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Collusion strategies of container shipping chain under supervision based on tripartite evolutionary game

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As over 80% of global trade relies on maritime transport, and container shipping accounts for more than 90% of the total value of maritime trade. The research on collusion strategies in a monitored container transport chain based on a tripartite evolutionary game, which this paper tackles, is a very interesting topic as an application of game theory. In today's world where global supply chains are becoming more complex, understanding the strategic interactions between the parties involved in container transport (shippers, carriers, port operators, etc.) is an essential task for improving logistics efficiency and realizing a fair competitive environment. This study investigates the strategic interactions among container terminals, liner enterprises, and Port Authorities under regulatory supervision, revealing two critical regimes. Firstly, when fines fall below regulatory costs, collusion persists despite lax supervision, stabilizing the system at a suboptimal equilibrium regardless of penalty-subsidy combinations. Secondly, when fines exceed costs, an evolutionary stable strategy (ESS) emerges if the total penalty-subsidy value undercuts collusion profits; otherwise, cyclical instability occurs as regulators oscillate between enforcement and relaxation due to fiscal constraints. Numerical simulations validate these dynamics, demonstrating how cost-profit thresholds govern strategic outcomes. Using a tripartite evolutionary game model and numerical simulations, we demonstrate how cost-profit thresholds govern these strategic outcomes. Our findings highlight the necessity of designing penalty structures that simultaneously ensure regulatory cost recovery and neutralize collusion incentives, providing actionable insights for maritime policymakers to balance deterrence effectiveness with enforcement sustainability in container shipping markets.

KEYWORDS

container shipping industry, evolutionary game theory, port authority, liner enterprise, strict supervision

1 Introduction

Over 80% of global trade is delivered through international shipping. As the most efficient and economical mode of transport for most goods, maritime shipping offers a reliable and affordable way to move products across borders. The vital industry supports global trade, fosters economic growth, and contributes

TABLE 1 Global capacity figures and share of top 10 liner operators in the world.

Ranking	Liner operators	General headquarters	Alliance	Capacity	Share
1	Mediterranean Shipping Company	Geneva, Switzerland	2 M	5,073,462	18.8%
2	Maersk	Copenhagen, Denmark	2 M	4,124,602	15.3%
3	CMA CGM Group	Marseille, France	OA	3,486,351	12.9%
4	COSCO Group	Beijing, China	OA	2,936,534	10.9%
5	Hapag-Lloyd	Hamburg, Germany	THE	1,854,386	6.9%
6	Evergreen Group	Taiwan, China	OA	1,656,550	6.1%
7	ONE (Ocean Network Express)	Tokyo, Japan	THE	1,618,269	6.0%
8	HMM Co. Ltd.	Seoul, South Korea	THE	792,074	2.9%
9	Yang Ming Marine Transport Corp.	Taiwan, China	THE	705,614	2.6%
10	Zim	Haifa, Israel	—	590,784	2.2%
Total	—	—		22,838,626	84.6%

Unit: TEU; Data source: Alphaliner, 15 August 2023. “OA” means Ocean Alliance, “THE” means The Alliance, “2 M” means 2 M Alliance.

to the prosperity of nations and communities around the world. The share of container shipping is about 60% by volume (tonnage), however, it accounts for over 90% of the total value of international maritime trade. Containerization is at the heart of modern shipping, as standardized containers have significantly improved loading and unloading efficiency and transportation safety, making them a critical pillar of global supply chains[1]. The top 10 Liner operators[2], reported by Alphaliner which is the world-renowned shipping consulting center, indicates that all liner operators are striving for new future, as shown in Table 1.

The One Hundred Container Ports 2024, published by the world’s oldest shipping newspaper Lloyd’s List, let the world see the strong growth in China and the Middle East region. The container throughput of global top 10 container ports in the world increased slowly from 264.2 million TEU in 2020 to 300.5 million TEU in 2024, with an annual growth rate (AGR) of 3.5%.

Port, which is the hub of maritime transportation, plays an important role in promoting international trade and economic [1]. Most container ports have entered the post-epidemic recovery phase of covid-19, but still face rural tests [2]. In short term, port shutdowns caused by the epidemic continue to be staged [3]; in long term, labor shortages and industrial shifts brought by the disappearance of China’s demographic dividend make the ports facing the more and more severe situation in the future [4]. With the increasing demand of total logistics and supply chain, container terminals have the motive for collusion [5].

This study addresses three critical research questions: (1) What are the long-term optimal equilibrium strategies for a container terminal, the Port Authority, and a liner company under varying scenarios? (2) How should these three stakeholders select their long-term optimal strategies in a game-theoretic framework? (3) Does the adoption of these optimal strategies lead to an improvement in overall social welfare? To investigate these questions, we propose a tripartite evolutionary game model to analyze the dynamic interactions and decision-making processes among the stakeholders.

The remainder of this paper is structured as follows. Section 2 reviews the literature on container shipping supply chains, evolutionary game theory, and collusion regulation. Section 3 develops the formal models for each scenario under study. In Section 4, we analyze evolutionary stable strategy. In Section 5, a numerical simulation is applied. Section 6 presents the policy implications derived from our analysis, while Section 7 concludes the study by summarizing key findings and suggesting promising avenues for future research.

2 Literature review

2.1 Container shipping chain

The literature on carrier-port collusion has evolved along three key dimensions: First, vertical integration strategies [6]; second, competitive dynamics in port clusters [7]; and third, network position analysis [8]. This progression reflects a methodological shift from case-based studies to formal game theory and ultimately to network science applications, collectively deepening our understanding of tacit collusion in maritime logistics systems.

Scholarly investigations of maritime cooperation have progressed from initial studies of carrier-downstream alliances [9] to contemporary analyses of major carriers’ strategic diversification [10], advanced network architectures including both conventional

1 https://www.imo.org/en/About/Pages/Default.aspx
2 https://alphaliner.axsmarine.com/PublicTop100

[11], and foldable container systems [12], and operational decision-making frameworks ranging from game-theoretic models [13] to risk assessment tools [14]. This evolution reflects the field's growing sophistication in addressing complex coordination challenges. Addressing the critical challenge of network reliability, Huang et al. [15] proposed a systematic approach for determining hub port locations and their associated non-hub port allocations in container shipping systems.

2.2 Evolutionary game theory

Evolutionary game theory, originally formalized through the Hawk-Dove game framework [16], has become an established methodology for examining strategic interactions among stakeholders and predicting industry dynamics over extended time horizons.

Evolutionary game theory has been widely applied across diverse industries to analyze multi-stakeholder interactions. In the sharing economy, scholars have employed tripartite evolutionary models to examine regulatory strategies [17], sustainable development mechanisms [18], and policy response dynamics [19]. Similar approaches have been adopted in energy systems research, including studies on thermal energy policy impacts [20] and behaviorally-augmented analyses of energy markets [21]. The framework has further demonstrated its versatility in business resilience studies [22] and maritime environmental governance [23], particularly regarding strategic interactions in ballast water management.

