Research Article

Mathematical Problems in Engineering Pharmaceutical Cold Chain Transportation Decision Making under the Government’s Reward–Penalty Mechanism: A Perspective of Evolutionary Game Theory

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In the context of the COVID-19 pandemic, the cold chain transportation of medicines is becoming more and more critical to the quality and safety of drugs. In order to better motivate the logistics service providers to adopt the cold chain transportation strategy, this paper constructs a multiparty evolutionary game model composed of the government, logistics service providers, and medical institutions, and models behavioral strategies. The interaction is simulated and analyzed. Focusing on the contradictions between cost and service level in cold chain transportation, the revenue-sharing coefficient between medical institutions and logistics service providers and the government’s reward and punishment mechanism are introduced. The results show the following: (1) a reasonable revenue sharing contract between the medical institution and logistics service provider will prompt the logistics service provider to use cold chain transportation. (2) With the government’s penalties and rewards being further increased, the logistics service provider will tend to use noncold chain transportation. Therefore, the government must set a reasonable reward and punishment mechanism to ensure drug safety. (3) With the increasing revenue of the medical institution, the probability of the logistics service provider using noncold chain transportation decreases. In order to avoid medical malpractice related to noncold chain transportation, the government should appropriately adjust drug price restrictions to increase drug sales revenue. (4) With the rate of medical malpractice being increased, the evolution of each stakeholder to the equilibrium point of the game is accelerated.

1. Introduction

The COVID-19 pandemic has lasted for about 2 years, from December 2019 to the present. As of 5 December 2021, about 260 million people have been infected with COVID-19 worldwide, from which about 5 million people have died [1]. During this period, mutation types have appeared, posing a huge threat to human life and health. Infected people need more types of medicine to recover, which poses severe challenges to cold chain transportation, especially when delivering vaccine products. For the current new coronavirus vaccine, the transportation and storage of inactivated vaccines need to be carried out at 2 to 8°C, while the mRNA vaccine must be transported at −70°C [2]. Moreover, the transportation of many additional temperature-sensitive medicines also requires a cold chain. For these pharmaceuticals, cold chain transportation is the best choice.

In contrast to the general food cold chain system, the pharmaceutical cold chain has high operating costs, many requirements for cold chain link coordination, strict enterprise qualification assessment, high drug quality standards, and strict monitoring [3]. Therefore, cold chain transportation requires logistics service providers (LSPs) to pay higher costs than they would with room-temperature logistics, including higher equipment and technical costs. It must also be fully inspected by the medical institution.
Unsafe drugs that result from noncold chain transportation put a large patient population at long-term risk of potential disease outbreaks. Thus, noncold chain transportation has drawn the attention of public and government. It has also taken center stage within the pharmaceutical supply chain research community. This paper is the first to determine the game players. The game players in the pharmaceutical cold chain are the local government, medical institution, and LSP. Strategies are determined by these players. LSP transportation services and medical institutions are responsible for inspecting cold chain shipping information. Both are subject to local government supervision. However, under the local government’s reward–penalty mechanism, what kind of strategy should the LSPs adopt? Should they participate in the pharmaceutical supply chain and use cold chain transportation (i.e., choose either cold chain or non-cold chain)? Furthermore, what kind of strategy should medical institutions adopt? Should they choose full inspection of the drugs throughout the entire cold chain (i.e., fully inspected and noninspected)?

In this paper, we discuss the LSP decision whether or not to use cold chain transportation, especially under the influence of the government’s reward–penalty mechanism. The optimal strategies under different circumstances are considered. To the best of our knowledge, this paper introduces the medical accident rate and benefit-sharing coefficient into the evolutionary game model for the first time and studies the optimal decision-making process of medical institutions and LSPs. On the one hand, it enriches the literature on cold chain transportation decision making. On the other hand, it also provides a decision-making basis for LSPs when choosing cold chain under different conditions.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature. In Section 3, we establish a multiagent evolutionary game under the government’s reward–penalty mechanism. In Section 4, we analyzed the stability of each equilibrium point and determine the evolutionary stability strategy (ESS) in different scenarios. In Section 5, we present the numerical simulation and discuss the influence of relevant parameters on the game’s evolutionary path. In Section 6, we summarize our work.

2. Literature Review

2.1. Pharmaceutical Cold Chain Transportation. Pharmaceutical cold chain transportation has become increasingly significant for the pharmaceutical supply chain [4]. The related research on pharmaceutical cold chain transportation covers three aspects.

2.1.1. The Role and Function of Pharmaceutical Cold Chain Transportation. Pharmaceutical cold chain transportation is crucial to ensuring the quality and safety of temperature-controlled medicines. Kumar and Jha [5] pointed out that pharmaceutical shipments have higher requirements than other commodities. The pharmaceutical cold chain can better meet the sensitivity of medicines to quality. Pharmaceutical cold chain transportation is crucial to ensuring the quality and safety of temperature-controlled medicines. Kumar and Jha [5] pointed out that pharmaceutical shipments have higher requirements than other commodities. The pharmaceutical cold chain can better meet the sensitivity of medicines to quality. Subzwari and Nasir [6] clarified that the cold chain can meet the temperature required for different refrigerated medicines in the circulation process. Ringo et al. [7] conducted a study to determine whether the cold chain of pharmaceuticals complies with WHO requirements for public health facilities. The study found that the lack of investment in cold chain transportation facilities and equipment is the main challenge for the safe circulation of refrigerated medicines. Markmann [8] cold chain shipping drives the commercialization of targeted therapies and specialty medicines.

2.1.2. The Optimization Research of Pharmaceutical Cold Chain Transportation. In the transportation decision-making process, the stakeholder’s participation is emerging as a basic component of success and high-quality [9–11]. Cai et al. [11] considered a long-distance transportation supply chain composed of distributors and manufacturers, in which the distributors must make appropriate efforts to maintain the freshness of products. Haial et al. [12] took the pharmaceutical supply chain as an example to design a model for pharmaceutical transportation decision making. Lan et al. [13] established a noncooperative game model of the secondary food supply chain composed of suppliers and retailers. The model also considers the impact of quality and price on demand and uses a collaborative replenishment strategy to analyze equilibrium solution. Yu and Xiao [14] used the Stackelberg game model to consider the impact of price and cold chain service levels on consumer demand and studied the pricing issues of distributors, LSPs, and retailers in the fresh food supply chain.

2.1.3. The Risk Research of Pharmaceutical Cold Chain Transportation. Kumar and Jha [5] indicated that maintaining a stable temperature during transportation avoids damage to medical products, and strict transportation management is also needed to avoid theft and mismanagement. Wen et al. [3] proposed an integrated model based on a combination of the SWARA and CoCoSo methods under the probabilistic linguistic environment to ensure the quality of medicine cold chain transportation. Wu and Hsiao designed and mailed out 566 relevant questionnaires about cold chain risks. The results showed that the top five food quality and safety risk factors are long loading and unloading times, inadequate temperature, product damage, risk of abuse, and poor driving conditions [15]. Lloyd et al. [16] studied the risk of accidental freezing of vaccines during cold chain transportation. By reviewing the existing literature, they found that the important reason is that the transportation link cannot guarantee the whole process of temperature control.
2.2. Government Reward and Punishment Mechanism. The government subsidy and punishment mechanism has an important influence on the decision-making behaviors of the main body of the supply chain. Research on government subsidies and punishment mechanisms can be simply divided into two categories. First, the first type of research considers the effect of a single government subsidy mechanism or punishment mechanism on the main body of the supply chain. For example, He et al. [17] considered the effect of government subsidies on manufacturers’ channel selection and proposed that an appropriate level of subsidies would help reduce channel competition. Based on the background of the COVID-19 epidemic, Li and Yang [18] discussed the innovation incentive effect of government subsidies on enterprises and the consumption stimulation effect on consumers. Yu et al. [19] designed a model on subsidies for home appliances to the countryside and found that subsidies can help improve consumer welfare. Alizamir et al. [20] discussed the protective effects of price subsidies and income subsidies for farmers to grow crops. The study found that both subsidies provided more incentives for farmers to grow crops than without the subsidy. Cohen et al. [21] considered the demand uncertainty and used the subsidy mechanism to coordinate the interests of consumers and green product manufacturers. Chemama et al. [22] compared the effect of fixed subsidies and dynamic subsidies on the promotion of new energy vehicles and pointed out that fixed subsidies are more conducive to reducing the risk of manufacturers’ overcapacity. Jaber et al. [23] established a low-carbon supply chain cooperation dynamic model and proved that when the government imposes penalties on excess emissions, supply chain managers will choose the cooperation model with the smallest inventory and emission reduction costs.

