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Evolutionary game analysis on behavioral strategies of multiple stakeholders under the process of shore power promotion

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Abstract. Shore power implementation was proved to be an effective way to reduce air pollution from vessels. Although central government has been promoting the implementation of shore power in China, the actual development of shore power is not ideal currently. The paper focuses on the mechanism of interaction among the strategic choices of multiple stakeholders including local government, port, and liner company under the process of shore power promotion. Based on an evolutionary game model, the influencing factors on the evolutionarily stable strategies (ESS) of the multiple stakeholders is discussed. The results of the study show that local governments can speed up the process of implementing shore power by increasing the incentives and penalties for enterprises, but excessive subsidies could undermine the enthusiasm of local governments to participate in the promotion of shore power; preferential pricing of shore power is of great significance to the promotion of shore power; when the economic benefit of implementing shore power is great enough, enterprises can implement shore power spontaneously even if local governments do not participate in the promotion of shore power.

1 Introduction

In the context of economic globalization, maritime industry has developed rapidly as an important part of the global supply chain, but while it has made great contributions to the economic development of foreign trade, it has also become one of the main sources of air pollution. Since vessels are generally powered by non-clean fuels such as diesel and heavy oil, they emit a lot of greenhouse gases and air pollutants such as SO_2 and NOx during driving or berthing [1]. Shore power technology means that during the loading and unloading operation of vessels in port, they are connected to the port shore power supply facilities to maintain their production and living electricity, thus replacing the use of their own auxiliary diesel engines for power generation, Shore power implementation has been proven to be effective in improving vessel pollution [2-3]. At the same time, the implementation of shore power also has certain economic benefits: for liner companies, the use of shore power charging when vessel calls at port can save a sum of fuel consumption costs, and the port can also provide shore power charging services to achieve industrial income diversification.

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The implementation of shore power technology is beneficial for the environment improvement and maritime development, but the implementation process is hampered by many obstacles. Many scholars have researched and summarized some of the main reasons such as high construction costs, insufficient government subsidies, and immature technology [4-6]. In addition, Winkel et al. [7] pointed out that the implementation of shore power may be caught in a "chicken and egg" dilemma: ports may be reluctant to build shore power supply facilities until the vessel is powered, and vessels will wait to see if the port will start building shore power supply facilities until the vessel is powered, a dilemma that also exists for electric vehicle infrastructure investments. This dilemma also exists in the investment in electric vehicle infrastructure [8-9]. Therefore, some scholars have applied game theory to the study of shore power implementation: Song et al. [10] constructed a Nash game between two liner companies on the decision of using shore power, and analyzes the impact of government intervention on the equilibrium of the game to demonstrate the importance of government price subsidy on the implementation of shore power. Wang et al. [11] proposed a Stackelberg game theoretic model for optimizing government subsidies considering the interaction between government, ports and liner companies, which aims to help government maximize the efficiency of shore power subsidies. Based on a game model, Xing et al. [12] investigates the design of bilateral (supply and demand) government green subsidies at target adoption levels under the influence of uncertain demand due to fluctuations in conventional energy prices. These scholars have applied traditional game theory to the study of onshore power implementation process, which fully considered the synergistic effects among multiple participants in the process and can provide

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theoretical basis for the government to formulate relevant policies, which has certain significance. However, in the traditional game theory, it is generally assumed that the participants are perfectly rational and the game is played under the condition of complete information, but the economic environment and the complexity of the game itself lead to incomplete information and the limited rationality of the participants is obvious.

Based on the inadequacy of the current research, considering that the shore power implementation system is a large and complex system consisting of multiple stakeholders including local governments, ports and liner companies, this paper constructs an evolutionary game model including local governments, ports and liner companies to analyze the stability of the equilibrium points of the evolutionary strategies in the shore power promotion system and conducts numerical simulation analysis using MATLAB software. In order to explore the influence of the local government's incentives and penalties, the economic benefits of implementing shore power on the strategy choice of each subject, and to show the evolutionary stability strategy at different stages, so as to provide a decision basis for the government to promote the implementation of shore power.

