Low-Carbon Supply Chain Emission Reduction Strategy Considering the Supervision of Downstream Enterprises Based on Evolutionary Game Theory

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Abstract: In order to explore the issue of multi-party collaborative governance of energy conservation and emission reduction under the perspective of the low-carbon supply chain, the participation of downstream enterprises as an effective source of local government supervision is included in the selection of low-carbon behaviors of suppliers. First, this paper establishes a tripartite evolutionary game model among local governments, suppliers and downstream enterprise groups. By calculating and copying dynamic equations, the asymptotic stability analysis of the three parties of the game is performed and the stability of the Jacobian matrix proposed by Friedman is used to analyze the local stability of the model equilibrium point and the evolutionary stability strategy of the system. Secondly, the evolution results and evolution paths of the model under different strategies are simulated by system dynamics and the influence of different parameters on the main body selection strategy of the tripartite game is analyzed. Finally, the paper puts forward corresponding policy suggestions from the perspectives of local government, suppliers and downstream enterprises in order to provide new ideas for the governance of China’s environmental problems from the perspective of low carbon.

Keywords: evolutionary game theory; low-carbon supply chain; evolutionary stability strategy (ESS) system dynamics; simulation

1. Introduction

Global climate change caused by a large number of “greenhouse gas” emissions is becoming the focus of public attention in the world. It is the consensus of all countries in the world to improve energy efficiency and reduce carbon emissions while developing the economy, that is, to develop a “low-carbon economy” [1]. As early as the 1820s, French scientist Jean Fouxier discovered the natural greenhouse effect and further demonstrated the importance of this effect to the survival of organisms. He believed that the natural greenhouse effect is an important part of the balance of the Earth’s energy system. Since the first World Climate Conference in 1979 identified the increase in carbon emissions as the main culprit leading to global warming, governments began to formulate relevant measures to vigorously carry out carbon emission reduction activities [2]. With the joint efforts of the international community, climate summits around the world are held regularly, and a series of legally binding international conventions are gradually standardized or expected to be reached [3]. In June 1992, the heads of governments of many countries signed the “United
Nations Framework Convention on Climate Change” that aimed at “reducing greenhouse gas emissions, reducing the harm of human activities to the climate system, mitigating climate change, enhancing the adaptability of ecosystems to climate change and ensuring food production and sustainable economic development,” and signed its supplementary clause, the “Kyoto Protocol,” again in December 1997. The “Paris Agreement” signed in April 2016 makes arrangements for the global response to climate change after 2020. The State Council of China has defined the low-carbon development goals and tasks in the “13th Five-Year Plan for Controlling Greenhouse Gas Emissions” and put forward the requirements for “exploring and launching pilot projects for carbon sinks in marine and other ecosystems”.

However, it is disappointing that although some countries have realized that they need to make efforts in forest carbon sinks, they have not done enough to effectively utilize blue carbon because their core focus is on controlling greenhouse gas emissions. At present, the Chinese government is focusing on blue carbon cooperation, optimizing the new pattern of development space in Europe and Asia through the Silk Road blue carbon cooperation, leading countries along the Maritime Silk Road to jointly respond to climate change and jointly manage the international environment [4]. Therefore, a rational and pragmatic climate strategy must be adopted. According to the latest “Global Emissions Gap Report” released by the United Nations Environment Program on 26 November 2019, if the global temperature is controlled at a level that is only 2 degrees Celsius higher than the pre-industrial temperature at the end of this century, global carbon emissions would have to be reduced by 2.7% annually until 2030. If the temperature rise target is 1.5 degrees, the annual emissions have to decrease at least at a rate of 7.6%. Over the past decade, global carbon emissions have grown at an average annual rate of 1.5%. As the economy continues to grow, and as the country with the largest carbon emissions in the world, the pressure on China to reduce carbon emissions from the international community will further increase.

Faced with such severe energy dilemmas and climate problems, how to reduce carbon emissions and improve energy efficiency is an urgent problem to be solved. With the understanding of the impact of greenhouse gas emissions on climate warming and the promulgation of carbon emission reduction policies in various countries, scholars have proposed that the low-carbon supply chain is one of the important ways to promote low-carbon economic development and solve environmental pollution [5,6]. Qu proposed the concept of a third-party international environmental audit, which contributed to the issue of government environmental supervision and corporate environmental behavior [7–11]. Matthews et al. pointed out that the carbon emission reduction behavior of enterprises is not isolated, and it is difficult to effectively achieve carbon emission reduction through the efforts of a single company. Only by promoting the coordinated management of carbon emission reduction by upstream and downstream enterprises in the supply chain can we truly reduce carbon emissions [12]. Cao et al. considered the decision-making optimization problem of carbon emission reduction in the supply chain in the two cases where the government imposes carbon tax policies on manufacturers and subsidies for emission reduction innovative technologies [13]. Wang et al. suggested that in practice, retailers only help to share the cost of emission reduction, and it is the manufacturer that really bears the main responsibility for emission reduction [14]. Zhang et al. studied the government and enterprise signal game model under the energy saving and emission reduction subsidy policy and analyzed the selection mechanism and influence of the two parties’ strategies. The results showed that due to the asymmetry and incompleteness of the information on both sides, the government and enterprises. In the game, there will be three equilibriums of partial success, complete success and complete failure in the market. The government should make efforts to further refine policies and standards, improve the efficiency of review and increase penalties [15].

In this paper, evolutionary game theory is applied to establish a tripartite evolutionary game model of local government, suppliers and downstream enterprises. We discuss the evolutionary process and stability of each game player’s strategy choice, and then use
the numerical simulation method to simulate the stability of its strategy choice and the influencing factors. Finally, according to the simulation results, several countermeasures are put forward for the three parties of the game.

The structure of the article is as follows—Section 2 reviews the literature from the two perspectives of low-carbon supply chain and the application of game theory in low-carbon supply chain. Section 3 analyzes the behavior of the game subject and makes basic assumptions. In Section 4, evolutionary game analysis is carried out on the strategic choices of the three game players, including the asymptotic stability analysis of the three parties and the local stability analysis of the entire system. Section 5 uses system dynamics theory to simulate the evolution process, substitute data and conduct sensitivity analysis. Finally, Section 6 draws conclusions and proposes policy recommendations from three perspectives of local governments, suppliers and downstream enterprises.