Second, the second type of research considers the effects of applying government subsidies and punishment mechanisms simultaneously. For example, Sheu and Chen [24] analyzed the impact of government financial intervention on competition in green supply chains. It was found that taking green subsidies and taxes together contributes to the sustainable production of green products. Wang et al. [25] designed a reward and punishment mechanism for a closed-loop supply chain under the third-party recycling model. They propose that manufacturers should increase the repurchase volume by raising the repurchase price and ultimately avoid government fines. Chen et al. [26] considered scenarios when food companies face limited input-generating capacity. This paper proposes a more effective food quality supervision mechanism—replacing a single punishment mechanism with a reward and punishment mechanism. Yu and Li [27] developed a low-carbon supply chain decision-making model consisting of manufacturers and retailers and reached similar conclusions. They pointed out that carbon emission reduction cannot be achieved only by increasing the level of carbon tax collection, and it needs to be combined with energy-saving subsidies.

To sum up, the government’s reward and punishment mechanism has a profound impact on the operational decisions of various entities in the supply chain. However, as a key link to ensure the quality and safety of temperature-controlled drugs, pharmaceutical cold chain transportation is also one of the decision-making contents of logistics service providers. Existing research has not considered the role of government incentives and punishments in the decision-making of pharmaceutical cold chain transportation. Therefore, this paper introduces the government’s cold chain transportation subsidies and noncold chain transportation penalties for logistics service providers.

2.3. Application of Evolutionary Game Theory. Evolutionary game theory takes the game of bounded rationality as the analysis framework [28, 29]. The two sides of the game achieve dynamic equilibrium through continuous learning and adaptation processes, which makes up for the defects of traditional game theory, such as the assumption that the participants are completely rational and have complete information. In the process of evolutionary games, individuals often adjust their strategies dynamically based on the observation and learning of other individual strategies. Because the participants are boundedly rational and face decision-making scenarios with incomplete information, there are many uncertainties in the strategic choices of all parties in the game. At present, many scholars use evolutionary game methods to solve various problems. Evolutionary games are mostly used in environmental protection, emergency handling, safety supervision, etc. (see Table 1).

2.3.1. Environmental Protection. Antoci et al. [30] proposed an environmental protection mechanism managed by the local government of a tourist region. This mechanism regulated the tourists entering the scenic spot and the enterprises operating the scenic spot. Then, Mahmoudi and Rasti [31] proved that imposed tariffs are the most effective government approach to minimizing environmental impacts. Additionally, government subsidies and incentives are conducive to the implementation of low-carbon strategies [32]. In terms of construction and demolition waste, Shen et al. [33] arrived at the same conclusion.

2.3.2. Emergency Handling. In the face of disasters such as typhoons, the government analyzes individual behavior decisions by establishing an evolutionary game model and then formulates effective emergency plans [34]. When facing a public health emergency, adopting a dynamic reward and punishment mechanism can better mobilize the enthusiasm of community residents [35]. In the same situation, by managing the spread of rumors and the end of demand, the government can maintain market stability and sustainable development by identifying the optimal ESS for SMEs [36].

2.3.3. Safety Supervision. Gong et al. [37] concluded from the evolutionary game between two parties that dynamic supervision significantly improves the efficiency of construction safety investment supervision. Liu et al. [38] and Lu et al. [39] applied the evolutionary game model to coal
2.3.4. Cooperation Mechanism. Evolutionary games have been used extensively to investigate cooperation. Lewis and Dumbrell [42] outlined common games and reviewed major findings and recent advancements. Then, an evolutionary game model was developed to explore the cooperation tendency of multisuppliers [43]. Luo et al. [44] used the evolutionary game model of complex networks to describe the evolution of environmental governance cooperation between enterprises. Liu et al. [45] studied the problem of multiagent collaborative innovation in the field of biomedical engineering through the evolutionary game model.

Regarding the issue of government supervision of corporate behavior, it can also be analyzed by applying the evolutionary game method. There are relatively few studies on drug safety issues using evolutionary game methods. For example, Qi et al. [46] studied the cold chain transportation decision-making problem in the vaccine supply chain based on the dynamic evolution game method.

2.4. Revenue Sharing Contracts in the Supply Chain. At present, revenue sharing contracts are widely recognized and applied, and the research on them is quite sufficient. In the green supply chain, some scholars have proposed that revenue sharing contracts are conducive to promoting the energy conservation and emission reduction of supply chain enterprises and improving the overall profit level of the supply chain. Song and Gao [47] first established a green supply chain game model under the revenue sharing contract. The research found that, compared with decentralized decision making, the revenue sharing contract led by the retailer is more conducive to improving greenness. Li et al. [48] and Yang et al. [49] also reached the same conclusion. Zhang and Liu [50] established a three-level green supply chain and introduced a revenue sharing mechanism to determine the optimal income distribution coefficient for participating members.

When dealing with channel conflicts, revenue sharing contracts also coordinate the interests of all parties in the system. Gamchi and Torabi [51] studied the influence of consumers’ risk appetite on setting the revenue sharing coefficient under a dual-channel market setting. Xu et al. [52] established a dual-channel supply chain composed of manufacturers and retailers. All members are generally risk-averse. By designing a two-way revenue sharing contract, a win–win situation for supply chain members was achieved. Hsueh [53] combined the revenue sharing contract with corporate social responsibility (CSR) to establish a new type of revenue sharing (RS)-CSR contract.

Subsequently, Li et al. [54] applied the new RS-CSR contract and found that encouraging manufacturers to properly undertake CSR can achieve a win–win situation for social welfare, consumers, and supply chain members. In addition, Liu et al. [55] used revenue sharing contracts as a coordination mechanism to study the recycling of waste electrical and electronic equipment (WEEE) under third-party recycling in a closed-loop supply chain. For a closed-loop supply chain dominated by manufacturers, revenue sharing contracts can still increase manufacturers’ profits [56].

As far as we know, the current research on cold chain transportation decision making has not yet considered the establishment of a revenue sharing contract coordination mechanism. In order to protect the entire cold chain of medicines, LSPs need to pay high cooling costs. Establishing a revenue sharing contract led by medical institutions will help reduce the cost pressure on LSPs and, at the same time, encourage LSPs to actively choose cold chain transportation. This is also one of the innovations of this article.
3. Multiparty Evolutionary Game Modeling

3.1. Behavior Descriptions of Players. In this paper, we consider a two-level pharmaceutical supply chain structure composed of an LSP and a medical institution and also consider the role of local governments in monitoring medical institutions’ inspection behavior. For the government, there are two strategies: to strictly supervise the inspection behavior of medical institutions (A1) and to passively supervise the inspection behavior of medical institutions (A2). For the medical institution, there are two strategies—fully inspected (B1) and noninspected (B2). For the LSP, there are two strategies: using cold chain (C1) and using noncold chain (C2). Thus, the three-party strategy game tree of the local government, the medical institution, and the LSP was constructed, as shown in Figure 1.

3.2. Basic Assumptions. To study the problem, the following assumptions were made. Table 2 provides definitions of the parameters involved in the assumptions.

Assumption 1. It is supposed that the probability of the local government adopting strict supervision is \( x \), and its probability adopting passive supervision is \( 1 - x \); the probability of the medical institution choosing full inspecting is \( y \), and the probability of the medical institution choosing uninspected is \( 1 - y \); the probability of the LSP using cold chain to transport drugs is \( z \), and the probability of the LSP using noncold chain is \( 1 - z \), and \( 0 \leq x \leq 1 \), \( 0 \leq y \leq 1 \), \( 0 \leq z \leq 1 \).

Assumption 2. When the local government has strict supervision, the medical institution that does not inspect the cold chain information will be punished with \( F_{m1} \), and it is assumed that the cost of strict supervision is set as \( C_{g1} \); when the local government has passive supervision, the cost of passive supervision is set as \( C_{g2} \). In addition, the degree of government regulation is positively related to its regulation cost. When the government’s supervision of the cold chain of drugs is strict, the number of times that drugs are sampled will increase, and the human, material, and financial resources will also increase. So, \( C_{g1} > C_{g2} \).

Assumption 3. Whether medical malpractice occurs is set as a 0–1 integer variable \( p \), according to whether the medical malpractice occurrence will impact the reward and punishment mechanism of the local government and medical institution.