Especially, the container liner shipping industry has seen extensive application of evolutionary game theory to analyze multi-stakeholder interactions. Jiang et al. [24] examined the divergent benefits between governments and shipping companies under China's Emission Control Area (ECA) regulations. Subsequent studies expanded this framework: Lin et al. [25] incorporated evolutionary stable strategies to assess green maritime markets, while Hu and Dong [26] modeled carrier interactions across peak and off-seasons. Further methodological advancements include tripartite model integrating prospect theory to evaluate electric ship adoption, supported by system dynamics simulations [27]. Meng et al. [28] similarly employed a three-party framework to study carbon emission reduction strategies among governments, ports, and carriers. Recent work has focused on policy-driven interactions, including analysis of marine pollution control [29] and investigation of cleaner production incentives in ports [30]. Gao et al. [31] further advanced this field through dynamic simulation of government-port enterprise relations. A comprehensive summary of these evolutionary game applications in container shipping is presented in Table 2.

2.3 Supervision on collusion

This section synthesizes key studies examining supervision mechanisms to deter collusion. Early theoretical work by Faure-Grimaud et al. [33] established a framework for evaluating supervisory efficiency in both centralized and decentralized organizational structures. Subsequent empirical research has explored diverse dimensions of supervision. In Organizational Dynamics, Fang et al. [34] demonstrated how social relationships between executives can compromise financial reporting integrity; Che et al. [35] revealed a critical trade-off in hierarchical systems between supervision inefficiency and supervisor-agent collusion risks. In Regulatory Policy Effects, Meng et al. [28] quantified how government regulatory costs and incentive structures influence emission control enforcement. Xiao and Cui [32] emphasized the necessity for adaptive regulatory policies responsive to market evolution. In Sector-Specific Applications, Lee et al. [36] identified emerging supervisory challenges of maritime sustainability. Xu et al. [27] modeled electric ship industry development through a tripartite evolutionary game framework. In Bargaining Power Dynamics, Mookherjee and Tsumagari [37] challenged conventional wisdom by proving supervisor hiring only benefits principals when supervisors maintain adequate bargaining power over agents.

2.4 Summary

While existing studies have examined the roles of central/local governments, ports, and liner companies in isolation, this study addresses a critical gap in the literature by investigating the long-term strategic interactions between container terminals and liner enterprises under Port Authority supervision. To achieve this, we develop a tripartite evolutionary game model that incorporates three key stakeholders (terminal operators, liner companies, and Port Authority) and applies evolutionary game theory to analyze sustained strategic adaptation.

This study makes three key contributions as follows: (1) Analysis of Port Authority supervision's long-term impact on collusion strategies in container shipping chains; (2) Development of a novel tripartite evolutionary game model integrating; (3) Port Authority, terminal, and liner enterprise dynamics Validation of equilibrium stability through systematic numerical simulations.

3 Model

3.1 Problem description

This study examines a tripartite container shipping system comprised of container terminals, liner enterprises, and the Port Authority. Within this framework, terminals and liners face strategic choices between collusion or non-collusion behaviors in long-term operations, while the Port Authority determines its regulatory intensity (strict vs. lax supervision). Figure 1 presents the evolutionary game framework depicting these strategic interactions.

3.2 Basic assumptions

Building on prior analysis, this study conceptualizes container shipping chain governance as a dynamic equilibrium process involving multi-period strategic interactions among key stakeholders. We develop a tripartite evolutionary game model to examine the equilibrium strategies emerging between container

TABLE 2 Studies of evolutionary game in container shipping industry.

	Stakeholders						Regulations	
Scholars	Central Gov.	Upstream/ local Gov.	Downstream/ Local Gov.	Port enterprise	Liner enterprise	SL	S	Fine
Jiang et al. [24]		√			√		—	—
Xu et al. [27]		√	√		√			√
Meng et al. [28]		√		√	√		√	
Yuan and Wang [30]	√	√		√			√	√
Gao et al. [31]		√		√				
Li and Jiang [29]	√	√			√		√	√
Lin et al. [25]						√	—	—
Xiao and Cui [32]		√			√		√	√

Notes: "SL" means Shipping line, "S" means Subsidy, "None" means there is no regulation in this game model.

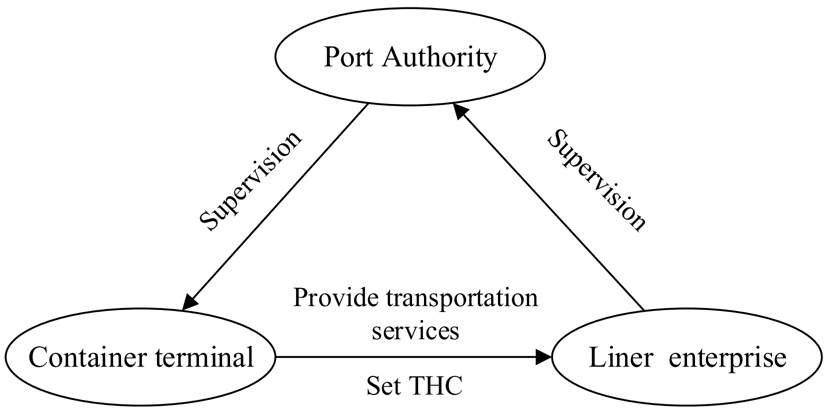

FIGURE 1
The interactive behavior of three stakeholders in the tripartite evolutionary game.

terminals, liner enterprises, and the Port Authority, their long-term interactive behaviors, and policy implications for effective governance. All notations are defined in Table 3 [17,18].

This is an incomplete information game, the payoffs of others are uncertain, the stakeholders' strategies evolve in the population through trial and error and natural selection, rather than static optimal solutions. The game model is grounded in the following key assumptions:

Assumption 1: The model comprises three boundedly rational actors - a container terminal, the Port Authority, and a liner enterprise - each making strategic decisions based on self-interest maximization [27]. The boundedly rational actors suggests three stakeholders do not have access to all information or accurately process complex information, and participants rely on limited data and simplified models for decision-making.

Assumption 2: This study characterizes the strategic choices of three agents using probability distributions, let x denote the probability of a container terminal opting for collusion (thus $1-x$ for non-collusion), y represent the Port Authority's probability of strict supervision (thus $1-y$ for lax supervision), and z indicate a liner enterprise's collusion probability ($1-z$ for non-collusion). These variables ($x, y, z \in [0,1]$) capture bounded rationality in evolutionary game theory, where agents dynamically adjust strategies based on payoff comparisons. The probability distributions establish the foundation for constructing replicator dynamic equations, with their temporal evolution revealing strategic adaptation patterns under varying scenarios. The rates of change in x, y, and z will quantitatively reflect how institutional pressures and market conditions shape stakeholders' long-term behavioral trajectories.

Assumption 3: When opting for collusion, a container terminal earns higher profit I_T^C but also incurs greater cost

TABLE 3 Notations and descriptions.