2. Literature Review

Scholars in related disciplines have conducted in-depth research on the hot topic of carbon emission reduction at multiple levels and angles. In order to make the research in this paper more intuitive, the relevant literature has been classified as follows: (1) researches related to carbon tax policy; (2) the application of classical game theory in low-carbon supply chain; (3) the application of evolutionary game theory in low-carbon supply chain.

2.1. Researches Related to Carbon Tax Policy

Through the sorting and summarization of relevant literature on emission reduction policies, the study found that there are different classifications of policies and measures for carbon emission reduction by domestic and foreign scholars. Wang [2] sorted out its classification, such as from legal measures, emission reduction measures can be divided into four types: government regulation, legal system, carbon tax and emission rights trading. In terms of emission reduction methods, they can be divided into direct emission reduction, adaptation and indirect emission reduction. There are three types of emission reduction measures. From the perspective of emission reduction measures, they can be divided into two types—quantity control and price control. From a theoretical perspective, emission reduction measures can be divided into five types: concept innovation, structural innovation, technological innovation, consumption mode innovation, and management innovation. In recent years, many scholars have analyzed the carbon emission reduction behavior of companies in the supply chain from the perspective of carbon taxes, subsidies and penalties.

Regarding the carbon tax policy, Miao [16] considered the manufacturer’s trade-in and remanufacturing decisions under the two conditions of limited carbon emissions and high emission reduction costs, namely the carbon tax policy and quota trading plan. At the same time, Miao et al. analyzed the production decisions and manufacturing decisions. Regarding optimal pricing, the result pointed out that when carbon emission regulations cause losses to manufacturers’ profits, they can be compensated or even offset by government subsidies. Yenipazarli used the Stackelberg game model to study the impact of carbon emission taxes on manufacturers’ optimal production and pricing decisions for remanufactured products [17]. Regarding the subsidy policy, Cao et al. studied the optimal production strategy and carbon emission reduction level under the carbon trading policy (CTP) and the low-carbon subsidy policy (LCSP) and compared the optimal social welfare results of the two policies. It is pointed out that, in order to promote the development of the low-carbon economy, the government can try some creative stimulus schemes to maximize social welfare [18]. Fan et al. studied the government’s optimal regulatory strategy for low-carbon subsidies, as well as regulatory efficiency and regulatory stability [19]. Dongbin et al. pointed out that ecological compensation policy is an important guarantee to improve economic development. According to the data of the Xiangjiang River, he established an evolutionary game model with a punishment mechanism and finally obtained the specific penalty under different scenarios [20].
2.2. The Application of Classical Game Theory in Low-Carbon Supply Chain

At present, there is much domestic and foreign literature using game theory to discuss the carbon emission reduction behavior of low-carbon supply chain members from different perspectives. Xiong et al. used the Nash bargaining game to analyze the game behaviors of suppliers and downstream enterprises on carbon emission reduction with or without government intervention and studied downstream companies urging suppliers to reduce emissions, and the government imposing penalty taxes on suppliers’ production pollution or subsidizing their emission reduction activities to achieve the goal of protecting the environment [21]. Aiming at the problems of low-carbon emission reduction, low-carbon promotion and brand strategy in the dual-channel supply chain, Zhou constructed a differential game model, using the Hamilton-Jacobi-Bellman equation to focus on decision-making and low-carbon emission reduction input and low-carbon under the Stackelberg game [22]. A comparison of publicity investment and low-carbon publicity sharing rate was conducted. In the end, it was concluded that the emission reduction of products under the centralized decision-making situation is always higher than that under the Stackelberg game. Aiming at low-carbon supply chain development, promotion and pricing issues, You et al. took product low-carbon degree and goodwill as state variables, constructed a differential game model to comprehensively consider the multiple impacts of price and non-price factors on market demand and compared the feedback equilibrium strategies of supply chain under different decisions. Finally, combined with numerical simulation, a sensitivity analysis of relevant parameters was carried out [23]. Similarly, Ji et al. also constructed a differential game model to study the combination of quota trading and consumer low-carbon preferences [24]. The study pointed out that when consumers have high low-carbon preferences, the quota transaction mechanism is easily accepted by supply chain members. In addition, scholars usually construct contract models to compare the advantages and disadvantages of manufacturers in terms of profit, recovery rate, and retail price, so as to improve the reward and punishment policies in the supply chain.

2.3. The Application of Evolutionary Game Theory in Low-Carbon Supply Chain

Nowadays, evolutionary game theory has gradually been widely used in various models as a universal method. For example, Mahmoudi et al. studied the problem of sustainable supply chain under government intervention, compared the government goal with the producer goal by using dual-species evolutionary game theory, and modeled the performance of supply chain members under different government levels. Finally, the proposed model was applied to the case of the Indian textile industry [25]. Wu et al. constructed a two-party evolutionary game model between government and enterprises in a complex network environment to explore the impact of government incentives on enterprises in terms of the diffusion of low-carbon policies. The results of the research showed that the expectations of enterprises on incentives such as government subsidies and supervision determine whether the low-carbon strategy can spread, and the speed of the spread [26].

The public, after the government and enterprises, is another subject participating in corporate environmental pollution control, and has a prominent role in the supervision of corporate environmental behavior. Tian et al. used evolutionary game theory and system dynamics (SD) to analyze the relationship among stakeholders such as the government, enterprises and consumers, and simulated the diffusion process of supply chain management with the example of China’s automobile manufacturing industry [27]. The results show that subsidies to manufacturers can promote the spread of green supply chains more than subsidies to consumers. In addition, environmental awareness is another key factor affecting the spread of green supply chains. However, in reality, due to information asymmetry and incomplete information, the government’s macro policies on low-carbon production of enterprises have not achieved the expected results. Therefore, scholars have to turn their attention to environmental non-governmental organizations (referred to as environmental NGOs). Environmental NGOs, as an independent third
party, can better realize information exchanges with government agencies. Based on this, Sun et al. constructed a tripartite evolutionary game model of enterprises, governments and environmental NGOs to analyze the stabilization strategies and impact mechanisms of enterprises in the process of reducing emissions, and performed numerical simulations with Matlab tools [28].

