU due to the 8.5% increase of freight rates in the shipping line over unsubsidized. The shipping line also relies on government subsidies to increase the price in disguised form, thus occupying a certain proportion of government subsidies.

TABLE 2. Meaning of the notations in the game model.

Variable	Optimal value	Variable	Optimal value
SP reliability	1.7	Disguised price rate	8.5%
Container throughput of SP terminal (TEU)	165497	Port price fee (CNY)	827.4
Government subsidy standard (CNY/TEU)	173.7	Shipping line's freight rate (CNY)	1854.9
Shipper's actual subsidy (CNY/TEU)	27.3	Total subsidy (CNY)	2.9 e+07
Government subsidy efficiency (TEU/10,000CNY)	55.8	Critical point θ_c	18737
Positive subsidy range (CNY/TEU)	[17.0, 354.6]	Expected rate of technological progress	2.01%

From the government's perspective, its monthly subsidy expenditure is 29 million CNY. Under this condition, the subsidy efficiency is 55.8 TEU, which means that for every 10,000 CNY invested, the SP terminals amount increases by 55.8 TEU than without subsidies. However, subsidies are not permanent. With green preferences unchanged, the scope for the government to allow shippers to receive positive subsidies is 17.0 to 354.6 CNY/TEU. When out of this range, subsidies may exceed fiscal ceilings or be ineffective for shippers. Thus, as analyzed in Section, when the sustainable preference

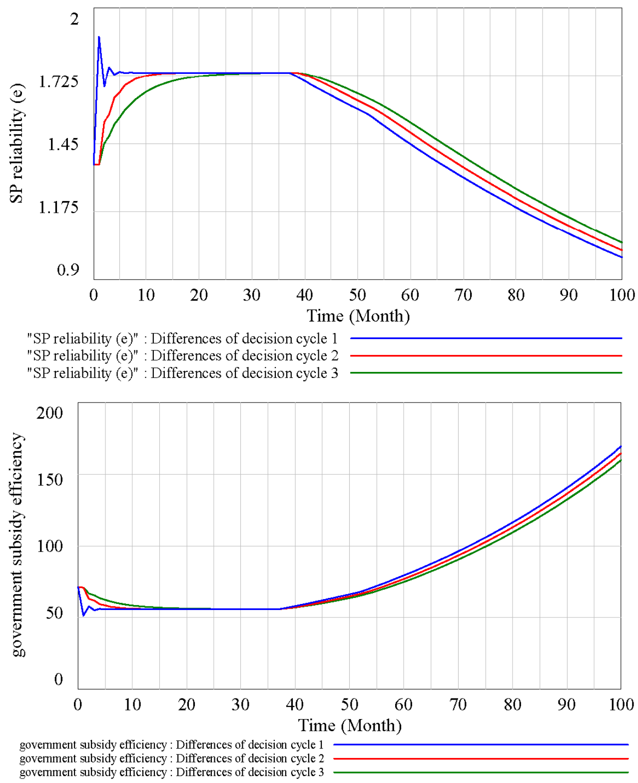

FIGURE 5. **The impact of decision period on SP reliability and government subsidies efficiency.**

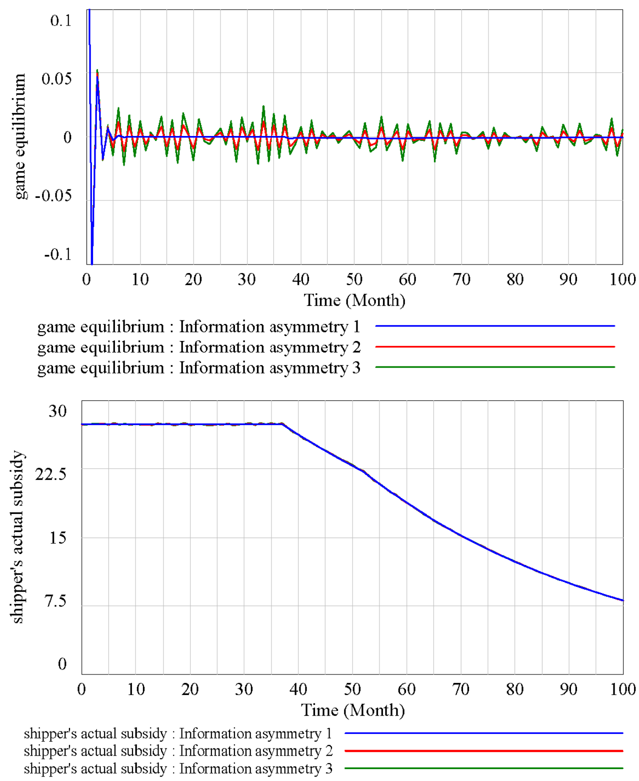

FIGURE 6. **The impact of information asymmetry on game equilibrium and shipper's actual subsidy.**