Notations	Descriptions
x	Share of container terminals employing collusion strategies
$1-x$	Share of container terminals employing non-collusion strategies
y	Share of strict supervision in Port Authority's regulatory strategy
$1-y$	Share of lax supervision in Port Authority's regulatory strategy
z	Share of a liner enterprise employing collusion strategies
$1-z$	Share of a liner enterprise employing non-collusion strategies
I_T^C / I_T^N	Profit of a container terminal employing the collusion/non-collusion strategy
C_T^C / C_T^N	Cost of a container terminal employing the collusion/non-collusion strategy
I_L^C / I_L^N	Profit of the liner enterprise employing the collusion/non-collusion strategy
C_L^C / C_L^N	Cost of the liner enterprise employing the collusion/non-collusion strategy
C_G	Cost of the Port Authority employing the strict supervision
F	Fine from the Port Authority employing the collusion strategy
S	Subsidy from the Port Authority employing the non-collusion strategy
W	Social welfare increased from non-collusion strategy
U_T^C / U_T^N	Profit of container terminal employing collusion/non-collusion strategy
U_T	Average expected benefit of the container terminal
U_P^S / U_P^L	Profit of the Port Authority from strict/lax supervision
U_P	Average expected benefit of the Port Authority
U_L^C / U_L^N	Profit of the liner enterprise employing collusion/non-collusion strategy
U_L	Average expected benefit of the liner enterprise
$F(x)$	Dynamic equation of the container terminal employing collusion strategy
$F(y)$	Dynamic equation of the Port Authority's strict supervision strategy
$F(z)$	Dynamic equation of the liner enterprise employing collusion strategy

C_T^C compared to non-collusion (I_T^N and C_T^N, respectively). The net benefit (I_T^C - C_T^C) from collusion exceeds that of non-collusion (I_T^N - C_T^N), as demonstrated by Dong et al. [5].

Assumption 4: Similarly, for liner companies, collusion generates profit I_L^C at cost C_L^C, while non-collusion yields I_L^N at C_L^N. The net benefit from collusion (I_L^C - C_L^C) exceeds that of non-collusion (I_L^N - C_L^N), demonstrating the economic incentive for collusion behavior, that is, $I_L^C - C_L^C > I_L^N - C_L^N$.

Assumption 5: Under strict supervision, the Port Authority imposes fines on colluding terminals or liner companies, earning revenue F. If firms choose non-collusion, social welfare increases by W, and the Port Authority may provide tax discounts or subsidies S. Strict supervision incurs costs C_G, whereas lax supervision costs nothing. Collusion yields no social welfare gain, while non-collusion contributes W.

3.3 Replicator dynamic equations

Consistent with the bounded rational behavior specified in Assumption 1, we design the tripartite evolutionary game's payoff matrix as presented in Table 4.

The respective payoffs for each stakeholder across different strategic scenarios are specified below:

$$(CT_1, PA_1, LE_1) = \left(I_T^C - C_T^C - F_T, F_T + F_L - C_G, I_L^C - C_L^C - F_L\right)$$

$$(CT_2, PA_2, LE_2) = \left(I_T^C - C_T^C - F_T, F_T + W_L - S_L - C_G, I_L^N - C_L^N + S_L\right)$$

$$(CT_3, PA_3, LE_3) = \left(I_T^C - C_T^C, 0, I_L^C - C_L^C\right),$$
$$(CT_4, PA_4, LE_4) = \left(I_T^C - C_T^C, W_L, I_L^N - C_L^N\right)$$

$$(CT_5, PA_5, LE_5) = \left(I_T^N - C_T^N + S_T, W_T + F_L - C_G - S_T, I_L^C - C_L^C - F_L\right)$$

$$(CT_6, PA_6, LE_6) = \left(I_T^N - C_T^N + S_T, W_T + W_L - C_G - S_T - S_L, I_L^N - C_L^N + S_L\right)$$

$$(CT_7, PA_7, LE_7) = \left(I_T^N - C_T^N, W_T, I_L^C - C_L^C\right),$$
$$(CT_8, PA_8, LE_8) = \left(I_T^N - C_T^N, W_T + W_L, I_L^N - C_L^N\right)$$

The container terminal's expected payoff under collusion is U_T^C, while its expected payoff under non-collusion is U_T^N, yielding an average expected payoff of U_T, where x represents the probability of collusion.

$$U_T^C = yzCT_1 + y(1-z)CT_2 + (1-y)zCT_3 + (1-y)(1-z)CT_4 \quad (1)$$

$$U_T^N = yzCT_5 + y(1-z)CT_6 + (1-y)zCT_7 + (1-y)(1-z)CT_8 \quad (2)$$

$$U_T = xU_T^C + (1-x)U_T^N \quad (3)$$

The Port Authority obtains expected payoff U_P^S under strict supervision and U_P^L under lax supervision, resulting in an average expected payoff of U_P, where $y \in [0,1]$ parameterizes its supervision intensity.

$$U_P^S = xzPA_1 + x(1-z)PA_2 + (1-x)zPA_5 + (1-x)(1-z)PA_6 \quad (4)$$

$$U_P^L = xzPA_3 + x(1-z)PA_4 + (1-x)zPA_7 + (1-x)(1-z)PA_8 \quad (5)$$

$$U_P = yU_P^S + (1-y)U_P^L \quad (6)$$

TABLE 4 Tripartite evolutionary game's payoff matrix.

		Port authority			
		Strict supervision (y)		Lax supervision ($1-y$)	
		Liner enterprise		Liner enterprise	
		Collusion (z)	Non-collusion ($1-z$)	Collusion (z)	Non-collusion ($1-z$)
Container terminal	Collusion (x)	(CT_1, PA_1, LE_1)	(CT_2, PA_2, LE_2)	(CT_3, PA_3, LE_3)	(CT_4, PA_4, LE_4)
	Non-collusion ($1-x$)	(CT_5, PA_5, LE_5)	(CT_6, PA_6, LE_6)	(CT_7, PA_7, LE_7)	(CT_8, PA_8, LE_8)

The liner enterprise achieves expected payoff U_L^C when colluding and U_L^N when not colluding, generating an average expected profit of U_L, where $z \in [0,1]$ quantifies its collusion propensity.

$$U_L^C = xyLE_1 + x(1-y)LE_3 + (1-x)yLE_5 + (1-x)(1-y)LE_7 \quad (7)$$

$$U_L^N = xyLE_2 + x(1-y)LE_4 + (1-x)yLE_6 + (1-x)(1-y)LE_8 \quad (8)$$

$$U_L = zU_L^C + (1-z)U_L^N \quad (9)$$

The evolutionary dynamics of the tripartite system, following Bomze [38], are expressed through these replicator dynamic equations:

The container terminal's collusion strategy:

$$F(x) = \frac{dx}{dt} = x\left(U_T^C - U_T\right) = x(1-x)\left(U_T^C - U_T^N\right) \quad (10)$$

The Port Authority's supervision strategy:

$$F(y) = \frac{dy}{dt} = y\left(U_P^S - U_P\right) = y(1-y)\left(U_P^S - U_P^L\right) \quad (11)$$

The liner enterprise's collusion strategy:

$$F(z) = \frac{dz}{dt} = y\left(U_L^C - U_L\right) = z(1-z)[\left(U_L^C - U_L^N\right) \quad (12)$$

The complete evolutionary dynamics can be obtained by substituting the payoff expressions (1)–(9) into the replicator dynamic Equations 10–12, resulting in:

$$F(x) = x(1-x)\left[\left(I_T^C - C_T^C - I_T^N + C_T^N\right) - y(F_T + S_T)\right]$$

$$F(y) = y(1-y)\left[x\left(F_T - C_G\right) + zF_L - (1-z)S_L + (1-x)\left(-C_G - S_T\right)\right]$$

$$F(z) = z(1-z)\left[\left(I_L^C - C_L^C - I_L^N + C_L^N\right) - y(F_L + S_L)\right]$$