2 Evolutionary game model

2.1 Problem description and basic assumptions

The implementation process of the shore power implementation policy is led by the central government and based on the regional promotion by local government promotion. The central government issued policies to speed up the implementation process of shore power to improve the atmospheric environment, and local governments cooperate with the central government to promote the implementation of shore power. The implementation of shore power requires the participation of several agents, besides the two relevant enterprises, ports and liner companies, the local government, as the party that supervises and provides incentives for the implementation, has an important influence on the decision of enterprises. Therefore, this paper will construct an evolutionary game model of three players including local government, ports and liner companies. The basic assumptions of the model are as follows.

(1) Limited rationality of local governments, ports and liner companies: At the beginning of the game, it is difficult for each player to predict the expected benefits of different strategies and choose their own optimal strategies to maximize their benefits, but they gradually adjust their own strategies to the optimal ones through trial and error and learning from others' experiences.

(2) The strategy space of the local government is $\alpha = (\alpha_1, \alpha_2)$ = (participate in shore power promotion, not participate in shore power promotion) and local government choose α_1 with probability of x while choose α_2 with probability of (1-x),$x \in [0,1]$.The strategy space of the port is $\beta=(\beta_1 , \beta_2)$ = (provide shore power, not provide shore power) and port choose β_1 with probability of y while choose β_2 with probability of (1-y) ,$y \in [0,1]$; the strategy space of the liner company is $\gamma =(\gamma_1, \gamma_2)$ = (use shore power, not use shore power), and local government choose γ_1 with probability of z while choose γ_2 with probability of (1-z),$z \in [0,1]$,and the game starts with $x= x_0$, $y= y_0$ and $z= z_0$.

(3) The initial social welfare of the local government is G_1 when they choose to participate in the shore power promotion strategy, the central government will provide local government financial allocation of R_1 when they choose to participate in the shore power promotion strategy. The local government will provide subsidies of A_1 to the port that provides shore power and A_2 to the liner company that uses shore power. Additionally, the local government also bear the costs of C_1 for policy promotion and regulation. If local government chooses to participate in the shore power promotion strategy, the local government can impose administrative penalties of E_1 on the port that chooses not to provide shore power. Generally, it is difficult for local governments to intervene and control liner companies, so liner companies are not within the scope of local governments' regulation and punishment. When local governments choose to participate in the shore power promotion strategy and ports and liner companies choose to provide shore power and use shore power strategies respectively, local governments will gain social and environmental benefits of R_2.

(4) The initial benefit for port is G_2. The total cost for port enterprises to provide shore power is C_2, mainly including the cost of construction and maintenance of shore power facilities, berth renovation and operation, etc. The input cost for port enterprises is greater than the subsidy provided by the local government for them, i.e. $C_2> A_1$; the initial benefit for liner companies is C_3, the total cost for liner companies to use shore power is C_3, mainly including the cost of renovating vessels, maintaining equipment, staff training, etc. The input cost for liner companies is greater than the subsidy provided by the local government for them, i.e. $C_3> A_2$.

(5) If the port and the liner company choose the strategy of providing shore power and using shore power respectively, both the port and the liner company will achieve the economic benefits of implementing shore power: the port will get the economic benefits of E_2 from providing shore power supply service. The liner company will gain economic benefits of E_3 from the use of shore power and fuel cost savings.

2.2. Captions/numbering

Based on the problem description and basic assumptions in 2.1, the payoffs of each subject under different combinations of strategies can be obtained as shown in Table 1.