To sum up, it is extremely urgent and important to study the carbon reduction ranking of enterprises in supply chain. Most of the existing literature reflects the government’s supervision of sewage disposal enterprises but the participation of other members in the supply chain is not high, and there are relatively few studies on multi-party coordinated supervision of carbon emission reduction behavior. At the same time, the behavior of local governments is “short-sighted.” In order to ensure the rapid growth of the regional economy, they form an economic community with production enterprises, and the phenomenon of “medium obstruction” is serious. For this reason, we take the interests of downstream enterprises, consumers and society to set out, the game model of downstream enterprises has been added to the scholars’ game model to discuss the incentive and restraint effects of the government’s low-carbon policy in the production and operation of suppliers and the supervision of downstream enterprises. We use evolutionary game theory to analyze the dynamic evolution process of the three parties and use system dynamics to simulate the evolution path and strive to explore the evolutionary stability strategy (ESS) of the low-carbon supply chain.

3. Evolutionary Game Model of Low Carbon Emission Reduction

In this article, we first classify and summarize the literature in the low-carbon supply chain related fields. Secondly, the behavior of the three players in the game is described and assumed, and then the profit matrix is derived. Then we construct an evolutionary game model and do an asymptotic stability analysis and a local stability analysis. Subsequently, the system dynamics simulation model is constructed, and the sensitivity analysis of the parameters affecting the player’s strategy choice is also carried out. Finally, we draw conclusions and give recommendations, as shown in Figure 1.

![Method flow and Specific operation process diagram](image)

Figure 1. The research framework.

3.1. Behavior Description of Players

In this paper, we consider a two-level supply chain structure composed of upstream suppliers and their downstream enterprises, and also consider the role of local governments in monitoring suppliers’ low-carbon behavior. For the government, there are two strategies to strictly supervise the carbon emission reduction behavior of suppliers (A1) and passively supervise the carbon emission reduction behavior of suppliers (A2). For suppliers, there are two strategies—producing low-carbon products (B1) and producing common products (B2).
For downstream enterprises, there are two strategies for participating in the supervision of suppliers’ carbon emission reduction behavior (C1) and not participating in the supervision of suppliers’ carbon emission reduction behavior (C2). Thus, the three-party game strategy game tree of local government, suppliers and downstream enterprises is constructed as shown in Figure 2.

![Figure 2. Game tree.](image)

### 3.2. Basic Assumptions

According to Liu’s research on the behavior of manufacturers to produce low-carbon products and high-carbon products, according to different government regulatory policies, three models of tax and subsidy mixed policy, single tax policy and single subsidy policy have been constructed [29]. The following assumptions are made in this article:

**Hypothesis 1.** For local governments, when the local government strictly supervises, the local government will subsidize the suppliers that produce low-carbon products, with a subsidy coefficient of α, and the suppliers who produce ordinary products will be punished, with a penalty coefficient of β, and assume that their strict supervision cost is \( C_{g1} \); when the local government is passively supervised, the cost of passive supervision is set as \( C_{g2} \).

**Hypothesis 2.** When the local government actively supervises the suppliers’ carbon emission reduction behavior, it will promptly implement environmental governance for the environmental losses caused by the supplier’s emission reduction behavior, so a certain environmental governance fee \( W \) must be paid.

**Hypothesis 3.** Due to the “short-sightedness” of the local government, it ignores the environmental benefits in order to maximize the overall benefits. Therefore, the local government only implements a carbon tax policy at this time but does nothing to the supplier’s carbon emission reduction behavior, and will not “actively discover” whether the supplier’s emission reduction behavior meets the standard. However, when the downstream enterprises jointly supervise and report to the local government, the local governments “have to discover” that the environment is polluted and take punitive measures.

**Hypothesis 4.** In addition, regardless of whether the local government adopts strict supervision or passive supervision strategies, suppliers are quantified and taxed based on their carbon emissions during production, and the carbon tax rate is \( \theta \). Moreover, it can be known from the fact that when the government is engaged in negative supervision, its expenditure of manpower, material
resources and financial resources is necessarily less than that when it is engaged in strict supervision, so $C_{g1} > C_{g2}$.

**Hypothesis 5.** For the supplier, the supplier manufactures retail parts and other products that are sold to downstream enterprises. It can produce two specifications of low-carbon products and ordinary products. It is assumed that the market revenue when producing low-carbon products is $R_l$ and the market income when they produce ordinary products is $R_h$.

**Hypothesis 6.** Assuming that $Q_0$ is the national low-carbon emission standard, the carbon emission of suppliers when producing low-carbon products is $Q_l$, and the carbon emission of producing ordinary products is $Q_h$, then $Q_l < Q_0 < Q_h$.

**Hypothesis 7.** In order to reduce carbon emissions when producing low-carbon products, suppliers need to introduce advanced technology and equipment and other emission reduction investment $M$ in the early stage. The environmental loss caused by the supplier when producing ordinary products is $S$ (relative to the environmental loss when producing low-carbon products).

**Hypothesis 8.** For the downstream enterprises, the downstream enterprises obtain raw materials for their products from suppliers. When they initially purchase products from their upstream suppliers without receiving feedback from consumers, their purchasing behavior is equivalent to black box testing, which is blind selection status, so downstream enterprises do not know whether the purchased products are low-carbon products or ordinary products.

**Hypothesis 9.** Starting from long-term considerations and consumer usage, however, ordinary products will reduce consumers’ demand for downstream enterprises’ products and will damage downstream enterprises’ reputation. Let the loss of consumer benefits when purchasing ordinary products be $H$. Furthermore, downstream enterprises can supervise suppliers’ emission reduction behaviors and report to local governments in order to improve consumers’ goodwill. Consumers will repurchase because of their active supervision behavior and trust in their brands.

**Hypothesis 10.** The cost of supervision of downstream enterprises is $C_e$, and the government reward is $P$ when their supervision is effective. At the same time, when it discovers that its upstream supplier’s emission reduction behavior does not meet the standards and causes losses to it, it will claim compensation $L$ from the supplier.