4 Evolutionary stability analysis

Following Friedman's [39] stability criteria: (i) A strategy proportion represents an evolutionary stable strategy (ESS) if it demonstrates asymptotic stability; (ii) An equilibrium point (EP) is ESS when all trajectories (tr) in its neighborhood converge to it under the replicator dynamic system (RDS); (iii) This stability is determined through Jacobian matrix analysis, obtained by partial differentiation of the dynamic system. Solving the partial derivative, the Jacobean Matrix can be obtained below:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}$$

In which, $J_{11} = (1-2x)\left[\left(I_T^C - C_T^C - I_T^N + C_T^N\right) - y(F_T + S_T)\right]$, $J_{12} = -x(1-x)(F_T + S_T)$, $J_{13} = 0$,

$$J_{21} = y(1-y)(F_T + S_T), J_{22} = (1-2y)\left[x(F_T - C_G) + zF_L - (1-z)S_L + (1-x)(-C_G - S_T)\right]$$

$$J_{23} = y(1-y)(F_L + S_L), J_{31} = 0, J_{32} = -z(1-z)(F_L + S_L)$$

$$J_{33} = (1-2z)\left[\left(I_L^C - C_L^C - I_L^N + C_L^N\right) - y(F_L + S_L)\right]$$

The EPs of the RDS are $E_1 = (0,0,0)$, $E_2 = (0,0,1)$, $E_3 = (0,1,0)$, $E_4 = (1,0,0)$, $E_5 = (1,0,1)$, $E_6 = (1,1,0)$, $E_7 = (0,1,1)$, $E_8 = (1,1,1)$, $E_9 = \left(0, \frac{I_L^C - C_L^C - I_L^N + C_L^N}{F_L - S_L}, \frac{C_G + S_L + S_T}{F_L + S_L}\right)$, $E_{10} = \left(1, \frac{I_L^C - C_L^C - I_L^N + C_L^N}{F_L - S_L}, \frac{C_G - F_T + S_L}{F_L + S_L}\right)$, $E_{11} = \left(\frac{C_G - F_L + S_T}{F_T + S_T}, \frac{I_T^C - C_T^C - I_T^N + C_T^N}{F_T - S_T}, 1\right)$, and $E_{12} = \left(\frac{C_G + S_L + S_T}{F_T + S_T}, \frac{I_T^C - C_T^C - I_T^N + C_T^N}{F_T - S_T}, 0\right)$.

Substituting $E_1 = (0,0,0)$ into the Jacobean Matrix, the following can be obtained:

$$J(0,0,0) = \begin{bmatrix} I_T^C - C_T^C - I_T^N + C_T^N & 0 & 0 \\ 0 & -C_G - S_L - S_T & 0 \\ 0 & 0 & C_T^N - C_T^C + I_T^C - I_T^N \end{bmatrix}$$

$$J(0,0,1) = \begin{bmatrix} I_T^C - C_T^C - I_T^N + C_T^N & 0 & 0 \\ 0 & F_L - C_G - S_T & 0 \\ 0 & 0 & -I_L^C + C_L^C + I_L^N - C_L^N \end{bmatrix}$$

$$J(1,0,0) = \begin{bmatrix} -\left(I_T^C - C_T^C - I_T^N + C_T^N\right) & 0 & 0 \\ 0 & F_T - C_G - S_L & 0 \\ 0 & 0 & I_L^C - C_L^C - I_L^N + C_L^N \end{bmatrix}$$

Through eigenvalue analysis of the Jacobian matrices, we classify equilibrium points according to Friedman [39]: (i) Evolutionary Stable Strategy (ESS): det(J) > 0 and trace(J) < 0; (ii) Unstable point: det(J) > 0 and trace(J) > 0; (iii) Saddle point: det(J) ≤ 0 or indeterminate. This stability classification establishes two crucial proportional relationships in the system:

Proportion 1: When regulatory fines fail to cover enforcement costs, the system converges to an evolutionary stable strategy profile (Collusion, Lax Supervision, Collusion). This equilibrium emerges irrespective of the relative magnitude between penalty-subsidy combinations (F + S) and the collusion profit differential, demonstrating inherent limitations of under-resourced regulatory regimes.

A. When the total fines imposed on colluding firms remain insufficient to offset the Port Authority's enforcement costs and subsidy expenditures:

While $F_T + F_L < C_G + S_T + S_L$, we can obtain $\frac{S+C_g}{F+S} > 1$, so $\left(\frac{S+C_g}{F+S}, \frac{I_c - C_c - I_n + C_n}{F+S}\right)$ is not the internal EP, thus, in this RDS has local EPs as (0, 0, 0), (1, 0, 0), (0, 1, 0), (0, 0, 1), (1, 1, 0), (1, 0, 1), (0, 1, 1), and (1, 1, 1), additionally, Assumptions 3 and 4 clearly show that $I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$ and $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$, therefore, the container terminal's strategic landscape presents two mutually exclusive contingencies:

Scenario 1: When $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L < C_G + S_T + S_L$, currently, at $E_1 = (0,0,0)$, we can obtain $\lambda_1 = -C_G - S_L - S_T < 0$, $\lambda_2 = I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$, and $\lambda_3 = I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$, since det $J < 0$, tr $J < 0$, E_1 is a saddle point; at $E_2 = (1,0,0)$, we can obtain $\lambda_1 < 0$, $\lambda_2 > 0$, and $\lambda_3 < 0$, since det $J > 0$, tr $J > 0$, indicating E_2 is an unstable point; at $E_3 = (0,1,0)$, we can obtain $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$, since det $J > 0$ and tr $J < 0$, confirming E_3 is an ESS point; at $E_4 = (0,0,1)$, we can obtain $\lambda_1 < 0$, $\lambda_2 < 0$, and $\lambda_3 > 0$, so, det $J > 0$ and tr $J < 0$, confirming E_4 is also an ESS point; the remaining points E_5, E_6, and E_7 are all saddle points, while E_8 is an ESS point. A summary of these results is provided in Table 5.

Scenario 2: When $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L < C_G + S_T + S_L$, currently, at $E_1 = (0,0,0)$, we can obtain $\lambda_1 = -C_G - S_L - S_T < 0$, $\lambda_2 = I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$, and $\lambda_3 = I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$, since det $J < 0$ and tr $J < 0$, E_1 is a saddle point; at $E_2 = (1,0,0)$, we can obtain $\lambda_1 < 0$, $\lambda_2 > 0$, and $\lambda_3 < 0$, so, det $J > 0$ and tr $J < 0$, indicating E_2 is an ESS point; at $E_3 = (0,1,0)$, we can obtain $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$, since det $J > 0$ and tr $J > 0$, confirming E_3 is an unstable point; at $E_4 = (0,0,1)$, we can obtain $\lambda_1 < 0$, $\lambda_2 < 0$, and $\lambda_3 > 0$, since det $J > 0$ and tr $J > 0$, confirming E_4 is also an unstable point; the remaining points E_5, E_6, and E_7 are all saddle points, while E_8 is an ESS point. A summary of these results is provided in Table 5.

Proportion 2: When fines exceed the Port Authority's operational costs, the evolutionary stable strategy (ESS) will stabilize at collusion under strict supervision if and only if the combined value of fines and subsidies is lower than the welfare gap generated by the container shipping chain's collusion strategy. Conversely, no ESS exists when this combined value surpasses the profit differential of the collusion strategy.