reaches 18737, the government reaches the financial ceiling and must reduce subsidies. The expected rate of technological progress is 2.01%, which means if technological progress reaches 2.01%, the government can reduce subsidies within 50%.

B. SENSITIVITY ANALYSIS

In this Section, the influence of parameter changes is analyzed from the following aspects.

1) SHIPPER' SUSTAINABILITY PREFERENCE

Environmental problems make enterprises like Huawei, Samsung, and other enterprises attach environmental protection importance to the transportation chain. Thus, we define the parameter of shipper's sustainability preference in APPENDIX function (20) as 0, 50, and 100 to see these changes. The results are shown in Fig.3, after 17 rounds of games, the SP reliability reached equilibrium and began to decline when the government subsidies dropped three years later due to lack of technological progress. High green preferences lead to high SP reliability and low efficiency of government subsidies. This shows that the increase of shippers' SP recognition helps in SP applications and replaces the government's subsidy effect to a certain extent.

2) TECHNOLOGICAL PROGRESS

To describe the impact of technological progress, we set the parameter of the actual rate of technological progress in APPENDIX function (1) as 0, 0.005, and 0.01. The results of technological progress are similar to the shipper's sustainability preference, as shown in Fig.4. Additionally, due to technological progress, SP reliability is not affected by the decline in subsidies but has steadily increased in the face of substantial technological progress. Therefore, the shipper's sustainability preference and technological progress have a dual-directional promotion effect on green SP construction.

3) DIFFERENCES IN DECISION PERIOD

Decisions are often not immediate. For example, port efforts to improve the reliability of SP may take time to reflect. We set the SP reliability decision period in APPENDIX function (27) as 0, 3, and 6; simulation results are shown in Fig.5. Long decision period took many game rounds to reach equilibrium, or never reached equilibrium. It took 35 rounds of games to reach equilibrium for an SP reliability period of 3, but periods of 6 could not reach equilibrium. However, although long-period decision-making requires more rounds to reach equilibrium, in the long run, a longer decision-making period is conducive to the SP reliability.

4) INFORMATION ASYMMETRY

In reality, customers' preference for SP reliability is not static. Traditional shippers only pay attention to transportation costs, but the deterioration of the environment makes shippers who fulfill corporate social responsibility (CSR) also pay attention to pollution and safety. The 'RANDOM

