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Research Article

Tripartite Evolutionary Game Analysis of a Logistics Service Supply Chain Cooperation Mechanism for Network Freight Platforms

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The rapid development of network freight platforms has directly increased the level of social logistics resource collaboration and improved both the efficiency and quality of logistics industry services. As a bilateral platform that connects freight shippers and freight carriers, the organizational structure and operational mode of network freight platforms differ substantially from those of traditional logistics service providers. In this paper, a tripartite evolutionary game model is constructed in which a network freight platform, freight shipper, and freight carrier are considered, and the evolutionary stability strategies of the parties and the tripartite system are dynamically analyzed. The reliability of the model is verified through a numerical case, and several countermeasures have been proposed to improve the stability of the system based on the sensitivity analysis of important parameters. This paper helps standardize the principal behavior of all parties under the network freight mode, reduce the default risk of all parties, and improve the overall cooperation stability of the logistics service supply chain.

1. Introduction

Although the overall development level of the logistics industry has been undergoing improvement for a long time, the problem of low logistics efficiency is still prominent [1, 2] due to various social logistics resources, such as private trucks, cargo ships, and small- and medium-sized third-party logistics companies, not being fully utilized [3, 4]. One example is the large number of small fleets and even private trucks that occupy the main position of the supply market in road transportation despite the fact that they have a very limited ability to obtain orders, which leads to a very high no-load rate, or empty vehicle travel rate [5].

With the rapid development of both the platform economy and information technology, the application of the network freight mode has emerged as an excellent means of solving these problems [6]. According to the statistics published by the Network Freight Information Exchange System of the Ministry of Transport of China, as of the end of 2022, there were 2537 network freight enterprises (including branch companies) in China that integrate 5.943 million pieces of scattered social transportation and 5.224 million drivers. These enterprises upload a total of 94.012 million waybills throughout the year. Logistics information platforms and network freight platforms, such as Luge, China's network freight platform (https://www.log56.com/), have sprung up like mushrooms after a rain. The mainstream service models of these network freight platforms are "uploading goods sources" and "finding cars to pull goods" [7]. The rapid development of network freight platforms has provided more opportunities for the logistics industry in the areas of resource integration, cost reduction, and efficiency enhancement [8, 9].

At present, most of the research on participant behavior in a network freight environment is based on formal or rational behavior, such as freight insurance pricing strategies [10], freight service matching [9, 11, 12], and freight assignment [13, 14]. However, there are also many problems in the actual operation process of network freight platforms. In traditional logistics service supply chains, the rights and responsibilities of upstream and downstream suppliers are clear, but in a network freight environment, the behavior of freight platforms, freight carriers, and freight shippers are more uncertain than those in a traditional service supply chain environment, and these uncertainties can affect the decision-making behavior of all parties and even lead to irrational behavior among some participants. There are few studies on the irrational behavior of participants in network freight environments, and there are few studies on the dynamic behavior of multiple participants.

As a response to these issues, the purpose of this paper is to explore the optimal decisions of the platform, shipper, and carrier in the network freight environment. To be specific, this paper will discuss the following research questions: How should network freight platforms regulate the logistics service providers registered on the platform and improve the stickiness of the cargo owners that use the platform? Are freight carriers willing to expend extra effort to ensure the quality of logistics services, and Are they willing to collude with freight shippers in private transactions? Are freight shippers willing to utilize this platform to access published requirement information? Are all transactions completed through the services provided by this platform? In order to solve the above problems, this paper uses an evolutionary game model to study the dynamic behavior of the three parties, and the contributions of this paper are as follows:

(1) A tripartite evolutionary game model involving network freight platforms, freight carriers, and freight shippers is proposed. Using this model, it is possible to dynamically observe the changes in the decision-making of various parties in a network freight environment. (2) Using this model, we consider some informal behaviors that can occur among participants in an online freight environment. Analyzing these informal market behaviors helps us to understand the current development status of the industry and to better regulate market behavior. (3) A sensitivity analysis was conducted on several parameters in the evolutionary game model to provide a reference for the long-term decision-making behavior of various entities under this logistics service model and to avoid the occurrence of short-sighted behaviors, such as profit-seeking.

This paper is structured as follows. In the first section, we introduce the connotations of network freight platforms and the specific problems encountered during their operation. In the second section, we review the relevant research progress on network freight platforms. In the third section, we describe the specific research issues studied and propose corresponding assumptions and conditions. In the fourth section, we construct a tripartite evolutionary game model based on network freight platforms, actual carriers, and shippers and then analyze the stability strategies of each party and those of the tripartite system as a whole. In the fifth section, we conduct numerical simulation experiments and sensitivity analysis experiments based on the model proposed in the fourth section. In the sixth section, we summarize the article and propose relevant management insights.

2. Literature Review

Due to the recent emergence of the online freight model, research on the online freight model is still in its infancy. In this paper, the decision-making behavior of multiple participants in a network freight environment is studied, and therefore, the development process of network freight platforms is first reviewed, and then, the research on the behavior of multiple participants in a network freight environment is tracked. By reviewing and analyzing these two streams of literature, the theoretical value of this paper's research is framed.

2.1. Network Freight Platform Development. The traditional freight model relies mainly on information departments, offline parking lots, and freight stations for freight transactions. With the development of digital platform technology, network freight platforms have rapidly emerged. The current network freight platforms in China are developed on the basis of vehicle cargo matching platforms and common nontruck operating carriers. The emergence of vehicle cargo matching platforms has shifted the freight mode from an offline to an online mode, and the transaction parties have transformed into strangers who are not familiar with each other, which directly leads to the decline of traditional logistics parks or parking lots [11, 15, 16]. The term "nontruck operating common carrier" evolved from the term "truck broker," which was coined after vehicle cargo matching platforms emerged. "Nontruck operating common carrier" refers to a road freight transport operator who does not own a carrier, signs a transportation contract with the shipper as a carrier, assumes the responsibilities and obligations of the carrier, and entrusts the actual carrier to complete the transportation task [17]. Accordingly, the network freight platform provides information services to both supply and demand parties in a more efficient manner while clarifying the rights and responsibilities of the platform, freight shippers, and freight carriers through a clear contract.

As a new efficient logistics model, online freight has developed rapidly and plays an important role in the integration of social transportation capacity and the improvement in the efficiency of social resource allocation. Using network freight platform and online freight platform as keywords, we searched the literature for nearly 8 years (2017–2024) in the Web of Science database, with a total of 153 papers. By selecting some representative literature from mainstream journals in the field of traffic management, it is found that the hot research issues on network freight platforms are shown in Table 1.

2.2. Research on the Behavior of Carriers, Shippers, and Platforms. Network freight platforms are bilateral trade markets for transport service procurement. These platforms first announce their rules, then shippers bid on their demands, and carriers bid on their supplies [23]. Lafkihi et al. reviewed the important research achievements in this field and noted that the auction mechanism is the most widely used mechanism for solving the transportation service procurement problem [24]. Specifically, auctions can be categorized into one-sided auctions and double auctions. When a one-sided auction is used to select carriers, each shipper must hold an independent auction to choose a carrier. The reverse auction mechanism is widely used for this. For instance, Xu et al. proposed efficient intermodal transportation auctions for the B2B e-commerce logistics problem and considered the transaction costs in auctions [25]. Chen proposed auction mechanism-based order allocation for third-party vehicle logistics platforms that could achieve the long-term operation of platforms through the weighing and adjusting of platform revenue and fleets with second prices [26]. In recent years, research on the application of bilateral auction mechanisms has increased. Double auctions are more time-efficient and more practical than one-sided auctions in the transport market [23]. For instance, Yu et al. investigated a truthful multiattribute multiunit double auction mechanism design problem for B2B e-commerce logistics service transactions [27].

In addition to the behavior of carriers and shippers, many scholars have also noted the impact of platform behavior on the overall value of online freight. For instance, Deng et al. developed a three-player evolutionary game model for analyzing the interactions among freight carriers, freight shippers, and logistics platforms. Then, these researchers analyzed the asymptotic equilibrium and evolutionary stability strategies of the three-player game [6]. Bai et al. studied the value cocreation impact mechanism of network freight platforms in the Internet of Things environment and found that service-dominant logic, transport demand subject participation, and relational embeddedness all promote value cocreation [7]. Liu et al. studied the effects of coinnovating with the provider when the platform requires the provider to innovate new value-added services [28].