B. When the combined penalties imposed on both the container terminal and the liner company exceed the total of the Port Authority's operational costs and any subsidies provided:

Under conditions $F_T + F_L > C_G + S_T + S_L$, the RDS' local EPs (0, 0, 0), (1, 0, 0), (0, 1, 0), (0, 0, 1), (1, 1, 0), (1, 0, 1), (0, 1, 1), and (1, 1, 1) can be obtained, as derived from Assumption 3 and 4, where $I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$ and $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$ hold, the container terminal's strategic options bifurcate into two distinct scenarios:

Scenario 3: When $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L > C_G + S_T + S_L$, currently, at $E_1 = (0,0,0)$, we can obtain $\lambda_1 = -C_G - S_L - S_T < 0$, $\lambda_2 = I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$, and $\lambda_3 = I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$, since det $J > 0$ and tr $J > 0$, E_1 is a saddle point; likewise, at $E_2 = (1,0,0)$, $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 < 0$ can be obtained, since det $J < 0$, E_2 is a saddle point; at $E_3 = (0,1,0)$, $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$ can be obtained, since det $J > 0$ and tr $J > 0$, E_3 is an unstable point; the remaining points E_4, E_5, E_8 are saddle points, E_6 and E_7 are ESS points. A summary of these results is provided in Table 6.

Scenario 4: Under $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L > C_G + S_T + S_L$, currently, at $E_1 = (0,0,0)$, we can obtain $\lambda_1 = -C_G - S_L - S_T < 0$, $\lambda_2 = I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > 0$, and $\lambda_3 = I_T^C - C_T^C - \left(I_T^N - C_T^N\right) > 0$, since det $J > 0$ and tr $J > 0$, E_1 is a saddle point; likewise, at $E_2 = (1,0,0)$, $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 < 0$ can be obtained, since det $J < 0$, then, E_2 is a saddle point; at $E_3 = (0,1,0)$, $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$ can be obtained, since det $J > 0$ and tr $J > 0$, E_3 is an unstable point; the remaining points E_4, E_5, and E_8 are saddle points; E_6 is an ESS point; E_7 is an unstable point. A summary of these results is provided in Table 6.

5 Numerical simulation

While the theoretical equilibria have been established, we conduct numerical simulations to elucidate the system's behavioral dynamics under varying initial conditions. Using MATLAB R2012a on a computational platform (Intel 8-core processor, 16GB RAM, NVIDIA GTX 2050), we examine the evolutionary trajectories among the three stakeholders through four distinct experimental scenarios. These simulations specifically investigate: (1) regulatory inattention to supply chain violations, (2) market adaptation mechanisms, and (3) sensitivity to initial strategy distributions. Then, the Initial parameters and their values of different scenarios are set and shown in Table 7.

Based on the aforementioned simulation framework, the obtained results are summarized below:

Scenario 1: Under $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L < C_G + S_T + S_L$, initial parameter values are assigned as follows, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 1$. Our profit sensitivity analysis, parameterized with $I_L^C = 12$, $I_L^C = 15$, $I_L^C = 18$, respectively, reveals (1,1,1) as the unique ESS. This equilibrium indicates coordinated collusion between the liner enterprise and the container terminal coupled with strict supervision enforcement. Figure 2 traces the evolutionary trajectories under varying initial strategy probabilities, demonstrating convergence to this ESS across all simulated scenarios.

As liner enterprises' collusion profits rise, their incentive to collude intensifies, prompting stronger regulatory intervention from the Port Authority to restore social welfare. Nevertheless, China's recent shipping policy reforms face implementation challenges: (1) regulatory frameworks are in a trial-and-error phase, (2) enforcement mechanisms remain ineffective, and (3) excessive

TABLE 5 Stabilities of the tripartite evolutionary game among three stakeholders.

		Scenario 1				Scenario 2			
EP	Eigenvalue of J	λ_1	λ_2	λ_3	Stability	λ_1	λ_2	λ_3	Stability
$E_1(0,0,0)$	$\lambda_1 = -C_G - S_L - S_T$, $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N)$, $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N)$.	−	+	+	Saddle point	−	+	+	Saddle point
$E_2(1,0,0)$	$\lambda_1 = F_T - C_G - S_L$, $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N)$, $\lambda_3 = I_T^N - C_T^N - (I_T^C - C_T^C)$.	−	+	−	Unstable point	−	+	−	ESS
$E_3(0,1,0)$	$\lambda_1 = C_G + S_L + S_T$, $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N) - F_L - S_L$, $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N) - F_T - S_T$.	+	+	+	ESS	+	+	+	Unstable point
$E_4(0,0,1)$	$\lambda_1 = F_L - C_G - S_T$, $\lambda_2 = I_L^N - C_L^N - (I_L^C - C_L^C)$, $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N)$.	−	−	+	ESS	−	−	+	Unstable point
$E_5(1,1,0)$	$\lambda_1 = C_G + S_L - F_T$, $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N) - F_L - S_L$, $\lambda_3 = I_T^N - C_T^N - (I_T^C - C_T^C) + F_T + S_T$.	+	+	−	Saddle point	+	+	−	Saddle point
$E_6(1,0,1)$	$\lambda_1 = F_L - C_G - S_T$, $\lambda_2 = I_L^N - C_L^N - (I_L^C - C_L^C)$, $\lambda_3 = I_T^N - C_T^N - (I_T^C - C_T^C)$.	−	−	−	ESS	−	−	−	ESS
$E_7(0,1,1)$	$\lambda_1 = C_G + S_T - F_L$, $\lambda_2 = I_L^N - C_L^N - (I_L^C - C_L^C) + F_L + S_L$, $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N) - F_T - S_T$.	+	−	+	Saddle point	+	−	+	Saddle point
$E_8(1,1,1)$	$\lambda_1 = C_G - F_L - F_T$, $\lambda_2 = I_L^N - C_L^N - (I_L^C - C_L^C) + F_L + S_L$, $\lambda_3 = I_T^N - C_T^N - (I_T^C - C_T^C) + F_T + S_T$.	+	−	−	ESS	+	−	−	ESS

Notes: "+" denotes greater than zero; "−" denotes less than zero.

supervision costs create perverse incentives for the Port Authority to ignore collusion. This regulatory vacuum has fostered rampant collusion, a suboptimal equilibrium that undermines the long-term viability of container shipping supply chains.

Scenario 2: When $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L > C_G + S_T + S_L$, initial parameter values are assigned as follows, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 3$. Through profit sensitivity analysis parameterized with $I_L^C = 12$, $I_L^C = 15$, $I_L^C = 18$, respectively, Figure 3 demonstrates the evolutionary trajectories of the tripartite game under varying initial strategy probabilities. The simulated dynamics reveal the absence of an ESS, indicating persistent instability in stakeholder interactions.

The Port Authority's limited regulatory capacity prevents sustained strict supervision, creating conditions conducive to collusion. Our dynamic model reveals an adaptive equilibrium where the container terminal and liner enterprise modulate collusion intensity in response to regulatory vigilance, while the Port Authority calibrates enforcement levels based on observed collusion prevalence (Figure 3). This tripartite strategic interdependence demonstrates continuous adaptation to market conditions.