Table 1. The value of benefits of the game among local governments, ports and liner companies

Combination Strategy	**Local Government**	**Port**	**Liner Company**
$(\alpha_1, \beta_1, \gamma_1)$	$G_1+R_1+R_2-A_1-A_2-C_1$	$G_2+A_1+E_2-C_2$	$G_3+A_2+E_3-C_3$
$(\alpha_1, \beta_1, \gamma_2)$	$G_1+R_1-A_1-C_1$	$G_2+A_1-C_2$	G_3
$(\alpha_1, \beta_2, \gamma_1)$	$G_1+R_1+E_1-A_2-C_1$	G_2-E_1	$G_3+A_2-C_3$
$(\alpha_1, \beta_2, \gamma_2)$	$G_1+E_1+R_1-C_1$	G_2-E_1	G_3
$(\alpha_2, \beta_1, \gamma_1)$	G_1	$G_2+E_2-C_2$	$G_3+E_3-C_3$
$(\alpha_2, \beta_1, \gamma_2)$	G_1	G_2-C_2	G_3
$(\alpha_2, \beta_2, \gamma_1)$	G_1	G_2	G_3-C_3
$(\alpha_2, \beta_2, \gamma_2)$	G_1	G_2	G_3

3 Model analysis

3.1 Expected return and dynamic equation

Expected return and dynamic equation of each player are calculated as follows.

(1) Set U_{11} be the expected benefits of local governments choosing to participate in the shore power promotion strategy, U_{12} is the expected benefit if the local government chooses not to participate in the shore power promotion strategy, $\overline{U_1}$ is the average expected benefit of local governments. The replication dynamic equation of the local government is F(x). Their formula is separately given as follows:

$$U_{11} = y(z-1)(A_1+C_1-G_1-R_1) - yz(A_1+A_2+C_1-G_1-R_1-R_2) - z(y-1)(E_1-C_1-A_2+G_1+R_1) + (y-1)(z-1)(E_1-C_1+G_1+R_1) \quad (1)$$

$$U_{12} = G_1(y-1)(z-1) + G_1 yz - G_1 y(z-1) - G_1 z(y-1) \quad (2)$$

$$\overline{U_1} = xU_{11} + (1-x)U_{12} = G_1 - C_1 x + E_1 x + R_1 x - A_1 xy - A_2 xz - E_1 xy + R_2 xyz \quad (3)$$

$$F(x) = \frac{dx}{dt} = x(U_{11} - \overline{U_1}) = x(x-1)(C_1 - E_1 - R_1 + A_1 y + A_2 z + E_1 y - R_2 yz) \quad (4)$$

(2) Set U_{21} be the expected benefit for the port to choose the strategy of providing shore power, U_{22} is the expected revenue if the port chooses the strategy of not providing shore power, $\overline{U_2}$ is the average expected revenue of the port under the two strategies. The replication dynamic equation of the port is F(y). Their formula is separately given as follows:

$$U_{21} = xz(A_1 - C_2 + E_2 + G_2) - x(z-1)(A_1 - C_2 + G_2) - z(x-1)(E_2 - C_2 + G_2) - (C_2 - G_2)(x-1)(z-1) \quad (5)$$

$$U_{22} = G_2(x-1)(z-1) - xz(E_1 - G_2) - G_2 z(x-1) + x(E_1 - G_2)(z-1) \quad (6)$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} = G_2 - C_2 y - E_1 x + A_1 xy + E_1 xy + E_2 yz \quad (7)$$

$$F(y) = \frac{dy}{dt} = y(U_{21} - \overline{U_2}) = y(1-y)(A_1 x - C_2 + E_1 x + E_2 z) \quad (8)$$

(3) Set U_{31} be the expected revenue of the liner company choosing to use shore power strategy, U_{32} is the expected revenue if the liner company chooses not to use shore power strategy, $\overline{U_3}$ is the average expected revenue of the liner company under the two strategies. The replication dynamic equation of the liner company is F(z). Their formula is separately given as follows:

$$U_{31} = xy(A_2 - C_3 + E_3 + G_3) - x(y-1)(A_2 - C_3 + G_3) - y(x-1)(E_3 - C_3 + G_3) - (C_3 - G_3)(x-1)(y-1) \quad (9)$$

$$U_{32} = G_3(x-1)(y-1) + G_3 xy - G_3 x(y-1) - G_3 y(x-1) \quad (10)$$

$$\overline{U_3} = G_3 - C_3 z + A_2 xz + E_3 yz \quad (11)$$

$$F(z) = \frac{dz}{dt} = z(U_{31} - \overline{U_3}) = z(1-z)(A_2 x - C_3 + E_3 y) \quad (12)$$