2.3. Limitations of the Existing Research. From the development process of online freight platforms and research on the behavior of various participants, it can be found that the behavior of online freight platforms, freight carriers, and freight shippers has dynamic and uncertain characteristics, and research on this characteristic is relatively scarce. Specifically, existing research has the following limitations.

First, relatively little research has been conducted on the dynamic evolution characteristics of participants' behaviors under the network freight logistics model. Most researchers focus on the static behavioral strategies of online freight participants, which means that their strategic behavior remains unchanged; for instance, Jiang et al. studied the problem of profit redistribution among driver groups in network freight platforms [20]. However, in reality, such participants often dynamically adjust their behavioral patterns.

Table 1: Hot topics in the research field of network freight platforms.

Topics	Representative literature
Operating mechanism and behavioral evolution characteristics	[3, 18]
Freight order allocation and profit distribution issues	[19–21]
Service matching, vehicle selection, and transportation capacity optimization	[9, 12, 22]
Pricing strategy and tax issues	[10, 11]

Second, relatively little research has been conducted on the irrational or abnormal behaviors of participants. Most studies assume that all participants in this model are rational individuals who strictly abide by contracts; for instance, Deng et al. investigated whether carriers and shippers are willing to share service capabilities and service information [6]. In real life, speculative behavior is likely to occur, and once such speculative behavior occurs, it inevitably affects the behavioral decisions of other participants. However, there is currently relatively little research on this type of behavior in the literature.

Third, in the research on network freight platform behavioral strategies, most scholars have focused on the relationship between shippers and carriers [29], as well as that between platforms and carriers [19, 20], while there is relatively little research on the mutual influence among the three.

In summary, the current research on the dynamic decision-making process involving both the rational and irrational behavior of multiparty participants in the network freight environment is relatively scarce, and research on this topic is conducted in this paper.

3. Problem Description and Assumptions

In the network freight environment, because participants come from all regions, the level of cooperation among them is not strong; thus, there may be a variety of irrational behaviors that emerge. For example, the logistics service providers on the platform come from different regions, and their service capabilities, scale, and reputation levels vary greatly. These service providers do not have a subordinate or hierarchical management relationship with the platform. Thus, the lack of supervision leads to logistics service providers providing low-quality services. In the case of excessive supervision, these service providers abandon the platform and turn to other platforms. On the other hand, due to increasing competition in the logistics industry, the demand for logistics service quality from shippers is increasing. When the logistics service quality obtained by shippers through the platform does not meet their expected level, it affects shippers' subsequent use of the platform. In addition, the platform should always be vigilant against customer "jump-dealing" (In many studies in the field of e-commerce, "showrooming" or "window shopping" are terms used to denote the behavior of two parties in a multiparty transaction who directly transact by conspiring to bypass a third party. In this paper, "jump dealing" is the term used to denote this behavior.) behavior, which occurs when shippers choose not to complete subsequent transactions on the platform after having found a suitable logistics service provider through the platform. These shippers then establish a private cooperative relationship with the service provider, which poses great operational risks and cost pressures to the platform.

Based on the above analysis, the behaviors of all parties may be either rational or irrational, and the behaviors of all parties are dynamic. In other words, the behaviors of participants may differ at different time points. Evolutionary game models usually focus on the group of participants, analyze the dynamic evolution process, explain why and how the group has reached its current state, and do not require participants to be completely rational or fully informed. Therefore, a tripartite evolutionary game model is constructed to explore the decision-making behaviors of network freight platforms, freight carriers, and freight shippers over time and to identify evolutionary equilibrium strategies for both individuals and systems.

The overall research methods of this paper are as follows: first, through investigation and enterprise visits, it summarizes the possible behavior patterns of various parties and the impacts of these behaviors on each other and abstracts these behavior patterns and impacts into commonly used expressions in game theory. Then, we utilized a tripartite evolutionary game model to analyze their dynamic decision-making behaviors and studied the stability of the system composed of three parties. Finally, numerical simulation experiments are conducted to further validate the reliability of our proposed model and analysis method.

Based on the above research ideas, the strategy set of the three parties is given, and the relationships among the three parties are shown in Figure 1. Assuming that all three parties have bounded rationality and a goal of maximizing profits, they dynamically adjust their strategies based on the behavior of other participants.

Network freight platforms, as bilateral platforms, provide information and resource-matching services for logistics supply and demand. However, in the actual operation process, the platform faces two options for ensuring the supervision intensity of freight carriers, namely, strict supervision and loose supervision. Strict supervision improves service quality, but it may also lead to freight carriers abandoning this platform and choosing to settle on other platforms. Loose supervision will increase the enthusiasm of freight carriers to settle on this platform, but it will reduce the satisfaction of freight shippers due to the uncertainty of service quality.

Freight carriers have two strategies: providing high-quality services and providing low-quality services. Providing high-quality services requires higher costs, but it also earns a better market reputation. Providing low-quality services is a speculative behavior that can save considerable operating costs. For irrational decision-makers, it is possible to provide low-quality services in the short term.

For freight shippers, there are two options: nonjump dealing (i.e., completing transactions through the platform, abbreviated as NJD) and jump dealing (i.e., directly trading with freight carriers, abbreviated as JD). If a nonjump dealing strategy is adopted, even if freight carriers provide low-quality services, freight shippers can receive corresponding compensation by complaining to the platform. However, if a jump-dealing strategy is adopted, freight shippers will not receive the services guaranteed by the platform.

To facilitate modeling, we propose the following basic assumptions, and the model parameters are given in Table 2.

Assumption 1. If freight shippers choose to publish logistics demands on a network freight platform, the platform is responsible for ensuring the completion of those logistics tasks. If freight shippers complain about low service quality, the platform directly compensates the client for a portion of the losses incurred.

Assumption 2. If a platform adopts a strict supervision strategy to monitor the service quality of freight carriers, the additional supervision cost is b (where the supervision cost b is less than the platform's total revenue a) and $b > c_1 - c_2$. Otherwise, the platform has no motivation to save such costs.

Assumption 3. If a platform discovers that logistics freight carriers who have contracted with the platform and accepted the platform's dispatch task are engaging in unauthorized transactions with freight shippers, the platform imposes penalties on the logistics freight carriers, including both direct economic penalties and indirect penalties, such as lowering the supplier's reputation rating and lowering the priority of the next dispatch. The punishment for JD is much greater than the punishment for providing low-quality services under the assumption that $f_1 > b$, $f_2 > b$, and $f_1 - f_2 > b$.

Assumption 4. When freight carriers provide low-quality services, they receive complaints on the platform from shippers; when they receive complaints, regardless of the supervision strategy adopted by the platform, the platform should provide compensation to the shippers.

Assumption 5. The probability of a logistics platform choosing a strict regulatory strategy is x, and the probability of their choosing a relaxed regulatory strategy is $1 - x$. The probability of choosing to provide a high-quality service strategy for freight carriers is y, and the probability of choosing to provide a low-quality service strategy is $1 - y$. The probability of choosing the NJD strategy for freight shippers is z, and the probability of choosing the JD strategy is $1 - z$. The values of x, y, and z all fall between 0 and 1.

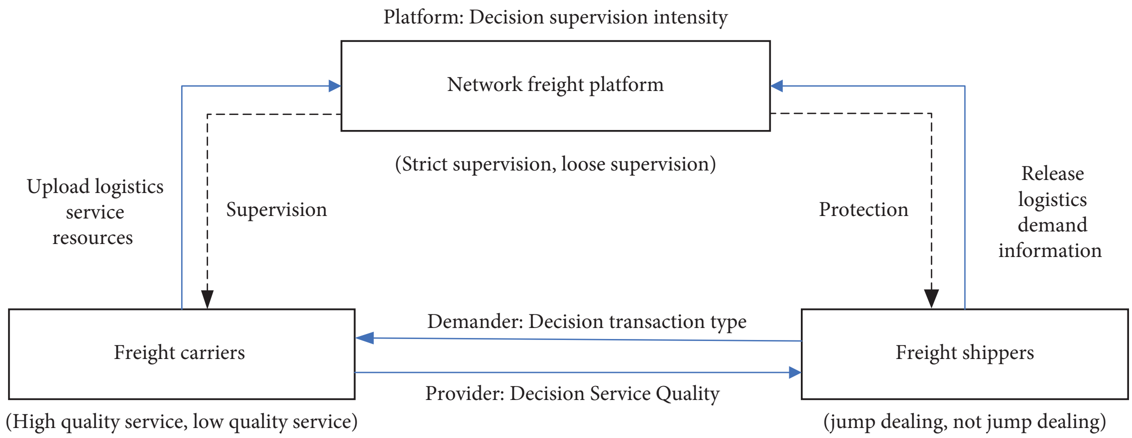

FIGURE 1: Operation mode between network freight platforms, freight carriers, and freight shippers.