Scenario 3: Under $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L > C_G + S_T + S_L$, initial parameter values are assigned as follows, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 1$. To examine profit-driven dynamics, we parameterize the model with $C_G = 1$, $C_G = 0.6$, $C_G = 0.2$, respectively, representing the marginal profit coefficients for respective stakeholders. Figure 4 illustrates the resulting evolutionary trajectories of the tripartite game under specified initial conditions.

Scenario 4: Under $I_L^C - C_L^C - \left(I_L^N - C_L^N\right) > I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L) > 0$ and $F_T + F_L > C_G + S_T + S_L$, initial parameter values are assigned below, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 3$. To examine cost-driven dynamics, we parameterize the Port Authority's operational costs as $C_G = 1$, $C_G = 0.6$, $C_G = 0.2$, respectively. Figure 5 illustrates the resulting evolutionary trajectories of the tripartite game under specified initial conditions, revealing how supervision cost structures influence equilibrium formation.

Scenario 5: When $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L < C_G + S_T + S_L$, the initial condition is set as follows, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 1$. Our profit sensitivity analysis, parameterized with $I_L^C = 12$, $I_L^C = 15$, $I_L^C = 18$, respectively, reveals (1,1,1) as the unique ESS. This

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TABLE 6 Stabilities of the tripartite evolutionary game among three stakeholders.

		Scenario 3				Scenario 4			
EP	Eigenvalue of J	λ_1	λ_2	λ_3	Stability	λ_1	λ_2	λ_3	Stability
$E_1(0,0,0)$	$\lambda_1 = -C_G - S_L - S_T$ $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N)$ $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N)$	−	+	+	Saddle point	−	+	+	Saddle point
$E_2(1,0,0)$	$\lambda_1 = F_T - C_G - S_L$ $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N)$ $\lambda_3 = I_T^N - C_T^N - \left(I_T^C - C_T^C\right)$	+	+	−	Saddle point	+	+	−	Saddle point
$E_3(0,1,0)$	$\lambda_1 = C_G + S_L + S_T,$ $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N) - F_L - S_L$ $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N) - F_T - S_T$	+	+	+	Unstable point	+	+	+	Unstable point
$E_4(0,0,1)$	$\lambda_1 = F_L - C_G - S_T,$ $\lambda_2 = I_L^N - C_L^N - \left(I_L^C - C_L^C\right),$ $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N).$	+	−	+	Saddle point	+	−	+	Saddle point
$E_5(1,1,0)$	$\lambda_1 = C_G + S_L - F_T,$ $\lambda_2 = I_L^C - C_L^C - (I_L^N - C_L^N) - F_L - S_L,$ $\lambda_3 = I_T^N - C_T^N - \left(I_T^C - C_T^C\right) + F_T + S_T.$	+	+	−	Saddle point	+	+	−	Saddle point
$E_6(1,0,1)$	$\lambda_1 = F_L - C_G - S_T,$ $\lambda_2 = I_L^N - C_L^N - \left(I_L^C - C_L^C\right),$ $\lambda_3 = I_T^N - C_T^N - \left(I_T^C - C_T^C\right).$	+	−	−	ESS	+	−	−	ESS
$E_7(0,1,1)$	$\lambda_1 = C_G + S_T - F_L,$ $\lambda_2 = I_L^N - C_L^N - \left(I_L^C - C_L^C\right) + F_L + S_L,$ $\lambda_3 = I_T^C - C_T^C - (I_T^N - C_T^N) - F_T - S_T.$	−	+	−	ESS	−	−	+	Unstable point
$E_8(1,1,1)$	$\lambda_1 = C_G - F_L - F_T,$ $\lambda_2 = I_L^N - C_L^N - \left(I_L^C - C_L^C\right) + F_L + S_L,$ $\lambda_3 = I_T^N - C_T^N - \left(I_T^C - C_T^C\right) + F_T + S_T.$	−	+	+	Saddle point	−	−	−	Saddle point

Notes: "+" denotes greater than zero; "−" denotes less than zero.

TABLE 7 Initial parameters and their values of different scenarios.

Scenarios	Difference of profit	Initial parameter	Difference of fine and subsidy	Initial parameter
Scenario 1	$I_L^C - C_L^C - (I_L^N - C_L^N)$ $> I_T^C - C_T^C - (I_T^N - C_T^N)$ $+C_G + S_T + S_L - (F_T + F_L) > 0$	$I_L^C = 12, I_L^C = 15, I_L^C = 18$	$F_T + F_L < C_G + S_T + S_L$	$F_L = 1$
Scenario 2			$F_T + F_L > C_G + S_T + S_L$	$F_L = 3$
Scenario 3		$C_G = 1, C_G = 0.6, C_G = 0.2$	$F_T + F_L < C_G + S_T + S_L$	$F_L = 1$
Scenario 4			$F_T + F_L > C_G + S_T + S_L$	$F_L = 3$
Scenario 5	$0 < I_L^C - C_L^C - (I_L^N - C_L^N)$ $< I_T^C - C_T^C - (I_T^N - C_T^N)$ $+C_G + S_T + S_L - (F_T + F_L)$	$I_L^C = 12, I_L^C = 15, I_L^C = 18$	$F_T + F_L < C_G + S_T + S_L$	$F_L = 1$
Scenario 6			$F_T + F_L > C_G + S_T + S_L$	$F_L = 3$
Scenario 7		$C_G = 1, C_G = 0.6, C_G = 0.2$	$F_T + F_L < C_G + S_T + S_L$	$F_L = 1$
Scenario 8			$F_T + F_L > C_G + S_T + S_L$	$F_L = 3$

equilibrium configuration indicates universal collusion adoption by the container terminal and the liner enterprise, and optimal strict supervision by the Port Authority. Figure 6 traces the convergence pathways from diverse initial strategy probabilities, demonstrating robust attraction to this ESS.

Scenario 6: Under $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L > C_G + S_T + S_L$, initial parameter values are assigned below, $I_L^C = 12$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 3$. Through cost-parameterized simulations $I_L^C =$

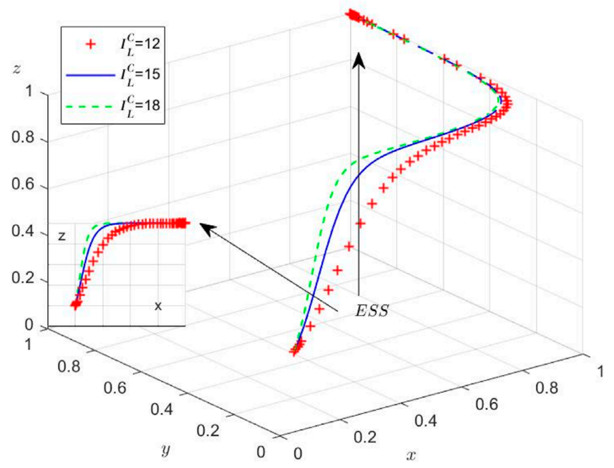

FIGURE 2
Evolutionary trajectories in Scenario 1 (Impact of the liner enterprise's profit when $F_L = 1$).

