



# Evolutionary Game Analysis of Carbon Emission Reduction Behaviour in Shipping Industry under Government Reward and Punishment

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## ABSTRACT

To promote the low-carbon transformation of the shipping industry, this study explores the impact of the government's reward and punishment mechanisms on carbon reduction behaviours in the shipping industry. Specifically, this study constructs a tripartite evolutionary game model among the government, shipping companies and port enterprises, and examines the factors involved. The main results of this study are as follows. First, government reward and punishment mechanisms have a significant effect on the sustainable development of the shipping industry. The probability of shipping companies and port enterprises adopting carbon emission reduction behaviour will rise when the government effectively implements the reward and punishment mechanism. Second, the regulatory cost has an important influence on the decision of the government. With a decrease in the cost of conducting government regulation, the government is inclined to adopt active regulation strategies. Third, the short operational time has adverse effects on the green transition of the shipping industry. However, when the ships' operational time is long, shipping companies are inclined to adopt proactive carbon reduction strategies. Besides, shipping companies tend to prioritise local port enterprises for the refuelling of clean energy ships. Therefore, the probability of port enterprises building clean energy refuelling stations will rise when shipping companies choose to adopt clean energy ships. The aim of this study is to offer policy suggestions for mitigating carbon emissions in the shipping industry and to help stakeholders choose the relatively optimal strategy.

## KEYWORDS

carbon emission reduction; tripartite evolutionary game; government; shipping companies; port enterprises.

## 1. INTRODUCTION

With the rapid development of global industrialisation, the annual carbon emissions from the shipping industry are nearly 1 billion tons [1]. Meanwhile, the International Maritime Organisation (IMO) indicated that carbon emissions are projected to rise by 50% by 2050 compared to 2018 levels [2]. Significant carbon emissions contribute to various environmental challenges, and they have become a barrier to achieving high-quality development [3]. Therefore, the low-carbon transformation of the shipping industry has become a necessary trend of the times.

Nowadays, to reduce the carbon emissions of the shipping industry, domestic and foreign governments and relevant institutions have proposed a series of policies. Such as in 1997, the International Maritime Organisation (IMO) formally enshrined the Code for the Prevention of Air Pollution from Ships as a by-law to the MARPOL Convention [4]. In 2003, the IMO General Assembly urged its subsidiary, the Marine Environment Protection Committee, to establish and supervise mechanisms for greenhouse gas emission reductions in international shipping [5]. Besides, the IMO proposed the Ship Performance Design Index and the Ship Energy Efficiency Management Plan in 2011 [6]. However, although the implementation of these policies has shown effectiveness, it has yet to achieve the anticipated objectives [7]. One possible reason is that the use of non-renewable ships still accounts for a significant proportion of the shipping industry [8, 9]. Therefore, promoting the use of low-carbon ships and the development of green ports is an effective strategy for the green transition of the shipping industry.

Despite the significant potential of clean energy in reducing carbon emissions, this strategy involves multiple stakeholders: government, shipping companies and port enterprises [10]. The diversity and complexity of their behavioural strategies influence the dynamic evolution of strategic equilibrium in various ways [11]. For the government, as a designer of policy, the government is not only necessary to formulate detailed carbon emission reduction policies for the shipping industry, but also to consider how to establish a regulatory system [12]. Besides, the government should formulate a reasonable reward and punishment mechanism for shipping companies and port enterprises to ensure that shipping companies and port enterprises choose to adopt carbon emission reduction behaviour actively on the basis of the original economic benefits [13]. For shipping companies, as an important part of the shipping industry, they should assume their due social responsibility. Furthermore, the shipping companies should actively research and develop clean energy ships and train clean energy technical personnel [14]. However, the cost could be expensive for shipping companies [15]. Similarly, for port enterprises, as a significant service industry, the port enterprises should provide due services for the shipping industry and consider the probability of the green port transformation [16]. Based on the above analysis, it is inferred that the government may not get the intended implementation effect of the policies when the government's reward and punishment mechanisms are not reasonable. In addition, it is presumable that the carbon emission behaviour of the shipping industry will also be hampered when there is a disparity in the low-carbon transition progress between shipping companies and port enterprises. Therefore, addressing the inherent interests among these three stakeholders and finding a tripartite equilibrium strategy are essential to encourage the use of clean energy in the shipping industry.

Based on the above discussion, this study aims to discuss the following three questions: (1) Should the government choose to adopt active regulation or passive regulation? (2) Should the government choose strong or weak reward and punishment mechanisms for shipping companies and port enterprises? (3) When the cost of green transformation is high, should shipping companies and port enterprises choose to adopt carbon emission reduction behaviour? In order to solve the above problem, this study establishes an evolutionary game model that includes the government, shipping companies and port enterprises. Furthermore, it verifies the internal impact of government reward and punishment mechanisms on the promotion of reduced carbon emission behaviour in the shipping industry.

The remainder of this study is organised as follows. Section 2 summarises the relevant literature. Section 3 defines parameters and proposes the tripartite evolutionary game model. In Section 4, this study analyses the stability of the tripartite evolutionary game system. In Section 5, simulation analysis is performed, and analyses of the effects of key parameters on the evolutionary results and evolutionary trajectories are carried out. Finally, this study summarises the results of the analysis and presents the conclusions.

## 2. LITERATURE REVIEW

To conduct thorough studies of the decision-making relationships among various stakeholders under differing policies, this section reviews literature on shipping enterprise management, low-carbon policies and tripartite evolutionary games.

The rapid growth of trade inevitably leads to increased energy consumption and greenhouse gas emissions. Therefore, the shipping industry must seek new green shipping management solutions to reduce emissions. For example, Zhuge et al. introduced three measures of emission reduction aimed at a speed, deployment and joint ship path problem. The results indicate that these measures result in substantial economic benefits for shipping enterprises, achieving significant cost reductions [17]. Tran and Lam noted that although the impact of sailing speed on costs is relatively small, it not only accounts for half of the delivery time but also contributes

to over 70% of carbon emissions [18]. Fan et al. studied an inland diesel-powered ship, analysing the carbon footprint and economics of methanol and liquefied natural gas (LNG) as alternative fuels, demonstrating that LNG is a green alternative fuel for ships [19]. Munim et al. assessed various energy sources and found that HFO-Wind, LNG-Wind and LNG are viable alternative energies [20]. Fan et al. found that optimal ship speed, torque and engine speed can effectively reduce ship exhaust emissions, which provides critical information for carbon reduction in the shipping industry [21]. Elmi Zeinab et al. introduced a new multi-objective approach for ship schedule recovery, and the  $\epsilon$ -constraint algorithm was developed and validated through extensive computational experiments [22]. Han et al. proposed an improved quantum genetic algorithm based on a “fork gene” and elite strategy. The improved algorithm significantly reduces the total cost in the context of emission reduction policies and strategies [23].

Green development is difficult to achieve without the support of the government and organisations. Therefore, reasonable policies are important factors in facilitating the green transition of the shipping industry. The United Nations Climate Change Conference officially proposed the concept of green ports in 2009 [24]. The European Union decided to include the shipping industry in the European Emission Trading System (EU ETS) in September 2020 [25]. Moreover, the updated proposal states that starting in 2027, voyages involving ports outside the European Economic Area will also be fully included in the EU ETS [26]. Besides, to enhance the cooperation between shipping ports and companies, the International Ports Association and the IMO signed a Strategic Partnership [27]. Wang et al. investigated the influence of marine emission trading system (METS) on emission reduction strategies used under ECA regulation. The results show that the optimal emission reduction strategy is installing a scrubber [28]. Dulebenets, Maxim A. proposed a new type of collaborative agreements amongst shipping lines and marine terminal operators for sustainable and environmentally friendly ship schedule design [29].

Tripartite evolutionary game models are often used to solve interaction problems involving three different agents. Examples include the interaction of businesses, governments and NGOs in the progress of green shipping. Meng et al. studied the benefits among port companies, the government and shipping enterprises under government regulation to accelerate the achievement of carbon emission reduction targets [30]. Li et al. analysed the benefits among enterprises, customers and the government to research the interactive behaviour of all parties, which helps enterprises identify the best approach to sustainable development [31]. Besides, Li et al. constructed a tripartite evolutionary game model that includes freight forwarders, shipping companies and ports to obtain key factors that have an impact on the behaviour selection of ship supply chain participants [32]. By Wu Kai et al., a tripartite evolutionary game model comprising government, enterprises and internal organisations was constructed to provide a solid theoretical foundation for enterprises considering the implementation of the ICP in the future [33]. Zhu Lequn et al. employed a combination of system dynamics (SD) and evolutionary game theory to examine the decision-making behaviours of these three parties and analyse their evolutionary pathways. The findings indicate that the intensity and stability of government regulatory policies are pivotal in driving the low-carbon transformation of the maritime supply chain [34]. Gao, Weichen et al. adopt dynamic simulation methods to analyse the game relationship between relevant stakeholders, including both governments and port enterprises. The results indicate that a reasonable profit allocation coefficient and compensation fee can promote advantageous development within a tripartite game system [35].

In summary, previous studies have mainly focused on carbon reduction measures, while research on multi-stakeholder collaboration analysis has been relatively scarce. Based on the aforementioned research, this study constructs a tripartite evolutionary game model that includes the government, shipping companies and port enterprises under the government’s reward and punishment mechanisms, and explores the impacts of mechanisms on carbon reduction in the shipping industry. The main contributions of this study are as follows.

First, this study constructs an evolutionary game model among shipping companies, the government and port enterprises under the reward and punishment mechanisms, and analyses the strategic stability of each game party.