4. Analysis of the Tripartite Evolutionary Game Model

4.1. Payoffs for All Parties under Various Strategy Combinations. Based on the above assumptions, we first calculate the payoff of all parties under various strategy combinations. The payoff matrix is shown in Table 3, where Π represents the platform return, F represents the return of freight carriers, and C z represents the return of freight shippers. The superscript represents the platform's strategy, with a superscript of 1 indicating that the platform adopts a strict supervision strategy and a superscript of 0 indicating that the platform adopts a loose supervision strategy. The subscript on the left represents the strategy of freight carriers. A left subscript of 1 indicates that the provider provides high-quality service, and a left subscript of 0 indicates that the provider provides low-quality service. The subscript on the right represents the strategy of freight shippers, with a right subscript of 1 indicating that the freight ship chooses not to engage in JD and a right subscript of 0 indicating that the freight ship chooses to engage in JD.

Scenario 6. The freight shipper does not adopt a JD strategy, and the platform adopts a strict supervision strategy:

(1) When freight carriers provide low-quality services, they receive complaints from freight shippers; in this case, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{01}^{1} &= a - b - d + c_1;\\ F_{01}^{1} &= g - i - c_1;\\ C_{01}^{1} &= j - k - l + d.\end{aligned} \tag{1}$$

(2) When freight carriers provide high-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{11}^{1} &= a - b;\\ F_{11}^{1} &= g - i - h;\\ C_{11}^{1} &= j - l.\end{aligned} \tag{2}$$

Scenario 7. The freight shipper does not adopt a JD strategy, and the platform adopts a loose supervision strategy:

(1) When freight carriers provide low-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{01}^{0} &= a - d + c_2;\\ F_{01}^{0} &= g - i - c_2;\\ C_{01}^{0} &= j - k - l + d.\end{aligned} \tag{3}$$

(2) When freight carriers provide high-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{11}^{0} &= a;\\ F_{11}^{0} &= g - h - i;\\ C_{11}^{0} &= j - l.\end{aligned} \tag{4}$$

Scenario 8. The freight shipper adopts a JD strategy, and the platform adopts a strict supervision strategy:

(1) When freight carriers provide low-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{00}^{1} &= a - b - s + f_1;\\ F_{00}^{1} &= m - i - f_1;\\ C_{00}^{1} &= j - m - k.\end{aligned} \tag{5}$$

Table 2: Summary of parameters.

Parameters	Description
Network freight platform (strict supervision, loose supervision)	Total revenue of network freight platforms: a
	Additional supervision costs are incurred when network freight platforms adopt strict supervision strategies
	If freight carriers provide low-quality services and receive complaints from freight shippers, when the network freight platform adopts a strict supervision strategy, the penalty for freight carriers is c_1. When the network freight platform adopts a loose supervision strategy, the penalty for the freight carriers is c_2, $c_1 > c_2$. For the convenience of calculations, let $c = c_1 - c_2$
	If freight carriers provide low-quality services and receive complaints from freight shippers, the compensation amount paid by the network freight platform to the freight shippers is d
	If the platform discovers private transactions occurring between freight carriers and freight shippers, when the network freight platform adopts a strict supervision strategy, the penalty for freight carriers is f_1. When the network freight platform adopts a loose supervision strategy, the penalty for the freight carriers is f_2. For the convenience of calculations, let $f = f_1 - f_2$
	The loss caused to the network freight platform due to freight shipper jump dealing is s
Freight carriers (high-quality services, low-quality services)	The total revenue of freight carriers, when they enter the network freight platform and receive task assignments, is g
	The additional cost of providing high-quality service by freight carriers, such as the cost of quick-response customer service and on-time delivery, is h and $h > c_1 - c_2$; otherwise, freight carriers have no motivation to save such costs
	The total cost of offline services for freight carriers is i, $g > i$
Freight shippers (nonjump dealing, jump dealing)	The total revenue earned by freight shippers due to meeting logistics needs is j
	The additional cost added to the shipper when freight carriers provide low-quality services, such as loss of stock or increased storage costs, is k
	The total online service fee paid by the freight shipper to the network freight platform is l
	When the freight shipper engages in private transactions with freight carriers, the fee paid by the freight shipper is m, which is also equal to the total revenue of the freight carrier in this situation

Table 3: Payoff matrix under various strategy combinations.

Participant strategy combination		Platform: strict supervision (x)		Platform: loose supervision $(1-x)$	
		Freight carriers: high-quality service (y)	Freight carriers: low-quality service $(1-y)$	Freight carriers: high-quality service (y)	Freight carriers: low-quality service $(1-y)$
Freight shippers	NJD (z)	Π_{11}^1 F_{11}^1 C_{11}^1	Π_{01}^1 F_{01}^1 C_{01}^1	Π_{11}^0 F_{11}^0 C_{11}^0	Π_{01}^0 F_{01}^0 C_{01}^0
	JD $(1-z)$	Π_{10}^1 F_{10}^1 C_{10}^1	Π_{00}^1 F_{00}^1 C_{00}^1	Π_{10}^0 F_{10}^0 C_{10}^0	Π_{00}^0 F_{00}^0 C_{00}^0

(2) When freight carriers provide high-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{10}^1 &= a - b - s + f_1;\\ F_{10}^1 &= m - i - h - f_1;\\ C_{10}^1 &= j - m.\end{aligned} \tag{6}$$

Scenario 9. The freight shipper adopts a JD strategy, and the platform adopts a loose supervision strategy:

(1) When freight carriers provide low-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{00}^0 &= a - s + f_2;\\ F_{00}^0 &= m - i - f_2;\\ C_{00}^0 &= j - m - k.\end{aligned} \tag{7}$$

(2) When freight carriers provide high-quality services, the profits of the platform, freight carriers, and freight shipper are as follows:

$$\begin{aligned}\Pi_{10}^0 &= a - s + f_2;\\ F_{10}^0 &= m - h - i - f_2;\\ C_{10}^0 &= j - m.\end{aligned} \tag{8}$$

4.2. Analysis of the Strategic Stability of the Three Parties. Based on the return function detailed in Section 4.1, we first calculate the expected and average returns for each party under various strategies and obtain the replication dynamic equations for each party, thereby obtaining stable strategies.

4.2.1. Strategic Stability Analysis of Network Freight Platforms. The expected returns under strict supervision, expected returns under loose supervision, and average returns for network freight platforms are as follows:

$$\begin{aligned}\Pi_{P1} &= yz\Pi_{11}^1 + y(1-z)\Pi_{10}^1 + (1-y)z\Pi_{01}^1 + (1-y)(1-z)\Pi_{00}^1,\\ \Pi_{P2} &= yz\Pi_{11}^0 + y(1-z)\Pi_{10}^0 + (1-y)z\Pi_{01}^0 + (1-y)(1-z)\Pi_{00}^0,\\ \overline{\Pi}_P &= x\Pi_{P1} + (1-x)\Pi_{P2}.\end{aligned} \tag{9}$$

Based on this, the replication dynamic equation for the strategy selection of the network freight platform is shown in the following equation:

$$\begin{aligned}F(x) &= \frac{dx}{dt}\\ &= x\left(\Pi_{P1} - \overline{\Pi}_P\right)\\ &= x(1-x)\left(\Pi_{P1} - \Pi_{P2}\right)\\ &= x(1-x)\left[(1-z)\left(f_1 - f_2\right) + yz\left(c_2 - c_1\right) + z\left(c_1 - c_2\right) - b\right].\end{aligned} \tag{10}$$

According to the stability theorem of differential equations, if the probability of a network freight platform choosing a strict supervision strategy is in a stable state, then it must meet $F(x) = 0$ and $\mathrm{d}F(x)/\mathrm{d}x < 0$. To obtain

$$\frac{\mathrm{d}F(x)}{\mathrm{d}x} = (1-2x)\left[(1-z)(f_1-f_2) + yz(c_2-c_1) + z(c_1-c_2) - b\right], \tag{11}$$

let $G(y) = (1-z)(f_1-f_2) + yz(c_2-c_1) + z(c_1-c_2) - b$.

Obviously, $G(y)$ is a monotonic decreasing function of y; let $G(y) = 0$, it is easy to obtain $y_1^* = z(c_1-c_2) - b + (1-z)(f_1-f_2)/(c_1-c_2)z$.