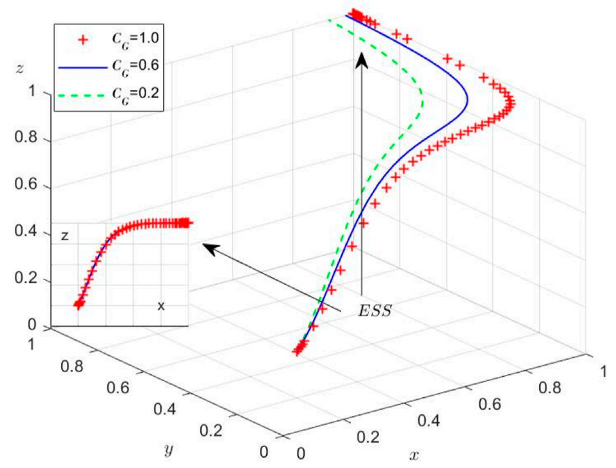

FIGURE 4
Evolutionary trajectories in Scenario 3 (impact of the Port Authority's cost when $F_L = 1$).

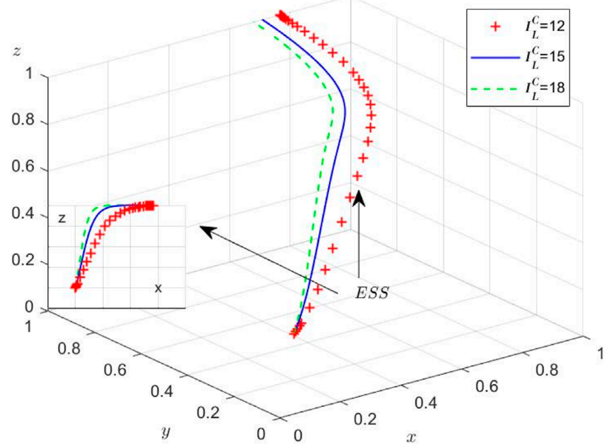

FIGURE 3
Evolutionary trajectories in Scenario 2 (Impact of the liner enterprise's profit when $F_L = 3$).

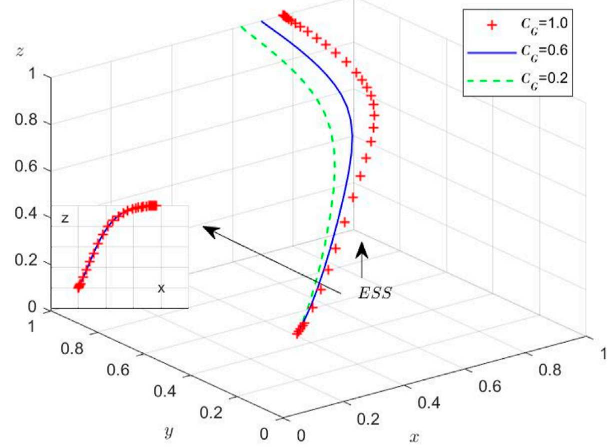

FIGURE 5
Evolutionary trajectories in Scenario 4 (impact of the Port Authority's cost when $F_L = 3$).

12, $I_L^C = 15$, $I_L^C = 18$, respectively, our analysis identifies (1,1,0) as the unique ESS, where the container terminal persistently collude, the Port Authority maintains strict supervision despite operational costs, and the liner enterprise unexpectedly defect from collusion due to regulatory pressure. Figure 7 phase portrait demonstrates robust convergence to this asymmetric equilibrium across all initial conditions, revealing critical thresholds in cost structures that shape strategic behaviors within the maritime supply chain ecosystem.

Scenario 7: Under $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L > C_G + S_T + S_L$, initial parameter values are assigned below, $I_L^C = 9.5$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 3$. Our cost-driven evolutionary game analysis, parameterized with regulatory cost components $C_G = 1$, $C_G = 0.6$, $C_G = 0.2$, respectively, demonstrates that (1,1,0) emerges as the sole ESS. This equilibrium configuration reveals three key behavioral patterns: (i) the container terminal exhibit persistent collusion due to profit incentives, (ii) the Port Authority maintains strict supervision despite cost burdens, while (iii) the liner company strategically avoid collusion under regulatory pressure. Figure 8's phase diagram traces the dynamic convergence pathways from diverse initial strategy combinations, confirming the global stability of this asymmetric equilibrium under the specified cost structure.

Scenario 8: When $0 < I_L^C - C_L^C - \left(I_L^N - C_L^N\right) < I_T^C - C_T^C - \left(I_T^N - C_T^N\right) + C_G + S_T + S_L - (F_T + F_L)$ and $F_T + F_L > C_G + S_T + S_L$, the initial parameter values are assigned below, $I_L^C = 9.5$, $C_L^C = 2$, $I_L^N = 8$, $C_L^N = 3$, $I_T^C = 7$, $C_T^C = 3$, $I_T^N = 6$, $C_T^N = 4$, $C_G = 1$, $S_T = 1$, $S_L = 1$, $F_T = 1$, and $F_L = 1$. Through a systematic examination of the Port Authority's cost structure, parameterized by $C_G = 1$, $C_G = 0.6$, $C_G = 0.2$, respectively, our evolutionary game simulations reveal (1,1,1) as the unique ESS. This equilibrium configuration indicates a stable state where both maritime operators (the container terminal

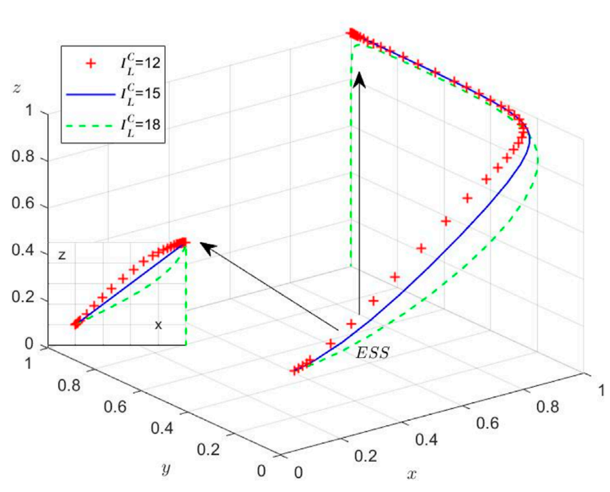

FIGURE 6
Evolutionary trajectories in Scenario 5 (Impact of the liner enterprise's profit when $F_L = 1$).

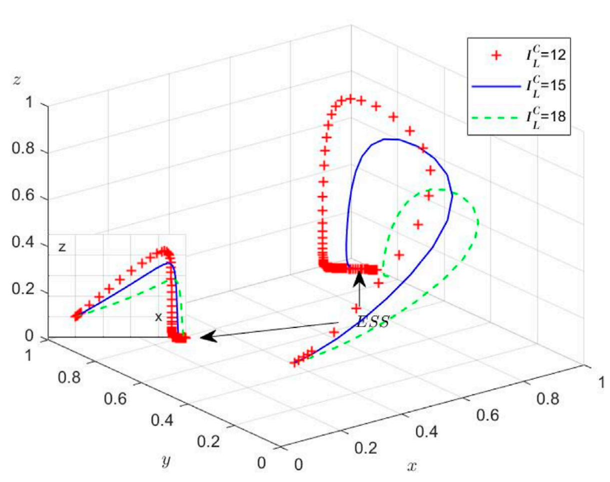

FIGURE 7
Evolutionary trajectories in Scenario 6 (Impact of the liner enterprise's profit when $F_L = 3$).

and the liner enterprise) persistently collude while regulators maintain strict supervision, despite the associated costs. The phase diagram of Figure 9 demonstrates robust convergence to this equilibrium from varied initial conditions, highlighting how the current cost framework sustains this strategic triad within the maritime supply chain ecosystem. The persistent collusion-supervision pattern suggests that existing cost structures may insufficiently deter collusion behavior, requiring potential policy interventions to alter the strategic landscape.

