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Evolutionary Game Analysis of Cross-Border E-Commerce Logistics Alliance Subject Considering Supply Chain Disruption Risk

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Abstract: Due to the quick rise in cross-border e-commerce and the expansion of global economic integration, cross-border e-commerce logistics alliances now present new opportunities and potential. Simultaneously, research on risk concerns in cross-border e-commerce in the modern era has drawn interest. This paper considers the special scenario of cross-border e-commerce supply chain disruptions, analyzes the main decision-making behaviors of key entities in the cross-border e-commerce logistics alliance under normal and risk scenarios, and based on this, constructs a tripartite evolutionary game model among cross-border e-commerce platforms, logistics service providers, and overseas merchants. The article analyzes the evolutionary stability of strategy choices for all participants, discusses the impact of various elements on the strategy choices of the three parties, and conducts a simulation analysis of the dynamic game of strategy choices for the three parties under the influence of different parameters using MATLAB 2021a software. The findings of the study demonstrate the following: (1) The reduction in the allocation coefficient for additional total costs of logistics service providers, the increase in the overall losses of the alliance due to customer complaints, and the increase in compensation rulings by the platform for supply chain risks faced by merchants will all encourage logistics service providers to actively pursue service innovation strategies and prompt overseas merchants to actively participate in alliance cooperation. However, an increase in overall risk costs and an increase in opportunity costs for merchants will raise the costs of tripartite alliance cooperation, thus hindering cross-border e-commerce logistics alliance collaboration. At the same time, when logistics service providers receive punishment from the platform and face potentially increased losses due to complaints, this will not only enhance the platform’s control over logistics service providers but also reduce the enthusiasm of logistics service providers to pursue service innovation strategies. (2) As the main body of the alliance, cross-border e-commerce platforms should coordinate the participants, constrain the behaviors of the participating entities within the alliance through setting reasonable reward and punishment mechanisms, and ensure the comprehensive benefits of the cross-border e-commerce logistics alliance through the combined effect of different exogenous variables. Finally, through the analysis, verification, and explanation of the established model and methods, the effectiveness and applicability of the model and methods are confirmed, providing certain strategic support and a development reference for actively establishing cross-border e-commerce logistics alliances to promote cross-border e-commerce trade.

Keywords: supply chain disruption risk; cross-border e-commerce logistics alliance; three-party evolutionary game; stability analysis; simulation analysis

1. Introduction

With the continuous development of global trade, the role of cross-border e-commerce in international trade has become increasingly prominent, leading to a growing demand for
service capacity and quality in the cross-border logistics industry. As a result, the concept of cross-border e-commerce logistics alliances has emerged. A cross-border e-commerce logistics alliance is a logistics solution that crosses national borders and incorporates various cultural, institutional, and standard differences among countries and regions, catering to the increasing demand for logistics services. It is a development model of logistics alliance in which cross-border e-commerce platforms take the lead, with logistics service providers, overseas merchants, domestic operation companies, and consumers participating collaboratively. By efficiently integrating logistics resources within the alliance, sharing logistics information and technology, and strengthening cross-border transportation capabilities, a cross-border e-commerce logistics alliance optimizes the entire process of cross-border logistics business and provides customers with integrated solutions for cross-border logistics [1]. Consequently, it has become a forefront of development and a research hotspot in the field of cross-border e-commerce logistics. The research indicates that cross-border e-commerce logistics alliances, as an increasingly popular competitive tool in the current global market, have become a source of competitive advantage for alliance members [2]. However, in practical operations, cross-border e-commerce logistics alliances often face various risks, such as supply chain risks, information risks [3], customs risks, technology risks, policy risks, and many other risk challenges. From the perspective of alliance operation, strengthening cooperation with suppliers, improving supply chain visibility and transparency, and assessing and preventing various risks in the supply chain are particularly important to mitigate the risk of supply chain disruption.

Currently, scholars have conducted related research on cross-border e-commerce logistics alliances focusing on four aspects: alliance development models, risk assessment and identification, technological innovation, and the mechanisms of role and impact. In terms of alliance development models, Li Zejian et al. [4] proposed that cross-border logistics models mainly include postal parcels, international express delivery, overseas warehouses, and dedicated logistics models. They used the multi-value-set qualitative comparative analysis (mvQCA) method to explore the factors and formation paths of cross-border e-commerce enterprises’ choice of different logistics models. Chen Nan et al. [5] proposed and verified that cross-border e-commerce, as an enterprise innovation, should include business model innovation, rather than just institutional or technological innovation, thus expanding the connotation of e-commerce. Wei Hairui and Wu Fan [6] constructed a coordinated alliance of the China Railway Express Platform based on cost-allocation models and empirically analyzed seven fast rail platforms in Chengdu, Chongqing, Guiyang, Kunming, Liuzhou, Nanning, and Zunyi, demonstrating that alliances are an effective way to control costs. Wang Ying et al. [7], focusing on Chinese cross-border e-commerce companies, understood how supply chain resources are deployed to create value in supply chain service-based business models from the perspective of resource arrangement. Based on this, they provided development references for enhancing the business model of cross-border e-commerce supply chain services. Du Zhiping et al. [8] took the cross-border logistics alliance model under information collaboration as the research object, promoting the effective integration of cross-border information systems, seamless connection of electronic documents, and real-time sharing of information. They constructed a three-party evolutionary game model from four aspects: a standardization level of information collaboration, cost of information collaboration, the distribution of benefits from information collaboration, and the risks of information collaboration, and conducted a simulation analysis. Du Zhiping et al. [9] explored the operation mode of a cross-border e-commerce logistics alliance under the 4PL framework and constructed evolutionary game models for dynamic game processes among cross-border e-commerce platforms, logistics service providers, and merchants. They combined system dynamics to conduct a simulation analysis. Wei Hairui et al. [10], taking the Silk Road Economic Belt as an example, discussed the issues existing in the establishment of domestic logistics links and established a collaborative horizontal alliance system for China Railway Express platforms with inland ports. Ji Mengche et al. [11], based on the geographical relationship between the coastal border area (Russia) and Jilin...
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(China), emphasized the importance of cross-border cooperation in regional development capacity. They constructed a value system of development potential by coupling economic, social, transportation, and resource and environmental modules. Port logistics, agriculture, fisheries, and mining industries are important directions for cross-border international cooperation with Russia. In terms of risk identification and assessment, Zhou Li et al. [12] studied the supply chain risk factors of B2C cross-border e-commerce, constructed an adaptability network model combining adaptability models and local world models, and verified the adaptability network model of dual local worlds based on risk dynamic simulation models. Liu Ting [13] established a cross-border e-commerce risk index for e-commerce logistics from five risk dimensions: platform risk, customs risk, organizational risk, process risk, and environmental risk. They proposed a new primary synchronization signal (PSS) timing synchronization algorithm for risk identification in IoT cross-border e-commerce, overcoming the problems of anti-frequency deviation and high computational complexity in improved PSS timing synchronization algorithms. Xie Sixin et al. [14] believed that as Sino–U.S. trade frictions escalate, this will have a significant impact on the development of China’s cross-border e-commerce logistics. In response to various external risks such as environmental, economic, and market risks, as well as internal risks such as financing, logistics capability, and management coordination risks, it is necessary to build risk early warning mechanisms and risk indicator systems. From a strategic level and operational level, strategic breakthrough directions and countermeasures need to be designed. Giuffrida et al. [15] classified the existing knowledge system supporting CBEC logistics and identified a series of possible development areas, including a distribution network design, which determines the distribution structure of CBEC, and logistics outsourcing, which determines whether to internally manage logistics activities or outsource them to third parties. Song Bo et al. [16] took into consideration the significant risks posed to the multi-variety, small-batch, cross-border, e-commerce transaction model (CBEC) by conflicts among national regulations in customs activities. Based on this, they proposed a semi-automatic quantitative assessment method for CBEC product risks using text mining and fuzzy rule reasoning to achieve an effective evaluation of the overall risk of CBEC products. In terms of technological innovation, Zhou Fuli et al. [17] considered the decentralized, traceable, and tamper-resistant characteristics of blockchain technology, which contribute to improvements in the operational management of cross-border e-commerce supply chains through innovative industry applications. They thoroughly explored the substantial application of blockchain technology in the management of cross-border e-commerce supply chains. Liu Zhiyong et al. [18] focused on the context of cross-border e-commerce and proposed a blockchain-based framework, along with the development of corresponding technologies and methods, to achieve traceable products and transactions in supply chain management. He Yi [19] considered the global fresh product supply chain composed of overseas merchants, local cross-border e-commerce platforms, and consumers. Based on this, they developed an analytical model to explore the impact of adopting blockchain technology (BCT) on the pricing decisions and profits of supply chain members. Ren Shuyun et al. [20] considered the rise in cross-border e-commerce as driving the development of third-party logistics (3PL) services. They proposed a deep-learning-based, integrated, optimization decision-making method called S2SCL (Seq2Seq-based CNN-LSTM) for this scenario, with intelligent integrating inventory optimization and demand forecasting processes. In terms of mechanisms and effects, Davis D.F. et al. [21] took into account the complex operations of cross-border logistics involving multiple entities, where efficiency primarily depends on government agencies providing a logistics infrastructure for global trade. They analyzed the nature and role of public–private partnerships (PPPs) in the context of cross-border logistics and proposed empirically based theoretical insights. Kim et al. [22] examined the influence of distance on cross-border e-commerce, particularly highlighting the importance of express delivery in reducing the temporal dimension of distance. Valarezo et al. [23], taking the European Union’s (EU) promotion of CBEC as the research background, regarded this as an important tool for achieving the European Digital Single Market strategy. They
explored the determining factors influencing individuals’ decision-making in cross-border e-commerce. Diao Shujie et al. [24] discussed the game process between integrators (LSIs) and service providers (FLSPs) in the logistics service supply chain (LSSC), introducing prospect theory into the game model and expanding the discussion on psychological factors such as the risk perception of players in the logistics service supply chain. Li Fang et al. [25] proposed the mechanism and path hypothesis for the collaborative development of cross-border e-commerce and industrial clusters from a systems theory perspective. The study showed that collaborative development between cross-border e-commerce and industrial clusters can promote the transformation and upgrading of industrial agglomeration and foreign trade. Lisa et al. [26] conducted an in-depth study on new research directions in horizontal logistics alliances, vertical logistics alliances, and the obstacles and negative impacts of logistics alliance establishment.