Assumption 4. Because of the “result-oriented” stance of the local government, regardless of whether the local governments have strict supervision or passive supervision, the local government will subsidize the medical institution with \( M_{m1} \) when the medical malpractice does not occur. Moreover, the local government will gain the benefits of a regulatory reputation, which is set as \( A_y \) when the medical malpractice does not occur.

Assumption 5. For medical institution, the profit from the sales of drugs is set as \( R_m \). When the medical institution fully inspects cold chain information, the LSP that uses a noncold chain to transport drugs will be punished by medical institution and the local government with \( F_{l2} \) and \( F_{l1} \), respectively. And it is assumed that the full inspection cost of cold chain transportation information is set as \( C_{m1} \). In addition, when the medical institution does not inspect cold chain information, the cost will be zero. The cold chain transportation information includes temperature records in vehicles such as refrigerated trucks, whether the packaging is damaged, etc.

Assumption 6. To promote the LSP using cold chain transportation, the medical institution will subsidize the LSP that uses cold chain transportation with a revenue sharing coefficient of \( \alpha \). Moreover, the medical institution will not honor the revenue sharing contract when medical malpractice occurs.

Assumption 7. The medical institution will outsource the cold chain transportation business of drugs to the LSP in order to focus on retailing drugs to the patient for market revenue with \( R_l \). Moreover, the cost of using cold chain is set as \( C_{c1} \) when the LSP uses cold chain to transport drugs; the cost of using noncold chain is set as \( C_{c2} \) when LSP uses cold chain to transport drugs. The cost of cold chain transportation is mainly the use cost of cold chain equipment such as refrigerated trucks and temperature and humidity recorders.

Assumption 8. The occurrence of medical malpractice indicates that the LSP has not used cold chain transportation. Regardless of whether the medical institution inspects or not, the LSP will be punished with \( F_{l1} \) by the local government and \( F_{l2} \) by the medical institution.

3.3. Formating of Mathematical Components. Based on the assumptions made in the previous section and the strategic combinations in Figure 1, we can calculate the return function of the three game parties under various strategy situations (see Table 3):

4. Discussion

4.1. Analysis of the Local Government’s Evolutionary Stability Strategy

4.1.1. Expected Benefits of Local Government. Assume that \( E_{11} \) represents the expected benefits of the local government under strict supervision, \( E_{12} \) represents the expected benefits of the local government under passive supervision, and \( E_1 \) represents the average expected benefits of the local government under supervision. According to the payoff matrix, we calculate the expected benefit under strict government supervision as follows:
In the same way, the expected benefit of the local government under passive supervision is calculated as

$$E_{12} = \left\{ \begin{array}{l}
yz(-C_g - M_m + A_g) + (1 - y)z(-C_g + A_g + F_m) + y(1 - z)(-C_g + (1 - p)(A_g - M_m) + F_l) + \\
(1 - y)(1 - z)(-C_g + (1 - p)A_g + F_m + pF_l)
\end{array} \right\}$$

In the same way, the expected benefit of the local government under passive supervision is calculated as

$$E_{12} = \left\{ \begin{array}{l}
yz(-C_g - M_m + A_g) + (1 - y)z(-C_g + A_g + F_m) + y(1 - z)(-C_g + (1 - p)(A_g - M_m) + F_l) + \\
(1 - y)(1 - z)(-C_g + (1 - p)A_g + F_m + pF_l)
\end{array} \right\}$$
Table 3: The payoff matrix between the local government, LSP, and medical institution.

| Strategic combination | Local government | Medical institution | LSP |
|-----------------------|------------------|---------------------|-----|
| \((A_1, B_1, C_1)\)   | \(-C_{g1} - M_{m1} + A_g\) | \((1 - a)R_{m1} - C_{m1} + M_{m1}\) | \(R_1 - C_{g1} + aR_{m1}\) |
| \((A_1, B_1, C_2)\)   | \(-C_{g1} + (1 - p)(A_g - M_{m1}) + F_{l1}\) | \(R_m - C_{m1} + F_{l1} + (1 - p)M_{m1}\) | \(R_1 - C_{g1} + aR_{m1}\) |
| \((A_1, B_2, C_1)\)   | \(-C_{g2} + A_g + F_{m1}\) | \((1 - a)R_{m1} - C_{m1} + M_{m1}\) | \(R_1 - C_{g1} + aR_{m1}\) |
| \((A_1, B_2, C_2)\)   | \(-C_{g1} + (1 - p)A_g + F_{m1} + pF_{l1}\) | \((1 - p)(1 - a)R_{m1}\) | \(R_1 + (1 - p)aR_{m1}\) |
| \((A_2, B_1, C_1)\)   | \(-C_{g2} - M_{m1} + A_g\) | \((1 - a)R_{m1} - C_{m1} + M_{m1}\) | \(R_1 + aR_{m1} - C_{l1}\) |
| \((A_2, B_1, C_2)\)   | \(-C_{g2} + (1 - p)(A_g - M_{m1}) + pF_{l1}\) | \(R_m - C_{m1} + F_{l1} + (1 - p)M_{m1}\) | \(R_1 + aR_{m1} - C_{l1}\) |
| \((A_2, B_2, C_1)\)   | \(-C_{g2} - M_{m1} + A_g\) | \((1 - a)R_{m1} + M_{m1}\) | \(R_1 + aR_{m1} - C_{l1}\) |
| \((A_2, B_2, C_2)\)   | \((-C_{g2} + (1 - p)(A_g - M_{m1}) + pF_{l1}) + p(F_{m1} + F_{l2})\) | \((pR_m + (1 - p)(1 - a)R_{m1})\) | \(R_1 + (1 - p)aR_{m1}\) |

According to (1) and (2), the average expected benefit of the local government is calculated as

\[
E_l = xE_{l1} + (1 - x)E_{l2}
\]

\[
E_l = x\left( (1 - z)(1 - p)(A_g - M_{m1}) - c_{g1} + F_{l1}) + (1 - y)(1 - z)(1 - p)(A_g - c_{g1} + pF_{l1} + F_{m1}) \right)
\]

\[
+ (1 - y)z(A_g - c_{g1} + F_{l1}) + yz(A_g - c_{g1} - M_{m1})
\]

\[
+ y(1 - z)((1 - p)(A_g - M_{m1}) - c_{g2} + F_{l2})
\]

\[
+ (1 - x)\left( (1 - y)(1 - z)(1 - p)(A_g - M_{m1}) - c_{g2} + p(F_{l1} + F_{m1}) \right)
\]

\[
+ (1 - y)z(A_g - c_{g2} + F_{m1}) + yz(A_g - c_{g2} - M_{m2})
\]

\[
(3)
\]

4.1.2. Replication Dynamic Equation Analysis of Local Government. According to Equations (1)-(3), the replication dynamic equation of the local government strategy is obtained:

\[
F(x) = \frac{dx}{dt} = x(E_{l1} - E)
\]

\[
F(x) = x(1 - x)\left( y(1 - z)(1 - p)(A_g - M_{m1}) - c_{g1} + F_{l1}) - y(1 - z)(1 - p)(A_g - M_{m1}) - c_{g2} + F_{l2}) \right)
\]

\[
+ (1 - y)z(A_g - c_{g1} + F_{m1}) + yz(A_g - c_{g1} - M_{m1})
\]

\[
+ (1 - y)z(A_g - c_{g2} + F_{m1}) + yz(A_g - c_{g2} - M_{m2})
\]

\[
(4)
\]

To further analyze the impact of the local government with different strategies on the stable equilibrium of the government’s strategy evolution, we obtain the derivative of the replicator dynamics equation with respect to

\[
\frac{dF(x)}{dx} = (1 - 2x)\left( C_{g1} - C_{g2} - (z - 1)F_{l1} (p(y - 1) - y) - y(z - 1)pF_{l1} \right)
\]

\[
+ (y - 1) (p(z - 1)(F_{l1} + F_{m1} + M_{m1}) + F_{m1} + M_{m1})
\]

\[
(5)
\]

For the local government, we can make the following summary according to (5):
(1) When \( y_0 = C_{q1} - C_{q2} + p(z - 1)(F_{11} - F_{12}) - (p(z - 1) + 1)(F_{m1} + M_{m1})/(2p - 1)(z - 1)F_{11} + F_{12}(p - pz) - (p(z - 1) + 1)(F_{m1} + M_{m1}) < y < 1, \) \( \frac{dy(x)}{dx} = 1 > 0, \) and \( \frac{dy(x)}{dx}|x = 0 < 0, \) the evolutionary stable strategy (ESS) of the government group is \( x^* = 0. \) In this scenario, when the probability of the medical institution choosing the "full inspecting" strategy \( y \) is high, the government group will tend to choose the "passively supervises" strategy.

