Research on the Cross border Logistics Alliance stability

Junjun Ai*, Hongyu Zhang

School of Economics, Wuhan University of Technology, Wuhan 430070, Hubei, China

*Corresponding author: 1257786902@qq.com

Abstract. The evolutionary process of cross-border logistics alliances is often influenced by instability, posing challenges to global supply chains. This paper integrates evolutionary game theory, stochastic differential equations, and synergy theory to study mutations in the Cross-border Logistics Alliance caused by major emergencies. Specifically, it extends the evolutionary game model using the stochastic differential equation. Based on synergy theory, it introduces the limiting probability density function to transform the stochastic dynamic model into a synergy model. This approach explores structural and perturbation-induced mutations in the nonlinear evolutionary process of the Cross-border Logistics Alliance, analyzes the probability of mutations, and reveals synergize control strategies for the alliance.

Keywords: Cross-border Logistics Alliance, Synergy theory, stability

1 Introduction

Cross-border logistics alliances integrate the advantages of logis-tics enterprises and cross-border eco-mmerce platforms, which have become an important trend in the development of cross-border trade.However, in recent years, major emergencies (such as pandemics, wars, etc.) have occurred frequently, leading to issues such as logistics delays and supply chain disruptions[1], posing stability challenges to cross-border logistics alliances. Therefore, Re-search on the stability of cross-border logistics alliance under emergen-cies is pressing for enhancing their risk resilience.

The stability of dynamic alliances refers to the system's self-protection and recovery capabilities under external disturbances. However, factors such as the urgency of major emergencies and the uncertainty of logistics transportation[2] often lead to insufficient alliance stability[3], resulting in nonlinear changes (catastrophes) within the alliance. Therefore, researching the catastrophe mechanisms and control strategies of cross-border logistics alliances is of significant importance.

Existing research primarily focuses on the influencing factors of logistics alliance stability (such as strategic management[4], collaborative regulation, incentive policies, etc.) and research methods (such as quantitative models[5] structural equation models[6], multi-objective optimization models[7], etc.). However, these studies generally rely on deterministic models and do not fully consider the impact of disturbance factors in real-world scenarios. This paper, based on the evolutionary game model of cross-border

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logistics alliances, introduces white noise to establish stochastic dynamic equations, describing the influence of disturbance factors on alliance evolution in uncertain environments.

Moreover, existing research lacks in-depth exploration of the nonlinear evolution of alliances. Catastrophe theory is regarded as an effective tool for studying the nonlinear evolution of systems, capable of capturing the dynamic changes of complex systems between equilibrium points under emergencies.

In summary, this paper integrates evolutionary game theory and catastrophe theory to study the evolutionary stability of cross-border logistics alliances. By introducing the limit probability density function, the stochastic dynamic model is transformed into a stochastic cusp catastrophe model, enabling the investigation of the catastrophe mechanisms in cross-border logistics alliances.

2 Analysis of Evolutionary Game in the Cross-border Logistics Alliance

Cross-border Logistics Alliance consists of multiple cross-border and cross-enterprise entities, each possessing independent internal information systems. Due to differences in information architecture and proprietary terminology definitions, data circulation within the alliance faces challenges. Figure1 shows, the Cross-border Logistics Alliance includes cross-border e-commerce platforms, domestic logistics enterprises, foreign logistics enterprises, and other alliance entities. Through collaborative technologies, these entities have established logistics tracking subsystems, logistics operation subsystems, logistics information subsystems, and logistics financial subsystems based on information coordination. By implementing a unified information standard system, enterprises have achieved information coordination and seamless electronic document integration through information system interfaces. Driven by cross-border e-commerce platforms, an information coordination platform that transcends national borders, enterprise entities, languages, and information standard systems has been established, enabling efficient connectivity among diverse enterprise entities.