Second, this study carries out stability analysis of the equilibrium points of the replication dynamic system by using the Lyapunov first method, and the combination of evolutionary stability strategies under different conditions is obtained.

Third, this study verifies the effectiveness of the model analysis under different initial conditions, and suggestions are put forward for the government to improve the carbon tax policy and compensation policy according to the analysis conclusions. Besides, this study gives suggestions on the operating time of clean energy ships.

The content of this study is as follows. Section 3 defines parameters and establishes models. In Section 4, this study analyses the stability of the evolutionary game system under the reward and punishment mechanisms of the government. Section 5 performs simulation analysis and carries out analyses of the effects of key parameters. Finally, Section 6 gives some conclusions and suggestions.

### 3. MODELLING

#### 3.1 Assumptions and parameters

The active regulation by the government and the proactive engagement by stakeholders in fulfilling social responsibilities are crucial determinants for carbon reduction in shipping companies. The diagram of the benefits relationship among the game participants is shown in Figure 1. Based on that, the following assumptions are made [36].

**Assumption 1:** The behaviours of the shipping company, the government and the port enterprise are all bounded rationality. The stakeholders operate under conditions of incomplete and asymmetric information, where each party has access to different levels and types of information. Each stakeholder possesses two distinct options for strategy selection [37].

**Assumption 2:** The strategy of the government is divided into active regulation and passive regulation, and the probabilities are  $x$  and  $1-x$ , respectively. The shipping companies' strategies are to adopt clean energy ships and traditional energy ships, and the probabilities are  $y$  and  $1-y$ , respectively [38]. The port enterprises' strategies are to build clean energy refuelling stations and not to build clean energy refuelling stations, and the probabilities respectively are  $z$ ,  $1-z$  and  $x$ ,  $y$ ,  $z \in [0,1]$ .

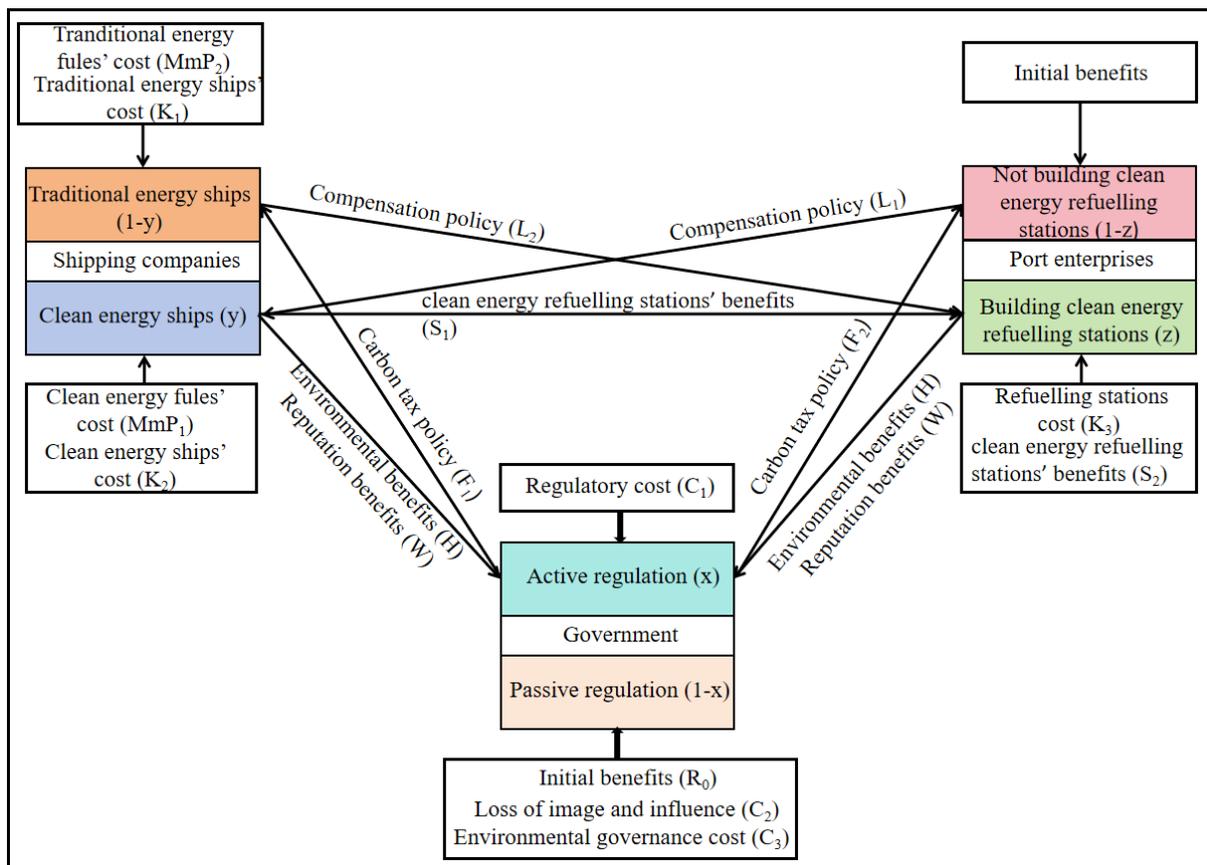


Figure 1 – Interactive strategic behaviour framework among tripartite participants

**Assumption 3:** The initial benefit of the government is  $R_0$ . When the government adopts a strategy of active regulation, it implements government reward and punishment mechanisms. Specifically, the reward mechanism is the compensation policy, and the punishment mechanism is the carbon tax policy. The economic benefit of government through the carbon tax policy is expressed as  $F = F_1 + F_2$ , the environmental benefits

are expressed as  $H$ , the reputation benefits are expressed as  $W$ , and the regulatory cost is expressed as  $C_1$  [39]. Besides, in scenarios where only one party, either shipping companies or the port enterprises, implements an emissions reduction strategy, the non-participating party is required to provide compensation to the participating party. When the government adopts a strategy of passive regulation, the government incurs a loss in its institutional image and influence, it is expressed as  $C_2$ , and the costs of environmental governance, it is expressed as  $C_3$ .

**Assumption 4:** The initial benefit of shipping companies is  $G$ . The ships’ operational time is expressed as  $M$ , and the annual average number of voyages is expressed as  $m$ . When shipping companies adopt a strategy of clean energy ships, the construction cost of clean energy ships is expressed as  $K_2$ , and the fuel cost per voyage is expressed as  $P_1$ . When shipping companies adopt a strategy of traditional energy ships, the construction cost of traditional energy ships is expressed as  $K_1$ ,  $K_2 > K_1$ , and the fuel cost per voyage is expressed as  $P_2$ ,  $P_2 > P_1$ . The carbon tax is expressed as  $F_1$  that shipping companies are required to pay, and the compensation is expressed as  $L_2$  [40].

**Assumption 5:** When port enterprises adopt a strategy of building clean energy refuelling stations, the construction cost of clean energy refuelling stations is expressed as  $K_3$ . When local shipping companies utilise the clean energy refuelling station, the revenue generated for the port enterprise is expressed as  $S_1$ . When only non-local shipping companies utilise the clean energy refuelling station, the revenue generated for port enterprises is expressed as  $S_2$ ,  $S_1 > S_2$ . When port enterprises adopt a strategy of not building clean energy refuelling stations, the carbon tax is expressed as  $F_2$  which port enterprises are required to pay, and the compensation is expressed as  $L_1$ ,  $L_2 > L_1$  [41].

According to the above assumptions, the parameter settings in this study are detailed in *Table 1*. The outcomes of the payoff matrix are presented in *Table 2*.

*Table 1 – The parameter settings*

Subjects	Symbol	Description
Government	$R_0$	The initial benefit of the government.
	$F$	The economic revenue of the carbon tax policy for the government.
	$H$	The environmental benefits.
	$W$	The reputation benefits.
	$C_1$	The regulatory cost.
	$C_2$	Loss of image and influence.
	$C_3$	Environmental governance cost.
Shipping companies	$G$	The initial benefit of shipping companies.
	$M$	The ships’ operational time.
	$m$	The annual average number of voyages.
	$K_1$	The construction cost of traditional energy ships.
	$K_2$	The construction cost of clean energy ships.
	$P_1$	The fuel cost per voyage of clean energy ships.
	$P_2$	The fuel cost per voyage of traditional energy ships.
	$F_1$	The cost of the carbon tax policy.
$L_2$	The cost of the compensation policy.	
Port enterprises	$K_3$	The cost of clean energy refuelling stations.
	$S_1$	The revenue generated from clean refuelling stations is utilised by local clean energy ships.
	$S_2$	The revenue generated from clean refuelling stations is utilised by non-local clean energy ships.
	$F_2$	The cost of the carbon tax policy.
	$L_1$	The cost of the compensation policy.