**Hypothesis 11.** When downstream enterprises do not participate in the supervision of suppliers’ carbon emission reduction activities, they believe that the downstream enterprises ignore the carbon reduction of their upstream suppliers because they have considered supervision costs and other reasons or have not taken into account consumers’ sense of use of their products and the benefits of word-of-mouth. At this time, downstream enterprises do not incur supervision costs, nor do they receive rewards from local governments and compensation from suppliers.

**Hypothesis 12.** When the local government strictly supervises, it will definitely make a contribution to the carbon reduction ranking of suppliers, while when the downstream enterprises supervise the carbon reduction ranking of their upstream suppliers, their supervision behavior cannot be completely effective due to the relatively weak authority and supervision means, so their supervision behavior has a certain success rate $\mu$. See Table 1 for the setting of related parameters.
Table 1. Setting and meaning of main parameters.

| Stakeholders | Parameters | Descriptions |
|--------------|-----------|--------------|
| Local governments | $C_{g1}$ | The cost of strict supervision by local governments |
| | $C_{g2}$ | The cost of passive supervision by local governments |
| | $\alpha$ | Subsidy coefficient of local government |
| | $\beta$ | Penalty coefficient of local government |
| | $\theta$ | Carbon tax rate |
| | $W$ | Environmental governance costs of local governments |
| | $x$ | Probability of strict supervision by local government |
| Suppliers | $R_l$ | Supplier’s market revenue when producing low-carbon products |
| | $R_n$ | Supplier’s market revenue when producing ordinary products |
| | $Q_l$ | Carbon emissions from suppliers producing low-carbon products |
| | $Q_h$ | Carbon emissions when suppliers produce ordinary products |
| | $Q_0$ | Carbon emissions of low-carbon products stipulated by the state |
| | $M$ | Input cost of emission reduction when suppliers produce low-carbon products |
| | $S$ | Environmental losses caused by suppliers’ production of ordinary products |
| | $L$ | Supplier’s compensation to downstream enterprises |
| | $y$ | Proportion of suppliers producing low-carbon products |
| Downstream enterprises | $C_r$ | Supervision cost of downstream enterprises |
| | $\mu$ | Success rate of downstream enterprises’ supervision |
| | $P$ | Obtain rewards from the government when downstream enterprises succeed in supervision |
| | $H$ | Repeat customers lost when downstream enterprises buy ordinary products |
| | $z$ | Probability of downstream enterprises participating in supervision |

3.3. Payoff Matrix

Based on the assumptions made in the previous section and the strategies combination in Figure 2, we can calculate the return function of the three game parties under various strategy situations (see Table 2):

Table 2. The payoff matrix among local government, suppliers and downstream enterprises.

| Strategies Combination | Local Government | Suppliers | Downstream Enterprises |
|------------------------|------------------|----------|------------------------|
| $(A_1, B_1, C_1)$     | $-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_1, B_1, C_2)$     | $-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_1, B_2, C_1)$     | $C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_1, B_2, C_2)$     | $-C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_2, B_1, C_1)$     | $-C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_2, B_1, C_2)$     | $-C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_2, B_2, C_1)$     | $-C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |
| $(A_2, B_2, C_2)$     | $-C_{g2} + \theta Q_l - \alpha(Q_0 - Q_l)$ | $R_l - \theta Q_l - \alpha(Q_0 - Q_l) - M$ | $-C_r$ |

4. Stability Analysis of Evolutionary Game Model

The proportion of local governments adopting strict supervision strategies is $x$, and the proportion of adopting passive supervision strategies is $1-x$; the proportion of suppliers adopting low-carbon product strategies is $y$, and the proportion of suppliers adopting production strategies is $1-y$; the proportion of downstream enterprises choosing to participate in the supervision strategy is $z$, and the proportion of choosing not to participate in the supervision strategy is $1-z$, and $0 \leq x \leq 1$, $0 \leq y \leq 1$, $0 \leq z \leq 1$.

4.1. Progressive Stability Analysis of Local Government

4.1.1. Expected Earnings of Local Government

Assuming that $U_{g1}$ represents the expected earnings of local government under strict supervision, $U_{g2}$ represents the expected earnings of local government under negative...
supervision, and \( \bar{U}_x \) represents the average expected earnings of local government under supervision. According to the payoff matrix, we can calculate the expected income under strict government supervision as follows:

\[
U_{x1} = yz[-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)] + y(1 - z)[-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)] + (1 - y)z[-C_{g1} + \theta Q_h + \beta(Q_h - Q_0) - W] + (1 - y)(1 - z)[-C_{g1} + \theta Q_h + \beta(Q_h - Q_0) - W].
\]

(1)

In the same way, the expected return of the local government under passive supervision can be calculated as:

\[
U_{x2} = yz(-C_{g2} + \theta Q_l) + y(1 - z)(-C_{g2} + \theta Q_l) + (1 - y)z[-C_{g2} + \theta Q_h + \mu \beta(Q_h - Q_0) - \mu P - S] + (1 - y)(1 - z)(-C_{g2} + \theta Q_h - S).
\]

(2)

According to Equations (1) and (2), the average expected income of the local government can be calculated as:

\[
\bar{U}_x = xU_{x1} + (1 - x)U_{x2} =
\]

\[
x\left\{\begin{array}{l}
yz[-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)] + y(1 - z)[-C_{g1} + \theta Q_l - \alpha(Q_0 - Q_l)] \\
+ (1 - y)z[-C_{g1} + \theta Q_h + \beta(Q_h - Q_0) - W] + (1 - y)(1 - z)[-C_{g1} + \theta Q_h + \beta(Q_h - Q_0) - W]
\end{array}\right\}
+ (1 - x)\left\{\begin{array}{l}
yz[-C_{g2} + \theta Q_l] + y(1 - z)(-C_{g2} + \theta Q_l) + (1 - y)z[-C_{g2} + \theta Q_h + \mu \beta(Q_h - Q_0) - \mu P - S] \\
+ (1 - y)(1 - z)(-C_{g2} + \theta Q_h - S)
\end{array}\right\}.
\]

(3)

4.1.2. Replication Dynamic Equation Analysis of Local Government

According to Equations (1)–(3), the replication dynamic equation of local government strategy can be obtained:

\[
F(x) = \frac{dx}{dt} = x(U_{x1} - \bar{U}_x) = x(1 - x)\left\{\begin{array}{l}
y[\beta(z\mu - 1)(Q_h - Q_0) - \alpha(Q_0 - Q_l) + W - S - z\mu P] \\
+ \beta(1 - z\mu)(Q_h - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P
\end{array}\right\}.
\]

(4)

Then, the replication dynamic equation of local government strategy is further analyzed:

1. If \( \beta(1 - z\mu)(Q_h - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P \), then no matter what value \( x \) is, it indicates that no matter whether the local government chooses to implement strict supervision strategy or passive supervision strategy on the carbon emission reduction behavior of suppliers, the local government's strategy will not change with the evolution of time, and the game is in a stable state.