When $y = y_1^*$ and $\mathrm{d}F(x)/\mathrm{d}x = 0$, we are unable to determine the stability strategy.

When $0 < y < y_1^*$, $G(y) > 0$; only when $x = 1$, $F(x) = 0$ and $\mathrm{d}F(x)/\mathrm{d}x < 0$ can be simultaneously met; that is, strict supervision is a stable strategy for freight network platforms.

When $1 > y > y_1^*$, $G(y) < 0$; only when $x = 0$, $F(x) = 0$ and $\mathrm{d}F(x)/\mathrm{d}x < 0$ can be simultaneously met; that is, loose supervision is a stable strategy for freight network platforms. A phase diagram of the evolution strategy of the network freight platform is shown in Figure 2.

Figure 2 shows that the probability of a network freight platform choosing a strict supervision strategy is the same as that in Figure 2(b), and the volume is calculated as follows:

$$\begin{aligned} V_1 &= \int_0^1\int_0^1 \frac{f-b}{cy-c+f}\,\mathrm{d}y\mathrm{d}x \\ &= \frac{f-b}{c}\left[\ln f - \ln(f-c)\right]. \end{aligned} \tag{12}$$

Therefore, the probability of choosing a loose supervision strategy for network freight platforms is $1 - V_1$. Obviously, the probability of network freight platforms adopting strict supervision strategies is negatively correlated with their supervision costs.

4.2.2. Strategic Stability Analysis of Freight Carriers. The expected benefits of providing high-quality services, providing low-quality services, and providing average benefits for freight carriers are as follows:

$$\begin{aligned} \Pi_{E1} &= xz(g-h-i) + x(1-z)(m-i-h-f_1) + (1-x)z(g-h-i) + (1-x)(1-z)(m-h-i-f_2), \\ \Pi_{E2} &= xz(g-i-c_1) + x(1-z)(m-i-f_1) + (1-x)z(g-i-c_2) + (1-x)(1-z)(m-i-f_2), \\ \overline{\Pi}_E &= y\Pi_{E1} + (1-y)\Pi_{E2}. \end{aligned} \tag{13}$$

Based on this, the replication dynamic equation for selecting a freight carrier strategy is shown in the following equation:

$$\begin{aligned} F(y) &= \frac{\mathrm{d}y}{\mathrm{d}t} \\ &= y(\Pi_{E1} - \overline{\Pi}_E) \\ &= y(1-y)(\Pi_{E1} - \Pi_{E2}) \\ &= y(1-y)\left[xz(c_1-c_2) + zc_2 - h\right]. \end{aligned} \tag{14}$$

If the probability of freight carriers adopting a high-quality service strategy is in a stable state, it must meet $F(y) = 0$ and $\mathrm{d}F(y)/\mathrm{d}y < 0$. It is easy to obtain $\mathrm{d}F(y)/\mathrm{d}y = (1-2y)\ \left[xz(c_1-c_2) + zc_2 - h\right]$, let $G(z) = xz(c_1-c_2) + zc_2 - h$; obviously, $G(z)$ is an increasing function. Let $G(z) = 0$; then, we can obtain $z^* = h/x(c_1-c_2) + c_2$.

When $z = z^*$ and $\mathrm{d}F(y)/\mathrm{d}y = 0$, we are unable to determine the stability strategy.

When $1 > z > z^*$, $G(z) > 0$; only when $y = 1$, $F(y) = 0$ and $\mathrm{d}F(y)/\mathrm{d}y < 0$ can be simultaneously met; that is, providing high-quality services is a stable strategy for freight carriers.

When $0 < z < z^*$, $G(z) < 0$; only when $y = 0$, $F(y) = 0$ and $\mathrm{d}F(y)/\mathrm{d}y < 0$ can be simultaneously met; that is, providing low-quality services is a stable strategy for freight carriers.

A phase diagram of the evolution strategy of freight carriers is shown in Figure 3.

Figure 3 shows that the probability of freight carriers choosing a low-quality service strategy is equal to the volume of (c) in Figure 3, which is obtained as follows:

$$\begin{aligned} V_2 &= \int_0^1\int_0^1 \frac{h}{cx+c_2}\,\mathrm{d}x\mathrm{d}y \\ &= \frac{h}{c}\left(\ln c_1 - \ln c_2\right). \end{aligned} \tag{15}$$

Therefore, the probability of freight carriers choosing a high-quality service strategy is $1 - V_2$. Obviously, the probability of a freight carrier choosing a high-quality service strategy is inversely proportional to its service cost.

4.2.3. Strategic Stability Analysis of Freight Shippers. The expected benefits of the freight shipper when not jumping, the expected benefits of the shipper when jumping, and the average benefits are as follows:

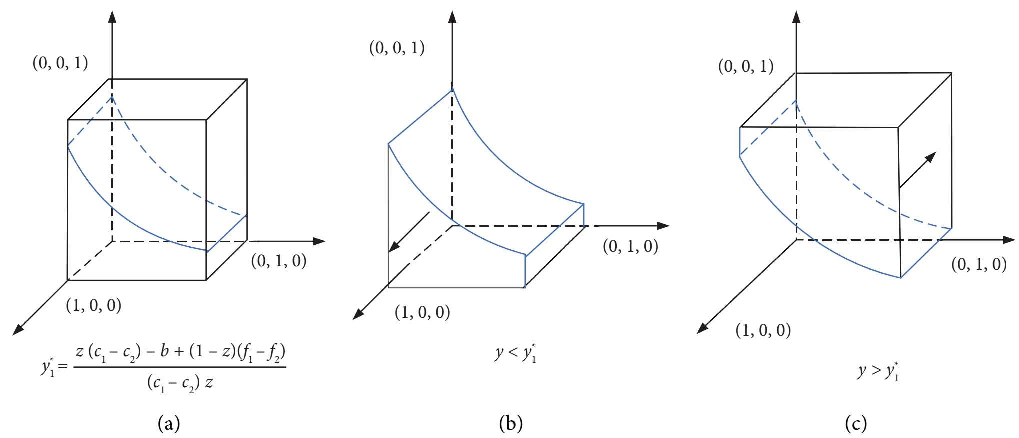

Figure 2: Evolutionary strategy phase diagram of the network freight platform.

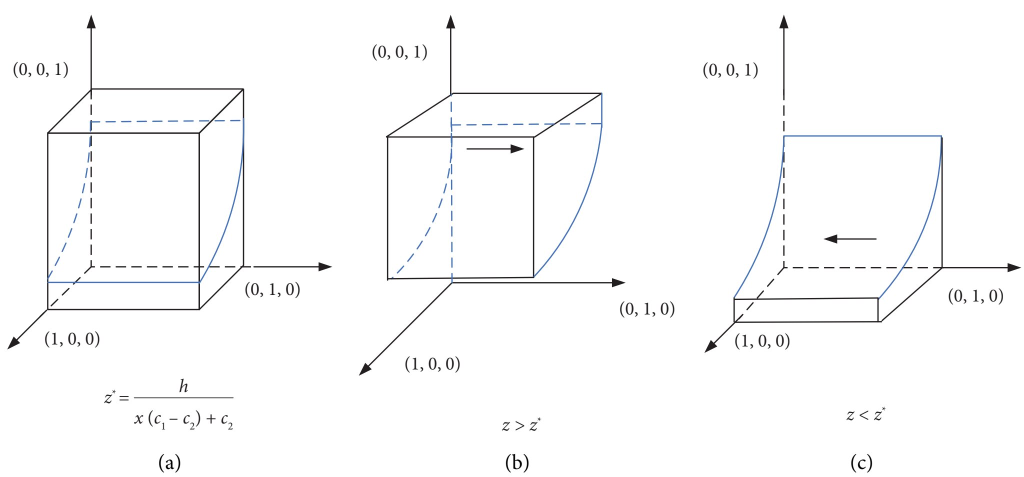

Figure 3: Evolutionary strategy phase diagram of freight carriers.

$$\begin{aligned}\Pi_{C1} &= xy(j-l) + x(1-y)(j-l-k+d) + (1-x)y(j-l) + (1-x)(1-y)(j-l-k+d),\\ \Pi_{C2} &= xy(j-m) + x(1-y)(j-m-k) + (1-x)y(j-m) + (1-x)(1-y)(j-m-k),\\ \overline{\Pi}_C &= z\Pi_{C1} + (1-z)\Pi_{C2}.\end{aligned} \tag{16}$$

Based on this, the replication dynamic equation for selecting the freight shipper strategy is shown in the following equation:

$$\begin{aligned}F(z) &= \frac{\mathrm{d}z}{\mathrm{d}t}\\ &= z\left(\Pi_{C1} - \overline{\Pi}_C\right)\\ &= z(1-z)\left(\Pi_{C1} - \Pi_{C2}\right)\\ &= z(1-z)[(1-y)d + m - l].\end{aligned} \tag{17}$$

If the probability of freight shippers not jumping is in a stable state, it must meet $F(z) = 0$ and $\mathrm{d}F(z)/\mathrm{d}z < 0$. It is easy to obtain $\mathrm{d}F(z)/\mathrm{d}z = (1-2z)[(1-y)d + m - l]$. Let $D(y) = (1-y)d + m - l$, then $D(y)$ is a monotonic decreasing function.