Table 2 – The payoff matrix

Shipping companies	Port enterprises	Government	
		Active regulation ( $x$ )	Passive regulation ( $1-x$ )
Clean energy ships ( $y$ )	Building clean energy refuelling stations ( $z$ )	$\begin{bmatrix} R_0 + H - C_1 + W \\ G - K_2 - MmP_1 \\ MmS_1 - K_3 \end{bmatrix}$	$\begin{bmatrix} R_0 - C_2 + H \\ G - K_2 - MmP_1 \\ MmS_1 - K_3 \end{bmatrix}$
	Not building clean energy refuelling stations ( $1-z$ )	$\begin{bmatrix} R_0 + H - C_1 + F_2 + W \\ G - K_2 - MmP_1 + L_1 \\ -F_2 - L_1 \end{bmatrix}$	$\begin{bmatrix} R_0 - C_2 - C_3 \\ G - K_2 - MmP_1 \\ 0 \end{bmatrix}$
Traditional energy ships ( $1-y$ )	Building clean energy refuelling stations ( $z$ )	$\begin{bmatrix} R_0 + H - C_1 + F_1 + W \\ G - K_1 - MmP_2 - F_1 - L_2 \\ MmS_2 - K_3 + L_2 \end{bmatrix}$	$\begin{bmatrix} R_0 - C_2 - C_3 \\ G - K_1 - MmP_2 \\ MmS_2 - K_3 \end{bmatrix}$
	Not building clean energy refuelling stations ( $1-z$ )	$\begin{bmatrix} R_0 + H - C_1 + F_1 + F_2 + W \\ G - K_1 - MmP_2 - F_1 \\ -F_2 \end{bmatrix}$	$\begin{bmatrix} R_0 - C_2 - C_3 \\ G - K_1 - MmP_2 \\ 0 \end{bmatrix}$

### 3.2 Stability analysis of the government’s strategies

According to the payoff matrix, the benefits of government under active regulation  $E_{11}$  and the benefits under passive regulation  $E_{12}$  are, respectively, as follows.

$$E_{11} = z \cdot (1-y) \cdot (R_0 - C_1 + W + F_1) + y \cdot (1-z) \cdot (R_0 - C_1 + W + H + F_2) + y \cdot z \cdot (R_0 + H - C_1 + W) + (1-y) \cdot (1-z) \cdot (R_0 - C_1 + W + H + F_1 + F_2) \tag{1}$$

$$E_{12} = z \cdot (1-y) \cdot (R_0 - C_2 - C_3) + y \cdot (1-z) \cdot (R_0 - C_2 - C_3) + y \cdot z \cdot (R_0 - C_2 + H) + (1-y) \cdot (1-z) \cdot (R_0 - C_2 - C_3) \tag{2}$$

Then, the mean utilities of the government  $\bar{E}_x$  is as follows.

$$\bar{E}_x = x \cdot E_{11} + (1-x) \cdot E_{12} \tag{3}$$

Consequently, the replicating dynamic equation for the government  $F(x)$ , the first derivative and  $G(y)$  are obtained as follows.

$$F(x) = x \cdot (E_{11} - \bar{E}_x) = x \cdot (1-x) \cdot (C_2 - C_1 + C_3 + F_1 + F_2 + H + W + y \cdot F_1 - z \cdot F_2 - y \cdot z \cdot C_3 - y \cdot z \cdot H) \tag{4}$$

$$\frac{d(F(x))}{dx} = (1-2x) \cdot (F_1 + F_2 + H + W - C_1 + C_2 + C_3 - y \cdot F_1 - z \cdot F_2 - y \cdot z \cdot C_3 - y \cdot z \cdot H) \tag{5}$$

$$G(y) = F_1 + F_2 + H + W - C_1 + C_2 + C_3 - y \cdot F_1 - z \cdot F_2 - y \cdot z \cdot C_3 - y \cdot z \cdot H \tag{6}$$

Based on the stability theorem of the differential equation, the probability of the government choosing to adopt active regulation must satisfy the following conditions for stability:  $F(x) = 0$  and  $d(F(x))/dx < 0$ . Since  $dG(y)/dy < 0$ ,  $G(y)$  is a decreasing function of  $y$ . Therefore, when  $y = (F_1 + F_2 + W - C_1 + C_2 + C_3 + H - zF_2) / (F_1 + zC_3 + zH) = y^*$ , then  $G(y) = 0$ . Meanwhile,  $d(F(x))/dx = 0$ , and government has not determined a stable strategy. Additionally, when  $y < y^*$ ,

$G(y) > 0$ , at this time,  $d(F(x))/dx|_{x=0} < 0$ , and  $x=0$  is the Evolution Stable Strategy (ESS) for the government [42]. Similarly, when  $x=1$ , it is the ESS for the government. Specifically, the strategy diagram of the government is shown in Figure 2.

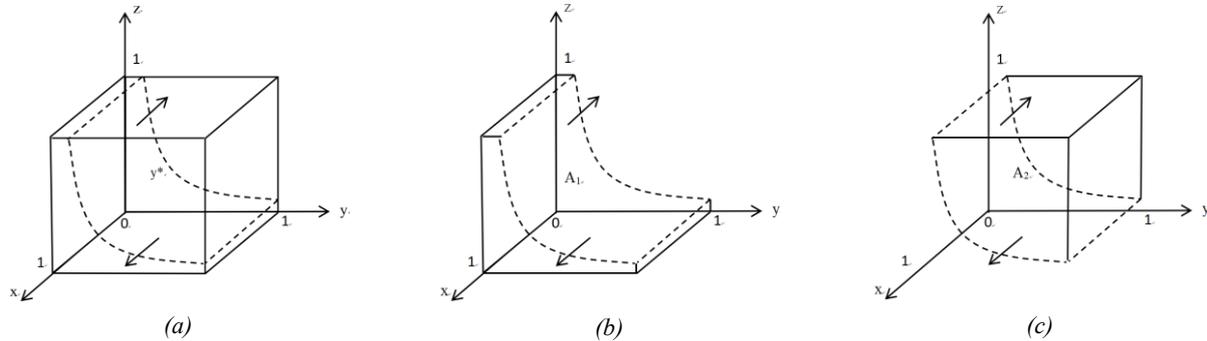


Figure 2 – Strategy evolution phase diagram of the government with three subplots: a)  $y=y^*$ ; b)  $y < y^*$ ; c)  $y > y^*$

From Figure 2, it is observed that the volume  $V_{A_1}$  of  $A_1$  represents the probability of the government choosing to adopt active regulation, while the probability of the government choosing to adopt passive regulation is represented by  $V_{A_2}$  of  $A_2$ . The  $V_{A_1}$  and  $V_{A_2}$  are defined as follows.

$$V_{A_1} = \int_0^1 \int_0^1 (y^*) dx dz = \frac{2F_1 + 2F_2 + W - C_1 + C_2 + 2C_3 + 2H}{(C_3 + H)^2} \cdot \ln\left(\frac{F_1 + C_3 + H}{F_1}\right) - \frac{F_2}{C_3 + H} \tag{7}$$

$$V_{A_2} = 1 - V_{A_1} = 1 - \left( \frac{2F_1 + 2F_2 + W - C_1 + C_2 + 2C_3 + 2H}{(C_3 + H)^2} \cdot \ln\left(\frac{F_1 + C_3 + H}{F_1}\right) - \frac{F_2}{C_3 + H} \right) \tag{8}$$

**Inference 1:** The possibility of the government adopting active regulation is positively correlated with the strength of the carbon tax collected, the environmental benefits and the reputation benefits obtained by the government. Meanwhile, it is negatively correlated with the regulation cost that the government needs to pay when it is actively regulating, the reputation loss that the government needs to bear when it is passively regulating, and the environmental governance cost that the government needs to bear.

**Proof:** According to Equation (7) and  $\frac{C_3 + H - F_1}{C_3 + H} < \ln \frac{C_3 + H + F_1}{F_1} < \frac{C_3 + H_1}{F_1}$ , the first-order partial derivatives of each factor are calculated, yielding the following results:  $\partial V_{A_1} / \partial F_1 > 0$ ,  $\partial V_{A_1} / \partial F_2 > 0$ ,  $\partial V_{A_1} / \partial H > 0$ ,  $\partial V_{A_1} / \partial W > 0$ ,  $\partial V_{A_1} / \partial C_2 > 0$ ,  $\partial V_{A_1} / \partial C_1 < 0$ ,  $\partial V_{A_1} / \partial C_3 < 0$ . Therefore, the probability of the government adopting active regulation increases when increasing  $F$ ,  $H$  and  $W$  or decreasing  $C_1$ ,  $C_2$  and  $C_3$ .

**Inference 1** suggests that the increase in the amount of carbon tax and the reputation benefits prompt the government to adopt active regulation strategies. At the same time, the reduction of regulation costs increases the probability of active regulation. However, the reduction in environmental governance costs erodes the inclination of the government to adopt active regulation. This means that the public support for the sustainable development of the shipping industry enhances the inclination of the government to adopt active regulation.

**Inference 2:** The probability of active regulation by government increases as the rate of shipping companies choosing to adopt clean energy ships and the rate of port enterprises constructing clean energy refuelling stations increase, when the evolutionary process is considered.

**Proof:** According to the stability analysis of government strategies, it is inferred that when  $y < y^*$ , and  $y < (F_1 + F_2 + W - C_1 + C_2 + C_3 + H - zF_2) / (F_1 + zC_3 + zH)$ ,  $x=0$  serves as the ESS. At the same time, as  $y, z$  gradually increase, the probability of the government adopting active regulation rises from  $x=0$  to  $x=1$ . Thus, there is  $x$  which increase as  $y$  and  $z$  increase.

**Inference 2** shows that the possibility of the government adopting active regulation is impacted by the strategic decisions made by port enterprises and shipping companies. When the probability of shipping companies choosing to adopt clean energy ships is high or the probability of port enterprises building clean energy refuelling stations is high, the government tends to adopt active regulation.