Currently, with the continuous increase in external risks in cross-border trade, such as Sino–US trade frictions, tariff fluctuations, consumer downgrading, and epidemic risks, China’s reform and opening up are entering deep waters. China is actively implementing national development strategies such as “Belt and Road”, “Maritime Silk Road”, and domestic and international dual circulation, while actively expanding overseas business to accelerate integration into the new development pattern. In order to seek the long-term development of cross-border e-commerce business, the establishment of a cross-border e-commerce logistics alliance has become the primary strategic choice for Chinese cross-border e-commerce logistics enterprises to cope with Sino–US trade frictions [27]. Currently, the research on the game theory of cross-border e-commerce mainly focuses on the evolutionary game analysis of the strategic choices of two or three parties, including cross-border e-commerce platforms, overseas merchants, domestic agents, logistics service providers, and consumers. Ji Jialu et al. [28] consider the second-tier supply chain composed of cross-border e-commerce companies and third-party logistics companies, and establish a Stackelberg game model among various game entities to achieve joint decision-making, considering factors such as exchange rates and demand fluctuations. Qiu Yiwen et al. [29] study the impact of government behavior on the development of cross-border e-commerce B2B export enterprises under the background of the “dual circulation” policy. Based on the LDA topic model, they select relevant policies related to the cross-border e-commerce industry in the “dual circulation” policy and construct an evolutionary game model between the government and cross-border e-commerce B2B export enterprises. Chen Sihua et al. [30] explore the partner selection of cross-border e-commerce companies under the B2B model, and construct a multi-agent model based on the mathematical division of asymmetric evolutionary game model. Guo Libin et al. [31] establish a Stackelberg game model between two competing retailers, considering market demand uncertainty from the perspectives of information sharing and free shipping, and explore the operational strategies of cross-border e-commerce platforms. Wang Ying et al. [32] describe how cross-border e-commerce companies provide the supply chain service with the ability to improve the quality of supply chain relationships between e-retailers and other platform users, and validate the conclusions through data collected from multiple case studies of Chinese cross-border e-commerce companies (Osell, Zongteng, BizArk, and Linca). Zhou Fuli et al. [33] discussed the application of blockchain technology in the field of e-commerce, shifting towards the application of blockchain technology in CBEC by constructing an evolutionary game model composed of cross-border e-commerce platforms and merchants. Du Shan [34] utilized the network structure characteristics of cross-border e-commerce platforms, and adopted a two-stage evolutionary game model for the CBEC platform, consumers, and sellers, combined with model simulation methods to investigate the role of cross-network effects in cooperation.

In summary, the current research on cross-border e-commerce logistics alliances has been explored in depth from four main aspects, including alliance development models, risk assessment and identification, technological innovation, and roles and impact mechanisms. Both domestic and international studies have mainly utilized in-depth ex-
ploration, combining theories such as synergy theory, game theory, prospect theory, and network theory to conduct comprehensive research in this field. Although some scholars have discussed risk management, risk assessment, risk identification, and risk control in the logistics field from different perspectives, none of the literature specifically considers the impact of supply chain disruption risks on the strategic behavior of participants in cross-border e-commerce alliances. As a complex operational organization involving multiple stakeholders, including cross-border e-commerce platforms, logistics companies, and platform merchants, the cross-border e-commerce logistics alliance is directly influenced by the strategic behavior of its members, who engage in multiple dynamic and complex games in their operational choices. Therefore, the application of evolutionary game theory can be used to analyze the dynamic game between the decision-making behaviors of different stakeholders in the alliance and explore the behavioral mechanisms behind their decision-making choices. Therefore, this paper first analyzes the decision-making behavior of various alliance entities in the supply chain under the risk of interruption, focusing on cross-border e-commerce platforms, logistics service providers, and overseas merchants, to clarify the responsibilities and decision-making basis of each party in different scenarios. Based on this analysis, evolutionary game theory is employed to explore the dynamic characteristics of decision-making behavior among multiple participants in cross-border e-commerce logistics alliances under the risk of supply chain interruption, analyzing the decision-making behavior of multiple alliance members and investigating the changing trajectory of behaviors among cross-border e-commerce platforms, logistics enterprises, and overseas merchants in the context of supply chain interruption, as well as the stable evolution strategies during alliance operations. Finally, in combination with MATLAB 2021a software, a simulation analysis is conducted of the dynamic decision-making behavior of multiple alliance participants, studying the impact of the different decision-making behaviors of alliance members on the stability of their operations to reveal the internal operating mechanism of the alliance, providing strong support for the stability and security of cross-border e-commerce logistics alliances, and offering a practical basis for strategy formulation in actual operations.