3.2 Portfolio strategy stability analysis

3.2.1 Evolutionary game equilibrium point solution

Set F(x)=0, F(y)=0, F(z)=0, In an asymmetric game, if the equilibrium of game evolution is an evolutionary stable strategy, it must be a strict Nash equilibrium, which in turn is a pure strategy equilibrium. In other words, the mixed strategy equilibrium in asymmetric game dynamics must not be an evolutionary stable equilibrium. Therefore, we only need to analyze the pure strategy equilibrium in the system, they are E_1 (0,0,0), E_2 (0,1,0), E_3 (0,0,1), E_4 (0,1,1), E_5 (1,0,0), E_6 (1,1,0), E_7 (1,0,1), E_8 (1,1,1).

3.2.2 Stability analysis of the equilibrium point of the evolutionary game

The Jacobi matrix of the system is as follows.

$$J = \begin{pmatrix} (2x-1)(C_1 - E_1 - R_1 + A_1 y + A_2 z + E_1 y - R_2 yz) & x(x-1)(A_1 + E_1 - R_2 z) & x(A_2 - R_2 y)(x-1) \\ -y(y-1)(A_1 + E_1) & -(2y-1)(A_1 x - C_2 + E_1 x + E_2 z) & -E_2 y(y-1) \\ -A_2 z(z-1) & -E_3 z(z-1) & -(2z-1)(A_2 x - C_3 + E_3 y) \end{pmatrix} \quad (13)$$

Then the eigenvalues corresponding to each equilibrium point can be obtained. According to Lyapunov method: only when the eigenvalues of Jacobi matrix are all negative, the strategy combination corresponding to this equilibrium is an asymptotically stable strategy (ESS). Stability analysis of the equilibrium points is shown in Table 2.

Table 2. Equilibrium stability analysis results

Equilibrium Points	**Eigenvalue 1**	**Eigenvalue 2**	**Eigenvalue 3**	**Eigenvalue Symbol**	**ESS Condition**
$E_1(0,0,0)$	$-C_2$	$-C_3$	$E_1+R_1-C_1$	(−,−,+)	①
$E_2(0,1,0)$	C_2	E_3-C_3	$R_1-A_1-C_1$	(+,×,×)	Unstable
$E_3(0,0,1)$	C_3	E_2-C_2	$E_1+R_1-C_1-A_2$	(+,×,×)	Unstable
$E_4(0,1,1)$	C_2-E_2	C_3-E_3	$R_1+R_2-A_1-A_2-$	(×,×,×)	②

			C_1		
$E_5(1,0,0)$	A_2-C_3	A_1+E_1-C_2	C_1-E_1-R_1	(−,×,×)	③
$E_6(1,1,0)$	A_2+E_3-C_3	A_1+C_1-R_1	C_2-A_1-E_1	(×,×,×)	④
$E_7(1,0,1)$	C_3-A_2	A_2+C_1-E_1-R_1	A_1+E_1+E_2-C_2	(+,×,×)	Unstable
$E_8(1,1,1)$	C_3-A_2-E_3	C_2-A_1-E_1-E_2	A_1+A_2+C_1-R_1-R_2	(×,×,×)	⑤

Note: "×" indicates positive or negative uncertainty, and conditions ①~⑤ are as follows: ①$E_1+R_1-C_1$②$C_2-E_2<0$, $C_3-E_3<0$, $R_1+R_2-A_1-A_2-C_1<0$③$A_1+E_1-C_2<0$, $C_1-E_1-R_1<0$④$A_2+E_3-C_3<0$, $A_1+C_1-R_1<0$, $A_1+E_1+E_2-C_2<0$⑤$C_3-A_2-E_3<0$, $C_2-A_1-E_1-E_2<0$, $A_1+A_2+C_1-R_1-R_2<0$

As can be seen from Table 2, there are five possible asymptotically stable equilibrium points in the system, and each of them will be analyzed in the following with the actual situation.