(2) When \( y = y_0 = C_{q1} - C_{q2} + p(z - 1)(F_{11} - F_{12}) - (p(z - 1) + 1)(F_{m1} + M_{m1})/(2p - 1)(z - 1)F_{11} + F_{12}(p - pz) - (p(z - 1) + 1)(F_{m1} + M_{m1}), \) \( F(x) = 0, \) in this scenario, any probability \( x \) that the government will choose the "strictly supervises" strategy is an evolutionary stable strategy.

(3) when \( 0 < y < y_0 = C_{q1} - C_{q2} + p(z - 1)(F_{11} - F_{12}) - (p(z - 1) + 1)(F_{m1} + M_{m1})/(2p - 1)(z - 1)F_{11} + F_{12}(p - pz) - (p(z - 1) + 1)(F_{m1} + M_{m1}), \) \( \frac{dy(x)}{dx}|x = 0 > 0, \) and \( \frac{dy(x)}{dx}|x = 1 < 0, \) the evolutionary stability strategy (ESS) of the government group is \( x^* = 1. \) In this scenario, when the probability of the medical institution choosing "full inspecting" is low, the government group tends to choose the "strictly supervises" strategy.

Based on the above analysis, we drew a dynamic replication phase diagram of the local government, as shown in Figure 2. We can see from the figure that the feasible region of each game participant is divided into two adjacent regions by the intersection space of \( y \) and \( z. \) When the feasible region is located in space \( v_1, x \) converges to \( x^* = 0, \) and it is the optimal decision for the government group to adopt a "passively supervises" strategy. When the feasible region is located in space \( v_2, x \) converges to \( x^* = 1, \) and it is the optimal decision for the government to adopt a strictly supervises strategy.

4.2. Analysis of the Medical Institution’s Evolutionary Stability Strategy

4.2.1. Expected Earnings of the Medical Institution. Assume that \( E_{11} \) represents the expected earnings of the medical institution under full inspection, \( E_{22} \) represents the expected earnings of the medical institution under non-inspection, and \( E_{22} \) represents the average expected earnings of the medical institution under inspection. According to the payoff matrix, we calculate the expected profit of the medical institution under full inspection as follows:

\[
E_{11} = \left( xz(1 - \alpha)R_m - C_{m1} + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right) \right. \\
+ \left( 1 - x \right) \left( -C_{m1} + (1 - \alpha)R_m + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right)
\]  

(6)

In the same way, the expected profit of the medical institution under passive supervision is calculated as

\[
E_{22} = \left( xz(1 - \alpha)R_m - C_{m1} + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right) \right. \\
+ \left( 1 - x \right) \left( -C_{m1} + (1 - \alpha)R_m + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right)
\]  

(7)

According to (6) and (7), the average expected profit of the medical institution is calculated as

\[
E_2 = \left( xz(1 - \alpha)R_m - C_{m1} + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right) \right. \\
+ \left( 1 - x \right) \left( -C_{m1} + (1 - \alpha)R_m + M_{m1} \right) + \left( 1 - x \right) \left( -C_{m1} + F_{l2} + R_m + (1 - p)M_{m1} \right)
\]  

(8)

4.2.2. Replication Dynamic Equation Analysis of Medical Institution. According to equations (6)-(8), the replication dynamic equation of medical institution strategy is obtained:
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\[ F(y) \frac{dy}{dt} = y(E_2 - E_1) \]

\[ = y(1 - y) \begin{pmatrix}
    xz((1 - \alpha)R_m - C_{m_1} + M_{m_1}) + x(1 - z)(-C_{m_1} + F_{l_2} + R_m + (1 - p)M_{m_1}) \\
    + z(1 - x)(-C_{m_1} + (1 - \alpha)R_m + M_{m_1}) + (1 - x)(1 - z)(-C_{m_1} + F_{l_2} + R_m + (1 - p)M_{m_1}) \\
    xz((1 - \alpha)R_m - F_{m_1}) + x(1 - z)(pF_{l_2} - F_{m_1} + (1 - \alpha)(1 - p)R_m + pR_m) \\
    +(1 - x)z((1 - \alpha)R_m + M_{m_1}) + (1 - x)(1 - z)(-p(F_{m_1} - F_{l_1}) + (1 - \alpha)(1 - p)R_m + pR_m) 
\end{pmatrix} \] (9)

To further analyze the impact of the medical institution with different strategies on the stable equilibrium of the medical institution’s strategy evolution, we obtain the derivative of the replicator dynamics equation with respect to \( y \):

\[ \frac{dF(y)}{dy} = -2y(1 - y) \begin{pmatrix}
    -C_{m_1} + pF_{l_1}((1 - z)(x - 1) + (z - 1)F_{l_2} + pxF_{m_1}(z - 1) - pzf_{m_1}) \\
    + pF_{m_1} + xF_{m_1} - (p - 1)(z - 1)R_mz\alpha + (z - 1)pM_{m_1} + xzM_{m_1} - zM_{m_1} + M_{m_1} 
\end{pmatrix} \] (10)

For the medical institution, we can make the following summary according to (10):

1. When \( x = x_0 = (z - 1)(pF_{l_1} - F_{l_2} - pF_{m_1} + (p - 1)(\alpha R_m + M_{m_1})) - C_{m_1} / p(z - 1)(F_{l_1} - F_{l_2} - F_{m_1}) - F_{m_1} - zM_{m_1} < x < 1 \), \( dF(y)/dy|y = 0 > 0 \), and \( dF(y)/dy|y = 1 < 0 \), the evolutionary stable strategy (ESS) of the medical institution is \( y^* = 1 \). In this scenario, when the probability of the local government choosing the “strictly supervises” strategy \( x \) is high, the medical institution will tend to choose the “full inspecting” strategy.

2. When \( x = x_0 = (z - 1)(pF_{l_1} - F_{l_2} - pF_{m_1} + (p - 1)(\alpha R_m + M_{m_1})) - C_{m_1} / p(z - 1)(F_{l_1} - F_{l_2} - F_{m_1}) - F_{m_1} - zM_{m_1}, F(y) \equiv 0 \), in this scenario, any probability \( y \) that the medical institution will choose the “full inspecting” strategy is an evolutionary stable strategy.

3. When \( 0 < x < x_0 = (z - 1)(pF_{l_1} - F_{l_2} - pF_{m_1} + (p - 1)(\alpha R_m + M_{m_1})) - C_{m_1} / p(z - 1)(F_{l_1} - F_{l_2} - F_{m_1}) - F_{m_1} - zM_{m_1}, dF(y)/dy|y = 1 > 0 \), and \( dF(y)/dy|y = 0 < 0 \), the evolutionary stability strategy (ESS) of the medical institution is \( y^* = 0 \). In this scenario, when the probability of the local government choosing the “strictly supervises” strategy is low, the medical institution will tend to choose the “unsupervised” strategy.

Based on the above analysis, we drew a dynamic replication phase diagram of the medical institution, as shown in Figure 3. We can see from the figure that the feasible region of each game participant is divided into two adjacent regions by the intersection space of \( x \) and \( z \). When the feasible region is located in space \( v_1 \), \( y \) converges to \( y^* = 1 \), and it is the optimal decision for the medical institution to adopt a full inspection strategy. When the feasible region is
located in space $\nu_4$, $y$ converges to $y^*$ = 0, and it is the optimal decision for the medical institution to adopt a noninspection strategy.