2. Analysis of Alliance Members’ Game Behaviors Considering Supply Chain Disruption Risk

To analyze the behavior of cross-border e-commerce logistics alliances in the context of supply chain interruption risk, it is necessary to consider the strategies that cross-border e-commerce platforms, logistics service providers, and overseas merchants will adopt to mitigate the risk and ensure the stability and long-term development of cross-border e-commerce business. Within the theoretical framework of evolutionary game theory, it is believed that the participants in the alliance, as bounded rational individuals, seek to maximize their own interests [35–37]. Therefore, the strategic choices of the three entities have an impact on the other two parties and the overall alliance, resulting in continuous dynamic changes in their business strategies. This analysis aims to explore the evolutionary stable equilibrium under the overall strategy and separately analyze the operational behavior of the three entities within the context of evolutionary game theory. Firstly, the cross-border e-commerce platform needs to fully consider the impact of supply chain disruption risk on cross-border business and anticipate its extent of influence. Therefore, during the selection of logistics service providers, those who implement service innovation strategies will be chosen to provide integrated logistics and distribution services to the alliance. Necessary technological and financial support will also be provided to support their cross-border logistics business. At the same time, certain punitive measures will be taken against logistics service providers that cause damage to the overall alliance due to their lack of initiative in implementing service innovation strategies. For overseas merchants, the cross-border e-commerce platform will focus on optimizing its own service functions, enhancing informatization levels, and establishing a rapid risk protection mechanism to
attract and encourage merchants to join the alliance. This will expand the range of products available on the platform and leverage the advantages of integrated alliance operations.

As the primary affected party facing the supply chain disruption risk, logistics service providers need to provide faster, more flexible, and reliable logistics services when confronted with such risks. This heavily relies on innovative management models, the adoption of advanced technologies, the optimization of logistics networks, and the achievement of sustainable development to enhance their logistics service capabilities [38,39]. In the context of the supply chain disruption risk, the strategic choices of logistics service providers need to balance the benefits and costs. For instance, actively implementing service innovation strategies will lead to increased costs, and in this case, the platform and merchants should share a portion of the service innovation budget. If service innovation strategies are not pursued, all three parties will suffer losses due to risk disruptions and bear a portion of the penalty costs resulting from customer complaints.

As the secondary affected party facing supply chain disruption risk, overseas merchants need to adjust their business strategies in a timely manner to ensure the supply of products and stability of prices in the face of such risks [40]. To achieve this, merchants can cooperate with cross-border e-commerce platforms and logistics service providers, as well as strengthen their collaboration with suppliers, in order to collectively respond to risks and reduce significant financial losses caused by risk disruptions. In terms of strategic choices, when merchants join the alliance to expand into foreign markets, they will face a series of opportunity costs, such as decreased domestic resource development, increased transportation costs, and uncertainties in foreign policies. Simultaneously, merchants will encourage and support logistics service providers’ innovative service strategies to minimize unnecessary risk losses. Additionally, merchants also need to pay attention to customer feedback. In the event of customer complaints, they will jointly bear the penalty costs incurred due to customer losses with logistics service providers.

According to the above analysis, the game strategy behaviors of the three main entities in the cross-border e-commerce logistics alliance under the risk of supply chain interruption are shown in Figure 1.

Figure 1. Operation system of cross-border e-commerce logistics alliance under the risk of supply chain disruption.
3. Establishment of Evolutionary Game Model of Cross-Border E-Commerce Logistics Alliance

3.1. Model Basic Assumption

(1) Model assumptions

The game-theoretical behavior of the cross-border e-commerce logistics alliance mainly involves three types of entities. Based on the theoretical analysis of evolutionary games, it is generally believed that there are no barriers or obstacles to communication and collaboration among the participating entities in the alliance, and the decision-making behaviors of each entity are independent. All three parties have limited rationality, meaning that all participants will choose the strategy that is most advantageous to themselves. Accordingly, this article puts forward the following assumptions:

Assumption 1. The strategy sets corresponding to the cross-border e-commerce platform, logistics service provider, and overseas merchants are as follows: \{control logistics service provider: not control logistics service provider\}, \{implement service innovation strategy: not implement service innovation strategy\}, and \{participate in cooperation: not participate in cooperation\}, respectively. The corresponding strategy selection probabilities are \(x, y, z\), and \(x, y, z \in [0, 1]\).

Assumption 2. The cross-border e-commerce platform, as the leading core of the cross-border e-commerce logistics alliance, is responsible for controlling the behavior of logistics service providers and encouraging them to implement service innovation strategies. It is also capable of responding promptly to the needs of overseas merchants and minimizing the overall economic losses within the alliance. Moreover, during the evolutionary game process, all participants’ strategies are adjustable, meaning that they can adjust their own strategies in a timely manner based on changes in the environment.

Assumption 3. The supply chain disruption risk is known and certain, meaning that all participants can clearly identify and evaluate the risk of supply chain disruption. Moreover, when facing the risk of supply chain disruption, they all tend to reduce risks and costs through alliance cooperation. Additionally, during the evolutionary game process, all participants can accurately assess the impact of their strategy selection on the stability of the entire system.

(2) Parameter Settings

Let us denote the overall direct benefit of establishing a cross-border e-commerce logistics alliance as \(A\). The distribution coefficients for the overall benefits of the different tripartite entities, namely the cross-border e-commerce platform, logistics service provider, and overseas merchants, are denoted as \(\alpha_1\), \(\alpha_2\), and \(\alpha_3\), respectively. Furthermore, let us designate the total risk cost shared by the three parties under the supply chain disruption risk as \(B\), with corresponding distribution coefficients as \(\beta_1\), \(\beta_2\), and \(\beta_3\). Additionally, denote the total additional budgetary cost for implementing logistics service innovation strategies under the cross-border e-commerce logistics alliance as \(C\), with distribution coefficients as \(\theta_1\), \(\theta_2\), and \(\theta_3\).

Lastly, assuming that customer complaints lead to an overall loss for the alliance under the supply chain disruption risk, let us denote this loss as \(D\). The logistics service provider and overseas merchants jointly bear this loss, with corresponding distribution coefficients as \(\gamma\) and \(1 - \gamma\), respectively (\(a_1 + a_2 + a_3 = \beta_1 + \beta_2 + \beta_3 = \theta_1 + \theta_2 + \theta_3 = 1\)).

Based on the above model assumptions and parameter settings, the model parameters and symbols of the main body of the cross-border e-commerce logistics alliance under the risk of supply chain interruption are shown in Table 1, and the corresponding game payoff matrix is obtained as shown in Table 2.
Out of Control (1)

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Table 1. Model parameters and their meanings.