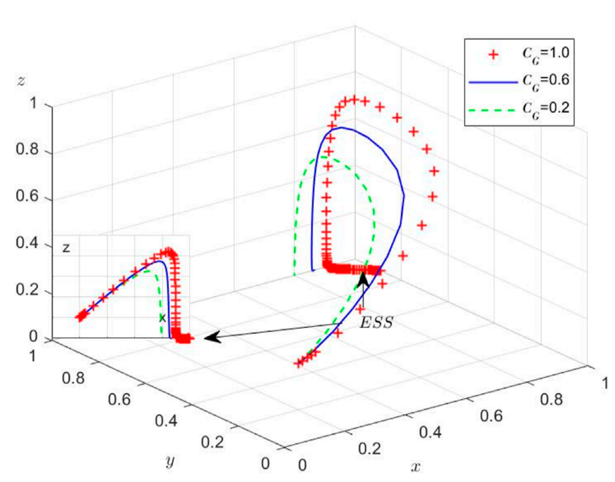

FIGURE 8
Evolutionary trajectories in Scenario 7 (impact of the Port Authority's cost when $F_L = 3$).

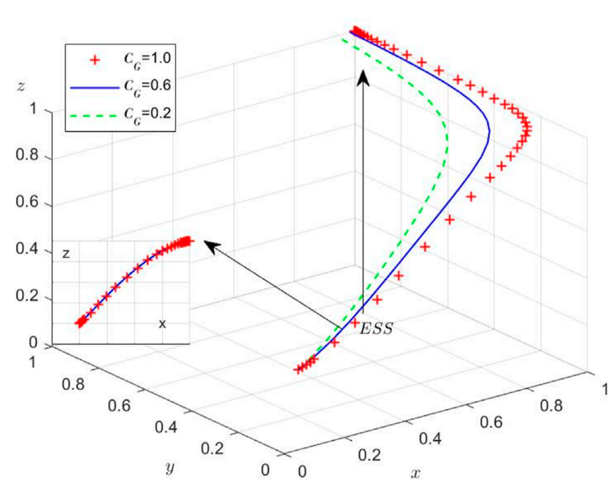

FIGURE 9
Evolutionary trajectories in Scenario 8 (impact of the Port Authority's cost when $F_L = 1$).

6 Policy implication

From a game-theoretic perspective, the container terminal and liner enterprise will rationally adopt non-collusion strategies when the combined value of regulatory penalties and incentives exceeds the welfare differential generated by collusion practices. For the Port Authority, optimizing enforcement mechanisms through either increased penalty for collusion or enhanced subsidies for compliance represents a viable pathway to promote industry health and social welfare enhancement. However, this regulatory calculus must satisfy the fundamental economic constraint whereby the total penalty-subsidy outlay exceeds supervisory costs, as otherwise fiscal unsustainability would inevitably drive regulators toward lax enforcement strategies. This equilibrium analysis reveals the critical financial thresholds necessary for effective maritime supply chain governance.

From the social welfare perspective, explicitly incorporating the negative externalities (welfare losses) to third parties (society as a whole) caused by bilateral collusion into the current payoff matrix, this can provide a path to answer the more profound policy question of "what is the optimal level of monitoring from the perspective of social welfare?"

7 Conclusion

The analysis reveals a dual-threshold regulatory dynamic in container shipping markets. When collusion proves more profitable than compliance, two distinct regimes emerge: if fines remain below the Port Authority's operational costs, terminals and liners persistently collude despite strict supervision, creating a stable but socially suboptimal equilibrium. Conversely, when fines surpass regulatory costs, the system exhibits either disciplined operations (if penalties and subsidies jointly undercut collusion profits) or chronic instability (if they exceed them). In the latter case, cyclical behavior develops - the Port Authority initially crack down on collusion but eventually relax enforcement due to unsustainable costs, triggering renewed collusion attempts and perpetuating a regulatory pendulum effect. These findings highlight the delicate balance required in maritime governance, where penalty structures must simultaneously cover enforcement costs while remaining proportionally calibrated to the economic incentives driving collusion.

The study demonstrates that effective anti-collusion frameworks require fine-tuning three interdependent levers: penalty severity must first clear the cost-recovery threshold for regulators, then the combined value of sanctions and incentives must be strategically positioned between operational costs and illicit profits to prevent either regulatory capture or enforcement collapse. This "goldilocks zone" for maritime regulation emerges when ensuring fiscal sustainability and neutralizing profit motives without triggering oscillatory behavior. Real-world policy applications should therefore incorporate dynamic adjustment mechanisms that respond to evolving market conditions and cost structures within shipping networks.

8 Discussions

However, it is important to acknowledge that due to challenges in acquiring real-world operational data, the numerical simulations in our model employ hypothetical initial conditions to demonstrate the theoretical outcomes. While this approach effectively illustrates the fundamental dynamics of the tripartite evolutionary game, incorporating realistic demand and price uncertainties inherent in container shipping markets would further enhance the model's practical relevance. Future research could productively expand this framework by integrating stochastic elements to better capture the volatility of shipping demand, freight rate fluctuations, and other market uncertainties that significantly influence strategic decision-making among terminals, liners, and regulators. In order to make the theoretical suggestions of this study more certain, it is essential to conduct empirical research to investigate the financial data of shipping companies and port terminals, the actual state of port usage fees, and the amount of fines in past cases of antitrust violations, and to set each parameter of the model in a realistic numerical range.

In the current model, each player's strategy is set to a simple binary choice such as "collude/not collude" and "strict/lax supervision." However, real strategic interactions are more complex. For example, the "surveillance intensity" may be a continuous variable, and collusion should involve "exploitation of third parties (e.g., shippers and end consumers) through bilateral collusion." In addition, factors such as a "reputation system" or more sophisticated "counterstrategies" are not considered in the current model.

The current model assumes perfect detection of collusion under strict supervision, as reflected in Assumption 5 and the payoff matrix, where fines are always imposed on colluding firms when the Port Authority adopts strict supervision. However, in reality, the detection is rarely perfect, the Port Authority should take lots of resources to regulate, which is not possible in reality, nor is it possible to regulate all collusion, it is just an ideal state of affairs.

In particular, it is recommended that the introduction of agent-based modeling (ABM) as a direction for future research. Argue that ABM, which allows each player (agent) to have individual information, learning abilities, and heterogeneous rules of behavior, may enable analysis of emergent collusion patterns and system vulnerability to external shocks that cannot be captured by our homogeneous evolutionary game model. In addition, point out the importance of incorporating into the model how cultural and institutional factors such as business practices and the independence of regulatory authorities affect the content of players' bounded rationality. This will pave the way for broader theory construction that explains why collusion patterns differ across countries and regions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZL: Data curation, Conceptualization, Writing – review and editing, Writing – original draft, Software, Formal Analysis. YX: Resources, Writing – review and editing, Data curation, Investigation. YG: Writing – review and editing, Software, Validation, Investigation. YL: Methodology, Data curation, Writing – review and editing.

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