4.3. Analysis of the LSP’s Evolutionary Stability Strategy

4.3.1. Expected Earnings of the LSP. Assume that $E_{31}$ represents the expected earnings of the LSP when using cold chain, $E_{32}$ represents the expected earnings of the LSP when using non-cold chain, and $E_3$ represents the average expected earnings of the LSP. According to the payoff matrix, we calculate the expected profit of the LSP when using cold chain as follows:

$$E_{31} = xy(-C_{l1} + R_l + aR_m) + (1 - y)x(-C_{l1} + R_l + aR_m) + y(1 - x)(-C_{l1} + R_l + aR_m) + (1 - y)(1 - x)(-C_{l1} + R_l + aR_m).$$  \hfill (11)

In the same way, the expected profit of the LSP under passive supervision is calculated as

$$E_{32} = xy(-C_{l2} - F_{l1} - F_{l2} + R_l) + (1 - y)x(-C_{l2} - p(F_{l1} + F_{l2}) + R_l + a(1 - p)R_m) + y(1 - x)(-C_{l2} - pF_{l1} - F_{l2} + R_l) + (1 - x)(1 - y)(-C_{l2} - p(F_{l1} + F_{l2}) + R_l + a(1 - p)R_m).$$  \hfill (12)

According to (11) and (12), the average expected profit of the LSP is calculated as

$$\overline{E}_3 = z\left(\begin{array}{c}
    xy(-C_{l1} + R_l + aR_m) + (1 - y)x(-C_{l1} + R_l + aR_m) \\
    + y(1 - x)(-C_{l1} + R_l + aR_m) + (1 - y)(1 - x)(-C_{l1} + R_l + aR_m) \\
    + x y(-C_{l2} - F_{l1} - F_{l2} + R_l) + (1 - y)x(-C_{l2} - p(F_{l1} + F_{l2}) + R_l + a(1 - p)R_m) \\
    + y(1 - x)(-C_{l2} - pF_{l1} - F_{l2} + R_l) + (1 - x)(1 - y)(-C_{l2} - p(F_{l1} + F_{l2}) + R_l + a(1 - p)R_m) \\
  \end{array}\right).$$  \hfill (13)

4.3.2. Replication Dynamic Equation Analysis of the LSP. According to equations (11)-(13), the replication dynamic equation of the LSP strategy is obtained:
To further analyze the impact of the LSP with different strategies on the stable equilibrium of the LSP’s strategy evolution, we obtain the derivative of the replicator dynamics equation with respect to $Z$:

$$
\frac{dF(x)}{dz} = -(2z - 1)(-C_{11} + C_{12} + (p + xy - yp)F_{11} - (p + xy - yp)(F_{12} + aR_m)/yF_{11}, F(z) = 0, \text{ in this scenario, any probability } z \text{ that the LSP will choose the "use cold chain" strategy is an equilibrium stable strategy.}
$$

For the LSP, we made the following summary according to (15):

1. When $x_0 = C_{12} + (p + xy)F_{11} - (p + xy - yp)(F_{12} + aR_m)/yF_{11}, F(z) = 0$, and $\frac{dF(z)}{dz} = z < 1$, the evolutionary stable strategy (ESS) of the LSP is $z^* = 1$. In this scenario, when the probability of the local government choosing the “strictly supervises” strategy $x$ is high, the LSP will tend to choose the “use cold chain” strategy.

2. When $x = x_0 = C_{11} - C_{12} + (p + xy)F_{11} - (p + xy - yp)(F_{12} + aR_m)/yF_{11}, \frac{dF(z)}{dz} = z = 1 < 0$, and $\frac{dF(z)}{dz} = z = 1 > 0$, the evolutionary stability strategy (ESS) of the LSP is $z^* = 0$. In this scenario, when the probability of the local government choosing the “strictly supervises” strategy is low, the LSP will tend to choose the "use noncold chain" strategy.

Based on the above analysis, we drew a dynamic replication phase diagram of the LSP, as shown in Figure 4. We can see from the figure that the feasible region of each game participant is divided into two adjacent regions by the intersection space of $x$ and $y$. When the feasible region is located in space $v_g$, $z$ converges to $z^* = 1$, and it is the optimal decision for the LSP to adopt a "use cold chain" strategy. When the feasible region is located in space $v_g$, $z$ converges to $z^* = 0$, and it is the optimal decision for the LSP to adopt a "use noncold chain" strategy.

4.4. Local Stability Analysis of the Tripartite Evolutionary Game System. We analyzed the stability of the evolutionary game of the whole system. It is a nonlinear system with first-order continuous derivatives. Based on Lyapunov’s first stability theorem [57], the Jacobian of the system is obtained by

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

where

\[
a_{11} = \frac{dF(x)}{dx} = (1 - 2x)\left(\frac{C_{12} + C_{11} - (z - 1)F_{11}(p(y - 1) - y)(z - 1)F_{11}}{F_{11} + aR_m + F_{12} + F_{11} + M_{m_1} + M_{m_1}}\right),
\]

\[
a_{12} = \frac{dF(x)}{dy} = (1 - x)\left((1 - z)(1 + p) + p(z - 1)(F_{12} + F_{11} + F_{11} + F_{12} + F_{12} + M_{m_1} + M_{m_1})\right),
\]

\[
a_{13} = \frac{dF(x)}{dz} = (x - 1)\left((p - 1 - y)(F_{12} + F_{11} + F_{12} + M_{m_1} - F_{11}(p + y))\right),
\]

\[
a_{21} = \frac{dF(y)}{dx} = (1 - y)\left((1 - z)(F_{11} - F_{12} + F_{12} + M_{m_1}) + F_{11} + zM_{m_1})\right),
\]

\[
a_{22} = \frac{dF(y)}{dy} = (1 - y)\left((p - 1 - y)(F_{12} + F_{11} + F_{12} + M_{m_1} - F_{11}(p + y))\right),
\]

\[
a_{23} = \frac{dF(y)}{dz} = (x - 1)\left((p - 1 - y)(F_{12} + F_{11} + F_{12} + M_{m_1} - F_{11}(p + y))\right),
\]

\[
a_{31} = \frac{dF(z)}{dx} = (1 - 2x)\left(\frac{C_{12} + C_{11} - (z - 1)F_{11}(p(y - 1) - y)(z - 1)F_{11}}{F_{11} + aR_m + F_{12} + F_{11} + M_{m_1} + M_{m_1}}\right),
\]

\[
a_{32} = \frac{dF(z)}{dy} = (1 - x)\left((1 - z)(1 + p) + p(z - 1)(F_{12} + F_{11} + F_{12} + F_{12} + M_{m_1} + M_{m_1})\right),
\]

\[
a_{33} = \frac{dF(z)}{dz} = (x - 1)\left((p - 1 - y)(F_{12} + F_{11} + F_{12} + M_{m_1} - F_{11}(p + y))\right).
\]
When \( x, y \) and \( z \) belong to \([0, 1]\) and satisfy all of the, and \((4)\) and \((9)-(14)\) are 0, the equilibrium point is the point \((x, y, z)\). Obviously, the equilibrium point of this evolutionary game system includes the points \((0, 0, 0),(1, 0, 0),(0, 0, 1),(1, 0, 1),(0, 1, 0),(1, 1, 0)\). In addition, when \( 0 \leq x', y', z' \leq 1 \) and they make equations \((18)-(20)\) work, the point \((x, y, z)\) will also be an equilibrium point.

\[
\begin{align*}
\frac{a_{22}}{dy} &= (1-2y) \left( -C_{m1} + p(1-z)(F_{l1}(x-1) - xF_{m1} - M_{m1}) + (px + 1)(z-1)F_{l2} \right), \\
\frac{a_{23}}{dz} &= (y-1)y(p(x-1)(F_{l1} - F_{m1}) + F_{l2}(1 - px) - \alpha(p-1)R_m - (p + x - 1)M_{m1}), \\
\frac{a_{31}}{dx} &= y(z - z^2)(-C_{l2} - F_{l2} + R_l - pF_{l1}), \\
\frac{a_{32}}{dy} &= (z-1)y(x(C_{l2} + F_{l2} - R_l + pF_{l1}) + (p-1)F_{l2} + \alpha(p-1)R_m), \\
\frac{a_{33}}{dz} &= (1-2z) \left( -C_{l1} + C_{l2} + (p + xy - xy)pF_{l1} \right), \\
&\quad + (-py + p + y)(F_{l2} + \alpha R_m). \tag{17}
\end{align*}
\]

Based on modern control theory, the positive and negative numbers of eigenvalues \(\lambda_i (i = 1, 2, 3)\) of the Jacobian matrix are an effective condition for judging the stability of the equilibrium point. When the eigenvalues \(\lambda_i\) are all negative, the equilibrium point is asymptotically stable. At this point, the strategy for the equilibrium point is ESS. Table 4 shows the stability and stability conditions for all equilibrium points. It can be found that there are two stable points in this model, points \((1, 0, 1)\) and \((1, 1, 1)\).
5. Simulation of Evolutionary Game Model

In order to intuitively analyze the influence of different parameters on the result of strategy evolution, we consider using MATLAB R2019 software to simulate the policy evolution process of local governments, medical institutions, and LSPs under different conditions. Based on two sets of randomly set parameters, we represent different stable states of the evolutionary game system. Subsequently, the effect of these variables on stability of evolutionary game was evaluated by the medical institution’s market revenue, revenue sharing coefficient, the LSP’s market revenue, the occurrence of medical malpractice, different rewards and penalties for medical institutions and LSPs from the local government, and penalties for LSPs from the medical institution. Based on two sets of parameters, we represent different stable states of the evolutionary game system in two different stable states. The values of all parameters in different scenarios were set as shown in Table 5.