2. If \( \beta(1 - z\mu)(Q_h - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P \), let \( F(x) = 0 \), then we get two stable points \( x = 0 \) and \( x = 1 \), indicating that when the local government chooses strict supervision strategy/passive supervision strategy, as long as there is no sudden condition that makes the local government change its strategy, then the local government's strategy will be stabilized in a state of strict supervision/passive supervision.

According to the nature of the evolutionary game, if the derivative of the replication dynamic equation at the equilibrium point is less than 0, it means that the evolutionary entity has reached an evolutionary stable strategy. Therefore, the derivative of the replication dynamic equation of the local government is obtained:

\[
\frac{dF(x)}{dx} = (1 - 2x)\left\{\begin{array}{l}
y[\beta(z\mu - 1)(Q_h - Q_0) - \alpha(Q_0 - Q_l) + W - S - z\mu P] + \beta(1 - z\mu)(Q_h - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P
\end{array}\right\}
\]

(5)

To determine the positive and negative values at \( x = 0 \) and \( x = 1 \), we construct an auxiliary function \( g_1(y) \): let \( g_1(y) = y[\beta(z\mu - 1)(Q_h - Q_0) - \alpha(Q_0 - Q_l) + W - S - z\mu P] + \beta(1 - z\mu)(Q_h - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P] \). Because \( \alpha, \beta > 0; 0 \leq z, \mu \leq 1 \) and \( Q_i < Q_0 < Q_h \), so \( z \mu \leq 1 \), then \( \beta(z\mu - 1)(Q_h - Q_0) < 0, \alpha(Q_h - Q_0) > 0 \). Therefore, all items except \( W \) in the \( k_1 \) expression are negative, but the magnitude of the relationship between \( W \) and the other items is
not clear, and the positive and negative of $k_1$ cannot be judged. Now, the other items in the $k_1$ expression and $W$ will be compared and analyzed. To facilitate calculation, let

$$y = \beta(1-zu)(Q_h-Q_0)+a(Q_0-Q_1)+S+z\mu P.$$  

When $W > \beta(1-zu)(Q_h-Q_0)+a(Q_0-Q_1)+S+z\mu P$, then $k_1 > 0$, so $g_1(y)$ is a linear increasing function of $y$. According to the function image of $g_1(y)$, it can be seen from Figure 3a:

1. When $y < y_0$, $g_1(y) < 0$, at this time, $\frac{dF(x)}{dx} = g_1(y) < 0$, so $\frac{dF(x)}{dx} = g_1(y) < 0$, so $x = 0$ is an evolutionary stability strategy (ESS), and local governments tend to choose passive supervision strategy.

2. When $y > y_0$, $g_1(y) > 0$, at this time, $\frac{dF(x)}{dx} = g_1(y) > 0$, so $\frac{dF(x)}{dx} = g_1(y) > 0$, so $x = 1$ is an evolutionary stability strategy (ESS), and local governments tend to choose strict supervision strategy.

When $W < \beta(1-zu)(Q_h-Q_0)+a(Q_0-Q_1)+S+z\mu P$, then $k_1 < 0$, $g_1(y)$ is a linear decreasing function of $y$. According to the function image of $g_1(y)$, it can be seen from Figure 3b:

1. When $y < y_0$, $g_1(y) > 0$, at this time, $\frac{dF(x)}{dx} = g_1(y) > 0$, so $\frac{dF(x)}{dx} = g_1(y) > 0$, so $x = 1$ is an evolutionary stability strategy (ESS), and local governments tend to choose strict supervision strategy.

2. When $y > y_0$, $g_1(y) < 0$, at this time, $\frac{dF(x)}{dx} = g_1(y) < 0$, so $\frac{dF(x)}{dx} = g_1(y) < 0$, so $x = 0$ is an evolutionary stability strategy (ESS), and local governments tend to choose passive supervision strategy.

In summary, the dynamic trend diagram of local government selection strategies is shown in Figure 3:

1. When the initial state of local government strategy is in space $V_1$, as shown in Figure 3d, $x = 1$ is the stable point. Therefore, when the local government’s environmental governance costs are relatively small and the probability of suppliers producing low-carbon products is relatively small, or the local government’s environmental governance costs are relatively large and the probability of suppliers producing low-carbon products is relatively high, local governments will choose a strict supervision strategy. When the probability of suppliers producing low-carbon products is relatively small, that is, when the probability of producing ordinary products increases, the environmental pollution is relatively serious. Therefore, local governments will impose penalties on suppliers’ carbon emission reduction actions out of consideration of environmental benefits, regardless of the environmental governance costs they spend, so local governments will choose strict supervision strategies.

2. When the initial state of the local government strategy is in space $V_2$, as shown in Figure 3e, $x = 0$ is the stable point. Therefore, when the environmental governance
costs of local governments are relatively large and the probability of suppliers producing low-carbon products is relatively small, or the environmental governance costs of local governments are relatively small and the probability of suppliers producing low-carbon products is relatively large, local governments will choose a passive regulatory strategy. No matter the suppliers produce low-carbon products or ordinary products, the degree of environmental pollution is relatively light or heavy. Local governments have relaxed their environmental supervision out of consideration of economic benefits, so local governments will choose strict supervision strategy.