### 3.3 Stability analysis of shipping companies’ strategies

Based on the payoff matrix, the expected benefits of shipping companies adopting clean energy ships  $E_{21}$  and not adopting clean energy ships  $E_{22}$  are as follows.

$$E_{21} = x \cdot (1-z) \cdot (G - K_2 - M \cdot m \cdot P_1 + L_1) + z \cdot (1-x) \cdot (G - K_2 - M \cdot m \cdot P_1) + x \cdot y \cdot (G - K_2 - M \cdot m \cdot P_1) + (1-x) \cdot (1-z) \cdot (G - K_2 - M \cdot m \cdot P_1) \tag{9}$$

$$E_{22} = x \cdot (1-z) \cdot (G - K_1 - M \cdot m \cdot P_2 - F_1) + z \cdot (1-x) \cdot (G - K_1 - M \cdot m \cdot P_2) + x \cdot z \cdot (G - K_1 - M \cdot m \cdot P_2 - F_1 - L_1) + (1-x) \cdot (1-z) \cdot (G - K_1 - M \cdot m \cdot P_2) \tag{10}$$

Then, the mean utilities of shipping companies  $\bar{E}_y$  is as follows.

$$\bar{E}_y = y \cdot E_{21} + (1-y)E_{22} \tag{11}$$

Consequently, the replicating dynamic equation for shipping companies  $F(y)$ , the first derivative and  $J(x)$  are obtained as follows.

$$F(y) = y \cdot (1-y) \cdot (E_{21} - \bar{E}_y) = (1-y) \cdot (K_1 - K_2 + x \cdot F_1 + x \cdot L_1 - M \cdot m \cdot P_1 + M \cdot m \cdot P_2 - x \cdot z \cdot L_1 + x \cdot z \cdot L_2) \tag{12}$$

$$\frac{d(F(y))}{dy} = (1-2y) \cdot (K_1 - K_2 + x \cdot F_1 + x \cdot L_1 + M \cdot m(P_2 - P_1) - x \cdot z \cdot L_1 + x \cdot z \cdot L_2) \tag{13}$$

$$J(x) = K_1 - K_2 + x \cdot F_1 + x \cdot L_1 + M \cdot m(P_2 - P_1) - x \cdot z \cdot L_1 + x \cdot z \cdot L_2 \tag{14}$$

Similarly, the probability that shipping companies adopt clean energy ships must satisfy the following conditions for stability: when  $F(y) = 0$  and  $d(F(y))/dy < 0$ . Since  $dJ(x)/dy > 0$ ,  $J(x)$  is an increasing function of  $x$ . Therefore, when  $x = [K_1 - K_2 + Mm(P_1 - P_2)] / (zL_1 - L_1 - F_1 - zL_2) = x^*$ ,  $J(x) = 0$ . At this point,  $d(F(y))/dy = 0$ , and shipping companies cannot determine a stable strategy. Additionally, when  $x < x^*$ ,  $J(x) < 0$ , at the same time,  $d(F(y))/dy|_{y=0} < 0$ , and  $y = 0$  is the ESS for shipping companies. Likewise, when  $y = 1$ , it is also the ESS for shipping companies. The strategy evolution phase diagram of shipping companies is shown in *Figure 3*.

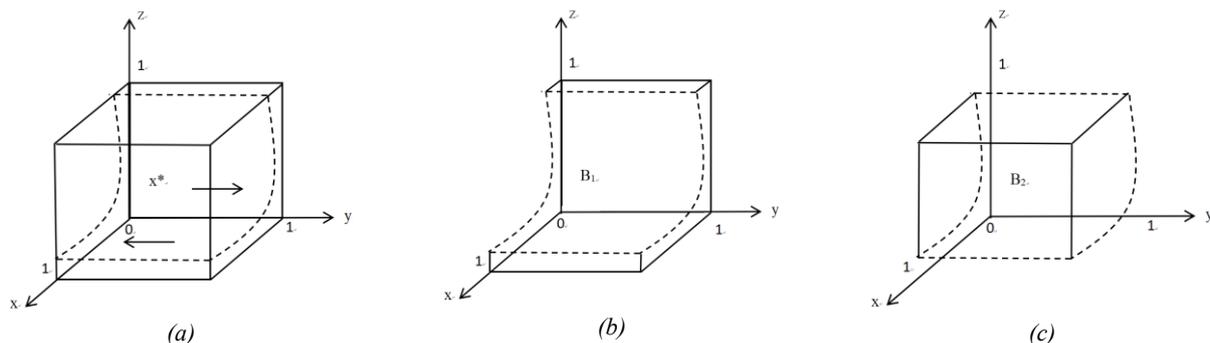


Figure 3 – Strategy evolution phase diagram of shipping companies with three subplots: a)  $x \rightarrow x^*$ ; b)  $x < x^*$ ; c)  $x > x^*$

From Figure 3, it is observed that the volume  $V_{B_1}$  of  $B_1$  represents the probability of shipping companies choosing to adopt clean energy ships, while the probability of shipping companies choosing to adopt traditional energy ships is represented by  $V_{B_2}$  of  $B_2$ . Specifically, the  $V_{B_1}$  and  $V_{B_2}$  are defined as follows.

$$V_{B_1} = \int_0^1 \int_0^1 (x^*) dx dy = \frac{(K_1 - K_2 + M \cdot m \cdot (P_2 - P_1)) \cdot \ln\left(\frac{F_1 + L_2}{F_1 + L_1}\right)}{L_2 - L_1} \tag{15}$$

$$V_{B_2} = 1 - V_{B_1} = 1 - \left( \frac{(K_1 - K_2 + M \cdot m \cdot (P_2 - P_1)) \cdot \ln\left(\frac{F_1 + L_2}{F_1 + L_1}\right)}{L_2 - L_1} \right) \tag{16}$$

**Inference 3:** The probability of shipping companies adopting clean energy ships is positively correlated with the construction cost of traditional energy ships, the fuel cost difference during the ship’s operating cycle, the amount of carbon tax shipping companies are required to pay, and the compensation that port enterprises need to provide to the shipping companies. Besides, it is inversely proportional to the compensation that shipping companies need to provide to port enterprises and the cost of clean energy ships.

**Proof:** Based on Equation (15) and  $\ln\left[\frac{(F_1 + L_2)}{(F_1 + L_1)}\right] = \ln(F_1 + L_2) - \ln(F_1 + L_1)$ , the first-order partial derivatives of each factor are calculated, yielding the following results:  $\partial V_{B_1} / \partial K_1 > 0$ ,  $\partial V_{B_1} / \partial (P_2 - P_1) > 0$ ,  $\partial V_{B_1} / \partial F_1 > 0$ ,  $\partial V_{B_1} / \partial Mm > 0$ ,  $\partial V_{B_1} / \partial L_1 > 0$ ,  $\partial V_{B_1} / \partial L_2 < 0$ ,  $\partial V_{B_1} / \partial K_2 < 0$ . Therefore, an increase in  $K_2$ ,  $F_1$ ,  $Mm$ ,  $L_1$ ,  $(P_2 - P_1)$  or a decrease in  $K_1$  and  $L_2$  all increase the probability of shipping companies adopting clean energy ships.

**Inference 3** suggests that the increase in benefits during shipping companies’ operational cycles and the decrease in the costs of clean energy ships encourage shipping companies to adopt clean energy ships. Simultaneously, the rising costs of traditional energy ships also enhance the likelihood of shipping companies’ adoption of new energy ships. This indicates that shipping companies prioritise both direct and indirect economic benefits, while the government can intensify its incentives and penalties to promote the low-carbon transition of shipping companies.

**Inference 4:** The probability of shipping companies adopting clean energy ships increases with the rise of the government’s active regulation rates and the rates at which port enterprises build clean energy refuelling stations during the evolutionary process.

**Proof:** According to the stability analysis of shipping company strategies, it is inferred that when  $x < x^*$ , specifically  $x < \left[ \frac{K_1 - K_2 + Mm(P_1 - P_2)}{zL_1 - L_1 - F_1 - zL_2} \right] = x^*$ ,  $y = 0$  represents an ESS. Conversely,  $y = 1$  represents an ESS. When  $x$ ,  $z$  gradually increase, the stable strategy of shipping companies increases from  $y = 0$  to  $y = 1$ .

**Inference 4** shows that increasing the probability of port enterprises building clean energy refuelling stations is beneficial for shipping companies to adopt clean energy ships as a stable strategy. On the other hand, the government can promote the transition of shipping companies to clean energy ships not only by increasing the likelihood of active regulation but also by enhancing the compensation provided by port enterprises to shipping companies.

### 3.4 Stability analysis of port enterprises’ strategies

Based on the payoff matrix, the expected benefits of port enterprises of building clean energy refuelling stations  $E_{31}$  and not building clean energy refuelling stations  $E_{32}$  are as follows.

$$E_{31} = y \cdot (1-x) \cdot (M \cdot m \cdot S_1 - K_3) + x \cdot (1-y) \cdot (M \cdot m \cdot S_2 - K_3 + L_2) + x \cdot y \cdot (M \cdot m \cdot S_1 - K_3) + (1-x) \cdot (1-y) \cdot (M \cdot m \cdot S_2 - K_3) \tag{17}$$

$$E_{32} = -x \cdot y \cdot (F_2 + L_1) - x \cdot (1-y) \cdot F_2 \tag{18}$$

Then, the mean utilities of port enterprises  $\bar{E}_z$  is as follows.

$$\bar{E}_z = zE_{31} + (1-z) \cdot E_{32} \tag{19}$$

Consequently, the replicating dynamic equation for port enterprises  $F(z)$ , the first derivative and the set  $H(x)$  are respectively as follows.

$$F(z) = z \cdot (E_{31} - \bar{E}_z) = z \cdot (1-z) \cdot (x \cdot F_2 - K_3 + x \cdot L_2 + M \cdot m \cdot S_2 + x \cdot y \cdot L_1 - x \cdot y \cdot L_2 + y \cdot M \cdot m \cdot S_1 - y \cdot M \cdot m \cdot S_2) \tag{20}$$

$$\frac{d(F(z))}{dz} = (1-2z) \cdot (x \cdot F_2 - K_3 + x \cdot L_2 + M \cdot m \cdot S_2 + x \cdot y \cdot L_1 - x \cdot y \cdot L_2 + y \cdot M \cdot m \cdot S_1 - y \cdot M \cdot m \cdot S_2) \tag{21}$$

$$H(x) = x \cdot F_2 - K_3 + x \cdot L_2 + M \cdot m \cdot S_2 + x \cdot y \cdot L_1 - x \cdot y \cdot L_2 + y \cdot M \cdot m \cdot S_1 - y \cdot M \cdot m \cdot S_2 \tag{22}$$

Similarly, the probability that port enterprises choose to adopt to build clean energy refuelling stations must satisfy the following conditions for stability:  $d(F(z))/dz < 0$ , where  $dH(x)/dx > 0$ ,  $H(x)$  is an increasing function of  $x$ . Thus, when  $x = [K_3 - MmS_2 - yMm(S_1 - S_2)] / (F_2 + L_2) + y(L_1 - L_2) = x^{**}$ , then  $H(x) = 0$ . At this time,  $d(F(z))/dz = 0$ , port enterprises do not determine a stabilisation strategy. Additionally, when  $x < x^{**}$  and  $H(x) < 0$ ,  $d(F(z))/dz|_{z=0} < 0$  is obtained.  $z = 0$  is the equilibrium point of the evolutionary stability strategy of port enterprises. Similarly, when  $z = 1$ , it also represents an evolutionary stable strategy equilibrium point for port enterprises. Specifically, the strategy evolution phase diagram of port enterprises is shown in Figure 4.