The value range of $x$, $y$ and $Z$ in Scenario 1 of Table 5 is $[0, 1]$, and the evolution time is set to $[0, 15]$. Figure 5(a) clearly shows the evolution paths of $x$, $y$ and $Z$ to the equilibrium point $(1,1,1)$.

The evolution path of Scenario 1 is clearly shown in Figure 5. Figure 5(a) shows that this system has an asymptotically stable point $(1,1,1)$. The local government strictly supervises the medical institution, the medical institution fully inspects the cold chain transportation information, and the LSP using cold chain to transport the drugs is the final stable strategy. Moreover, some horizontal lines appear in plane $(0 \leq x \leq 1, 0 \leq y \leq 1, z = 1)$ in Figure 5(a). When $z = 1$, the change in the local government and medical institution strategies will not affect each other. It shows that the government’s supervision and the inspection of medical institutions have no effect on the decision-making of logistics service providers at this time, and adopting cold chain transportation is the only best choice for logistics service providers. Therefore, the points in the line $(0 \leq x \leq 1, 0 \leq y \leq 1, z = 1)$ are stable but not asymptotically stable.

On the basis of Scenario 1, the cost of strict and passive supervision by the local government, the inspection cost of the cold chain transportation information by the medical institution, and the occurrence probability of medical malpractice and local government penalties when the medical institution fails to fully inspect the cold chain shipping information have all changed in Scenario 2. The evolution path of Scenario 2 is shown in Figure 6. The point $(1,0,1)$ is the only asymptotic stability point in Scenario 2. It indicates that, in the likelihood of medical malpractice, under both strategies, the cost of government supervision will increase, and the inspection cost of the cold chain transportation information by medical institutions will increase significantly. For the government, the strict supervision strategy is still its evolutionary and stable strategy. However, for medical institutions, the increase in the

### Table 5: The value of all parameters in different scenarios.

| Parameter value | Scenario 1 | Scenario 2 |
|-----------------|------------|------------|
| $C_{g1}$        | 15         | 20         |
| $C_{g2}$        | 10         | 15         |
| $A_g$           | 50         | -          |
| $B_m$           | 60         | -          |
| $C_{m1}$        | 10         | 15         |
| $\alpha$        | 0.2        | -          |
| $p$             | 0.2        | 0.4        |
| $M_{m1}$        | 10         | -          |
| $F_{m1}$        | 15         | 10         |
| $R_l$           | 40         | -          |
| $C_{r1}$        | 10         | -          |
| $C_{r2}$        | 5          | -          |
| $F_{r1}$        | 5          | -          |
| $F_{r2}$        | 5          | -          |

### Table 4: Analysis of equilibrium stability.

| Equilibrium point | Nonnegativity of matrix J's eigenvalues | Locally asymptotically stable | Asymptotically stable condition |
|-------------------|----------------------------------------|-------------------------------|--------------------------------|
| $(0,0,0)$         | $\checkmark$                           | Unstable                      | -                              |
| $(1,0,0)$         | $\checkmark$                           | Unstable                      | -                              |
| $(0,1,0)$         | $\checkmark$                           | Unstable                      | -                              |
| $(0,0,1)$         | $\checkmark$                           | Unstable                      | -                              |
| $(1,0,1)$         | $\checkmark$                           | $(C_{g1} - C_{g2} - F_{m1} - M_{m1}) < 0$ |
| $(1,1,0)$         | $\checkmark$                           | Unstable                      | -                              |
| $(0,1,1)$         | $\checkmark$                           | $(C_{g1} - C_{g2} + C_{m1} - F_{m1} - M_{m1}) < 0$ |
| $(1,1,1)$         | $\checkmark$                           | $(C_{g1} - C_{g2} + C_{m1} - F_{m1} - M_{m1} + C_{r1} - C_{r2} - (F_{r1} + F_{r2} + aR_m)) < 0$ |
The frequency of medical malpractice will lead to an increase in inspection costs, causing them to no longer choose the inspection strategy. This strategy will increase the frequency of medical accidents, leading to a vicious circle of further increases in the frequency of medical accidents.

To highlight the role of each factor, the evolution curve of point \((x = 0.2, y = 0.2, z = 0.2)\) was selected. Based on Scenario 2, the impacts of \(a, R_m, F_{1}, M_{m1}, p\) were evaluated.

As seen in Figure 7(a), 7(b), in Scenario 2, the increase in the profit coefficient can improve the evolution speed of the local government and LSP to a stable point. With the increase in \(a\), the probability that the local government will choose strict supervision will increase, and the probability that the LSP will use a cold chain transportation will also increase. Nevertheless, the increase in the profit coefficient will reduce the probability of the medical institution inspecting the cold chain information. Therefore, the revenue sharing contract can encourage the LSP to use cold chain transportation, but an excessively high profit coefficient will passively affect the enthusiasm of medical institutions to inspect. Signing a reasonable revenue sharing contract is the key to preventing medical malpractice.

According to Figure 8(a), 8(b), in the process of evolution, an increase in \(R_m\) will encourage the local government to choose the strict supervision strategy. Moreover, because of the revenue sharing contract, the revenue of the LSP will also increase, which prompts the LSP to use cold chain transportation. Therefore, the local government can appropriately reduce drug price restrictions to increase the revenue of medical institutions and LSPs, thereby promoting cold chain transportation.

In Figure 9(a), b, with the increase in \(F_{1}, F_{m1}\), the local government’s punishment of the medical institution and LSP gradually strengthens. Increasing the penalties of the local government to a certain extent will increase the probability of the medical institution adopting a non-inspection strategy and reduce the probability of the LSP using cold chain transportation. With a further increase in the government’s penalties, the LSP will choose noncold chain transportation. Moreover, Figure 10(a), 10b shows that unilaterally promoting the rewards for the medical institution from the local government will also increase the probability of the medical institution adopting a non-inspection strategy and will reduce the probability of the LSP...
Figure 6: (a) All evolution paths in Scenario 2. (b) Evolution paths of the local government. (c) Evolution paths of the medical institution. (d) Evolution paths of the LSP.

Figure 7: Continued.
Figure 7: (a) The impact of the revenue sharing coefficient on the tripartite evolution when $\alpha = 0.1, \alpha = 0.2, \alpha = 0.3$. (b) Right side view of (a).

Figure 8: Continued.
Figure 8: (a) The impact of the medical institution’s market revenue on the tripartite evolution when $R_m = 40, R_m = 60, R_m = 80$. (b) Right side view of (a).

Figure 9: Continued.
Figure 9: (a) The impact of local government penalties for medical institutions and LSPs on the tripartite evolution when $F_{m1} = 7$, $F_{m1} = 2, F_{m1} = 10, F_{m1} = 5, F_{m1} = 13, F_{m1} = 8$. (b) Left side view of (a).

Figure 10: Continued.
Figure 10: (a) The impact of rewards from the government when $M_{m1} = 5, M_{m1} = 10, M_{m1} = 15$. (b) Left side view of (a).

Figure 11: (a) The impact of medical malpractice occurrence probability when $p = 0.3, p = 0.4, p = 0.5$. (b) Right side view of (a).
using cold chain transportation. Therefore, in order to replace unilateral bonuses for medical institutions, local government should build a tripartite revenue sharing mechanism for the local government, medical institution, and LSP.

As shown in Figure 11, in the process of evolutionary stability, with the increased probability of medical malpractice, the speed at which the three entities evolve to stable point (I,0,1) increases. Therefore, the high incidence of medical malpractice will prompt the government to adopt a strict supervision strategy, the medical institution to inspect the cold chain transportation information, and the LSP to use cold chain transportation.

Based on the stability analysis of the evolutionary game in two situations, this paper clearly shows the different factors that affect the behavior of players through images. Comparing Scenario 1 and Scenario 2, it was found that the stability of the evolutionary game system is affected by $\alpha$, $R_m$, $F_{1l}$ and $M_{m1}$. This shows that a reasonable reward and punishment mechanism and a revenue sharing contract can promote the development of the pharmaceutical cold chain transportation industry.