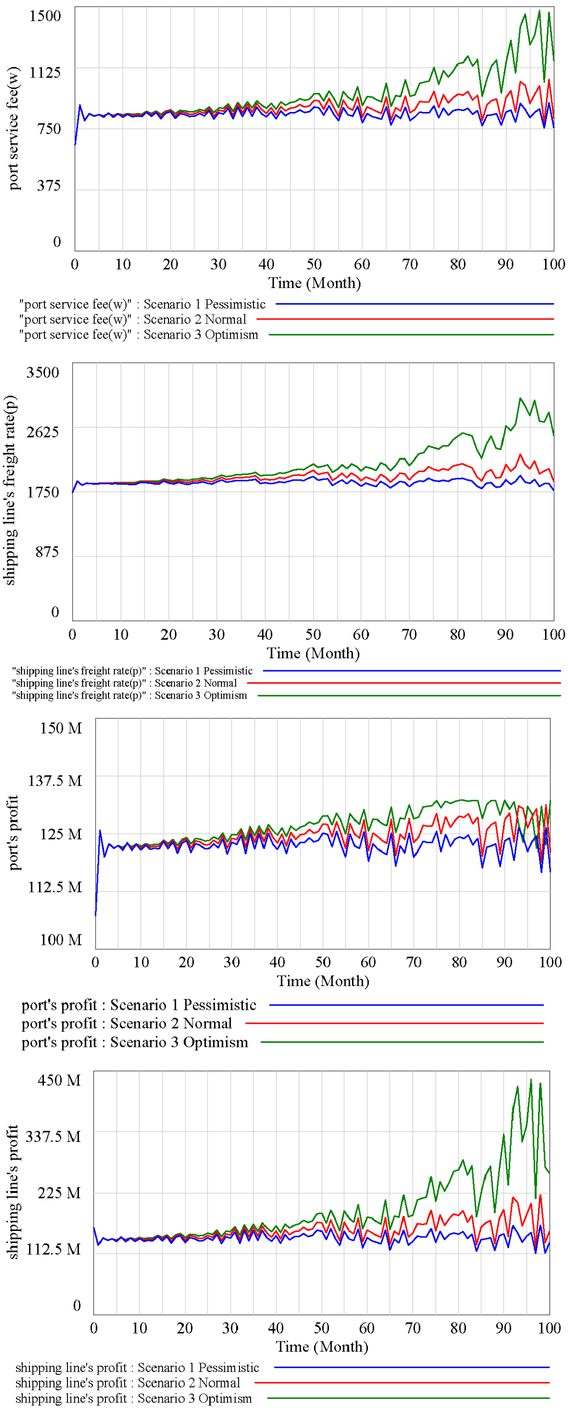

FIGURE 7. **The scenario analysis results (a).**

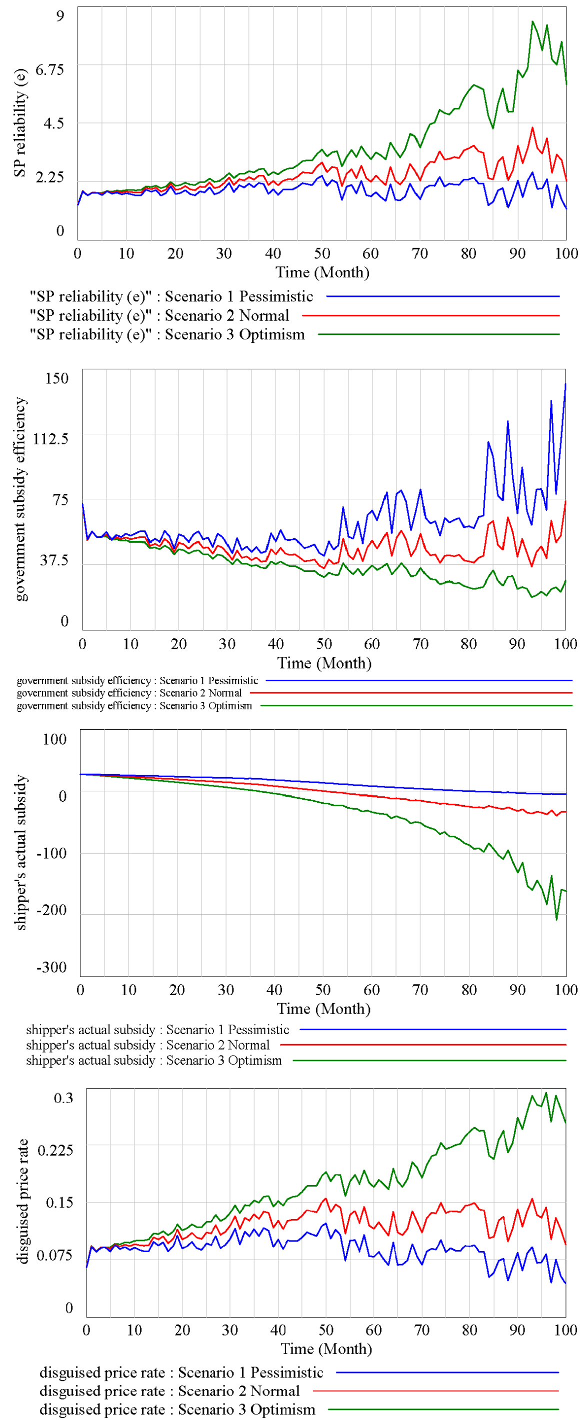

FIGURE 8. **The scenario analysis results (b).**

UNIFORM(min, max, seed)' function in *Vensim PLE* is used to reflect the heterogeneity of preference, which means generating a random number obeys the [min-max] uniform distribution, and 'seed' represents the initial value.

We set the model APPENDIX (8) random range as (1, 1, 1), (0.5, 1.5, 1), (0, 2, 1) to reflect uncertainty on market green preferences. Due to asymmetric information, the game equilibrium fluctuates, as shown in Fig.6. The higher the degree of information asymmetry, the higher the fluctuation.