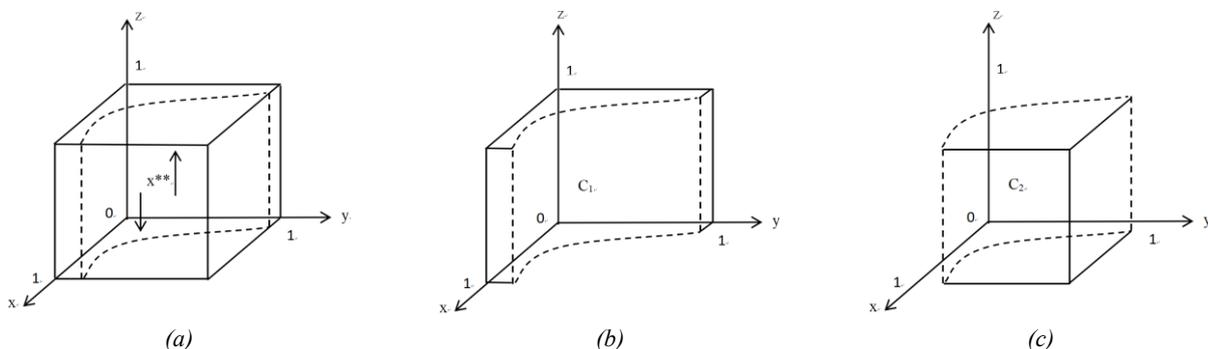


Figure 4 – Strategy evolution phase diagram of port enterprises with three subplots: a)  $x=x^{**}$ ; b)  $x < x^{**}$ ; c)  $x > x^{**}$

From Figure 4, it is observed that the volume  $V_{C_1}$  of  $C_1$  represents the probability of port enterprises constructing a clean energy refuelling station, while the probability of port enterprises not constructing a clean energy refuelling station is represented by the volume  $V_{C_2}$  of  $C_2$ . Specifically, the  $V_{C_1}$  and  $V_{C_2}$  are defined as follows.

$$\begin{aligned}
 V_{C1} &= \int_0^1 \int_0^1 (x^{**}) dy dz \\
 &= \left( \frac{M \cdot m \cdot S_1 \cdot (L_2 + F_2)}{M \cdot m \cdot S_2 \cdot (L_1 + F_2)} \right) \cdot \ln \left( \frac{L_2 + F_2}{L_1 + F_2} \right) - K_3 \cdot (L_2 - L_1) \cdot \ln \left( \frac{L_2 + F_2}{L_1 + F_2} \right) + (L_2 - L_1) \cdot (L_2 + F_2)
 \end{aligned} \tag{23}$$

$$\begin{aligned}
 V_{C2} &= 1 - V_{C1} \\
 &= 1 - \left( \frac{M \cdot m \cdot S_1 \cdot (L_2 + F_2)}{M \cdot m \cdot S_2 \cdot (L_1 + F_2)} \right) \cdot \ln \left( \frac{L_2 + F_2}{L_1 + F_2} \right) - K_3 \cdot (L_2 - L_1) \cdot \ln \left( \frac{L_2 + F_2}{L_1 + F_2} \right) + (L_2 - L_1) \cdot (L_2 + F_2)
 \end{aligned} \tag{24}$$

**Inference 5:** The probability of port enterprises choosing to build clean energy refuelling stations is positively correlated with the economic benefits of clean energy ships when they use the clean refuelling stations, port enterprise provides to the shipping companies' compensation and the carbon tax that the port enterprise pays. Conversely, it is negatively correlated with the construction costs of clean energy ships and the compensation that the shipping companies must provide to the local port enterprises.

**Proof:** Based on Equation (23), the first-order partial derivatives of each factor are calculated, yielding the following results:  $\partial V_{C1} / \partial S_1 > 0$ ,  $\partial V_{C1} / \partial L_1 > 0$ ,  $\partial V_{C1} / \partial F_2 > 0$ ,  $\partial V_{C1} / \partial K_3 < 0$ ,  $\partial V_{C1} / \partial L_2 < 0$ ,  $\partial V_{C1} / \partial S_2 < 0$ . Therefore, an increase in  $L_1$ ,  $F_2$ ,  $S_1$  or a decrease in  $K_3$ ,  $L_2$  and  $S_2$  lead to an increase in the probability of shipping companies adopting clean energy ships.

**Inference 5** shows that increasing the usage of clean energy ships by local shipping companies can effectively enhance the probability that a port enterprise chooses to construct a clean energy refuelling station. Furthermore, the government can raise carbon tax rates or increase the strength of the compensation policy to encourage the port enterprise to build clean energy refuelling stations.

**Inference 6:** During the evolutionary process, the probability of port enterprises choosing to build a clean energy refuelling station increases with the rise in the government's active regulation rate and the usage rate of clean energy ships by shipping companies.

**Proof:** From the stability analysis of shipping companies' strategies, it is inferred that when  $x < x^{**}$  and  $x < [K_3 - MmS_2 - yMm(S_1 - S_2)] / (F_2 + L_2) + y(L_1 - L_2) = x^{**}$ ,  $z = 0$  represents an ESS. Conversely,  $z = 1$  serves as an ESS. At the same time, as  $x$ ,  $y$  gradually increases, the stable strategy for shipping companies transitions from  $z = 0$  to  $z = 1$ .

**Inference 6** suggests that increasing the probability of shipping companies adopting clean energy ships facilitates port enterprises in building clean energy refuelling stations as a stable strategy. The government can enhance the probability of active regulation to encourage port enterprises to actively build clean energy refuelling stations. Additionally, increasing compensation from shipping companies to port enterprises can promote the green transition of port enterprises.

#### 4. STABILITY ANALYSIS OF THE MODEL

This study analyses the local stability of the game participants and determines the stability of each equilibrium point. Specifically, this study constructs the Jacobin matrix by combining the replicator dynamic equations for government, shipping companies and port enterprises [43]. The result is shown in Equation (25).

Based on research conclusions by Ritzbe et al., this study discusses 8 local equilibrium points when  $F(x) = 0$ ,  $F(y) = 0$ , and  $F(z) = 0$  to investigate the evolution of stable strategies of the game participants. The eigenvalues obtained by substituting equilibrium points into Equation (25), the details are presented in Table 3 [44].

Table 3 – Eigenvalues of each equilibrium point

Equilibrium points	Eigenvalue		
	$\lambda_1$	$\lambda_2$	$\lambda_3$
$E_1(0,0,0)$	$MmS_2-K_3$	$K_1-K_2+Mm(P_2-P_1)$	$C_2-C_1+C_3+F_1+F_2+H+W$
$E_2(1,0,0)$	$F_2+MmS_2-K_3+L_2$	$F_1+K_1-K_2+Mm(P_2-P_1)+L_1$	$C_1-C_2-C_3-F_1-F_2-H-W$
$E_3(0,1,0)$	$MmS_1-K_3$	$K_2-K_1+Mm(P_1-P_2)$	$C_2-C_1+C_3+F_2+H+W$
$E_4(0,0,1)$	$K_3-MmS_2$	$K_1-K_2+Mm(P_2-P_1)$	$C_2-C_1+C_3+F_1+H+W$
$E_5(1,1,0)$	$MmS_1-K_3+F_2+L_1$	$K_2-K_1+Mm(P_1-P_2)-F_1-L_1$	$C_1-C_2-C_3-F_2-H-W$
$E_6(1,0,1)$	$K_3-MmS_2-F_2-L_2$	$F_1+K_1-K_2+Mm(P_2-P_1)+L_2$	$C_1-C_2-C_3-F_1-H-W$
$E_7(0,1,1)$	$K_3-MmS_1$	$C_2-C_1+W$	$K_2-K_1+Mm(P_1-P_2)$
$E_8(1,1,1)$	$C_1-C_2-W$	$K_3-MmS_1-F_2-L_1$	$K_2-K_1+Mm(P_1-P_2)-F_1$

$$J = \begin{bmatrix} (1-2x) \cdot \begin{pmatrix} H + F_1 + F_2 + W \\ -C_1 + C_2 + C_3 \\ -y \cdot F_1 - z \cdot F_2 \\ -y \cdot z \cdot C_3 - y \cdot z \cdot H \end{pmatrix} & x \cdot (1-x) \cdot (z \cdot C_3 + z \cdot H + F_1) & x \cdot (1-x) \cdot (y \cdot C_3 + F_2 + y \cdot H) \\ y \cdot (1-y) \cdot F_1 & (1-2y) \cdot \begin{pmatrix} K_1 - K_2 + x \cdot F_1 \\ -z \cdot L_1 + z \cdot L_2 + L_1 \\ + M \cdot m \cdot (P_2 - P_1) \end{pmatrix} & y \cdot (1-y) \cdot (L_1 - L_2) \\ z \cdot (1-z) \cdot F_2 & z \cdot (1-z) \cdot \begin{pmatrix} L_1 - M \cdot m \cdot S_2 \\ -L_2 + M \cdot m \cdot S_1 \end{pmatrix} & (1-2z) \cdot \begin{pmatrix} L_2 + y \cdot M \cdot m \cdot S_1 \\ -y \cdot M \cdot m \cdot S_2 - K_3 \\ + M \cdot m \cdot S_2 + x \cdot F_2 \\ + y \cdot L_1 - y \cdot L_2 \end{pmatrix} \end{bmatrix} \tag{25}$$