Figure1 shows that the Cross-border Logistics Alliance integrates the information systems of multiple members through collaborative technologies, forming the Cross-border Logistics Alliance Information Coordination System. The advantages of this system are mainly reflected in two aspects: Firstly, it standardizes the independent information system structures of various entities, achieving seamless integration of cross-border digital document processes, full sharing of logistics information resources, and real-time transmission of logistics information data. Secondly, it standardizes the independent proprietary terminology definitions and norms of various entities, promoting consistency in information understanding, thereby driving the overall collaborative operation of the Cross-border Logistics Alliance and creating an information coordination effect.

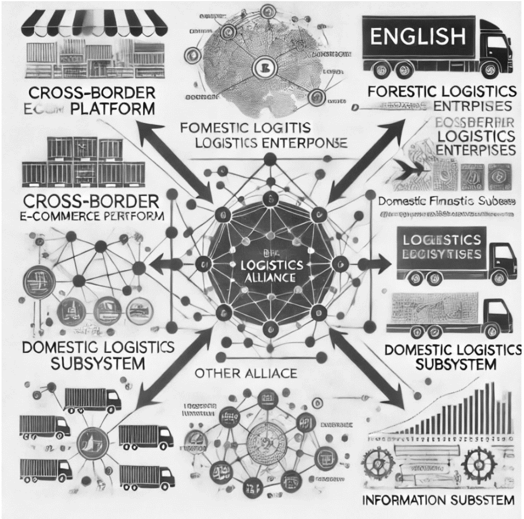

Fig. 1. Cross-border Logistics Alliance based on Information Coordination

3 Model Design

3.1 Evolutionary Game Model Building

The cross-border logistics alliance members considered in this paper primarily include cross-border e-commerce platforms and logistics enterprises. Specifically, the two parties complete the entire process of cross-border logistics business through a cooperative model of complementary advantages, resource sharing, and business collaboration. Table 1 shows the payoff matrix. Among these, the efficiency of alliance business integration and resource sharing is measured by the level of collaborative standards w. Alliance members choose collaborative strategies (such as coordinated delivery, shared warehousing, seamless electronic document integration, etc.) to promote alliance stability and receive benefits based on the collaborative profit distribution coefficient λ. When alliance members opt for non-collaborative strategies (such as monopolizing transportation, distorting information translation, etc.), the member who actively betrays the alliance can obtain speculative profits π, while the breached member receives economic compensation D. Considering cost-sharing and profit-sharing, let $\lambda = 1/2$. In this case, the total collaborative investment cost is $C/2$, and the collaborative profit is $w/2$.

Table 1. Cross-border Logistics Alliance Game Payoff Matrix.

Player1	Player 2	
	collaboration	Non-collaboration
collaboration	$R+w/2-c/2$ $R+w/2-c/2$	R_p+D $R_o+\pi-D$

Non-collaboration	$R_p + \pi - D$ $R_o + D$	R_p, R_o

Assuming that during the evolution of the cross-border logistics alliance, the probability of alliance members choosing collaboration is x, and the probability of abandoning collaboration due to the risks and benefits associated with collaboration is $1 - x$. At this point, the expected profit of members who continue to maintain collaboration, the expected profit after deducting penalties for abandoning collaboration, and the average expected profit are as follows:

$$U_1 = x(R + W/2 - C) + (1 - x)(R + D) \tag{1}$$

$$U_2 = x(R + \pi - D) + (1 - x)R \tag{2}$$

$$\overline{U} = xU_1 + (1 - x)U_2 \tag{3}$$

According to Erwin[8] , the rate of change of the probability $F(x)$ for alliance members in the cross-border logistics alliance choosing collaboration is:

$$\begin{aligned} \mathrm{F}(z) &= \frac{\mathrm{d}z}{\mathrm{d}t} = z(U_1 - \overline{U}) \\ &= x(1 - z)[z(W/2 - C/2 - \pi) + D] \\ &= -z^3(W/2 - C/2 - \pi) + z^2(W/2 - C/2 - \pi - D) + zD \end{aligned} \tag{4}$$

$$\begin{gathered} \frac{\mathrm{d}z}{\mathrm{d}t} = -dz^3 + bz^2 + cz \\ d = W/2 - C/2 - \pi\,, b = W/2 - C/2 - \pi - D\,, c = D \end{gathered} \tag{5}$$