By letting $D(y) = 0$, we can obtain $y_2^* = d + m - l/d$.

When $y = y_2^*$ and $\mathrm{d}F(z)/\mathrm{d}z = 0$, we are unable to determine the stability strategy. When $1 > y > y_2^*$, $D(y) < 0$; only when $z = 0$, $F(z) = 0$ and $\mathrm{d}F(z)/\mathrm{d}z < 0$ can be simultaneously met; that is, jump dealing is a stable strategy for freight shippers. When $0 < y < y_2^*$, $D(y) > 0$; only when $z = 1$, $F(z) = 0$ and $\mathrm{d}F(z)/\mathrm{d}z < 0$ can be simultaneously met; that is, not jumping is a stable strategy for freight shippers. A phase diagram of the evolution strategy of freight shippers is shown in Figure 4.

Figure 4 shows that the probability of freight shippers not jumping is equal to (c), which is obtained as $V_3 = d + m - l/d$; therefore, the probability of freight shippers choosing the jumping strategy is $1 - V_3$.

From this, we can see that the probability of freight shippers jumping is inversely proportional to the amount of compensation promised by the platform under low quality and is directly proportional to the cost difference between online and private transactions.

4.3. Strategic Stability Analysis of the Tripartite Systems. By combining (1), (2), and (3), we obtain a replication dynamic system for network freight platforms, freight carriers, and freight shippers:

$$\begin{cases} F(x) = \dfrac{\mathrm{d}x}{\mathrm{d}t} = x\left(\Pi_{P1} - \overline{\Pi}_P\right) = x(1-x)\left(\Pi_{P1} - \Pi_{P2}\right) = x(1-x)\left[(1-z)\left(f_1 - f_2\right) + yz\left(c_2 - c_1\right) + z\left(c_1 - c_2\right) - b\right], \\ F(y) = \dfrac{\mathrm{d}y}{\mathrm{d}t} = y\left(\Pi_{E1} - \overline{\Pi}_E\right) = y(1-y)\left(\Pi_{E1} - \Pi_{E2}\right) = y(1-y)\left[xz\left(c_1 - c_2\right) + zc_2 - h\right], \\ F(z) = \dfrac{\mathrm{d}z}{\mathrm{d}t} = z\left(\Pi_{C1} - \overline{\Pi}_C\right) = z(1-z)\left(\Pi_{C1} - \Pi_{C2}\right) = z(1-z)\left[(1-y)d + m - l\right]. \end{cases} \tag{18}$$

To achieve a stable state of the system, $F(x) = 0, F(y) = 0, F(z) = 0$; from this, the stable equilibrium points can be obtained (for the convenience of calculations, let $c = c_1 - c_2, f = f_1 - f_2$):

$$\begin{aligned} E_1 &= (0, 0, 0), \\ E_2 &= (0, 1, 0), \\ E_3 &= (0, 1, 1), \\ E_4 &= (0, 0, 1), \\ E_5 &= (1, 0, 0), \\ E_6 &= (1, 1, 0), \\ E_7 &= (1, 1, 1), \\ E_8 &= (1, 0, 1), \\ E_9 &= \left(\frac{-\left[c_2bd - c_2\mathrm{d}f + f\mathrm{d}h + ch(m-l)\right]}{\mathrm{d}c(b-f)}, \frac{d-l+m}{d}, \frac{\mathrm{d}f - bd}{\mathrm{d}f - c(l-m)}\right), \\ E_{10} &= \left(\frac{h-c_2}{c_1-c_2}, \frac{c-b}{c}, 1\right), \\ E_{11} &= \left(1, \frac{d-l+m}{d}, \frac{h}{c_1}\right), \\ E_{12} &= \left(0, \frac{d-l+m}{d}, \frac{h}{c_2}\right). \end{aligned} \tag{19}$$

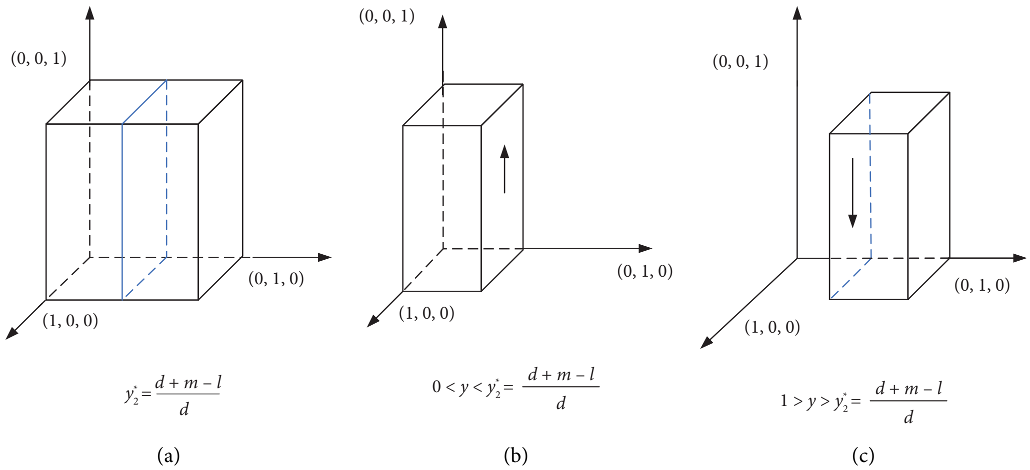

FIGURE 4: Evolutionary strategy phase diagram of freight shippers.

Because $x, y, z \in [0, 1]$, $E_9 \sim E_{10}$ are meaningless (Proof can be found in the Appendix), while $E_{11} \sim E_{12}$ are meaningful only when certain conditions, namely, ① and ② are met (Condition ①: $0 < d + m - l/d < 1$, $h < c_1$; Condition ②: $0 < d + m - l/d < 1$, $h < c_2$). $E_1 \sim E_8$ are pure strategy combinations, and $E_{11} \sim E_{12}$ are hybrid strategy combinations.

According to Friedman's method, the evolutionary stability strategy (ESS) of differential equation systems can be obtained through an analysis of the local stability of the Jacobian matrix of the system. According to (18), the Jacobian matrix of the system is as follows:

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}, \tag{20}$$

where

$$\begin{aligned}
\frac{\partial F(x)}{\partial x} &= (1-2x)[(1-z)f - yzc + zc - b],\\
\frac{\partial F(x)}{\partial y} &= x(x-1)zc,\\
\frac{\partial F(x)}{\partial z} &= x(1-x)(c - f - yc);\\
\frac{\partial F(y)}{\partial y} &= (1-2y)[xzc + zc_2 - h],\\
\frac{\partial F(y)}{\partial x} &= y(1-y)zc,\\
\frac{\partial F(y)}{\partial z} &= y(1-y)(cx + c_2);\\
\frac{\partial F(z)}{\partial z} &= (1-2z)[(1-y)d + m - l],\\
\frac{\partial F(z)}{\partial x} &= 0, \frac{\partial F(z)}{\partial y} = -z(1-z)d.
\end{aligned} \tag{21}$$

Next, the meaningful equilibrium points obtained above are substituted into the Jacobian matrix, and the eigenvalues of the corresponding Jacobian matrix are calculated; the specific content is shown in Table 4. According to Lyapunov's method, the necessary and sufficient condition for a system to achieve an ESS is that all the eigenvalues of the Jacobian matrix have negative real parts. Therefore, for these

Table 4: Eigenvalues and stability analysis of the equilibrium points.