The shipper's actual subsidy is largely unaffected by information asymmetry. This means that the subsidies received by shippers are not affected by the information asymmetry, which is entirely borne by shipping line and port.

C. SCENARIO ANALYSIS

Real-world scenarios are often more complex than the single variable analysis above. Therefore, we set three scenarios to descript the real case, known as 'Pessimistic,' 'Normal,' 'Optimism.'

The pessimistic scenario is an extreme case, indicating low green preference, a high degree of information asymmetry, and low technology progress. Therefore, we set the parameters of APPENDIX function (20), (1), (8) as 100, (0, 2, 1), 0.25 respectively. The optimism scenario is an ideal situation, and we set the parameters of the APPENDIX function (20), (1), (8) as 300, (0.7, 1.2, 1), 1 respectively. The normal scenario is based on the relationship between the above two scenarios. We set the parameters of model function (20), (1), (8) as 200, (0.5, 1.5, 1), 0.5 respectively.

In optimism scenario, port and shipping line outperformed the other two scenarios in terms of cost or profit, as shown in Fig.7. The fluctuation of port profit in the three scenarios is the same and is lower than the other three. This shows that the shipping line is located downstream of the port and shipping supply chain and directly docks with the shipper, which is greatly affected by information asymmetry, while the port is small.

The other four crucial results of scenario analysis are shown in Fig.8. Similar to Fig.7, for SP reliability, the shipper's actual subsidy and disguised price rate, values, and fluctuation in optimism scenario are more significant than the other two scenarios. However, for government subsidy efficiency, the results skew the opposite way. The value and volatility of government subsidy efficiency are higher in the optimistic scenario than in the other two scenarios. Therefore, the SP reliability has a more significant influence on the shipper's sustainability preferences, and government subsidy efficiency is more affected by asymmetric information.

VI. CONCLUSION

Ports contribute positively to the global economy and trade. However, ports have become primary air and water pollution sources in port cities, and governments have adopted policies such as emission control and subsidized clean technology to regulate the port's pollution. This paper examines a two-level maritime supply chain consisting of a port and a shipping line under the government subsidies, aiming to offer insights into policy choice toward a sustainable future in port industries. Traditional game theory was adopted in the analysis and shown that in the future, ships will have SP equipment and a shipper subsidy mechanism for the government to increase the port's control. Government subsidy efficiency and shipper's actual subsidy are proposed, and the optimal subsidy intensity, the critical point of subsidy reduction, and the expected technological progress rate are solved. Also, regarding the problems of multiple games in practice, information asymmetry, and inconsistent decision-making cycles, combined with game theory response functions, and the SD method are used to construct the DMGSM model. Additionally, the delay function, random function, and condition function are introduced to analyze the overall effects of subsidies on shippers' preferences and technological progress.

We found that the sustainability preference and technological progress of the shipper have a dual-directional promoting effect on SP reliability. This means, under high market acceptance, governments should reduce the standard of subsidy, because high subsidy is raised by the shipping line in a disguised price, leading to low efficiency of the government subsidy and the actual subsidy reaching the shipper. Different decision periods cause short-term fluctuations, but in the long-term, longer decision periods increase the reliability of SP. Subsidies actually reaching shippers are not affected by information asymmetry, which is entirely borne by shipping line and port. Of note, we found that shipping line downstream the supply chain are highly affected by information asymmetry. In contrast to the SP reliability, government subsidy efficiency is more affected by information asymmetric, which means governments should actively promote the construction of a transparent service platform for the maritime supply chain to reduce information asymmetry.

In our model, a two-echelon maritime supply chain composed of a port and a shipping line is examined. Nevertheless, in practical terms, a port may contain multiple shipping lines. Thus, further studies should explore this aspect. Moreover, since shipper' sustainability preference promotes the SP reliability, a preference prediction should be performed from the perspective of forecast information sharing between maritime supply chains [41]. Also, we note that this study did not incorporate elements of competition in the port. This need to be investigated in future [42].

APPENDIX

The model equations of DMGSM in Fig.2.