<table>
<thead>
<tr>
<th>Game Player</th>
<th>Parameter</th>
<th>Specific Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-border e-commerce platform</td>
<td>( A_{i1} )</td>
<td>Direct benefits of cross-border e-commerce platforms under the alliance</td>
</tr>
<tr>
<td></td>
<td>( B_{i1} )</td>
<td>Disruption risk alliances share the risk costs of cross-border e-commerce platforms</td>
</tr>
<tr>
<td></td>
<td>( C_{i1} )</td>
<td>The budget of implementing the innovative service strategy cross-border e-commerce platform under the alliance bears the cost</td>
</tr>
<tr>
<td></td>
<td>( a )</td>
<td>Punishment and potential losses in the platform when logistics service providers do not implement service innovation strategies and are complained about</td>
</tr>
<tr>
<td></td>
<td>( b )</td>
<td>When the logistics enterprise is not controlled, the compensation ruling of the merchant due to the supply chain risk</td>
</tr>
<tr>
<td></td>
<td>( c )</td>
<td>The control costs of cross-border e-commerce platforms on logistics service providers</td>
</tr>
<tr>
<td>Logistics service provider</td>
<td>( A_{i2} )</td>
<td>Direct benefits of logistics service providers under the alliance</td>
</tr>
<tr>
<td></td>
<td>( B_{i2} )</td>
<td>Disruption risk alliance shares the risk cost of logistics service providers</td>
</tr>
<tr>
<td></td>
<td>( C_{i2} )</td>
<td>The budget of the logistics service provider to implement the innovation service strategy under the alliance bears the cost</td>
</tr>
<tr>
<td></td>
<td>( \gamma D )</td>
<td>Customer losses incurred under the risk of supply chain disruption</td>
</tr>
<tr>
<td></td>
<td>( d )</td>
<td>The possibility of not pursuing a service innovation strategy and being complained about for disruption risk</td>
</tr>
<tr>
<td>Overseas merchant</td>
<td>( A_{i3} )</td>
<td>Direct income of overseas merchants under the alliance</td>
</tr>
<tr>
<td></td>
<td>( B_{i3} )</td>
<td>Break the risk alliance to share the risk cost of foreign merchants</td>
</tr>
<tr>
<td></td>
<td>( C_{i3} )</td>
<td>The cost of implementing the innovative service strategy under the alliance shall be borne by the budget of overseas merchants</td>
</tr>
<tr>
<td></td>
<td>( e )</td>
<td>Logistics service providers do not carry out service innovation strategy, which brings additional losses to merchants</td>
</tr>
<tr>
<td></td>
<td>( f )</td>
<td>The opportunity cost of merchants joining the alliance</td>
</tr>
<tr>
<td></td>
<td>((1 - \gamma)D)</td>
<td>Customer losses incurred under the risk of supply chain disruption</td>
</tr>
</tbody>
</table>

Table 2. Cross-border e-commerce logistics alliance agent behavior game payment matrix considering supply chain disruption risk.

<table>
<thead>
<tr>
<th>Alliance Members (Game Players)</th>
<th>Cross-Border e-Commerce Platform</th>
<th>Control (x)</th>
<th>Out of Control ((1 - x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry out Service Innovation strategy ((y))</td>
<td>Overseas merchant</td>
<td>Participate in cooperation ((z))</td>
<td>( A_{i1} - B_{i1} - C_{i1} - c )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-cooperation ((1 - z))</td>
<td>( A_{i2} - B_{i2} - C_{i2} )</td>
</tr>
<tr>
<td>No service Innovation strategy ((1 - y))</td>
<td>Overseas merchant</td>
<td>Participate in cooperation ((z))</td>
<td>( A_{i3} - B_{i3} - C_{i3} - c + ad )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-cooperation ((1 - z))</td>
<td>( A_{i4} - B_{i4} - C_{i4} - e - f - (1 - \gamma)D )</td>
</tr>
</tbody>
</table>

3.2. Evolutionarily Stable Strategy Solution

(1) Revenue expectation function construction

Cross-border e-commerce platforms, logistics service providers, and overseas merchants can each choose the optimal strategy based on their actual benefits and risks. In the three-party evolutionary game scenario under supply chain disruption risk, let \( U_{ij} \) represent the expected payoff for the i-th participant within the alliance when adopting strategy j, where i corresponds to P, L, M, representing the cross-border e-commerce platform, logistics service provider, and overseas merchant, respectively. The value of j can be 1 or 2. The average payoff is denoted as \( \bar{U}_i \), representing the expected payoff when adopting or not adopting the corresponding strategy. Therefore, for the cross-border e-commerce
platform, its corresponding expected payoff with control, expected payoff without control, and average payoff are:

\[ U_{P} = yz(Aa_{1} - B\beta_{1} - C\theta_{1} - c) + z(1 - y)(Aa_{1} - B\beta_{1} - c + ad) + y(1 - z)(Aa_{1} - B\beta_{1} - C\theta_{1} - c) + (1 - y)(1 - z)(Aa_{1} - B\beta_{1} - c + ad) \]

\[ = Aa_{1} - B\beta_{1} - c + ad - y(C\theta_{1} + ad) \]

\[ U_{L} = yz(Aa_{1} - B\beta_{1} - C\theta_{1}) + z(1 - y)(Aa_{1} - B\beta_{1}) + y(1 - z)(Aa_{1} - B\beta_{1} - C\theta_{1}) + (1 - y)(1 - z)(Aa_{1} - B\beta_{1}) \]

\[ = Aa_{1} - B\beta_{1} - yC\theta_{1} \]

\[ \Pi_{P} = xU_{P} + (1 - x)U_{L} \]

Similarly, the expected payoffs for logistics service providers when implementing a service innovation strategy or not implementing a service innovation strategy, and the average expected payoff, can be represented as \( U_{L1}, U_{L2}, \Pi_{L} \), respectively. The following expressions hold:

\[ U_{L1} = xz(Aa_{2} - B\beta_{2} - C\theta_{2}) + z(1 - x)(Aa_{2} - B\beta_{2} - C\theta_{2} - b) + x(1 - z)(Aa_{2} - B\beta_{2} - C\theta_{2}) + (1 - x)(1 - z)(Aa_{2} - B\beta_{2} - C\theta_{2} - b) + xz(Aa_{2} - B\beta_{2} - C\theta_{2} - b) + xb \]

\[ U_{L2} = xz(Aa_{2} - B\beta_{2} - \gamma D - ad) + z(1 - x)(Aa_{2} - B\beta_{2} - \gamma D - b) + x(1 - z)(Aa_{2} - B\beta_{2} - \gamma D - ad) + (1 - x)(1 - z)(Aa_{2} - B\beta_{2} - \gamma D - ad) \]

\[ = Aa_{2} - B\beta_{2} - \gamma D - b + xad \]

\[ \Pi_{L} = yU_{L1} + (1 - y)U_{L2} \]