Equilibrium points	Eigenvalues of Jacobian matrices: $\lambda_1, \lambda_2, \lambda_3$	Stability
$E_1 = (0,0,0)$	$-h, f-b, d-l+m$	③
$E_2 = (0,1,0)$	$h, m-l, f-b$	Unstable
$E_3 = (0,1,1)$	$h-c_2, l-m, -b$	Unstable
$E_4 = (0,0,1)$	$c_2-h, c-b, l-m-d$	④
$E_5 = (1,0,0)$	$b-(f_1-f_2), -h, d-l+m$	⑤
$E_6 = (1,1,0)$	$h, m-l, b-f$	Unstable
$E_7 = (1,1,1)$	$l-m, b, h-c_1$	Unstable
$E_8 = (1,0,1)$	$b-c, l-d-m, c_1-h$	⑥
E_{11}	$\lambda_1 = -\lambda_2 = \sqrt{c_1dh(c_1-h)(m-l)(d-l+m)}/c_1d, \lambda_3 = [(b-f)c_1d + dhf + ch(m-l)]/c_1d$	Unstable
E_{12}	$\lambda_1 = -\lambda_2 = \sqrt{c_2dh(c_2-h)(m-l)(d-l+m)}/c_2d, \lambda_3 = c_2df - c_2bd - dfh + ch(l-m)/c_2d$	Unstable

Table 5: Conditions of evolutionary stability of equilibrium points.

	Conditions
③	$f_1 - f_2 < b, d < l - m$
④	$c_2 < h, c_1 - c_2 < b, l - m < d$
⑤	$b < f_1 - f_2, d < l - m$
⑥	$b < c_1 - c_2, l - m < d, c_1 < h$

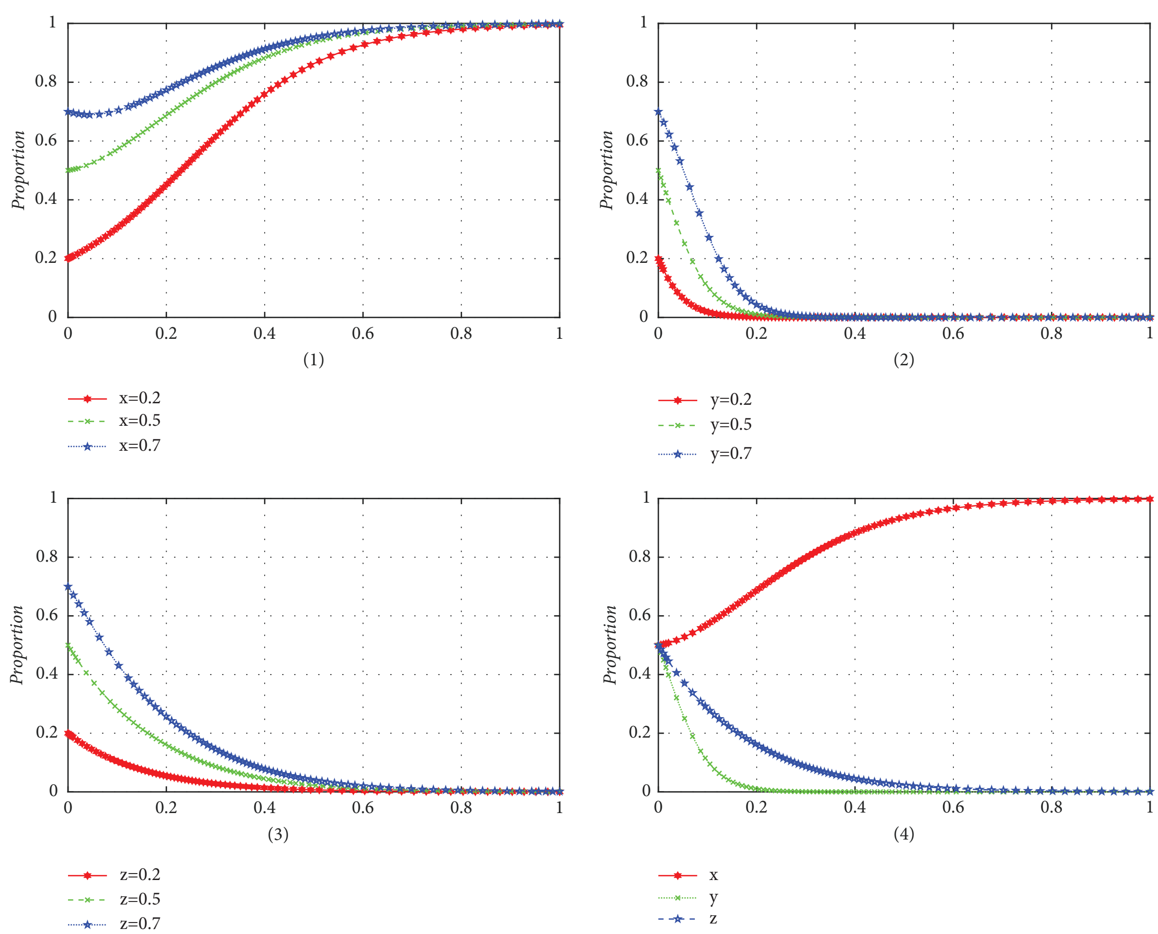

Figure 5: The evolution of ESS (1, 0, 0).

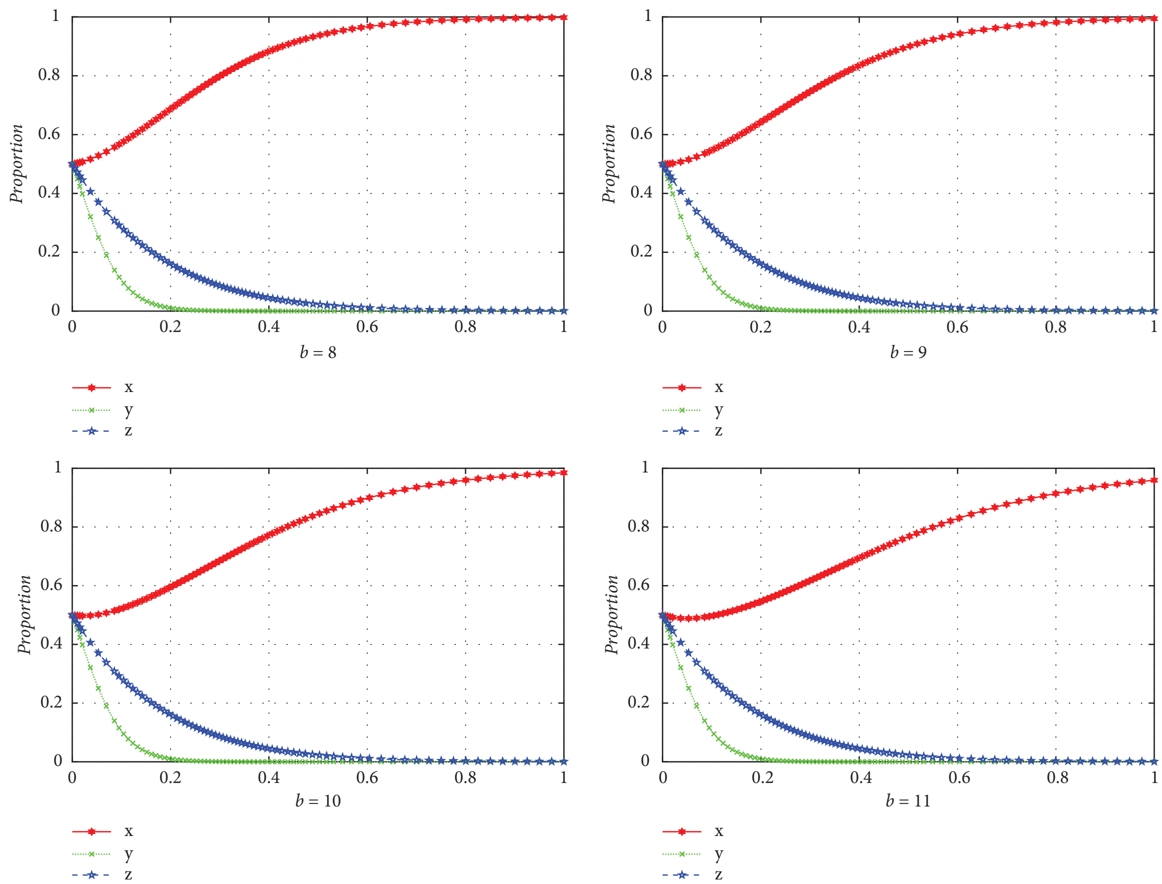

Figure 6: The strategic evolution process of the platform under different supervision costs.

equilibrium points to serve as ESSs, different constraint conditions need to be met, and these constraints are shown in Table 5.