**Proposition 1.** When other parameters remain unchanged, as $C_{g1}$ decreases (or $C_{g2}$ increases, or $\alpha$ decreases), the probability of local governments choosing strict supervision will be inclined to 1.

**Proof of Proposition 1.** Because $y_0 = \frac{\beta(1-z\mu)(Q_h-Q_0)-C_{g1}+C_{g2}-W+S+z\mu P}{\beta(1-z\mu)(Q_h-Q_0)+\alpha(Q_0-Q_1)-W+S+z\mu P}$, when $C_{g1}$ decreases, $y_0$ will increase instead, so the stable cross section in Figure 3c rises, and the volume of $V_1$ in Figure 3d increases, that is, the probability of strict supervision by the local government increases and finally stabilizes at 1, which is certificated. Similarly, when $C_{g2}$ increases or $\alpha$ decreases, $y_0$ will increase, which will eventually increase the probability of the government choosing strict supervision. That is, when the cost of strict government supervision becomes smaller, or the cost of passive supervision becomes larger, or the government’s subsidy coefficient for suppliers’ low-carbon production decreases, the government will tend to choose a strict supervision strategy.

4.2. Progressive Stability Analysis of Supplier

4.2.1. Expected Earnings of Supplier

Similar to the calculation process of the local government, assuming that $U_{y1}$ represents the expected earnings of the supplier for producing low-carbon products, $U_{y2}$ represents the expected earnings of the supplier for producing common products, and $\bar{U}_y$ represents the average expected earnings of the supplier for producing low-carbon products. We can still calculate the expected earnings of the supplier when producing low-carbon products based on the payoff matrix:

$$U_{y1} = xz[R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M] + x(1-z)[R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M] + (1-x)z[R_l - \theta Q_l - M] + (1-x)(1-z)(R_l - \theta Q_l - M)$$

(6)

And the expected earnings of the supplier when producing ordinary products is calculated as:

$$U_{y2} = xz[R_h - \theta Q_h - \beta(Q_h - Q_0) - \mu L] + x(1-z)[R_h - \theta Q_h - \beta(Q_h - Q_0)] + (1-x)z[R_h - \theta Q_h - \mu \beta(Q_h - Q_0) - \mu L] + (1-x)(1-z)(R_h - \theta Q_h)$$

(7)

According to the Equations (5) and (6), we can further calculate the average expected earnings of suppliers as follows:

$$\bar{U}_y = yU_{y1} + (1-y)U_{y2}$$

$$= y\left\{ xz[R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M] + x(1-z)[R_l - \theta Q_l + \alpha(Q_0 - Q_l) - M] + (1-x)z[R_l - \theta Q_l - M] + (1-x)(1-z)(R_l - \theta Q_l - M) \right\}$$

$$= y\left\{ xz[R_h - \theta Q_h - \beta(Q_h - Q_0) - \mu L] + x(1-z)[R_h - \theta Q_h - \beta(Q_h - Q_0)] + (1-x)z[R_h - \theta Q_h - \mu \beta(Q_h - Q_0) - \mu L] + (1-x)(1-z)(R_h - \theta Q_h) \right\}$$

(8)
4.2.2. Replication Dynamic Equation Analysis of Supplier

According to the Equations (6)–(8), the dynamic equation of supplier strategy replication can be obtained:

$$F(y) = \frac{dy}{dt} = y(1-y) \left\{ x [a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)] + z\mu\beta(Q_h - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M \right\}.$$  \hspace{1cm} (9)

Next, we will further analyze the replication dynamic equation of supplier strategy:

1. If \( x = \frac{M - z\mu\beta(Q_h - Q_0) - z\mu L - R_l + R_h - \theta(Q_h - Q_l)}{a(Q_0 - Q_l) + (1 - z\mu)\beta(Q_h - Q_0)} \), no matter what value \( y \) takes, \( F(y) = 0 \). It indicates that no matter whether the supplier chooses the strategy of producing low-carbon products or the strategy of producing ordinary products, the supplier’s strategy will not change over time, and the game is in a stable state.

2. If \( x \neq \frac{M - z\mu\beta(Q_h - Q_0) - z\mu L - R_l + R_h - \theta(Q_h - Q_l)}{a(Q_0 - Q_l) + (1 - z\mu)\beta(Q_h - Q_0)} \), let \( F(y) = 0 \), we could get two stable points \( y = 0 \) and \( y = 1 \), it shows that when the supplier chooses the strategy of producing low-carbon products/ordinary product strategy, as long as there is no sudden condition that makes the supplier change its strategy, then the strategy will be stabilized in the state of low-carbon products/common products.

The derivative of the replication dynamic equation of the supplier’s strategy should be less than 0 if the supplier’s strategy can achieve evolutionary stability as calculated by the local government. Therefore, the derivative of the supplier’s replication dynamic equation should be as follows:

$$\frac{dF(y)}{dy} = (1 - 2y) \{ x[\theta + \alpha(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)] + (z\mu\beta + \theta)(Q_h - Q_0) + z\mu L - M \}$$

To determine the positive and negative values at \( y = 0 \) and \( y = 1 \), the auxiliary function \( g_2(x) \) is constructed as:

$$g_2(x) = x[a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)] + z\mu\beta(Q_h - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M,$$

and \( k_2 = a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0) \), \( b_2 = z\mu\beta(Q_h - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M \), then \( g_2(x) = k_2 x + b_2 \). Because \( \alpha > 0 \) and \( Q_l < Q_0 < Q_h \), so \( a(Q_0 - Q_l) > 0 \); And because \( \beta > 0 \) and \( 0 \leq z \mu \leq 1 \), so \( (1 - z\mu)\beta(Q_h - Q_0) > 0 \), and \( k_2 > 0 \), therefore \( g_2(x) \) is a linearly increasing function of \( x \). Let \( x_0 = \frac{M - z\mu\beta(Q_h - Q_0) - z\mu L - R_l + R_h - \theta(Q_h - Q_l)}{a(Q_0 - Q_l) + (1 - z\mu)\beta(Q_h - Q_0)} \), according to the function image of \( g_2(x) \), it can be known from Figure 4a that:

![Figure 4](image_url)

**Figure 4.** The evolution process of supplier’s strategy selection. (a) \( k_2 > 0 \); (b) \( x = x_0 \); (c) \( x < x_0 \); (d) \( x > x_0 \).