Similarly, the expected payoffs for overseas merchants when participating in cooperation, not participating in cooperation, and the average expected payoff can be represented as \( U_{M1}, U_{M2}, \Pi_{M} \), respectively. The following expressions hold:

\[ U_{M1} = xy(Aa_{3} - B\beta_{3} - C\theta_{3} - f) + x(1 - y)(Aa_{3} - B\beta_{3} - f - (1 - \gamma)D - y)(1 - x)(Aa_{3} - B\beta_{3} - f + b) + (1 - x)(1 - y)(Aa_{3} - B\beta_{3} - f - (1 - \gamma)D - C\theta_{3} - yb) \]

\[ = Aa_{3} - B\beta_{3} - f + b - (1 - \gamma)D + [x + (1 - \gamma)D - C\theta_{3} - yb] \]

\[ U_{M2} = xy[(1 - \gamma)D + x(1 - y)[f - (1 - \gamma)D] + y(1 - x) - x(1 - y)] \]

\[ = (y - 1)[f - (1 - \gamma)D] - xy(1 - \gamma)D \]

\[ \Pi_{M} = zU_{M1} + (1 - z)U_{M2} \]

Based on the above analysis results and the basic principles of evolutionary game theory, we can derive the replicator dynamics equations for the cross-border e-commerce platform, logistics service provider, and overseas merchant, which can be represented as \( F(x), F(y), F(z) \), respectively.

\[ F(x) = \frac{dx}{dt} = x(U_{P} - \Pi_{P}) = x(1 - x)(U_{P1} - U_{P2}) = x(1 - x)(ad - yad - c) \]

\[ F(y) = \frac{dy}{dt} = y(U_{L} - \Pi_{L}) = y(1 - y)(U_{L1} - U_{L2}) = y(1 - y)(ad + \gamma D - C\theta_{2} - xad) \]

\[ F(z) = \frac{dz}{dt} = z(U_{M} - \Pi_{M}) = z(1 - z)(U_{M1} - U_{M2}) = z(1 - z)(ad - yad - c) \]

(2) Evolutionary path analysis

1. Analysis of the evolution path of cross-border e-commerce platforms

According to the replicator dynamics equations, the first derivative of \( F(x) \) with respect to \( x \) and the specified \( G(y) \) can be expressed as follows:

\[ \frac{dF(x)}{dx} = (1 - 2x)(ad - yad - c) \]

\[ G(y) = ad - yad - c \]

According to the stability theorem of differential equations, the probability that cross-border e-commerce logistics platforms choose to control logistics service providers is in a stable state, which must satisfy \( F(x) = 0 \) and \( dF(x)/dx < 0 \). Since \( \frac{dG(y)}{dy} < 0 \), \( G(y) \) is a decreasing function of \( y \). Therefore, for \( y' = 1 - c/ad \), there exists \( G(y) = 0 \), such that \( dF(x)/dx \equiv 0 \), and the cross-border e-commerce platform cannot determine a stable strategy.
(1) When \( y < y^* \) occurs, \( G(y) > 0 \) holds for \( dF(x)/dx|_{x=1} < 0 \) and \( F(x) = 0 \), which means \( x = 1 \) is the evolutionary stable strategy (ESS) for the cross-border e-commerce platform.

(2) When \( y > y^* \) occurs, \( G(y) < 0 \) holds for \( dF(x)/dx|_{x=0} < 0 \) and \( F(x) = 0 \), which means \( x = 0 \) is the evolutionary stable strategy for the cross-border e-commerce platform. Based on this, the phase diagram of strategy evolution for the cross-border e-commerce platform is shown in Figure 2.

\[
\begin{align*}
V_{A1} &= \int_{y<y^*} G(y)dydx = \frac{c}{ab} \\
V_{A2} &= 1 - V_{A1} = 1 - \frac{c}{ab}
\end{align*}
\]

2. Evolution path analysis of logistics service providers

According to the replicator dynamics equations, the first derivative of \( F(y) \) with respect to \( y \) and the specified \( H(x) \) can be expressed as follows:

\[
\begin{align*}
\frac{dF(y)}{dy} &= (1 - 2y)(xb + \gamma D - C\theta_2 - xad) \\
H(x) &= xb + \gamma D - C\theta_2 - xad
\end{align*}
\]

Similarly, it can be inferred that the probability of logistics service providers choosing to implement service innovation strategies is in a stable state, which must satisfy \( F(y) = 0 \) and \( dF(y)/dy < 0 \). Since \( \partial H(x)/\partial x = b - ad > 0 \), \( H(x) \) is an increasing function of \( x \). Therefore, for \( x^* = \frac{C\theta_2 - D}{b - ad} \), there exists \( H(x) = 0 \) such that \( dF(y)/dy \equiv 0 \), and the cross-border e-commerce platform cannot determine a stable strategy.

(1) When \( x < x^* \) occurs, \( H(x) < 0 \) holds for \( dF(y)/dy|_y = 0 < 0 \) and \( F(y) = 0 \), which means \( y = 0 \) is the ESS.

(2) When \( x > x^* \) occurs, \( H(x) > 0 \) holds for \( dF(y)/dy|_y = 1 < 0 \) and \( F(y) = 0 \), which means \( y = 1 \) is the ESS. Based on this, the phase diagram of strategy evolution for the cross-border e-commerce platform is shown in Figure 3.
Based on the evolutionary path of strategy for logistics service providers under the risk of supply chain disruption, it can be observed that when \( x < x^* \) and \( y \) tends toward 0, the logistics service providers choose to implement service innovation strategies with a probability represented by the volume \( V_{B1} \), corresponding to B1. When \( x > x^* \) and \( y \) tends toward 1, the logistics service providers choose not to implement service innovation strategies with a probability represented by the volume \( V_{B2} \), corresponding to B2. After calculation, it is found that:

\[
V_{B1} = \int_{x < x^*} H(x)dxz = \frac{c_{b_2} - \gamma D}{b_0 - ad} \\
V_{B2} = 1 - V_{B1} = 1 - \frac{c_{b_2} - \gamma D}{b_0 - ad}
\]

### Analysis of the evolution path of overseas merchants

According to the replicator dynamics equations, the first derivative of \( F(z) \) with respect to \( z \) and the specified \( f(y) \) can be expressed as follows:

\[
\frac{dF(z)}{dz} = (1 - 2z)[Aa_3 - B\beta_3 - f + b + yC\theta_3 - bx + xy(1 - \gamma)D] \\
f(y) = Aa_3 - B\beta_3 - f + b + yC\theta_3 - bx + xy(1 - \gamma)D
\]

Similarly, it can be inferred that the probability of overseas merchants actively participating in alliance cooperation is in a stable state, which must satisfy \( F(z) = 0 \) and \( dF(z)/dz < 0 \). Due to \( df(y)/dy = C\theta_3 + x(1 - \gamma)D > 0 \), \( f(y) \) is an increasing function of \( y \). Therefore, for \( y^* = \frac{B\beta_3 + f - b - Aa_3}{C\theta_3 + x(1 - \gamma)D} \), there exists \( f(y) = 0 \) such that \( dF(z)/dz \equiv 0 \), and the cross-border e-commerce platform cannot determine a stable strategy.

1. When \( y < y^* \) occurs, \( f(y) < 0 \) holds for \( dF(z)/dz \equiv 0 < 0 \) and \( F(z) = 0 \), which means \( z = 0 \) is the ESS (Evolutionarily Stable Strategy).