Based on the Lyapunov stability theorem, when  $\lambda$  of the Jacobin matrix satisfy  $\lambda < 0$ , the equilibrium point is stable, which is the ESS [45]. Therefore, this study proposes the assumption as  $F_1 + Mm(P_2 - P_1) + L_1 < K_2 - K_1$  and  $F_2 + MmS_2 + L_2 < K_3$ , which indicates that the cost of constructing a new energy refuelling station for the port enterprise is higher than the net revenue generated during its operation without constructing the station. Given the numerous model parameters, the signs of most eigenvalues are determined based on the eigenvalues at the equilibrium point (1,1,1). Specifically, the eigenvalues at the equilibrium point (1,1,1) contain  $C_1 - C_2 - W$ ,  $K_3 - MmS_1 - F_2 - L_1$ ,  $K_2 - K_1 + Mm(P_1 - P_2) - F_1 - L_2$ . Therefore, an analysis of the sign properties of the above three equations indicates that the stability of the equilibrium point is determined by eight scenarios, which are shown in Table 4. Meanwhile, the stability analysis results of equilibrium points under different scenarios are shown in Tables 5–8.

Table 4 – Scenario settings

Eigenvalue	Scenario							
	1	2	3	4	5	6	7	8
$C_1-C_2-W$	+	-	+	+	-	+	-	-
$K_3-MmS_1-F_2-L_1$	+	-	-	+	+	-	-	+
$K_2-K_1+Mm(P_1-P_2)-F_1-L_2$	+	-	-	-	+	+	+	-

Table 5 – Stability analysis of equilibrium points for the tripartite game under different scenarios

Equilibrium points	Scenario 1				Scenario 2			
	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability
$E_1$	-	-	-	ESS	-	-	+/-	Unstable
$E_2$	-	-	+/-	Unstable	-	-	-	ESS
$E_3$	-	+	-	Unstable	+/-	+	+/-	Unstable
$E_4$	+	-	-	Unstable	+	-	+/-	Unstable
$E_5$	-	+/-	+/-	Unstable	+	+/-	-	Unstable
$E_6$	+	-	+/-	Unstable	+	+	-	Unstable
$E_7$	+	-	+	Unstable	+/-	+	+	Unstable
$E_8$	+	+	+	Unstable	-	-	-	ESS

Table 6 – Stability analysis of equilibrium points for the tripartite game under different scenarios

Equilibrium points	Scenario 3				Scenario 4			
	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability
$E_1$	-	-	-	ESS	-	-	-	ESS
$E_2$	-	-	+/-	Unstable	-	-	+/-	Unstable
$E_3$	+/-	+	-	Unstable	-	+	-	Unstable
$E_4$	+	-	-	Unstable	+	-	-	Unstable
$E_5$	+	+/-	+/-	Unstable	-	+/-	+/-	Unstable
$E_6$	+	+	+/-	Unstable	+	+	+/-	Unstable
$E_7$	+/-	-	+	Unstable	+	-	+	Unstable
$E_8$	+	-	-	Unstable	+	+	-	Unstable

Table 7 – Stability analysis of equilibrium points for the tripartite game under different scenarios

Equilibrium points	Scenario 5				Scenario 6			
	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability
$E_1$	-	-	+/-	Unstable	-	-	-	ESS
$E_2$	-	-	-	ESS	-	-	+/-	Unstable
$E_3$	-	+	+/-	Unstable	+/-	+	-	Unstable
$E_4$	+	-	+/-	Unstable	+	-	-	Unstable
$E_5$	-	+/-	-	Unstable	+	+/-	+/-	Unstable
$E_6$	+	-	-	Unstable	+	-	+/-	Unstable
$E_7$	+	+	+	Unstable	+/-	-	+	Unstable
$E_8$	-	+	+	Unstable	+	-	+	Unstable

Table 8 – Stability analysis of equilibrium points for the tripartite game under different scenarios

Equilibrium points	Scenario 7				Scenario 8			
	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability	$\lambda_1$	$\lambda_2$	$\lambda_3$	Stability
$E_1$	-	-	+/-	Unstable	-	-	+/-	Unstable
$E_2$	-	-	-	ESS	-	-	-	ESS
$E_3$	+/-	+	+/-	Unstable	-	+	+/-	Unstable
$E_4$	+	-	+/-	Unstable	+	-	+/-	Unstable
$E_5$	+	+/-	-	Unstable	-	+/-	-	Unstable
$E_6$	+	-	-	Unstable	+	+	-	Unstable
$E_7$	+/-	+	+	Unstable	+	+	+	Unstable
$E_8$	-	-	+	Unstable	-	+	-	Unstable

Based on the aforementioned tables, the stability analysis results of equilibrium points for the tripartite game are as follows. In scenario 2, the simulation results reach equilibrium at (1,0,0) and (1,1,1), where there are two ESS combinations. In other scenarios, there is only one ESS combination.

According to the numerical stability obtained, the following conclusions are obtained. Firstly, for the government, active regulation is favoured when regulatory costs are relatively low and the potential reputation benefits are significant. Secondly, for the shipping companies, the decision to utilise clean energy ships is influenced by factors such as the ships’ operational time, the construction costs of traditional and clean energy ships, the fuel cost differentials between these types of ships, and the intensity of carbon tax policies and compensation measures. Specifically, when other influencing factors are held constant, if the compensation and carbon taxes imposed on shipping companies are substantial, the shipping companies are more likely to adopt clean energy ships. Thirdly, for the port enterprises, whether to construct clean energy refuelling stations has a significant impact on the operations of port enterprises. In the same case, when local shipping companies opt for clean energy ships, port enterprises experience higher revenues, which incentivises them to invest in clean energy refuelling stations. Furthermore, port enterprises are more inclined to adopt low-carbon behaviours when the government effectively implements reward and punishment measures.

### 5. SIMULATION

To analyse the evolving patterns’ behaviour of stakeholders involved in the promotion of carbon emission mitigation in the shipping industry, this study conducted numerical simulations utilising MATLAB 2022a. Based on assumptions, this study assigned values to parameters and conducted simulations to determine the equilibrium points of the evolutionary game. The parameter values mainly reference the practice of previous scholars [46]. The primary aim of these simulations is to verify the accuracy and reliability of the model and its associated parameters. Subsequently, the details in Table 9 are as follows.

Table 9 – Set of parameter values

Set 1 of parameter values				Set 2 of parameter values			
Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
$H$	5	$F$	3	$H$	5	$F$	3
$R_0$	5	$F_1$	2	$R_0$	5	$F_1$	2
$C_1$	5	$F_2$	1	$C_1$	100	$F_2$	1
$C_2$	30	$W$	3	$C_2$	2	$W$	3
$C_3$	10	$M$	2	$C_3$	10	$M$	2
$G$	1	$m$	2	$G$	1	$m$	2

Set 1 of parameter values				Set 2 of parameter values			
Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
$K_1$	1	$P_1$	1	$K_1$	1	$P_1$	1
$K_2$	10	$P_2$	2	$K_2$	10	$P_2$	2
$K_3$	40	$S_1$	10	$K_3$	40	$S_1$	5
$L_1$	2.5	$S_2$	1	$L_1$	2.5	$S_2$	1
$L_2$	20			$L_2$	20		

### 5.1 Evolutionary trajectory

Based on the stability point parameters and constraints, specific values are assigned to the respective parameters. For Scenario 1, a Set 1 of parameter values is utilised, while for Scenario 2, a Set 2 of parameter values is employed. To ensure the scientific validity of the simulation, these two sets of parameter arrays undergo 50 iterations, and the outcomes of these iterations are depicted in Figures 5–7.