In fact, the results shown in Tables 4 and 5 are also consistent with the actual situation. Taking equilibrium points E_1, E_4, and E_5 as examples, the situation at other equilibrium points can be seen to be similar and do not repeat. In the early stages of the development of network freight platforms, the supervision ability and efficiency of such platforms were relatively low, and at that time, the supervision cost of the platform was relatively high. To attract more free carriers to settle on this platform, the penalty for breaching contracts for free carriers was relatively low, which can easily lead to the establishment of inequality $f_1 - f_2 < b$. On the other hand, in the early stage of network freight platform development, the market competition was not fierce, the platform's compensation to the shipper was low, and the online service cost was high; thus, inequality easily occurred $d < l - m$. Based on the above analysis, in the early stages of network freight platform development, condition ③ is met, and the equilibrium point E_1 is the evolutionary equilibrium point. This means that the network freight platform adopts a loose supervision strategy, freight carriers provide low-level logistics services, and shippers adopt JD to save costs. With the improvements in the management level and supervision efficiency, the supervision cost of the platform is gradually reduced, which leads to the establishment of inequality $b < (f_1 - f_2)$; at this time, condition ⑤ is met, and the equilibrium point E_5 becomes an ESS. With the rapid development of the online freight model, the level of competition between platforms is becoming increasingly fierce. As the compensation amount for shippers becomes increasingly higher, the discount for freight shippers becomes greater, making it easier to meet condition 4. At this time, freight shippers are strongly motivated to use the network freight platform, and E_4 becomes an ESS.

5. Numerical Simulation

In Sections 4.2 and 4.3, we theoretically explored the stability strategies of the three parties and the evolutionary stability strategies of the system as a whole. Next, we use MATLAB R2021b software to conduct numerical simulations on the proposed evolutionary model to verify its effectiveness and conduct sensitivity analysis on several parameters to explore the impact of these parameters on the behavior of the three parties.

First, to verify whether the strategy combination (1, 0, 0) is an evolutionary equilibrium strategy, we set the following parameters: $b = 8, c_1 = 20, c_2 = 14, h = 28, f_1 = 40, f_2 = 25, l = 60, m = 45, d = 8$. This group of parameters meets condition ③. We set the initial values of x, y, and z to 0.2, 0.5, and 0.7, respectively, and observe the evolution results of the

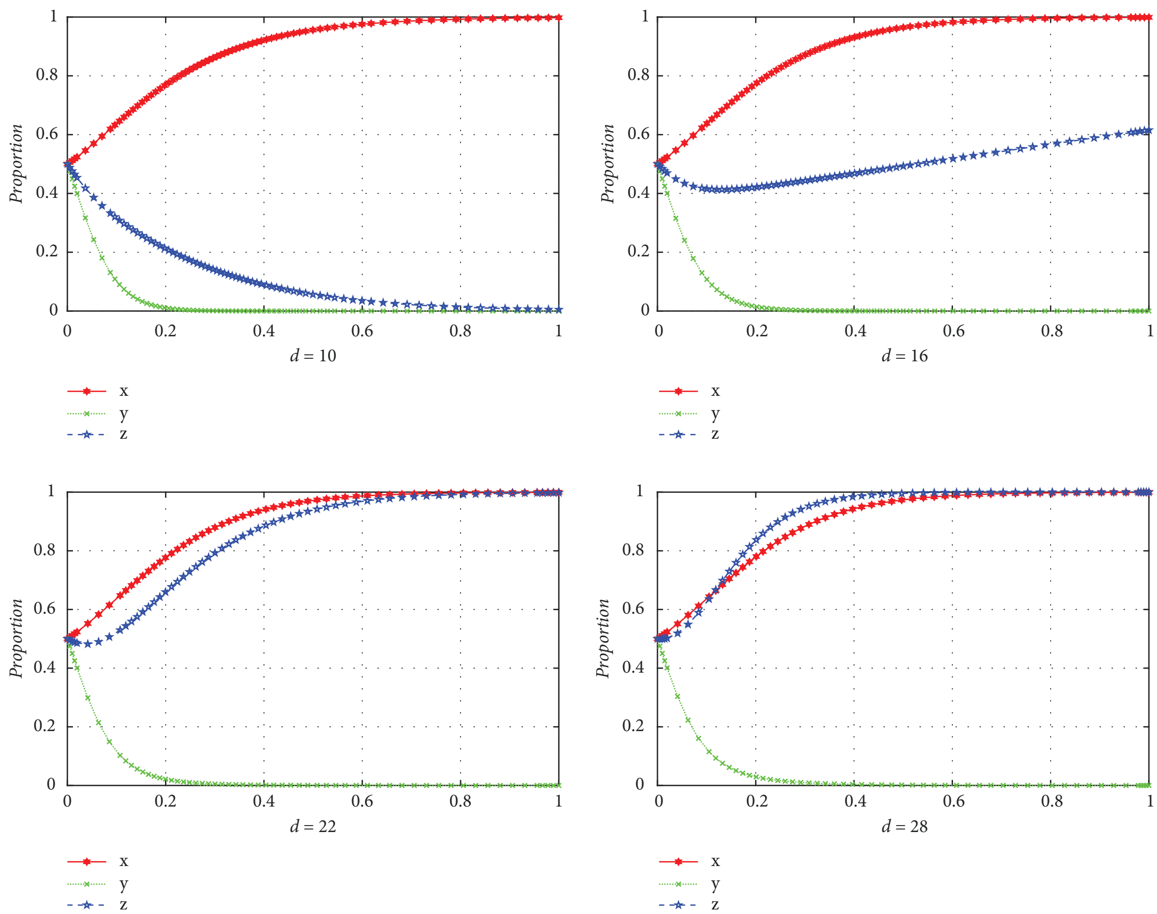

FIGURE 7: The evolution process of the freight shipper strategy under changing platform compensation.

three parties, as shown in (10), (14), and (17) in Figure 5. Figure 5 shows the final strategy evolution results of the three parties when the initial probabilities of all parties are 0.5.

Figure 5 shows that when condition ③ is met, the strategy evolution results of the three parties are indeed consistent with our theoretical analysis; that is, regardless of the initial probability, all parties ultimately tend to stabilize the strategy ESS (1, 0, 0). Using the same approach, we adjust the parameters to meet different conditions and obtain the evolutionary results for various strategies. This result is also consistent with our calculated theoretical results. Due to space limitations, we do not present this again.

Next, based on the above, we begin to explore the impact of the changes in some parameters on their respective strategies. First, we observe the strategy evolution process of all parties when the supervision cost of the platform changes. The supervision costs of the platform are set to 8, 9, 10, and 11, and the initial values of x, y, and z are set to 0.5, while the other parameters are held constant. The resulting evolution process is shown in Figure 6.

Figure 6 shows that when the supervision cost of the platform is very low, the platform's strategy quickly evolves into a strict supervision strategy, and as the supervision cost increases, the platform's willingness to choose a strict supervision strategy gradually decreases. In addition, changes in the supervision cost of the platform have no impact on the behavioral strategies of other participants.

Then, we explore the strategic evolution process of various parties when the platform's compensation for freight shippers changes. When the compensation amounts d are set to 10, 16, 22, and 28, the evolution process of the three-party strategy is shown in Figure 7. Figure 7 shows that when d is small, freight shippers tend to adopt a jump dealing strategy. However, as the compensation amount gradually increases, freight shippers tend to choose an NJD strategy because trading through the platform can better protect their own rights and interests. Thus, the ESS transition is from $E_5\,(1,\ 0,\ 0)$ to $E_8\,(1,\ 0,\ 1)$.

Finally, the impact of the carrier's service cost on its evolution strategy can be verified. The values of h are set to 2, 5, 19, and 23, and the other parameters are set as $b = 15, c_1 = 20, c_2 = 12, f_1 = 35, f_2 = 25, l = 60, m = 45, d = 22$. The impact of the different values of h on the evolution path of the freight carrier is shown in Figure 8.

Figure 8 shows that when the service cost is high, freight carriers choose a low-quality service strategy, and E_4 becomes the evolutionary equilibrium point. When the service cost is low, condition ④ is no longer satisfied, and there is no stable point. Therefore, freight carriers do not have a stable pure strategy, which means they can choose either a high-quality service strategy or a low-quality service strategy.