1) Actual rate of technological progress = Expected rate of technological progress*1
2) Container throughput of shore power terminal = " potential demand (a)"- ("price-sensitive parameter (b)"*" shipping line's freight rate (p)")+ ("parameter ($b\lambda + \theta$)"*" SP reliability (e)")
3) Disguised price rate = ("government subsidy intensity (λ)"*"SP reliability (e)"-shipper's actual subsidy)/("shipping line's freight rate (p)"- (("government subsidy intensity (λ)"*"SP reliability (e)"-shipper's actual subsidy)))
4) Expected rate of technological progress = "subsidy reduction rate (r)"*"government subsidy intensity (λ)"* ("subsidy reduction rate (r)"*" price-sensitive parameter (b)"*"government subsidy intensity (λ)"*"parameter ($b\lambda + \theta$)"+"parameter ($b\lambda + \theta$)"^2-4*"price-sensitive parameter (b)"*"SP reliability cost coefficient (k)")/(4*"SP reliability cost coefficient (k)"*"parameter ($b\lambda + \theta$)")
5) Game equilibrium = (new port service fee-"port service fee (w)")/"port service fee (w)"
6) Government subsidy efficiency = (container throughput of shore power terminal-initial shore power terminal container volume) / total subsidy expenditure* 10000

7) "Government subsidy intensity (λ)" = INTEG (-"government subsidy intensity (λ)"*"subsidy reduction rate (r)", 100)
8) Information asymmetry = RANDOM UNIFORM (1, 1, 1)*"shipper' sustainability level preference (θ)"
9) Initial shore power terminal container volume = 5000 TEU
10) Maritime total profit = port's profit + shipping line's profit
11) Maximum subsidy intensity = "subsidy upper bound (I) "/("SP reliability (e)"* container throughput of shore power terminal)
12) New port service fee = ("potential demand (a)"-"price-sensitive parameter (b)"* ("shipping line's freight rate (p)")+"parameter (b λ + θ)"*"SP reliability (e)")/"price-sensitive parameter(b)"
13) "Parameter (bλ + θ)" = "price-sensitive parameter (b)" *"government subsidy intensity (λ)"+ information asymmetry
14) "Port service fee (w)" = INTEG ((1+ game equilibrium) *"port service fee (w)"-"port service fee (w)", 600CNY)
15) Port's profit = ("port service fee (w)")* container throughput of shore power terminal-SP cost
16) "Potential demand (a)"= 500000
17) "Price-sensitive parameter (b)"= 200
18) Regular freight rate = 650CNY
19) Shipper' actual freight charges "=" shipping line's freight rate (p)"-"subsidy standard
20) "Shipper' sustainability level preference (θ)" = INTEG (0* (("SP reliability (e)"+ shore power efficiency) /2+ regular freight rate/shipper' actual freight charges) *0.5, 1000)
21) Shipper's actual subsidy = ("government subsidy intensity (λ)"* ("potential demand (a)"-"price-sensitive parameter (b)"*"SP extra cost (f)")* ("price-sensitive parameter (b)"*"SP reliability cost coefficient (k)"* ("price-sensitive parameter (b)"*"government subsidy intensity (λ)"−2*"shipper' sustainability level preference (θ)")-"shipper' sustainability level preference (θ)"^2*"parameter (bλ + θ)"))/((4* "price-sensitive parameter (b)"*"SP reliability cost coefficient (k)"-"parameter (bλ + θ)"^2)* (4*"price-sensitive parameter (b)"*"SP reliability cost coefficient (k)"-"shipper' sustainability level preference (θ)"^2))
22) "Shipping line's freight rate (p)"= ("potential demand (a)"+"price-sensitive parameter (b)"* ("port service fee (w)"+"SP extra cost (f)")+"parameter (bλ + θ)"*"SP reliability (e)")/(2*"price-sensitive parameter (b)")
23) Shipping line's profit = ("shipping line's freight rate (p)"-"port service fee (w)"-"SP extra cost (f)") * container throughput of shore power terminal
24) Shore power efficiency = 0.2
25) SP cost = 0.5*"SP reliability cost coefficient (k)"*"SP reliability (e)"^2
26) "SP extra cost (f)" = 200CNY
27) "SP reliability (e)" = ("port service fee (w)")*" parameter (bλ + θ)"/"SP reliability cost coefficient (k)"
28) "SP reliability cost coefficient (k)"= INTEG ("SP reliability cost coefficient (k)"* actual rate of technological progress, 2.5e+07)
29) Subsidy gap = IF THEN ELSE (total subsidy expenditure >="subsidy upper bound (I)", total subsidy expenditure-"subsidy upper bound (I)",0)
30) "Subsidy standard (/TEU)"= "SP reliability (e)"*" government subsidy intensity (λ)"
31) "subsidy reduction rate (r)"= (STEP (0.0063,37) + (STEP (0.0031,52)))
32) "Subsidy upper bound (I)"= 6e +07 CNY
33) Total subsidy expenditure = "subsidy standard (/TEU)" * container throughput of shore power terminal

ACKNOWLEDGMENT

The authors deeply appreciate all the specialists and anonymous reviewers for their insightful comments.