(i) When \( x < x_0 \), \( g_2(x) < 0 \), at this time, \( \left. \frac{dF(y)}{dy} \right|_{y=0} = g_2(x) < 0 \), \( \left. \frac{dF(y)}{dy} \right|_{y=1} = -g_2(x) > 0 \), so \( y = 0 \) is an evolutionary stable strategy (ESS) and suppliers tend to produce ordinary products.

(ii) When \( x > x_0 \), \( g_2(x) > 0 \), at this time, \( \left. \frac{dF(y)}{dy} \right|_{y=0} = g_2(x) > 0 \), \( \left. \frac{dF(y)}{dy} \right|_{y=1} = -g_2(x) < 0 \), so \( y = 1 \) is an evolutionary stable strategy (ESS), and suppliers tend to produce low-carbon products.
To sum up, the dynamic trend diagram of supplier’s selection strategy is shown in Figure 4:

1. When the initial state of the supplier strategy is in the space $V_1$, as shown in Figure 4c, $x[a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)] + z\mu\beta(Q_h - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M < 0$, that is, when $x < x_0$, $y = 0$ is the stable point, and the supplier will choose the strategy of producing ordinary products at this time. Therefore, when the probability of strict supervision by the local government is relatively small, that is, the probability of passive supervision increases, the local government passively supervises without subsidizing suppliers’ low-carbon behavior and does not punish ordinary products that do not meet emission reduction standards. It is easy for suppliers to have a fluke mentality and lead to them being opportunistic, so at this time the supplier will choose the strategy of producing ordinary products.

2. When the initial state of the supplier strategy is in space $V_2$, as shown in Figure 4d, $x[a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)] + z\mu\beta(Q_h - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M > 0$, when $x > x_0$, $y = 1$ is the stable point, and the supplier will choose the strategy of producing low-carbon products at this time. Therefore, when the probability of strict supervision by the local government is relatively increased, that is, the probability of passive supervision is relatively small, suppliers want to receive government subsidies because of the local government’s strict supervision and the strategy of subsidizing low-carbon behaviors and penalizing ordinary products that do not meet emission reduction standards. Free from punishment, so at this time suppliers will choose to produce low-carbon products strategy.

Proposition 2. When other parameters remain unchanged, with the increase of $M$ (or $R_h$), the probability of suppliers choosing to produce low-carbon products will be inclined to 0.

Proof of Proposition 2. Because $x_0 = \frac{M - z\mu\beta(Q_h - Q_0) - z\mu L - R_l + R_h - \theta(Q_l - Q_1)}{a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)}$, with the increase of $M$ (or $R_h$), $x_0$ will also increase, then the stable section in Figure 4b will move to the right, so the volume of $V_1$ in Figure 4c will become larger, and the probability of the supplier producing ordinary products will also increase accordingly. Since the stable point in the space $V_1$ is $y = 0$, the probability that the supplier chooses to produce low-carbon products will tend to be 0, which is proved. □

Proposition 3. When other parameters remain unchanged, as $L$ (or $R_l$) increases, the probability of suppliers choosing to produce low-carbon products will tend to 1.

Proof of Proposition 3. Because $x_0 = \frac{M - z\mu\beta(Q_h - Q_0) - z\mu L - R_l + R_h - \theta(Q_l - Q_1)}{a(Q_0 - Q_1) + (1 - z\mu)\beta(Q_h - Q_0)}$, when $L$ (or $R_l$) increases, $x_0$ decreases instead, the stable section in Figure 4b shifts to the left, and the volume of $V_2$ in Figure 4d becomes larger, that is, the probability of suppliers producing low-carbon products increases. Because the stable point in the space $V_2$ is $y = 1$, the probability that the supplier chooses to produce low-carbon products will tend to 1, which is proved. □

Therefore, suppliers tend to choose to produce ordinary products when the cost of abatement for the production of low-carbon products is too high or the market revenue of the supplier’s production of ordinary products is too high. While downstream enterprises demand too much compensation from suppliers that produce ordinary products, or when the market benefits of the two products produced by the suppliers are almost the same, the suppliers tend to produce low-carbon products.
4.3. Progressive Stability Analysis of Downstream Enterprises

4.3.1. Expected Earnings of Downstream Enterprises

Consistent with the calculation methods of the first two stakeholders, assuming that \( U_3 \) represents the expected earnings when the downstream enterprises participate in supervision, \( U_2 \) represents the expected earnings when the downstream enterprises do not participate in supervision, and \( U_4 \) represents the average expected earnings of the downstream enterprises. According to the payoff matrix, we can calculate the expected earnings of downstream enterprises when they choose to participate in supervision:

\[
U_{21} = xy(-C_e) + x(1-y)\{(-C_e + \mu L) + (1-x)y(-C_e) + (1-x)(1-y)[-C_e + \mu(P + L)]\}. \tag{10}
\]

when downstream enterprises choose not to supervise, their expected earnings can be obtained as follows:

\[
U_{22} = x(1-y)(-H) + (1-x)(1-y)(-H). \tag{11}
\]

According to Equations (10) and (11), the average expected earnings of downstream enterprises can be calculated:

\[
\bar{U}_2 = zU_{21} + (1-z)U_{22} = z\{xy(-C_e) + x(1-y)\{(-C_e - H + \mu L) + (1-x)y(-C_e) + (1-x)(1-y)[-C_e - H + \mu(P + L)]\}\} + (1-z)\{x(1-y)(-H) + (1-x)(1-y)(-H)\}. \tag{12}
\]

4.3.2. Replication Dynamic Equation Analysis of Downstream Enterprises

According to the Equations (10)–(12), the replication dynamic equation of the downstream enterprise strategy can be obtained:

\[
F(z) = \frac{dz}{dt} = z(1-z)\{y[(x-1)\mu P - \mu L - H] - x\mu P - C_e + \mu(P + L) + H\}. \tag{13}
\]

We also need to analyze the dynamic equation of replication of downstream enterprises' strategies:

1. If \( y = 1 - \frac{C_e}{(1-x)\mu P + \mu L + H} \), then no matter what value \( z \) is taken, \( F(z) = 0 \). It indicates that no matter whether the downstream enterprises choose to participate in the supervision of the supplier’s carbon emission reduction behavior or not, the strategies of the downstream enterprises will not change with the evolution of time, and the game is in a stable state.