For E_1 (0,0,0), when the condition ① is satisfied, there is a combination of stable evolutionary strategies in the system at this time (not participate in the promotion of shore power, not provide of shore power, not use shore power). For the local government, because the policy promotion and supervision cost of participating in the promotion of shore power exceeds the sum of the central government financial allocation and port fines, the local government tends to choose not to participate in the shore power promotion strategy, and the enterprises, due to the lack of incentives and regulations from the local government, are stable to choose not to implement the shore power strategy. Therefore, the central government should provide sufficient financial allocations to local governments that participate in shore power promotion. At the same time, higher penalties for ports that do not provide shore power can also help local governments to participate in the promotion of shore power and take responsibility to monitor the companies.

For E_4 (0,1,1), when the condition ② is satisfied, there exists a stable evolutionary strategy combination of the system at this time (not participate in the promotion of shore power, provide shore power, use shore power). This shows that when the economic benefits of implementing shore power for both players are higher than its costs, both players can implement shore power spontaneously even if the local government is not involved in promoting shore power. It is worth noting that, in addition to the technological development factor, the economic benefits of implementing shore power for ports and liner companies depend mainly on the pricing policy of the government and power companies for shore power. Considering that the implementation of shore power is of great significance to the improvement of atmospheric environment, the relevant government can appropriately provide preferential pricing for shore power to increase the motivation of enterprises to implement shore power.

For E_5 (1,0,0), E_6 (1,1,0), corresponding conditions, the effect generated by local governments even if they participate in promoting shore power is not ideal. For E_5 (1,0,0), it is known from condition ③ that when the sum of subsidies and penalties from the local government to the port is lower than the cost of providing shore power to the port, and when the liner companies choose not to use shore power strategy, the port will tend to choose not to provide shore power strategy, and then the liner companies cannot get the economic benefits of using shore power and will stabilize in choosing not to use shore power strategy; for E_6 (1,1,0), we can see from condition ④ that when the sum of the subsidies from local government and the economic benefits of using shore power for liner companies is less than the cost of using shore power for liner companies, even if the port provides shore power, the liner companies will tend to choose the strategy of not using shore power. Therefore, in order to avoid the failure of local government policy promotion, the sum of local government subsidies and penalties to ports should be greater than the cost of providing shore power to ports, and the liner companies should not charge too much for using shore power.

For E_8 (1,1,1), when condition ⑤ is satisfied, there exists a stable evolutionary strategy combination for the system at this time (participate in shore power promotion, provide shore power, use shore power). This is the ideal combination of stable evolutionary strategy in the early stage of shore power implementation. From condition ⑤, it can be seen that in the early stage of shore power implementation, in order to maintain the ideal situation that local government, ports and liner companies jointly participate in the promotion and application of shore power. For the local government, the sum of social and environmental benefits brought to the local government by the joint implementation of shore power and the funding from the central government should be higher than the subsidies provided to the enterprises and the cost of policy promotion and supervision. The sum of the economic benefits of providing shore power should exceed the cost of providing shore power for liner companies.