REFERENCES

[1] *United Nations Conference on Trade and Development–UNCTAD, Review of Maritime Transport*, United Nations publication, Geneva, Switzerland, 2019.

[2] (2014). *Third IMO GHG Study 2014*. [Online]. Available: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

[3] R. Winkel, U. Weddige, D. Johnsen, V. Hoen, and S. Papaefthimiou, "Shore side electricity in Europe: Potential and environmental benefits," *Energy Policy*, vol. 88, pp. 584–593, Jan. 2016, doi: 10.1016/j.enpol.2015.07.013.

[4] The Intergovernmental Panel on Climate Change. (2014). *AR5 Synthesis Report: Climate Change*. [Online]. Available: https://www.ipcc.ch/report/ar5/syr/

[5] K. Cullinane and R. Bergqvist, "Emission control areas and their impact on maritime transport," *Transp. Res. D, Transp. Environ.*, vol. 28, pp. 1–5, May 2014, doi: 10.1016/j.trd.2013.12.004.

[6] V. Kosmas and M. Acciaro, "Bunker Levy schemes for greenhouse gas (GHG) emission reduction in international shipping," *Transp. Res. D, Transp. Environ.*, vol. 57, pp. 195–206, Dec. 2017, doi: 10.1016/j.trd.2017.09.010.

[7] H. N. Psaraftis, "Speed optimization for sustainable shipping," in *Sustainable Shipping: A Cross-Disciplinary View*, H. N. Psaraftis, Ed. Cham, Switzerland: Springer, 2019, pp. 339–374.

[8] T. Zis and H. N. Psaraftis, "Operational measures to mitigate and reverse the potential modal shifts due to environmental legislation," *Maritime Policy Manage.*, vol. 46, no. 1, pp. 117–132, Jan. 2019, doi: 10.1080/03088839.2018.1468938.

[9] European Commission. (2005). *Directive 2005/33/EC Amending Directive 1999/32/EC as Regards the Sul-Phur Content of Marine Fuels*. [Online]. Available: http://www.ops.wpci.nl/_images/_downloads/_original/1264149906_2005eudirectivesulphurcontentofmarinefuels2005_33.pdf

[10] Chinese Ministry of Transport. (2018). *Implementation Plan of Ship Air Pollutant Emission Control Areas*. [Online]. Available: http://www.gov.cn/xinwen/2018-12/20/5350451/files/92419c6c912a4a34a428291d413c498f.pdf

[11] T. Zis, R. J. North, P. Angeloudis, W. Y. Ochieng, and M. G. H. Bell, "Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports," *Maritoring Econ. Logist.*, vol. 16, no. 4, pp. 371–398, 2014, doi: 10.1057/mel.2014.6.