2. When \( y > y^* \) occurs, \( f(y) > 0 \) holds for \( dF(z)/dz \equiv 0 < 0 \) and \( F(z) = 0 \), which means \( z = 1 \) is the ESS (Evolutionarily Stable Strategy). Based on this, the phase diagram of strategy evolution for overseas merchants can be seen in Figure 4.

Based on the evolutionary path of strategy for overseas merchants under the risk of supply chain disruption, it can be observed that when \( y < y^* \) and \( z \) tends toward 0, overseas merchants choose to actively participate in alliance cooperation strategies with a probability represented by the volume \( V_{C1} \), corresponding to C1. When \( y > y^* \) and \( z \) tends toward 1, overseas merchants choose not to actively participate in alliance cooperation strategies with a probability represented by the volume \( V_{C2} \), corresponding to C2. After calculation, it is found that:

\[
V_{C1} = \int_{x < x^*} f(y)dxz = \frac{(B\beta_3 + f - b - Aa_3)(1 - \gamma)D - bc\theta_3}{(1 - \gamma)^2 D^2} \ln[1 + \frac{(1 - \gamma)D}{bC\theta_3}] + \frac{(1 - \gamma)D}{b} \\
V_{C2} = 1 - V_{C1} = 1 - \frac{(B\beta_3 + f - b - Aa_3)(1 - \gamma)D - bc\theta_3}{(1 - \gamma)^2 D^2} \ln[1 + \frac{(1 - \gamma)D}{bC\theta_3}] - \frac{(1 - \gamma)D}{b}
\]
Figure 4. Strategy evolution phase diagram of overseas merchants.

(3) Strategy stability analysis

Combining the replicator dynamics equations of each game group in the alliance mentioned above, when \( F(x) = 0, F(y) = 0, F(z) = 0 \) is held, the equilibrium points of the system can be obtained as follows:

\[
E_1 = (0, 0, 0), \quad E_2 = (0, 1, 0), \quad E_3 = (0, 0, 1) \\
E_4 = (1, 0, 0), \quad E_5 = (1, 0, 0), \quad E_6 = (1, 0, 1) \\
E_7 = (1, 1, 0), \quad E_8 = (1, 1, 1), \quad E_9 = \left( \frac{1}{b-ad}, 1 - \frac{c}{b-ad}, 0 \right) \\
E_{10} = \left( \frac{1}{b-ad}, 1 - \frac{c}{b-ad}, 1 \right)
\]

and \( x, y, z \in (0, 1) \). According to the determination method of equilibrium points in evolutionary games proposed by Friedman [41], the Jacobian matrix of the three-player evolutionary game system is obtained as follows:

\[
J = \begin{bmatrix}
I_1 & I_2 & I_3 \\
I_4 & I_5 & I_6 \\
I_7 & I_8 & I_9 \\
\end{bmatrix} = \begin{bmatrix}
\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\
\frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial y} \\
\frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial y} \\
\end{bmatrix} = \begin{bmatrix}
(1 - 2x)(ad - (a + c)) & (a + c)(x - 1) & 0 \\
(b - ad)(y - 1) & (b + yD - yd - xad)(1 - 2y) & 0 \\
y(1 - (1 - y)D - b)(1 - z) & (b + x(1 - y)D)(1 - z) & (1 - 2z)[A_1 - B_2 - f + b + yC_2 - bx + y(1 - y)D] \\
\end{bmatrix}
\]

According to the research conclusions of evolutionary game theory, when all the eigenvalues of the Jacobian matrix are negative, the equilibrium points of the system are considered to be Evolutionarily Stable Strategies (ESS). Based on this, the stability of each equilibrium point is analyzed, as shown in Table 3.

In this study, following reference [42] and for the sake of generality, it is assumed that the benefits of cross-border e-commerce logistics alliances jointly facing supply chain risks exceed the individual benefits of facing these risks separately, resulting in \( A_{i1} - B_{i1} - C_{ii} > 0 \) and \( A_{i1} - B_{i1} - C_{ii} + b - f > 0 \). The evolutionary stable strategies under these two assumptions will be discussed separately.

Table 3. Stability analysis of equilibrium points.

<table>
<thead>
<tr>
<th>Equilibrium Point</th>
<th>Jacobian Matrix Eigenvalues</th>
<th>Hypothesis 1</th>
<th>Hypothesis 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1(0,0,0) )</td>
<td>( \gamma D - Cb_2, ad - c, A_{13} - B_{13} + b - f )</td>
<td>(+,+,+) Saddle point</td>
<td>(-,+,+) Unstable point</td>
</tr>
<tr>
<td>( E_2(0,1,0) )</td>
<td>( Cb_2 - \gamma D, -c, A_{13} - B_{13} +)</td>
<td>(-,-,-) Unstable point</td>
<td>(+,-,+) Unstable point</td>
</tr>
<tr>
<td>( E_3(0,0,1) )</td>
<td>( \gamma D - Cb_2, ad - c, B_{13} - A_{13} - b + f )</td>
<td>(+,+,-) Unstable point</td>
<td>(-,+,-) Unstable point</td>
</tr>
</tbody>
</table>
Table 3. Cont.

<table>
<thead>
<tr>
<th>Equilibrium Point</th>
<th>Jacobian Matrix Eigenvalues</th>
<th>Hypothesis 1</th>
<th>Hypothesis 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_4(0,1,1)$</td>
<td>$c\theta_2 - \gamma D - c, B\beta_3 - A\alpha_3 - C\theta_3 - b + f$</td>
<td>$\lambda_1, \lambda_2, \lambda_3$</td>
<td>Eigenvalue Symbol</td>
</tr>
<tr>
<td>$E_5(1,0,0)$</td>
<td>$c - ad, A\alpha_3 - B\beta_3 - f, b - C\theta_2 + \gamma D - ad$</td>
<td>$\lambda_1, \lambda_2, \lambda_3$</td>
<td>-,-,-</td>
</tr>
<tr>
<td>$E_6(1,0,1)$</td>
<td>$c - ad, B\beta_3 - A\alpha_3 + f, b - C\theta_2 + \gamma D - ad$</td>
<td>$\lambda_1, \lambda_2, \lambda_3$</td>
<td>-,-,-</td>
</tr>
<tr>
<td>$E_7(1,1,0)$</td>
<td>$c\theta_2 - b - \gamma D + ad, A\alpha_3 - B\beta_3 + C\theta_3 + D - f - \gamma D$</td>
<td>$\lambda_1, \lambda_2, \lambda_3$</td>
<td>+,-,+</td>
</tr>
<tr>
<td>$E_8(1,1,1)$</td>
<td>$c\theta_2 - b - \gamma D + ad, B\beta_3 - A\alpha_3 - C\theta_2 - D + f + \gamma D$</td>
<td>$\lambda_1, \lambda_2, \lambda_3$</td>
<td>+,-,-</td>
</tr>
<tr>
<td>$E_9(x_1, y_1, 0)$</td>
<td>$A\alpha_3 - B\beta_3 + b - f + y_1 C\theta_3 - b x_1 + D x_1 y_1$</td>
<td>$\lambda_1, \lambda_2$</td>
<td>+,-</td>
</tr>
<tr>
<td>$E_{10}(x_2, y_2, 1)$</td>
<td>$B\beta_3 - A\alpha_3 - b + f - y_1 C\theta_3 + b x_1 - D x_1 y_1$</td>
<td>$\lambda_1, \lambda_2, \lambda_3, \lambda_4$</td>
<td>-,-,-,-</td>
</tr>
</tbody>
</table>