4 Numerical simulation

In this part, the fourth part of stability analysis will be examined by means of numerical simulation, and the effects of adjusting different parameter sizes on the evolutionary path and steady state at the early stage of shore power implementation, and finally the numerical simulation will be carried out in two stages for the initial stage and the mature stage of shore power implementation, so as to verify the validity of the model and provide a basis for the government's policy formulation. In this paper, we use MATLAB 2021b to simulate game among tripartite stakeholders

4.1 Stability analysis verify

The initial parameters and variables of the model are assigned with the actual situation. Set A_1 =5, A_2 =4, C_1 =8, E_1 =4, G_1 =20, R_1 =10, R_2 =8, C_2 =10, E_2 =6, G_2 =20, C_3 =6, E_3 =4, G_3 =20, x_0 =0.5, y_0 =0.5, z_0 =0.5.According to the equilibrium stability analysis, there are two asymptotically stable evolutionary strategies (ESS) in the evolutionary game system in this case, and the corresponding evolutionary stable equilibria are E_5 (1,0,0) and E_8 (1,1,1). The array is evolved 50 times with time from different initial strategy combinations, and the results are shown in Fig. 1. It can be seen that the different initial strategy combinations finally evolve to (1,0,0) and (1,1,1) respectively, which is consistent with the conclusion of equilibrium stability analysis in this paper.

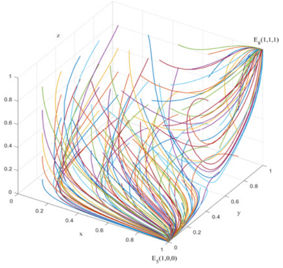

Fig. 1. Evolution of different initial strategy combinations

4.2 Sensitivity analysis of key parameters

Continuing the assignment in the previous section, the following section analyzes the impact of the central government's financial allocation, local administrative penalties on ports and the economic benefits of implementing shore power on the evolutionary path of implementing shore power and the evolutionary strategies of each subject.

4.2.1 Central government financial allocation

The other parameters remain unchanged, and the R_1 are assigned by 3, 10 and 17, then the simulation results of replicating the dynamic equation system evolving 50 times with time are shown in Figure 2.The final evolution strategy of each subject is very different: when R_1 = 3, the final evolution strategy combination is (not participate in shore power promotion, not provide shore power, not use shore power); when R_1 = 10, the final evolutionary strategy combination is (participate in shore power promotion, not provide shore power, not use shore power); when R_1 = 17, the final evolutionary strategy combination is (participate in shore power promotion, provide shore power, use shore power), which is the ideal evolutionary strategy combination in the early stage of shore power implementation. This indicates that the amount of financial allocation from the central government directly affects the strategy choice of local governments, and indirectly affects the strategy choice of ports and liner companies. It can be seen that the high financial allocation from the central government to local governments is a necessary condition for the smooth implementation of shore power construction, and only by fully motivating local governments to choose the implementation policy can we indirectly guide enterprises to implement shore power.

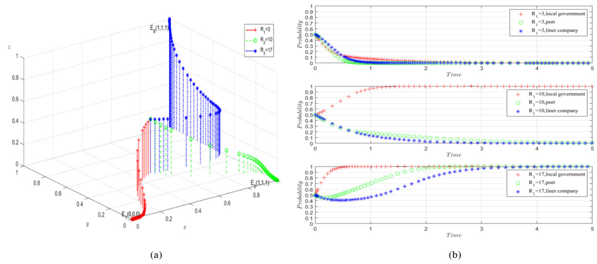

Fig. 2. Impact of R_1 on the evolutionary path of the system and the evolution of each subject's strategy

4.2.2 Local administrative penalties for ports

The other para meters remain unchanged, and set E_1 be 4,6 and 8, and the simulation results of replicating the system of dynamic equations evolving 50 times with time are shown in Figure 3. When E_1 = 4, the strategy combination of local government, port and liner company finally evolves to (participate in shore power promotion, not provide shore power, not use shore power); this indicates that the local government's regulation and punishment have an important influence on whether the implementation of shore power can be implemented smoothly, and the port, when facing high cost of shore power construction and minor administrative punishment, will prefer to choose When ports are faced with high shore power construction costs and minor administrative penalties, they may prefer not to implement shore power considering the high investment costs and long payback period, while increasing the administrative penalties for ports can not only effectively prevent the speculative behavior of ports, but also accelerate the overall process of shore power implementation.