[12] Shenzhen Municipal Government. (2019). *Detailed Rules of Subsidy for Green and Low Carbon Port Construction in Shenzhen*. [Online]. Available: http://jtys.sz.gov.cn/zwgk/xxgkml/zcfgjjd/gfxwjcx/201909/t20190902_18190492.htm
[13] A. Innes and J. Monios, "Identifying the unique challenges of installing cold ironing at small and medium ports—The case of aberdeen," *Transp. Res. D, Transp. Environ.*, vol. 62, pp. 298–313, Jul. 2018, doi: 10.1016/j.trd.2018.02.004.
[14] H. Davarzani, B. Fahimnia, M. Bell, and J. Sarkis, "Greening ports and maritime logistics: A review," *Transp. Res. D, Transp. Environ.*, vol. 48, pp. 473–487, Oct. 2016, doi: 10.1016/j.trd.2015.07.007.
[15] Y.-T. Chang, H. Park, S. Lee, and E. Kim, "Have emission control areas (ECAs) harmed port efficiency in europe?" *Transp. Res. D, Transp. Environ.*, vol. 58, pp. 39–53, Jan. 2018, doi: 10.1016/j.trd.2017.10.018.
[16] Y.-T. Chang, Y. Roh, and H. Park, "Assessing noxious gases of vessel operations in a potential emission control area," *Transp. Res. D, Transp. Environ.*, vol. 28, pp. 91–97, May 2014, doi: 10.1016/j.trd.2014.03.003.
[17] H. Sampson, M. Bloor, S. Baker, and K. Dahlgren, "Greener shipping? A consideration of the issues associated with the introduction of emission control areas," *Maritime Policy Manage.*, vol. 43, no. 3, pp. 295–308, Apr. 2016, doi: 10.1080/03088839.2015.1040862.
[18] Y. Zhao, J. Zhou, Y. Fan, and H. Kuang, "An expected utility-based optimization of slow steaming in sulphur emission control areas by applying big data analytics," *IEEE Access*, vol. 8, pp. 3646–3655, 2020, doi: 10.1109/ACCESS.2019.2962210.
[19] L. Dai, H. Hu, Z. Wang, Y. Shi, and W. Ding, "An environmental and techno-economic analysis of shore side electricity," *Transp. Res. D, Transp. Environ.*, vol. 75, pp. 223–235, Oct. 2019, doi: 10.1016/j.trd.2019.09.002.
[20] T. P. V. Zis, "Prospects of cold ironing as an emissions reduction option," *Transp. Res. A, Policy Pract.*, vol. 119, pp. 82–95, Jan. 2019, doi: 10.1016/j.tra.2018.11.003.
[21] P.-H. Tseng and N. Pilcher, "A study of the potential of shore power for the port of Kaohsiung, Taiwan: To introduce or not to introduce?" *Res. Transp. Bus. Manage.*, vol. 17, pp. 83–91, Dec. 2015, doi: 10.1016/j.rtbm.2015.09.001.
[22] J. Chen, T. Zheng, A. Garg, L. Xu, S. Li, and Y. Fei, "Alternative maritime power application as a green port strategy: Barriers in China," *J. Cleaner Prod.*, vol. 213, pp. 825–837, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.177.
[23] A. J. Baird, "State subsidy system for remote island liner services in Japan," *Int. J. Maritime Econ.*, vol. 3, no. 1, pp. 102–120, Mar. 2001, doi: 10.1057/palgrave.ijme.9100005.
[24] S. Farrell, "The subsidization of seaports: An alternative approach," *Maritime Policy Manage.*, vol. 13, no. 2, pp. 177–184, Jun. 1986, doi: 10.1080/03088838600000061.
[25] X. Li, H. Kuang, and Y. Hu, "Carbon mitigation strategies of port selection and multimodal transport operations—A case study of Northeast China," *Sustainability*, vol. 11, no. 18, p. 4877, Sep. 2019, doi: 10.3390/su11184877.
[26] F. Medda and L. Trujillo, "Short-sea shipping: An analysis of its determinants," *Maritime Policy Manage.*, vol. 37, no. 3, pp. 285–303, May 2010, doi: 10.1080/03088831003700678.
[27] C. Qu, G. W. Y. Wang, and Q. Zeng, "Modelling port subsidy policies considering pricing decisions of feeder carriers," *Transp. Res. E, Logistics Transp. Rev.*, vol. 99, pp. 115–133, Mar. 2017, doi: 10.1016/j.tre.2017.01.004.
[28] M. Ishii, P. T.-W. Lee, K. Tezuka, and Y.-T. Chang, "A game theoretical analysis of port competition," *Transp. Res. E, Logistics Transp. Rev.*, vol. 49, no. 1, pp. 92–106, Jan. 2013, doi: 10.1016/j.tre.2012.07.007.
[29] D.-P. Song, A. Lyons, D. Li, and H. Sharifi, "Modeling port competition from a transport chain perspective," *Transp. Res. E, Logistics Transp. Rev.*, vol. 87, pp. 75–96, Mar. 2016, doi: 10.1016/j.tre.2016.01.001.
[30] S. Hidalgo-Gallego, R. Núñez-Sánchez, and P. Coto-Millán, "Game theory and port economics: A survey of recent research," *J. Econ. Surv.*, vol. 31, no. 3, pp. 854–877, Jul. 2017, doi: 10.1111/joes.12171.