**Hypothesis 1.** Assuming that when conditions $C\theta_2 - \gamma D < 0, c - ad < 0, b - C\theta_2 + \gamma D - ad < 0$ are met, namely, the control cost for logistics service providers is lower than the punishment and potential losses incurred by not implementing service innovation strategies and being complained about, and the compensation awarded to merchants for supply chain risks is lower than the punishment and potential losses incurred by not implementing service innovation strategies and being complained about, in this case, the eigenvalues corresponding to equilibrium points $E_4(0,1,1)$ and $E_5(1,0,1)$ are non-positive. Therefore, $E_4(0,1,1)$ and $E_5(1,0,1)$ are stable points in the replicator dynamics system, and the corresponding Evolutionarily Stable Strategies (ESS) are [no control, engage in service innovation strategy, participate in cooperation] and [actively control, no service innovation strategy, participate in cooperation], respectively. Equilibrium point $E_5(1,0,0)$ has non-negative eigenvalues, indicating that it is a saddle point, while the others are unstable points.

According to Hypothesis 1, depending on the initial point of the three-party strategy selection, the strategy combination evolves to two stable points: [no control, engage in service innovation strategy, participate in cooperation] and [actively control, no service innovation strategy, participate in cooperation]. At this point, cross-border e-commerce platforms lack effective regulatory power to control the behavior of logistics service providers and overseas merchants. Thus, when faced with the risk of supply chain disruption, logistics service providers and overseas merchants cooperate with each other to mitigate the risk. However, this cooperation entails significant risk costs. In order to avoid the occurrence of the stable strategy combination [no control, engage in service innovation strategy, participate in cooperation], cross-border e-commerce platforms must set sufficiently large penalties or rewards to fully utilize the effectiveness of the incentive mechanism.

**Hypothesis 2.** When condition $C\theta_2 - \gamma D > b - ad$ is satisfied, the system has at least one stable point $E_6(1,0,1)$. Meanwhile, when conditions $C\theta_2 - \gamma D > 0$ and $ad - c > 0$ are both satisfied, the replicator dynamic system has one, and only one, stable point, which is denoted as $E_6(1,0,1)$. The corresponding Evolutionarily Stable Strategy (ESS) for this stable point is [actively control, no service innovation strategy, participate in cooperation]. Point $E_7(1,1,0)$ is the saddle point, while the remaining points are unstable points.

**4. Alliance Main Body Evolution Simulation Analysis**

To validate the effectiveness of the evolutionary stability analysis, numerical values are assigned to the model based on real-life scenarios. Matlab 2021a is employed for numerical experimental simulations. Under the premise of satisfying Hypothesis 2, that is, the existence of $A\alpha_1 - B\beta_1 - C\theta_1 > 0, A\alpha_1 - B\beta_1 - C\theta_1 = b - f > 0, C\theta_2 - \gamma D > 0$
and \( b - C\theta_2 + \gamma D - ad < 0 \), parameters are set through discussions with cross-border logistics practitioners and system simulation experts. The actual operational situation of the cross-border e-commerce logistics alliance is also taken into account. Considering these conditions, the initial parameter values are set as follows: \( a = 50, d = 0.5, c = 20, b = 20, \gamma = 0.6, D = 60, C = 100, \theta_1 = 0.3, \theta_2 = 0.4, \theta_3 = 0.3, A = 200, a_3 = 0.3, b = 80, \beta_3 = 0.4, f = 40 \). Based on Array 1, the influence of \( B, \theta_2 \) and \( \theta_3 \), \( D, a, b, f \) on the process and outcome of evolutionary games is analyzed.

Firstly, in order to analyze the impact of changes in the overall risk cost \( B \) on the process and outcome of evolutionary games, we assign \( B \) values of 60, 80, and 100. The simulation results of the replicator dynamic equations evolving over 50 time periods are shown in Figure 5. Secondly, to analyze the effect of variations in the allocation coefficients \( \theta_2 \) and \( \theta_3 \) on the process and outcome of evolutionary games, we assign \( \theta_2 = 0.6 \) and \( \theta_3 = 0.2; \theta_2 = 0.4 \) and \( \theta_3 = 0.3; \theta_2 = 0.2 \) and \( \theta_3 = 0.4 \). The simulation results are presented in Figure 6.

From Figure 5, it can be observed that, during the process of system evolution towards a stable point, an increase in the overall risk cost leads to a decrease in the evolutionary speed of logistics service providers when implementing service innovation strategies. As \( B \) increases, the probability of overseas merchants actively participating in alliance cooperation decreases, and the probability of logistics service providers choosing to implement service innovation strategies also decreases. Therefore, in the context of supply chain disruption risk, cross-border e-commerce platforms must strengthen control over logistics service providers while reducing the level of losses suffered by cross-border e-commerce alliances when facing risks. Only by doing so can we enhance the enthusiasm of logistics service providers in pursuing service innovation strategies and encourage overseas merchants to actively participate in logistics alliances to jointly resist risk losses, thereby maintaining the overall benefits of cross-border e-commerce logistics alliances.

![Figure 5. The impact of different aggregate risk costs.](image-url)
Figure 6. The effect of different additional total cost distribution coefficients.

Figure 6 indicates that, during the evolutionary process, as $\theta_2$ gradually decreases, $\theta_1$ and $\theta_3$ increase, leading to an increase in the probability of cross-border logistics service providers choosing to implement service innovation strategies, and an increase in the probability of overseas merchants actively participating in alliance cooperation. Specifically, as the self-budget cost of logistics service providers for service innovation gradually decreases, accompanied by an increase in the budget costs of cross-border e-commerce platforms and overseas merchants, in the context of supply chain disruption risk, logistics service providers will actively pursue service innovation strategies and accelerate the formation of a pattern of cross-border e-commerce logistics alliances. At the same time, the probability of cross-border e-commerce platforms strengthening control over logistics service providers will also increase.

Next, the simulation results obtained through assigning $D = 40, 60, 80$, respectively, are shown in Figure 7; when assigning $a = 20, 50, 80$, respectively, the simulation results are shown in Figure 8.

Figure 7. The impact of customer complaints resulting in different overall losses to the alliance.
Figure 7 shows that, during the evolutionary process, as D increases, the probability of cross-border e-commerce platforms exercising control increases, along with an increase in the probability of logistics service providers implementing service innovation strategies and overseas merchants actively participating in cooperation. In other words, as customer complaints lead to an overall increase in alliance losses, this will facilitate the accelerated construction of cross-border e-commerce logistics alliances by the three parties in the game to jointly defend against operational risks stemming from customer complaints. It will also promote an increase in the probability of cross-border e-commerce platforms exerting control over logistics service providers.