6. Conclusion

This paper used the evolutionary game method and stakeholder theory to study the pharmaceutical cold chain transportation decision-making process between the local government, medical institution, and LSP from the perspectives of a reward and punishment mechanism, revenue sharing contract, and the incidence of medical malpractice, in relation to noncold chain transportation. We analyzed the stability of each stakeholder’s strategy. Then, we discussed how these factors affected the evolution of each stakeholder through the simulation of two scenarios and verified the validity of the analysis conclusions. The results show that (1) the cold chain transportation decision of logistics service providers is affected by the government’s reward and punishment mechanism. (2) The probability that the government adopts strict supervision is positively related to the effect of the reward and punishment mechanism. (3) Reducing the inspection cost of medical institutions for drug cold chain information helps realize the whole process of drug cold chain. (4) The revenue sharing coefficient affects the cold chain transportation decision of logistics service providers.

According to the simulation results, the following are the conclusions obtained. (1) A reasonable revenue sharing contract between the medical institution and LSP encourages the LSP to use cold chain transportation and ensure the safety of drug transportation. However, unreasonable revenue sharing contracts will reduce the inclination of medical institutions to inspect cold chain transportation information. (2) Increased unilateral penalties and rewards will encourage the medical institution to inspect cold chain transportation information and the LSP to use cold chain transportation. With a further increase in the government’s penalties and rewards, however, the LSP will tend to use noncold chain transportation. Therefore, the government must set a reasonable reward and punishment mechanism to ensure drug safety. (3) With the increasing revenue of the medical institution, the probability of the LSP using a noncold chain transportation decreases. In order to avoid medical malpractice related to noncold transportation, the government should appropriately adjust drug price restrictions to increase drug sales revenue. (4) The higher the rate of medical malpractice is, the faster each stakeholder will evolve to an equilibrium point. With the decrease in the incidence of medical malpractice, the probability that the medical institution chooses not to inspect cold chain transportation information will increase. Because of fluctuations in the incidence of medical malpractice, the government should adopt a dynamic reward and punishment mechanism to increase the probability that medical institutions will choose to inspect cold chain information.

According to the above conclusions, this paper puts four relevant suggestions as follows: (1) An inflexible reward and punishment mechanism is an important factor leading to an increase in the incidence of medical malpractice. A dynamic reward and punishment mechanism can continuously and steadily impact the medical institution and LSP. Therefore, the government should set a dynamic reward and punishment mechanism based on the incidence of medical malpractice and LSP. Therefore, the government should set a dynamic reward and punishment mechanism based on the incidence of medical malpractice to ensure that the medical institution and LSP will protect the safety of drug transportation. (2) The revenue sharing contract is an important measure to ensure smooth operation of the pharmaceutical supply chain. In order to prevent the medical institution from being too overbearing in the contract formulation, the government should set up an expert group to participate in the income contract negotiation process to ensure that LSP companies can profit from it. Besides, to enhance the LSP’s initiative when negotiating revenue sharing contracts, LSPs that can provide pharmaceutical transportation services should cooperate to build a logistics alliance to integrate pharmaceutical transportation resources. (3) Data related to medical malpractice (incidence of medical malpractice, cold chain transportation information, etc.) are important factors that affect the strategies of each stakeholder. In order to improve the response speed of all stakeholders in the face of medical accidents, the government, medical institutions, and LSP should cooperate to build an open and transparent information sharing platform to ensure that information is shared.

In the future, we believe that the following aspects are worth continuing research. First, this paper assumes that the cold chain transportation decision of logistics service providers depends on whether it is profitable or not. The impact of corporate social responsibility on cold chain transportation decisions has been underappreciated. Second, we demonstrate that revenue-sharing contracts can help solve the problem of excessive cold chain transportation costs. However, it is unknown whether other types of contracts, such as cost-sharing contracts, have the same effect. Third, we consider a static government reward and punishment mechanism. This may make our conclusions less practical. Designing a dynamic reward and punishment mechanism is a further research direction.
Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors’ Contributions
Conceptualization was done by K.Z. and Z.Y.; methodology was developed by Z.Y. and K.Z.; software was provided by Z.Y.; validation was done by Z.Y.; formal analysis was performed by K.Z.; and investigation was done by Q.G.

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References

[1] World Health Organization, “WHO Coronavirus (COVID-19) Dashboard,” WHO Coronavirus (COVID-19) Dashboard With Vaccination Data, https://covid19.who.int/, 2021.
[2] Medical Trend, “Pfizer COVID-19 Vaccine Needs to Be Kept in -70 °C,” 2021, https://medicaltrend.org/.
[3] Z. Wen, H. Liao, R. Ren et al., “Cold chain logistics management of medicine with an integrated multi-criteria decision-making method,” International Journal of Environmental Research and Public Health, vol. 16, p. 4843, 2019.
[4] S. M. H. Bamakan, S. G. Moghaddam, and S. D. Manshadi, "Blockchain-enabled pharmaceutical cold chain: applications, key challenges, and future trends," Journal of Cleaner Production, vol. 302, p. 127021, 2021.
[5] N. Kumar and A. Jha, “Application of principles of supply chain management to the pharmaceutical good transportation practices,” International Journal of Pharmaceutical and Healthcare Marketing, vol. 13, no. 3, pp. 306–330, 2019.
[6] M. Subzvari and S. Nasir, “Preserving efficacy of temperature sensitive medicines-logistics management in pharmaceutical supply chain,” South Asian Journal of Management Sciences, vol. 9, no. 1, pp. 1–9, 2015.
[7] S. Ringo, V. Mugoyela, E. Kaale, and J. Sempombe, “Cold chain medicines storage temperature conformity by the world health organisation in Tanzania,” Pharmacology &amp; Pharmacy, vol. 08, no. 10, pp. 325–338, 2017.
[8] N. Markmann, “Innovations and adaptations in the cold chain,” Biopharm International, vol. 28, no. 5, pp. 35–49, 2015.
[9] E. Gagatsi, G. Giannopoulos, and G. Aifandopoulou, “Supporting Policy Making in Maritime Transport by Means of Multifactors Multi-Criteria Analysis: A Methodology Developed for the Greek Maritime Transport System,” in Proceedings of the 5th Transport Research Arena (TRA), pp. 14–17, Paris, France, April 2014.
[10] M. Le Pira, G. Inturri, M. Ignaccolo, and A. Pluchino, “Analysis of AHP methods and the pairwise majority rule (PMR) for collective preference rankings of sustainable mobility solutions,” Transportation Research Procedia, vol. 10, pp. 777–787, 2015.
[11] X. Cai, J. Chen, Y. Xiao, and X. Xu, “Optimization and coordination of fresh product supply chains with freshness-keeping effort,” Production and Operations Management, vol. 19, no. 3, pp. 261–278, 2010.
[12] A. Haial, L. Benabou, and A. Berrado, “Designing a transportation-strategy decision-making process for a supply chain: case of a pharmaceutical supply chain,” International Journal of Environmental Research and Public Health, vol. 18, no. 4, p. 2096, 2021.
[13] H. J. Lan, L. Zhao, L. Su, and Z. G. Liu, “Food cold chain equilibrium based on collaborative replenishment,” Journal of Applied Research and Technology, vol. 12, no. 2, pp. 201–211, 2014.
[14] Y. Yu and T. Xiao, “Pricing and cold-chain service level decisions in a fresh agri-products supply chain with logistics outsourcing,” Computers & Industrial Engineering, vol. 111, pp. 56–66, 2017.
[15] J. Wu and H. Hsiao, “Food quality and safety risk diagnosis in the food cold chain through failure mode and effect analysis,” Food Control, vol. 120, p. 107501, 2021.
[16] J. Lloyd, P. Lydon, R. Ouhichi, and M. Zaffran, “Reducing the loss of vaccines from accidental freezing in the cold chain: the experience of continuous temperature monitoring in Tunisia,” Vaccine, vol. 33, no. 7, pp. 902–907, 2015.
[17] P. He, Y. He, and H. Xu, “Channel structure and pricing in a dual-channel closed-loop supply chain with government subsidy,” International Journal of Production Economics, vol. 213, pp. 108–123, 2019.
[18] J. Li and S. Yang. “Analysis of a multiparticipant game under a subsidy and punishment mechanism: an evolutionary theory perspective,” Mathematical Problems in Engineering, vol. 2021, Article ID 1984676, 20 pages, 2021.
[19] J. J. Yu, C. S. Tang, and Z.-J. M. Shen, “Improving consumer welfare and manufacturer profit via government subsidy programs: subsidizing consumers or manufacturers?” Manufacturing & Service Operations Management, vol. 20, no. 4, pp. 752–766, 2018.
[20] S. Alizamir, F. Iravani, and H. Mamani, “An analysis of price vs. revenue protection: government subsidies in the agriculture industry,” Management Science, vol. 65, no. 1, pp. 32–49, 2019.
[21] M. C. Cohen, R. Lobel, and G. Perakis, “The impact of demand uncertainty on consumer subsidies for green technology adoption,” Management Science, vol. 62, no. 5, pp. 1235–1258, 2016.
[22] J. Chemama, M. C. Cohen, R. Lobel, and G. Perakis, “Consumer subsidies with a strategic supplier: commitment vs. flexibility,” Management Science, vol. 65, no. 2, pp. 681–713, 2019.
[23] M. Y. Jaber, C. H. Glock, and A. M. A. El Saadany, “Supply chain coordination with emissions reduction incentives,” International Journal of Production Research, vol. 51, no. 1, pp. 69–82, 2013.
[24] J.-B. Sheu and Y. J. Chen, “Impact of government financial intervention on competition among green supply chains,” International Journal of Production Economics, vol. 138, no. 1, pp. 201–213, 2012.
[25] W. Wang, J. Lv, N. An, J. Guan, and S. Quan, “The reward-penalty mechanism in a closed-loop supply chain with asymmetric information of the third-party collector,” Mathematical Problems in Engineering, vol. 2021, Article ID 4659019, 20 pages, 2021.
[26] Y.-h. Chen, S.-j. Huang, A. K. Mishra, and X. H. Wang, “Effects of input capacity constraints on food quality and
regulation mechanism design for food safety management,” *Ecological Modelling*, vol. 385, pp. 89–95, 2018.