The dynamic equation describes the evolution of the cross-border logistics alliance under certain conditions. If F(z)=0, it indicates that the alliance is in a stable state regardless of the proportion of collaboration, remaining unchanged over time. However, complex systems involving human factors such as live e-commerce supply chains, joint ventures, and counter-terrorism alliances, decision-making behaviors cannot ignore disturbances from psychological fluctuations, emotional preferences, and past experiences. The randomness of these factors is difficult to quantify but directly affects decision outcomes. For example, alliance members may actively withdraw from the alliance due to unilateral opportunism, market competition, or exchange rate fluctuations. Drawing on related research, incorporating the randomness of alliance members into the game model is more aligned with real-world scenarios. Therefore, this paper introduces white noise, expanding equation into stochastic dynamics, generating a one-dimensional stochastic differential model.

3.2 Catastrophe Model Building

Members of the cross-border logistics alliance exchange logistics information, integrate logistics resources, and improve the cross-border logistics operation process to form a temporary collaborative network organization.

During the COVID-19 pandemic, the evolution of cross-border logistics alliances exhibited abrupt jumps (sudden transitions from collaboration to non-collaboration) and multi-stability (coexisting states of collaboration and non-collaboration). The fundamental cause lies in some alliance members engaging in opportunistic behavior and abandoning collaboration. When the proportion of defectors reaches a certain threshold, cross-border logistics alliances face disintegration. Therefore, this paper constructs a stochastic synergy model for cross-border logistics alliances based on synergy theory.

Synergy theory is a nonlinear theory based on singularity theory. Thom[9]demonstrated that a synergy model can be constructed using a function describing one state variable and two control variables. Clearly, the stochastic differential model conforms to the synergy form, thus serving as our classical synergy model.

4 Analysis of Mutation Mechanisms

4.1 Structural Catastrophe

Figure 2 shows that if only considering the continuous changes in the internal parameters π and D of the alliance, $\alpha - \beta$ forms evolutionary paths in different directions. When the path crosses the boundary of the bifurcation point set, the Cross-border Logistics Alliance undergoes a structural catastrophe.

$M - N$ Path: Initially, the cross-border e-commerce platform and logistics enterprises exist outside the alliance (in a non-cooperative state). At this stage, the balance between coordination risk benefits and risk costs remains stable. As π increases along the evolutionary trajectory, the proportion of cooperative enterprises gradually grows. Once the benefits of coordination significantly outweigh the risk losses from abandoning collaboration at a critical juncture, enterprises promptly adopt a cooperative stance, and the alliance transitions back to a cooperative state.

$N - M$ Path: The alliance begins its evolution from a cooperative steady state. Along its developmental route, the interplay between coordination risk benefits and costs shifts. Due to the rise in speculative profits, the alliance mutates from its cooperative state back to a non-cooperative one. Subsequently, the intensification of risk losses disrupts the benefits-cost balance, reverting it to the initial level, pushing the alliance to the brink of disintegration.

$M - N'$ Path: Starting from the same origin as the $M - N$ path but yielding an opposite evolutionary result. When control parameters change continuously while avoiding the bifurcation point set, the alliance evolves toward the upper-right direction $(M - N')$, ultimately achieving stability.

In summary, crossing the bifurcation point set often triggers abrupt changes. For the Cross-border Logistics Alliance, two strategies are critical:

Pre-synergize Intervention: When structural synergize signs have not fully emerged, implementing effective control policies promptly can prevent the evolutionary path from crossing the Synergize bifurcation point set. This ensures the control-plane strategy avoids the bifurcation critical surface, safeguarding the alliance from structural catastrophes. It grants companies ample time to coordinate resources and address sudden shifts.