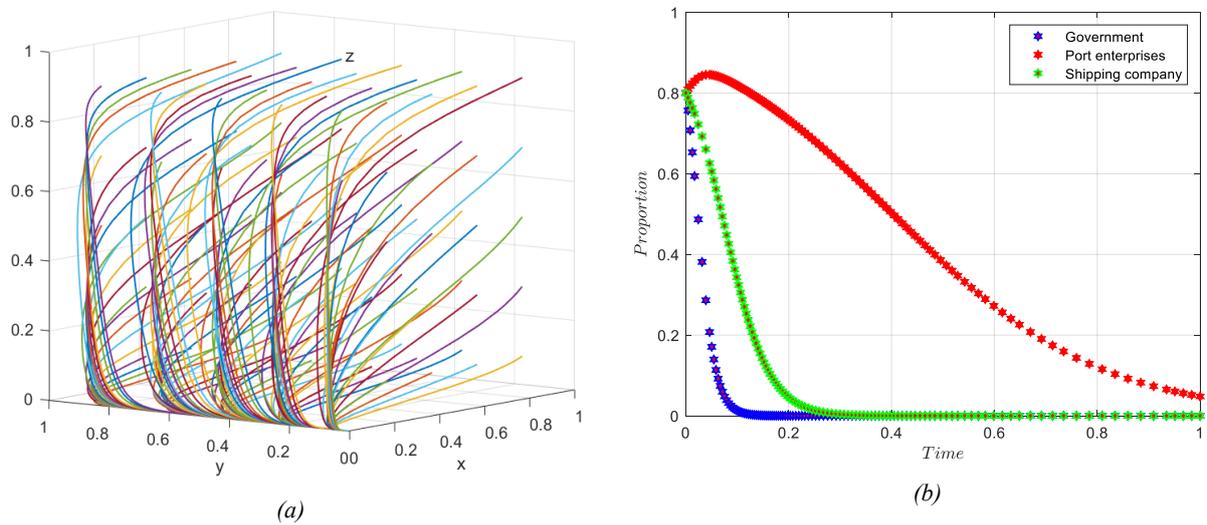


Figure 5 – Evolutionary trajectory of  $E_1$  with two subplots: a) the Sets 1 of values evolved 50 times over time; b) the evolutionary trajectory when the initial willingness is  $x = y = z = 0.8$

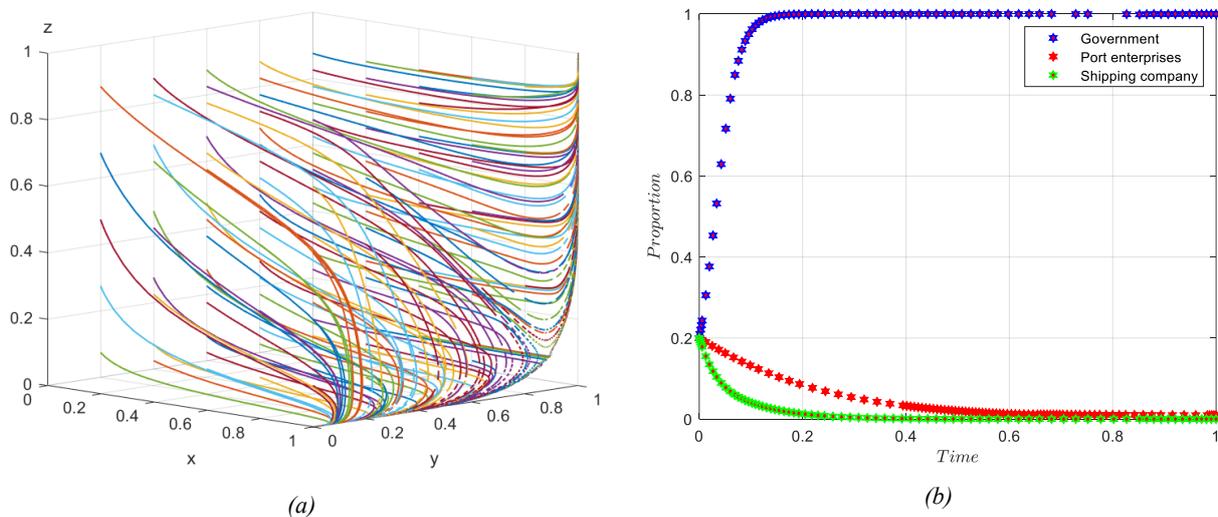


Figure 6 – Evolutionary trajectory of  $E_2$  with two subplots: a) the Sets 2 of values evolved 50 times over time; b) the evolutionary trajectory when the initial willingness is  $x = y = z = 0.2$

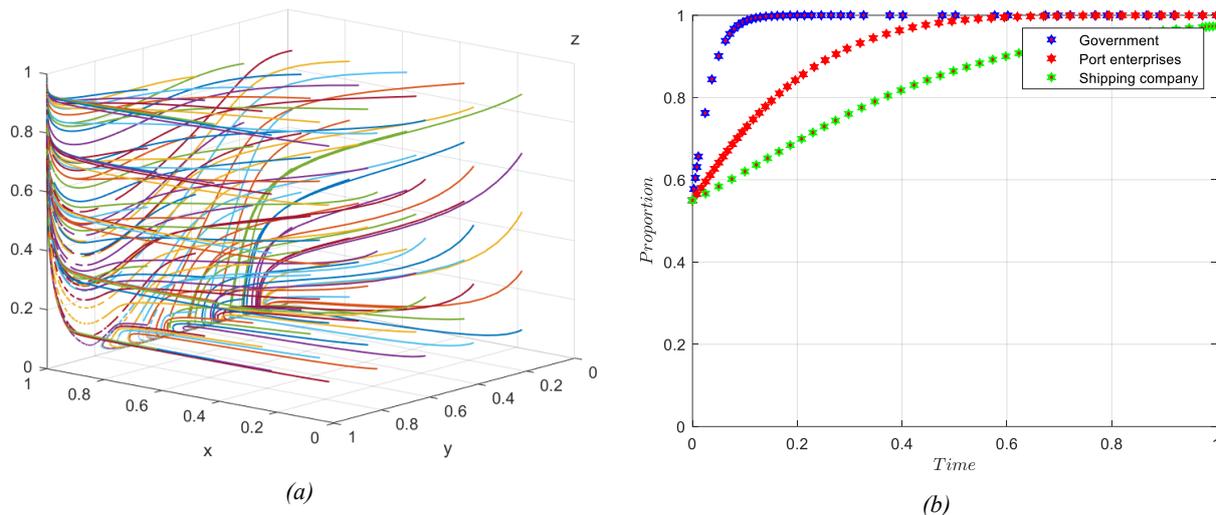


Figure 7 – Evolutionary trajectory of  $E_s$  with two subplots: a) the Sets 2 of values evolved 50 times over time; b) the evolutionary trajectory when the initial willingness is  $x = y = z = 0.5$

In Scenario 1, simulation results reach equilibrium at  $(0,0,0)$ . In this case, the government is not willing to make policy adjustments. Shipping companies and port enterprises give up on green transformation because of the low direct economic benefits. In response to this situation, the government needs to make timely policy adjustments. Meanwhile, the public must also enhance their environmental awareness to increase the reputation benefits when the government chooses to adopt active regulations. Besides, shipping companies and port enterprises should strengthen their collaboration and actively coordinate with the government to accelerate the green transition of the shipping industry.

In Scenario 2, the results reach equilibrium at  $(1,0,0)$  and  $(1,1,1)$ . In this case, the choices of the government directly affect the decision choices of shipping companies and port enterprises. In response to this situation, the government needs to intensify the policies of incentives and penalties. It aims to offset the high initial costs incurred by shipping companies and port enterprises during the early stages of their green transition. Additionally, shipping companies and port enterprises should capitalise on favourable government policies to vigorously develop the clean energy sector and collaboratively promote the low-carbon transformation of the shipping industry.

### 5.2 Impacts of key parameters

Due to the uncertainty in the implementation of reward and punishment mechanisms and the rapid advancements in clean energy technology, the volatility of the strength of policy implementation and ships’ operational time is relatively high. Thus, the parameters selected include  $F_1, F_2, L_1, L_2, C_1, M$ , then select parameter value 2 as the initial parameter, consider a set of participants as  $x = y = z = 0.5$ . The dynamic equation system is evolved for 50 iterations.

#### The impact of $F_1$ and $F_2$

Maintaining the other parameters constant and letting  $F_1 = 2, 2.6, 10, F_2 = 1, 1.7, 4$ , the impact of  $F_1$  and  $F_2$  on evolutionary results and trajectories are shown in Figure 8. Based on the results of Figure 8, the intensity of the carbon tax policy affects the evolutionary equilibrium point. Besides, the influence of carbon tax policy on port enterprises is relatively minor, whereas its influence on shipping companies is pronounced. This is due to the high carbon emissions of shipping companies, which primarily originate from the fuel combustion of traditional energy ships, whereas the carbon emissions of port enterprises primarily stem from the port handling equipment. In contrast, the carbon emissions of shipping companies are higher than those of port enterprises when other conditions are equal. Thus, the implementation of carbon tax policies exerts a more significant impact on shipping companies than on port enterprises.