[31] F. Oztanriseven, L. Pérez-Lespier, S. Long, and H. Nachtmann, "A review of system dynamics in maritime transportation," in *Proc. IIE Annu. Conf.*, 2014, p. 2447.
[32] H. Cui and T. Notteboom, "Modelling emission control taxes in port areas and port privatization levels in port competition and co-operation subgames," *Transp. Res. D, Transp. Environ.*, vol. 56, pp. 110–128, Oct. 2017, doi: 10.1016/j.trd.2017.07.030.
[33] H. Park, Y.-T. Chang, and B. Zou, "Emission control under private port operator duopoly," *Transp. Res. E, Logistics Transp. Rev.*, vol. 114, pp. 40–65, Jun. 2018, doi: 10.1016/j.tre.2018.03.010.
[34] J.-K. Woo, D. S. H. Moon, and J. S. L. Lam, "The impact of environmental policy on ports and the associated economic opportunities," *Transp. Res. A, Policy Pract.*, vol. 110, pp. 234–242, Apr. 2018, doi: 10.1016/j.tra.2017.09.001.
[35] D. Sheng, Z.-C. Li, X. Fu, and D. Gillen, "Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition," *Transp. Res. E, Logistics Transp. Rev.*, vol. 101, pp. 99–114, May 2017, doi: 10.1016/j.tre.2017.03.004.
[36] L. Yang, Y. Cai, Y. Wei, and S. Huang, "Choice of technology for emission control in port areas: A supply chain perspective," *J. Cleaner Prod.*, vol. 240, Dec. 2019, Art. no. 118105, doi: 10.1016/j.jclepro.2019.118105.
[37] X. Lai, Y. Tao, F. Wang, and Z. Zou, "Sustainability investment in maritime supply chain with risk behavior and information sharing," *Int. J. Prod. Econ.*, vol. 218, pp. 16–29, Dec. 2019, doi: 10.1016/j.ijpe.2019.02.021.
[38] G. Dong, S. Zheng, and P. T.-W. Lee, "The effects of regional port integration: The case of Ningbo-Zhoushan port," *Transp. Res. E, Logistics Transp. Rev.*, vol. 120, pp. 1–15, Dec. 2018, doi: 10.1016/j.tre.2018.10.008.
[39] W. Ma, R. Zhang, and Z. Cheng, "Analysis of internal and external funding mechanisms considering green consumer loyalty: A game-theoretic approach," *IEEE Access*, vol. 8, pp. 2931–2947, 2020, doi: 10.1109/ACCESS.2019.2962311.
[40] S. Saha, S. Majumder, and I. E. Nielsen, "Is it a strategic move to subsidized consumers instead of the manufacturer?" *IEEE Access*, vol. 7, pp. 169807–169824, 2019, doi: 10.1109/ACCESS.2019.2954376.
[41] S. Wang and X. Qu, "Blockchain applications in shipping, transportation, logistics, and supply chain," in *Smart Transportation Systems*. Singapore: Springer, 2019, pp. 225–231, doi: 10.1007/978-981-13-8683-1_23.
[42] C.-Y. Lee and D.-P. Song, "Ocean container transport in global supply chains: Overview and research opportunities," *Transp. Res. B, Methodol.*, vol. 95, pp. 442–474, Jan. 2017, doi: 10.1016/j.trb.2016.05.001.

XIAODONG LI received the M.S. degree in industrial engineering from Dalian Maritime University, Dalian, China, in June 2016, where he is currently pursuing the Ph.D. degree with the College of Transportation Engineering, under the supervision of Prof. H. Kuang. He published his work in sustainability. His research interests include green shipping management, optimization analysis, multimodal transportation, and game models.

HAIBO KUANG received the Ph.D. degree in management from the Dalian University of Technology, China. He is currently a Professor with the School of Maritime Economics and Management, Dalian Maritime University (DMU), where he is also the President of the Collaborative Innovation Center for Transport Studies. He has served as the Team Leader of Port Synergistic Development and Green Growth. He has published more than 100 reviewed journal articles and earned more than 20 provincial and industrial awards of China. His researches focus on maritime policy and management, green supply chain management, and maritime big data. He was awarded a grant by the Program of Innovative Research Team in University of Ministry of Education of China.

YAN HU received the B.S. degree in transportation engineering from Dalian Maritime University, Dalian, China, in June 2017, where she is currently pursuing the Ph.D. degree in management science and engineering.

She has published several EI/CSSCI articles. Her researches focus on green shipping management and smart ports.