Post-Synergize Recovery: When structural catastrophes have already occurred, seeking alternative logistics enterprises for temporary support prioritizing the restoration of logistics operations—becomes essential. This strategy guides the alliance's evolution along the shortest path perpendicular to the right boundary of the bifurcation point set, transitioning it from an initial state of information dis-coordination to one of coordination.

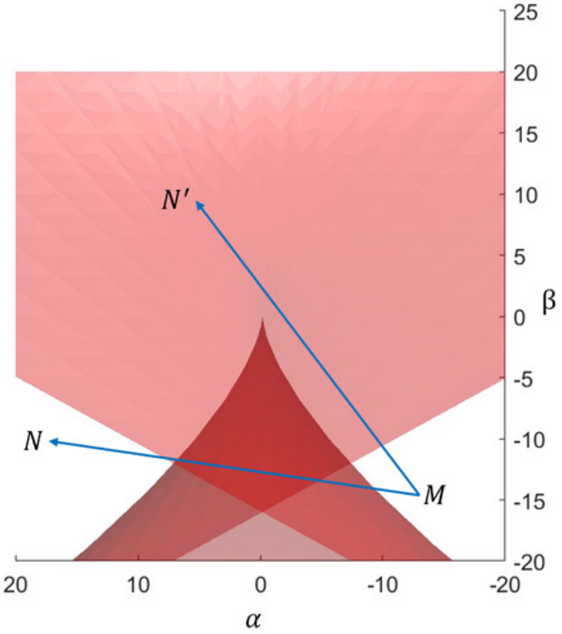

Fig. 2. Stability of the Cross-border Logistics Alliance.

Above all, crossing the bifurcation point set often leads to abrupt changes. For the Cross-border Logistics Alliance, on one hand, when structural catastrophe phenomena have not yet fully emerged, effective control policies can be swiftly implemented to prevent the evolutionary path from crossing the catastrophe bifurcation point set and to ensure that the control plane strategy combination avoids the bifurcation critical surface. This approach can help avoid structural catastrophes in the Cross-border Logistics Alliance, providing companies with sufficient time to coordinate resources and respond to sudden changes. On the other hand, when structural catastrophes have already occurred in the Cross-border Logistics Alliance, it is advisable to seek alternative logistics enterprises to provide temporary support services, prioritizing the restoration of logistics operations. This strategy allows the evolution of the Cross-border Logistics Alliance to proceed along the shortest path perpendicular to the right boundary of the bifurcation point set, transitioning from an initial state of information dis-coordination to a state of information coordination.

4.2 Perturbation-induced Catastrophe

Figure 3 shows that within the bifurcation point set region, a bimodal phenomenon exists. Under the same parameter combination, the alliance exhibits two steady states: coordination and non-coordination. Perturbation-induced catastrophes indicate that the alliance is highly sensitive to external disturbances. At the onset of the pandemic, border control measures in various countries led to disruptions in cross-border logistics, necessitating simultaneous attention to the external environment and the alliance's own risk resilience. To ensure the stable evolution of the alliance, it is essential, firstly, to establish a risk early warning mechanism to prevent crossing the bifurcation point set, and secondly, to closely monitor external factors such as customs regulations to mitigate risks like logistics interruptions caused by external disturbances.

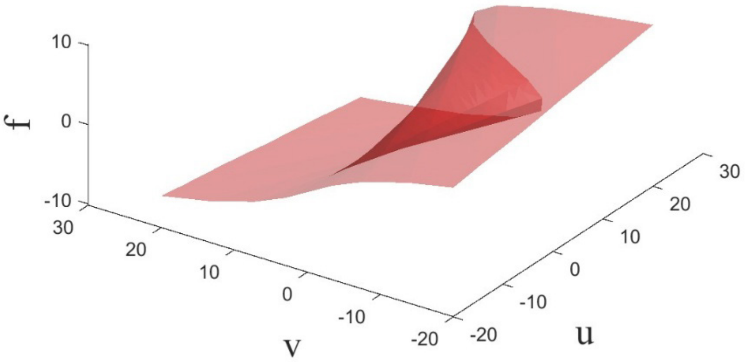

Fig. 3. Perturbation-induced catastrophe of the Cross-border Logistics Alliance.