[27] Y. Yuin and L. Jinxi, “The effect of governmental policies of carbon taxes and energy-saving subsidies on enterprise decisions in a two-echelon supply chain,” *Journal of Cleaner Production*, vol. 181, pp. 675–691, 2018.

[28] J. M. Smith and G. R. Price, “The logic of animal conflict,” *Nature*, vol. 246, no. 5427, pp. 15–18, 1973.

[29] J. Maynard Smith, “The theory of games and the evolution of animal conflicts,” *Journal of Theoretical Biology*, vol. 47, no. 1, pp. 209–221, 1974.

[30] A. Antoni, S. Borghesi, and P. Russu, “Environmental protection mechanisms and technological dynamics,” *Economic Modelling*, vol. 29, no. 3, pp. 840–847, 2012.

[31] R. Mahmoudi and M. Rasti-Barzoki, “Sustainable supply chains under government intervention with a real-world case study: an evolutionary game theoretic approach,” *Computers & Industrial Engineering*, vol. 116, pp. 130–143, 2018.

[32] B. Wu, P. Liu, and X. Xu, “An evolutionary analysis of low-carbon strategies based on the government-enterprise game in the complex network context,” *Journal of Cleaner Production*, vol. 141, pp. 168–179, 2017.

[33] H. Shen, Y. Peng, and C. Guo, “Analysis of the evolution game of construction and demolition waste recycling behavior based on prospect theory under environmental regulation,” *International Journal of Environmental Research and Public Health*, vol. 15, no. 7, p. 1518, 2018.

[34] D. Sun, L. Zhang, and Z. Su, “Evacuate or stay? a typhoon evacuation decision model in China based on the evolutionary game theory in complex networks,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 3, p. 682, 2020.

[35] R. Fan, Y. Wang, and J. Lin, “Study on multi-agent evolutionary game of emergency management of public health emergencies based on dynamic rewards and punishments,” *International Journal of Environmental Research and Public Health*, vol. 18, p. 8278, 2021.

[36] C. Zhao, L. Li, H. Sun, and H. Yang, “Multi-scenario application,” *Complexity*, vol. 13, no. 1, p. 360, 2021.

[37] S. Gong, X. Gao, Z. Li, and L. Chen, “Developing a dynamic supervision mechanism to improve construction safety investment supervision efficiency in China: theoretical simulation of evolutionary game process,” *International Journal of Environmental Research and Public Health*, vol. 18, no. 7, p. 3594, 2021.

[38] Q. Liu, X. Li, and M. Hassall, “Evolutionary game analysis and stability control scenarios of coal mine safety inspection system in China based on system dynamics,” *Safety Science*, vol. 80, pp. 13–22, 2015.

[39] R. Lu, X. Wang, H. Yu, and D. Li, “Multiparty Evolutionary Game Model in Coal Mine Safety Management and its Application,” *Complexity*, vol. 2018, Article ID 9620142, 10 pages, 2018.

[40] K. Li, W. Wang, Y. Zhang, T. Zheng, and J. Guo, “Game modelling and strategy research on the system dynamics-based quadruplicate evolution for high-speed railway operational safety supervision system,” *Sustainability*, vol. 11, no. 5, p. 1300, 2019.

[41] Y. Yu, Y. He, and X. Zhao, “Impact of demand information sharing on organic farming adoption: an evolutionary game approach,” *Technological Forecasting and Social Change*, vol. 172, p. 121001, 2021.

[42] H. M. Lewis and A. J. Dumbrell, “Evolutionary games of cooperation: insights through integration of theory and data,” *Ecological Complexity*, vol. 16, pp. 20–30, 2013.

[43] Q. Shi, J. Zhu, and Q. Li, “Cooperative Evolutionary Game and Applications in Construction Supplier Tendency,” *Complexity*, vol. 2018, Article ID 8401813, 13 pages, 2018.

[44] M. Luo, R. Fan, Y. Zhang, and C. Zhu, “Environmental governance cooperative behavior among enterprises with reputation effect based on complex networks evolutionary Game Model,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 5, p. 1535, 2020.

[45] W. Liu, J. Yang, and K. Bi, “Factors influencing private hospitals’ participation in the innovation of biomedical engineering industry: a perspective of evolutionary game theory,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 20, p. 7442, 2020.

[46] L. Qi, Q. H. Zhao, and L. Benjamin, “Cold chain transportation decision in the vaccine supply chain,” *European Journal of Operational Research*, vol. 283, no. 1, pp. 182–195, 2020.

[47] H. Song and X. Gao, “Green supply chain game model and analysis under revenue-sharing contract,” *Journal of Cleaner Production*, vol. 170, pp. 183–192, 2018.

[48] X. Liu, W. Du, and Y. Sun, “Green supply chain decisions under different power structures: wholesale price vs. revenue sharing contract,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 21, p. 7737, 2020.

[49] L. Yang, Q. Zhang, and J. Ji, “Pricing and carbon emission reduction decisions in supply chains with vertical and horizontal cooperation,” *International Journal of Production Economics*, vol. 191, pp. 286–297, 2017.

[50] C.-T. Zhang and L.-P. Liu, “Research on coordination mechanism in three-level green supply chain under non-cooperative game,” *Applied Mathematical Modelling*, vol. 37, no. 5, pp. 3369–3379, 2013.

[51] N. S. Gamchi and S. A. Torabi, “Supply chain coordination under revenue-sharing contract with value-added services considering risk-attitude of the customers,” *International Journal of Services and Operations Management*, vol. 29, no. 4, pp. 507–526, 2018.

[52] G. Xu, B. Dan, X. Zhang, and C. Liu, “Coordinating a dual-channel supply chain with risk-averse under a two-way revenue sharing contract,” *International Journal of Production Economics*, vol. 147, pp. 171–179, 2014.

[53] C.-F. Hsueh, “Improving corporate social responsibility in a supply chain through a new revenue sharing contract,” *International Journal of Production Economics*, vol. 151, pp. 214–222, 2014.

[54] S. Li, M. Li, and N. Zhou, “Pricing and coordination in a dual-channel supply chain with a socially responsible manufacturer,” *Plos One*, vol. 15, no. 7, p. e0236099, 2020.

[55] Y. Liu, Z.-j. Xia, Q.-q. Shi, and Q. Xu, “Pricing and coordination of waste electrical and electronic equipment under third-party recycling in a closed-loop supply chain,” *Environmental, Development and Sustainability*, vol. 23, no. 8, pp. 12077–12094, 2021.

[56] S. Yoon and S. Jeong, “Manufacturer’s collaborative business strategy with two different reverse channels in a closed-loop supply chain,” *Complexity*, vol. 2021, Article ID 9231877, 16 pages, 2021.

[57] L. Dieci and E. S. Van Vleck, “Lyapunov exponents: computation,” *Encyclopedia of Applied and Computational Mathematics*, pp. 834–838, 2015.