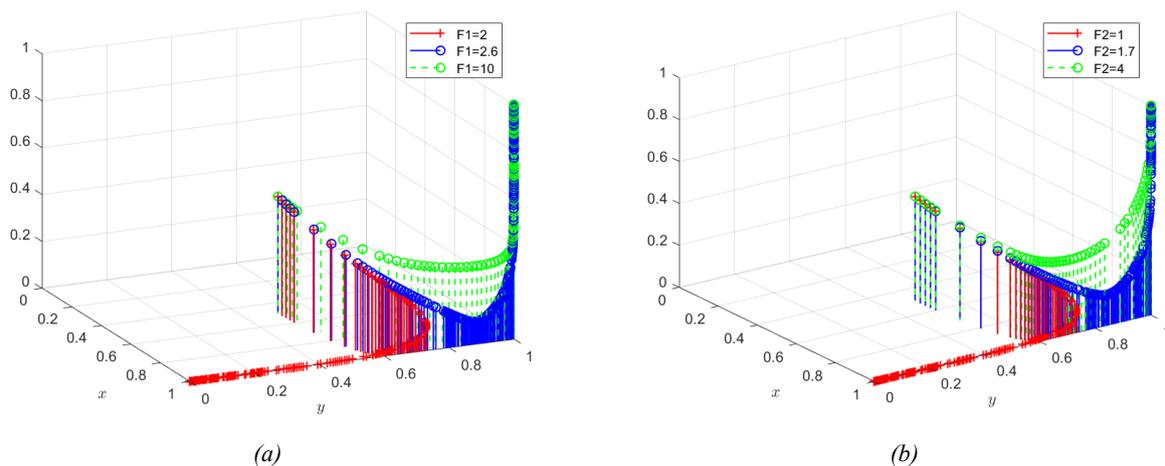


Figure 8 – Impact of  $F_1$  and  $F_2$  on evolutionary results and trajectories with two subplots: a) impact of  $F_1$ ; b) impact of  $F_2$

### The impact of $L_1$ and $L_2$

Maintaining the other parameters constant and letting  $L_1 = 1, 1.2, 1.5$ , and  $L_2 = 20, 21, 22$ , the impact of  $L_1$  and  $L_2$  on evolutionary results and trajectories are shown in Figure 9. Based on the results of Figure 9, the intensity of the compensation policy affects the evolutionary equilibrium point. Additionally, the impact of compensation policy on shipping companies is relatively minor, whereas its influence on port enterprises is pronounced. The reason for that is that the economic revenues of port enterprises are susceptible to impact from external factors, such as the utilisation status of clean energy ships by local shipping companies, the construction costs of clean energy refuelling stations and so on. In contrast, due to the lower fuel cost associated with clean energy ships, shipping companies can internalise high initial costs by extending the ships’ operational time. Therefore, port enterprises have a greater need for the compensation policy of the government to provide regulatory adjustments.

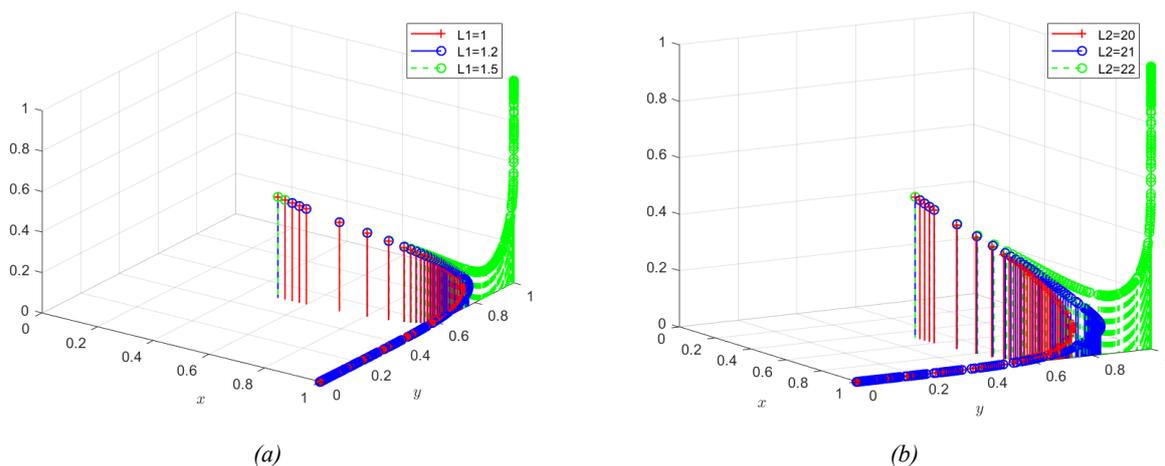


Figure 9 – Impact of  $L_1$  and  $L_2$  on evolutionary results and trajectories with two subplots: a) impact of  $L_1$ ; b) impact of  $L_2$

### The impact of $C_1$ and $M$

Maintain the other parameters constant and let  $C_1 = 50, 52, 55$ ,  $M = 0.5, 2.5, 30$ . The impact of  $C_1$  and  $M$  on evolutionary results and trajectories is shown in Figure 10. Based on the results of Figure 10, both the size of government regulatory costs and the length of ship operation affect the evolutionary equilibrium point. Moreover, the total revenue of shipping companies and port enterprises cannot offset the significant initial costs associated with adopting clean energy products when the ships’ operational time is short. Thus, when the operational time of ships is relatively short, they are unlikely to adopt behaviour in carbon emission reduction.

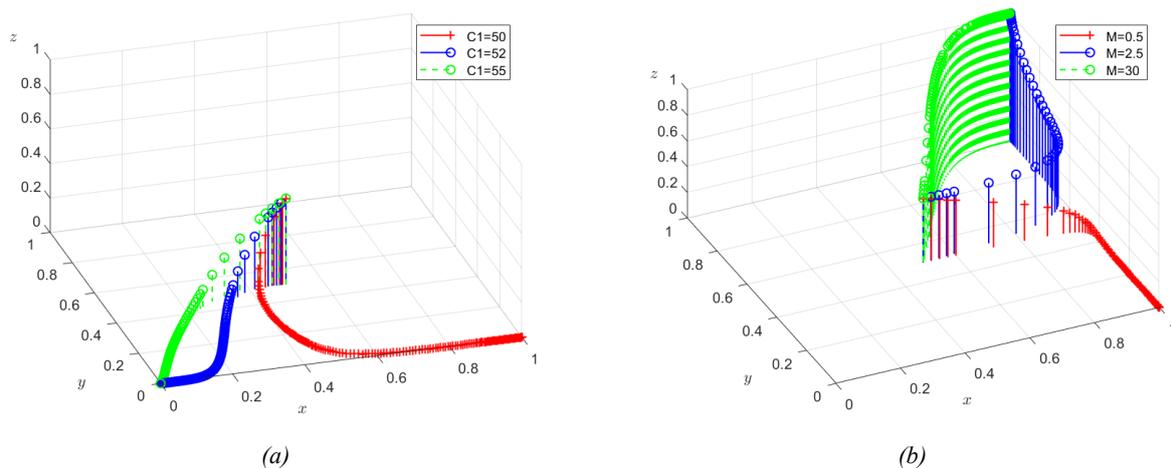


Figure 10 – Impact of  $C_1$  and  $M$  on evolutionary results and trajectories with two subplots: a) impact of  $C_1$ ; b) impact of  $M$

Based on the above parameter analysis, it is shown that the impact of carbon tax policy on shipping companies is more remarkable than that on port enterprises' behaviour. Meanwhile, the effect of compensation policy on port enterprises' behaviour is more remarkable than on shipping companies' behaviour. Besides, the impact of the ships' operational time on both shipping companies and port enterprises is significant. Moreover, the high internal costs associated with a low-carbon transition in the shipping industry are also a significant issue. The government should perfect the compensation policy regarding the relative initial costs and help the shipping industry achieve sustainable development. Therefore, it is crucial to implement targeted reward and punishment policies to promote collaboration between shipping companies and port enterprises.

## 6. CONCLUSIONS AND SUGGESTIONS

To investigate the effects of the government's reward and punishment mechanisms on low-carbon behaviour in the shipping industry, this study introduces a series of mathematical models and draws the following conclusions.

Firstly, under the government's reward and punishment mechanisms, the optimal strategy that the government, shipping companies and port enterprises finally achieve is that the government chooses to adopt active regulation, shipping companies choose to adopt clean energy ships, and port enterprises choose to adopt building clean energy refuelling stations. These findings indicate that the reward and punishment mechanisms could be effective in promoting the shipping industry to choose to adopt carbon emission reduction behaviour.

Secondly, as a key factor in promoting the sustainable transformation of the shipping industry, the government's decisions have a substantial influence on the behaviour adopted by shipping companies and port enterprises. This study reveals that when the government opts for active regulation, shipping companies and port enterprises are inclined to implement emission reduction strategies swiftly and proactively. Furthermore, a lower regulation cost can encourage the government to adopt active regulation. Therefore, the government must leverage its dominant position and formulate a well-structured reward and punishment mechanism. Additionally, the public should bolster their environmental awareness, thereby offering the government greater reputation benefits when it chooses active regulation.

Thirdly, shipping companies tend to prioritise local port enterprises for the refuelling of clean energy ships. Therefore, it effectively facilitates the establishment of clean energy refuelling stations at port enterprises when shipping companies choose to adopt clean energy ships. Moreover, the lower fuel cost associated with clean energy ships can sufficiently offset the significant initial capital expenditures required for their implementation when the ships' operational cycle is sufficiently long. Thus, the ships' operational cycle is an important factor in the low-carbon behaviour of the shipping industry. It is suggested that in the future, it is essential to enhance the technological capabilities related to clean energy, establish a mature clean energy products supply chain and prevent inflated prices for clean energy products. Additionally, refining government compensation policies collectively promotes the green development of the shipping industry.

Additionally, this study is conducted from the perspective of game and decision-making among stakeholders involved in carbon emission reduction associated with the shipping industry. Specifically, this study distils the strategic choice mechanisms for each stakeholder under the background of carbon emission

reduction. It elucidates the strategic decision-making frameworks available to each stakeholder in the context of carbon reduction initiatives. The findings of this study provide support for the implementation of carbon trading in the shipping industry and the imposition of carbon taxes on shipping companies. Although this study has yielded a set of conclusions, there are still some limitations on data collection and potential players. Firstly, even though the results of the simulation are consistent with the model analysis results in this study, the parameter values are still relatively abstract. The work of collecting data should be carried out in the future to make it more realistic. Secondly, this study mainly focuses on government, shipping companies and port enterprises, while overlooking other entities related to carbon emission reduction behaviour in the shipping industry, such as environmental organisations, the general public and climate change deniers. Future studies will aim to construct a more realistic model to consider more players. Thirdly, this study is conducted at the macro level and ignores the type of alternative fuels and ships, such as cargo ships, cruise ships and icebreakers. Different types of fuel and ships may restrict the model. Further research aims to construct more detailed fuel and ship models.

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