4.3 Catastrophe Probability

Admittedly, in the short term, these measures will significantly increase the cost investment of companies, cause a certain degree of waste of resources to some extent, and pose risks to the stable development of companies. However, considering the long - term benefits of the synergy strategy, this model can better control resources and the quality of allocation. Through collaborative decision - making among alliance members, logistics resources can be accurately allocated to the most needed links according to the business characteristics and needs of each member, so as to respond to logistics demands more flexibly. For example, when the logistics demand in a certain region suddenly increases, alliance members can quickly allocate resources from other regions through a collaborative mechanism and utilize the flexible scheduling capabilities of self - owned logistics centers to meet the logistics needs of that region in a timely manner.

At the same time, simply relying on the outsourced transportation model and local warehousing model, although it can significantly reduce the investment risks and costs of companies, from the perspective of synergy, this model has obvious limitations. In this model, it is difficult to achieve in - depth resource collaboration and sharing among alliance members, and it is impossible to effectively control resources and the quality of allocation. Moreover, due to the lack of collaborative planning, in the face of complex and changeable logistics demands, the response time is not flexible enough. Once unexpected events occur, such as regional traffic control or natural disasters, members cannot quickly adjust logistics strategies through a collaborative mechanism, and it is extremely easy to lead to the disintegration of cross - border logistics alliances.

Therefore, establishing a cross - border logistics alliance and integrating self - owned logistics centers and outsourced transportation models, incorporating a synergy strategy, can bring huge advantages. On the one hand, through the collaborative optimization of resource allocation between self - owned logistics centers and outsourced transportation, logistics costs can be minimized, and the overall risk - resistance ability can be enhanced by using the risk - sharing mechanism among alliance members. On the other hand, with the collaborative formulation of logistics standards and processes, logistics specialization and standardization can be achieved, ensuring the quality of logistics services. For example, in the goods transportation link, alliance members can optimize transportation routes and share transportation resources through collaborative cooperation, reducing transportation costs and improving transportation efficiency at the same time. In the goods warehousing link, through collaborative management, real - time sharing of inventory information can be achieved, increasing inventory turnover and enhancing the overall quality of logistics services.

5 Conclusion and Implication

To enhance the risk response level and recovery capability of the Cross-border Logistics Alliance during major emergencies, this paper integrates evolutionary game theory, stochastic differential equations, and catastrophe theory to construct a stochastic cusp catastrophe model for the Cross-border Logistics Alliance. It discusses the structural and perturbation-induced mutations of the alliance and analyzes the probability of mutations, thereby formulating corresponding mutation strategies. The following conclusions and insights are drawn:

(1) The structural catastrophe of the Cross-border Logistics Alliance stems from the self-organizing phase transition that occurs when the costs and benefits of coordination risk cross the boundary of the bifurcation point set. Timely adjustment of the catastrophe path can help control this process. However, when the parameter combination lies within the bifurcation point set, random external disturbances can trigger perturbation-induced catastrophes. Alliance members need to closely monitor customs regulations to promptly identify potential bifurcation points. Simultaneously, logistics enterprises should be encouraged to establish overseas and local warehouses to guard against perturbation-induced catastrophes. During high-risk periods, proactive promotion of coordinated distribution and multimodal transportation can help control the costs and benefits of coordination risk.

(2) The probability of catastrophe is significantly positively correlated with the area of the bifurcation point set, and control parameters can be adjusted to maximize

the stability of the alliance. Encouraging cross-border e-commerce platforms to integrate self-built logistics centers and outsourced transportation services can enhance their flexibility and control costs. By dynamically adjusting transportation routes and resource allocation according to the external environment, the bifurcation point set of mutations can be controlled within an optimal range, thereby addressing potential mutations.

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