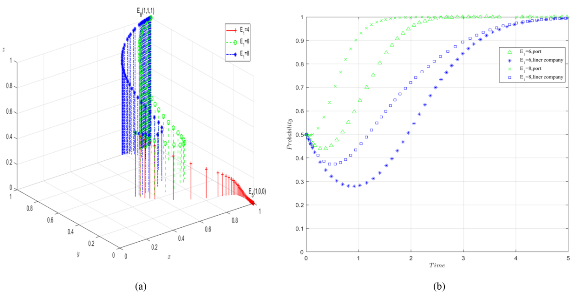

Fig. 3. Impact of E_1 on the evolutionary path of the system and the evolution of port and liner company strategies

4.2.3 Economic benefits arising from the implementation of shore power

The other parameters remain unchanged, we increase the value of E_2 and E_3, setting E_3 be 8 and E_3 be 6, the evolution of strategies of ports and liner companies before and after the enhancement is shown in Figure 4. This indicates that the economic efficiency of implementing shore power is an important factor in deciding whether companies jointly implement shore power. In order to improve the economic efficiency of implementing shore power, in addition to continuously improving shore power technology, the government and relevant power departments should clarify the electricity tariff items and standards implemented for ports and liner company implementing shore power as soon as possible, and considering the significant effect of implementing shore power on improving the atmospheric environment, preferential electricity tariff policies can be appropriately formulated so as to Considering the significant effect of implementing shore power on the improvement of air environment, preferential tariff policy can be formulated appropriately, so as to improve the enthusiasm of ports and liner companies to implement shore power.

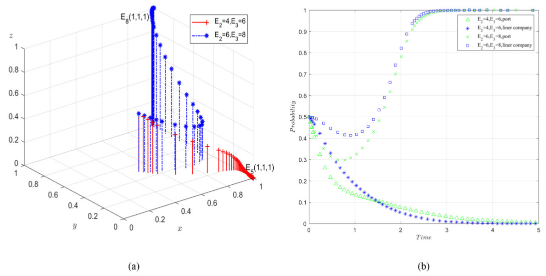

Fig. 4. Impact of E_2, E_3 on the evolutionary path and the evolution of port and liner company strategies

5 Conclusion

The implementation of shore power is the focus of governments and maritime industry. Based on the background of shore power promotion, this paper constructs a tripartite evolutionary game model with local government, port and liner company, explores the influence of each stakeholder on the choice of the tripartite strategy, and further analyzes the stability of the equilibrium point in the game system. Finally, the following conclusions and insights were obtained.

(1) The strategy of either player in the process of promoting shore power will influence the strategy choice of the other player or even multiple players. In the early stage of shore power implementation, the incentive of local government is a necessary prerequisite for the implementation of shore power. Since ports are more likely to be constrained by local government control than liner companies, ports usually implement shore power before liner companies, and liner companies will eventually choose to use shore power strategy in order to save fuel costs during port calls.

(2) The implementation process of policies is generally led by the central government and local governments are responsible for promotion. While local governments usually consider the impact on local social welfare in the process of implementing shore power implementation policy. Combined with the simulation analysis and the reality of this paper, it can be seen that although local government incentives for enterprises to implement shore power may provide potential social and environmental benefits to the local community, the large amount of financial expenditure incurred will seriously affect the motivation of local governments to choose to participate in shore power promotion strategies.

(3) When the implementation of shore power reaches a mature stage, the initial construction of shore power facilities has been completed, and the economic benefits brought by the implementation of shore power for enterprises have exceeded the costs of operation and equipment maintenance, enterprises will cooperate and implement shore power on their own initiative. At this point, the implementation of shore power will shift from policy-driven to market-driven, and the central government and local governments can gradually cancel the subsidies policies for enterprises to implement shore power.

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