Figure 8 demonstrates that as a increases, the probability of logistics service providers implementing service innovation strategies increases, while the probability of overseas merchants choosing to participate in cooperation decreases. That is, when logistics service providers incur losses due to supply chain disruption risks resulting from complaints, as the extent of the loss increases, logistics service providers will expedite the implementation of service innovation strategies. However, since these losses are primarily borne by logistics service providers, overseas merchants tend to be less inclined to actively engage in alliance cooperation. Therefore, for cross-border e-commerce platforms, it is necessary to strengthen control over logistics service providers and establish a mechanism of rewards and penalties to enhance all three parties’ enthusiasm for participating in alliance cooperation, effectively safeguarding the overall benefits of the alliance.

Furthermore, by assigning $b = 10, 20, 30$, respectively, the simulation results of the dynamic equation system evolving over 50 time-steps are shown in Figure 9; by assigning $f = 20, 40, 70$, respectively, the simulation results are shown in Figure 10.

Figure 9 demonstrates that, during the process of evolutionary stability, as b increases, the probability of logistics service providers choosing to implement service innovation strategies increases, and the probability of overseas merchants actively participating in alliance cooperation increases. That is, in the context of supply chain disruption risks, as the compensation judgments by cross-border e-commerce platforms for merchants affected by supply chain disruptions increase, this indicates an increase in the agency of cross-border e-commerce platforms as the main participants in the alliance. Implementing effective rewards and penalties will further promote the development of alliance cooperation in a healthier and more orderly direction.
the extent of the loss increases, logistics service providers will expedite the implementa-
tion of service innovation strategies. However, since these losses are primarily borne by 
logistics service providers, overseas merchants tend to be less inclined to actively engage 
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wards and penalties to enhance all three parties' enthusiasm for participating in alliance 
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dynamic equation system evolving over 50 time-
steps are shown in Figure 9; by assigning 
$f = 20, 40, 70$, respectively, the simulation results are shown 
in Figure 10.

**Figure 9.** The influence of platform on the different degree of compensation adjudication of merchants 
due to supply chain risk.

**Figure 10.** The influence of different degree of opportunity cost of merchants joining the alliance.

Figure 10 shows that as $f$ increases, the probability of logistics service providers 
choosing to implement service innovation strategies decreases, and the probability of 
overseas merchants actively participating in alliance cooperation decreases. That is, as the 
opportunity cost for overseas merchants to join the alliance increases, their willingness to 
participate in alliance cooperation diminishes. This, in turn, reduces the logistics service 
providers’ enthusiasm for implementing service innovation strategies, thereby affecting the 
role of cross-border e-commerce platforms within the cross-border e-commerce logistics 
alliance and ultimately impacting the overall operational efficiency of the alliance.

Array 1 satisfies the conditions in Hypothesis 2. Assign array 2 as $a = 50, d = 0.7, 
c = 20, b = 20, \gamma = 0.35, D = 60, C = 100, \theta_1 = 0.4, \theta_2 = 0.2, \theta_3 = 0.4, A = 200, a_3 = 0.5, 
B = 80, \beta_3 = 0.5, f = 40$, satisfying the conditions in Hypothesis 1. With different initial 
strategy combinations for each array, evolution is simulated over 50 time-steps, and the 
results are shown in Figures 11 and 12.
According to Figure 11, the simulation results indicate that E9 and E10 are unstable equilibrium points. At this stage, there is only one evolutionarily stable strategy combination in the system, which is “active control, no service innovation strategy, and participation in cooperation”, consistent with the conclusion of Hypothesis 2. Figure 12 shows that, under the conditions of satisfying Hypothesis 1, the system has two evolutionarily stable points, E4(0, 1, 1) and E6(1, 0, 1). The strategy combinations for cross-border e-commerce platforms, logistics service providers, and overseas merchants are “no control, implementation of service innovation strategy, and participation in cooperation” and “active control, no service innovation strategy, and participation in cooperation”. These two strategy combinations are evolutionarily stable strategy combinations. Therefore, cross-border e-commerce platforms should strengthen their control capabilities, protect the interests of logistics service providers and overseas merchants regarding multiple aspects, and ensure the overall benefits of the alliance after its formation, that risk costs shared by the alliance
in case of supply chain disruptions, and that the budget costs of implementing service innovation strategies are greater than the losses and speculative gains incurred by each party when facing supply chain risks individually. This will facilitate the unified strategy of all parties in the cross-border e-commerce logistics alliance, avoiding significant losses to their business activities caused by supply chain disruption risks. The consistent and effective results obtained from the simulation analysis align with the stability analysis of various strategies, indicating the practical guidance of conducting cross-border e-commerce logistics alliances under the risk of supply chain disruptions.

5. Conclusions and Trends

With the steady development of cross-border e-commerce, the increasing volume of cross-border business in China has brought significant risks and challenges to the logistics field, such as supply chain disruptions. In response, cross-border e-commerce logistics alliances have emerged as an effective solution. This paper applies the framework of evolutionary game theory to analyze the decision-making behavior among the three parties involved in cross-border e-commerce logistics alliances. Evolutionary game models are constructed to analyze the stable strategies among the participants. MATLAB 2021a software is then utilized to simulate and analyze the evolutionary process of participant behavior. The research findings indicate that:

(1) The reduction in the allocation coefficient of additional total costs for logistics service providers, the increase in overall losses due to customer complaints, and the platform’s compensation determination for merchants affected by supply chain risks all encourage logistics service providers to actively pursue service innovation strategies and motivate overseas merchants to actively participate in alliance cooperation. In addition, increasing the overall risk costs and opportunity costs for merchants will increase the cost of alliance cooperation among the three parties in the game, which is unfavorable for the development of cross-border e-commerce logistics alliances. At the same time, the penalties and potential losses imposed by the platform on logistics service providers when they receive complaints will not only enhance the platform’s control over logistics service providers but also reduce their enthusiasm for implementing service innovation strategies.

(2) Typically, participants in an alliance are highly sensitive to exogenous variables that are relevant to themselves. The aforementioned study also indicates that the behaviors of participants and exogenous variables in the cross-border e-commerce logistics alliance will have varying degrees of impact on the management practices of such alliances. As the leading body of the alliance, cross-border e-commerce platforms should coordinate the participants and constrain the behaviors of the participating entities within the alliance by establishing reasonable incentives and penalty mechanisms. Simultaneously, a thorough analysis of the specific roles played by different exogenous variables in the cross-border e-commerce logistics alliance should be conducted to assess their respective impacts. Furthermore, the alliance and cross-border e-commerce platforms should further balance the interests of all parties to maximize the overall benefits, thereby safeguarding the comprehensive benefits of the cross-border e-commerce logistics alliance.

This paper only conducts a game analysis and simulation under the special risk scenario of supply chain disruption among the three parties of cross-border e-commerce platforms, logistics service providers, and overseas merchants in the alliance. Some meaningful conclusions have been drawn. However, due to the limitations of the research objects and conditions, this study did not consider various influencing factors from multiple perspectives to explore the specific game operations among the three parties, nor did it consider the influence of psychological factors on the game behavior. In addition, the study did not consider the decision-making behavior of game alliances involving multiple stakeholders, such as consumers and governments. In the future, we will explore the establishment of mutual trust mechanisms and risk-sharing mechanisms among the three parties in the
game, which will reduce concerns about choosing alliance cooperation beyond cost–benefit analyses and provide more valuable development suggestions for building a more perfect cross-border e-commerce logistics alliance.

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