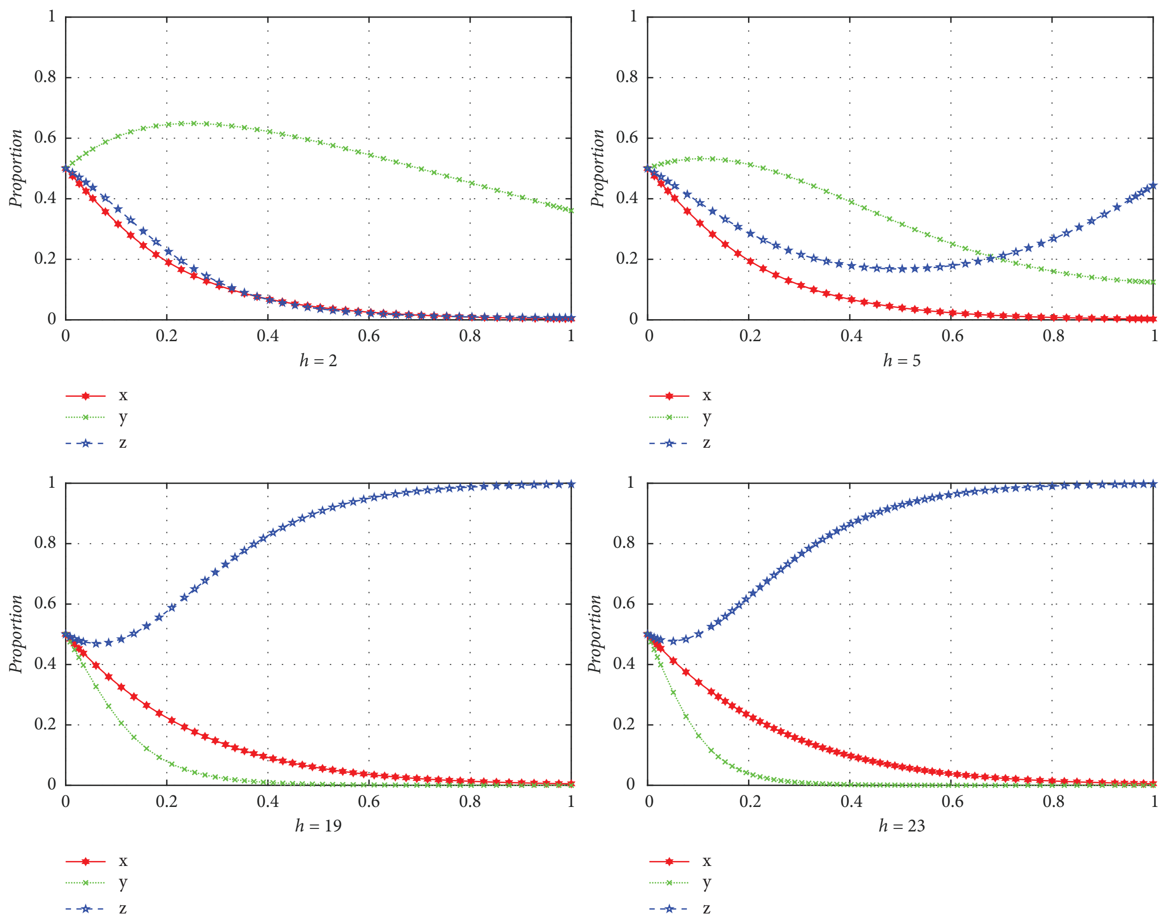

Figure 8: The evolution process of the freight carrier strategy under changing service costs.

6. Conclusion

6.1. Managerial Insights. In this paper, the evolution law of the behavioral strategies of important participants in the operation of the network freight mode is examined, with focus placed on the short-term irrational decision-making behavior of participants. We constructed a tripartite evolutionary game model for network freight platforms, freight carriers, and freight shippers; studied the strategic stability and stability of the tripartite system; and explored the rationality of this model through numerical examples. Based on the above analysis results, we offer the following managerial insights:

(1) In the early development stage of a new logistics model, it is very common for all participants to exhibit short-term irrational behaviors. Under the action of a fierce market competition mechanism or the cost changes brought about by the management level and technological progress, all participants shift from one stable state to another stable state; that is, the strategic choices of the participants do not remain unchanged.

(2) At different stages of network freight platform development, the evolutionary equilibrium points of the tripartite system differ. At present, the online freight model is in the early stage of rapid development in which it is easy for the three parties to engage in negative behaviors, thus forming a balanced situation that does not exploit the long-term development of the industry. That is, freight carriers and freight shippers conspire to engage in private transactions, and freight platforms also adopt a loose regulatory strategy. To address this situation, network freight platforms should properly improve the protection of freight shipper rights and interests to attract more shippers to use the platform while simultaneously strengthening the level of carrier supervision. Many of these measures are currently being implemented by government departments.

(3) The continuous promotion of the credit system construction of logistics service providers can help network freight platforms improve their regulatory efficiency and reduce their regulatory costs. A reduction in regulatory costs for online platforms can help guide logistics supply and demand parties to complete transactions of higher quality, provide better services for freight shippers, and promote the healthy development of this logistics model.

6.2. Research Implications and Future Research Directions. From the perspective of research subjects, most studies focus on the rational and static behavior of participants; for instance, Deng et al. investigated whether carriers and shippers are willing to share service capabilities and service information [3]. Changbing et al. proposed an order allocation mechanism for network freight transportation with carbon tax constraints [19]. However, research on irrational behaviors of participants, such as low-quality services and jump dealing, is relatively lacking. The emergence of irrational decisions is an inevitable market behavior, and studying the evolution law of these irrational behaviors is conducive to regulating the behavior of market players. Therefore, this research contributes to standardizing the behavior of all parties under the network freight mode and promoting the long-term and healthy development of the network freight mode. Moreover, the three-party evolutionary game model and analysis method proposed in this paper also have certain reference significance in the game behavior analysis of multiple agents.

In addition, from the perspective of research methods, this paper provides a reference method for the game analysis between multiple agents. Many literature have analyzed the cooperative relationship between freight carriers and freight shippers; for instance, Wang et al. studied risk management and coordination between carriers and shippers in the spot freight market [29]. Acocella et al. conducted an empirical analysis of carrier reciprocity in the dynamic freight market [30]. Cooperative relationships between multiple agents are more complex, especially involving dynamic decision-making processes. This paper provides a way to study the stability of a three-party system composed of a network freight platform, freight carrier, and freight shippers.

This study has several limitations. We consider only market players and do not consider the role of government agencies in this sector. For example, in the early stage of network freight mode development, government departments issued many support policies and financial subsidies and constantly worked to improve the relevant laws and regulations for regulating market behaviors. For example, the Chinese government has provided preferential tax policies for the development of network freight platforms and built relevant supporting facilities for network freight platforms [6]. All these measures affect the behavioral strategies of freight carriers and freight shippers. In the future, we will continue to consider the evolutionary process of multiparty behavior strategies under the network freight model incorporating government regulatory mechanisms.

Appendix

A. Proof That E9 is Meaningless

Prove:

$E_9 = (-[c_2bd - c_2\mathrm{d}f + f\mathrm{d}h + ch(m-l)]/\mathrm{d}c(b-f),\ d - l + m/d, \mathrm{d}f - bd/\mathrm{d}f - c(l-m)), E_{10} = (h - c_2/c_1 - c_2, c - b/c, 1)$ are meaningless.

Proof. According to Assumption 2, $b > c_1 - c_2$ and $c - b/c < 0$; therefore, E_{10} is meaningless.

Because $h > c_1 - c_2, m < l$,

(1) When $f > b$: $-[c_2bd - c_2df + fdh + ch(m-l)]/dc(b-f) = c_2d(b-f) + fdh + ch(m-l)/dc(f-b) > fdh/dc(f-b) > fdc/dc(f-b) = f/f-b > 1$, so E_9 is meaningless

(2) When $f < b$. Assuming that E_9 is meaningful, then $0 < d - l + m/d < 1$, so $d > l - m$. Similarly,

$0 < df - bd/df - c(l-m) = d(f-b)/df - c(l-m) < 1$ because $f < b$, so $d(f-b) < 0$; therefore, $df - c(l-m) < 0$, and $-d\ (f-b) < -[df - c(l-m)]$. It is easy to obtain $l - m/d > b/c > 1$; this conclusion contradicts the hypothesis that $d > l - m$; thus, E_9 is meaningless. □

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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