2. If \( y \neq 1 - \frac{C_e}{(1-x)\mu P + \mu L + H} \), let \( F(z) = 0 \), then \( z = 0 \) and \( z = 1 \) are obtained. It shows that when the downstream enterprise chooses the supervision strategy/unsupervised strategy, as long as there is no sudden condition that causes the downstream enterprise to change its strategy, then the downstream enterprise’s strategy will be stable in the state of supervised strategy/unsupervised strategy.

The derivative of the replication dynamic equation of the downstream enterprise strategy needs to be less than 0 if the strategy of the downstream enterprise strategy can achieve the evolutionary stable strategy, which is the same as the previous two game players. Therefore, the derivative of the replication dynamic equation of the downstream enterprise is as follows:

\[
\frac{dF(z)}{dz} = (1-2z)y[(x-1)\mu P - \mu L - H] - x\mu P - C_e + \mu(P + L) + H.
\]

To determine the positive and negative values at \( z = 0 \) and \( z = 1 \), the auxiliary function \( g_3(y) \) is constructed:

\[
\text{Let } g_3(y) = y[(x-1)\mu P - \mu L - H] - x\mu P - C_e + \mu(P + L) + H, \text{ and } y_0 = 1 - \frac{C_e}{(1-x)\mu P + \mu L + H}.
\]
When \((1 - x)\mu P + \mu L + H < C_e\), then \(\frac{C_e}{\mu (p + L)} > 1\), and \(y_0 < 0\) at this time, it means that when the supervision cost of the downstream enterprise is greater than the total income obtained from the local government and suppliers when the supervision is successful, the probability of the downstream enterprise choosing the supervision strategy is negative, which means that it is impossible for downstream enterprises to choose the supervision strategy under this circumstance.

When \((1 - x)\mu P + \mu L + H > C_e\), according to the function image of \(g_3 (y)\), as shown in Figure 5a, the following conclusions can be drawn:

(i). When \(y < y_0\), then \(g_3 (y) > 0\), and \(\frac{dF(z)}{dz} \bigg|_{z=0} = g_3 (y) > 0\), \(\frac{dF(z)}{dz} \bigg|_{z=1} = -g_3 (y) < 0\) at this time, so \(z = 1\) is an evolutionary stability strategy (ESS), and downstream enterprises tend to choose supervision strategy.

(ii). When \(y > y_0\), then \(g_3 (y) < 0\), and \(\frac{dF(z)}{dz} \bigg|_{z=0} = g_3 (y) < 0\), \(\frac{dF(z)}{dz} \bigg|_{z=1} = -g_3 (y) > 0\) at this time, so \(z = 0\) is an evolutionary stability strategy (ESS), and downstream enterprises tend to choose unsupervised strategy.

In summary, the dynamic trend diagram of downstream enterprises’ selection strategies is shown in Figure 5:

1. When the initial state of the downstream enterprise strategy is in space \(V_1\), as shown in Figure 5c, \(g_3(y) > 0\), that is, \(z = 1\) is the stable point and the downstream enterprise will choose to participate in the supervision strategy at this time. Therefore, when the probability of suppliers producing low-carbon products is relatively small, that is, the probability of producing ordinary products increases, the downstream enterprises take the initiative to supervise the carbon reduction ranking of their upstream suppliers from the consumers’ demand for their products and the reputation benefits of their enterprises.

2. When the initial state of the downstream enterprise strategy is in space \(V_2\), as shown in Figure 5d, \(g_3(y) < 0\), that is, \(z = 0\) is the stable point, and the downstream enterprise will choose not to participate in the supervision strategy at this time. Therefore, when the probability of suppliers producing low-carbon products is relatively small, that is, the probability of producing ordinary products is reduced, downstream enterprises have no sense of supervision for cost and other considerations and adopt an unsupervised strategy for their upstream suppliers’ carbon emission reduction behaviors.

**Proposition 4.** When other parameters remain unchanged, with the increase of \(C_e\), the probability of downstream enterprises choosing to participate in supervision is inclined to 0.

**Proof of Proposition 4.** Because \(y_0 = 1 - \frac{C_e}{(1 - x)\mu P + \mu L + H}\), with the increase of \(C_e\), \(y_0\) will decrease instead, then the stable section in Figure 5b moves back, the volume of \(V_1\) in Figure 5c becomes smaller, and the volume of \(V_2\) in Figure 5d becomes larger, that is, the
probability of downstream enterprises choosing not to participate in supervision increases. Since the stable point in the $V_2$ space is $z = 0$, the probability of downstream enterprises choosing to participate in supervision will tend to be 0, which is proved. □

**Proposition 5.** When other parameters remain unchanged, as $\mu$ (or P or L or H) increases, the probability of downstream enterprises choosing to participate in supervision will tend to 1.

**Proof of Proposition 5.** As $\mu$ increases, $y_0$ increases, the stable section in Figure 5b moves forward, and the volume of $V_1$ in Figure 5c becomes larger, that is, the probability of downstream enterprises choosing to participate in supervision increases. Since the stable point in space $V_1$ is $z = 1$, then the probability that the supplier chooses to produce low-carbon products will tend to 1, which is proved. In the same way, when $P$ or $L$ or $H$ increases, $y_0$ will also increase, which will eventually increase the probability of downstream enterprises choosing to participate in supervision. □

Therefore, when the cost of supervising suppliers is too high, downstream enterprises tend to choose not to participate in the supervision strategy; while the success rate of downstream enterprises monitoring increases, or the rewards from local governments become larger, or the compensation from suppliers increases and there are too many losing consumers repeat customers, downstream enterprises tend to choose to participate in the supervision strategy.

### 4.4. Local Stability Analysis of Tripartite Evolutionary Game System

We analyze the stability of the evolutionary game of the whole system. Firstly, the three-dimensional dynamic system $A$ is composed of (4), (8) and (12):

$$
A = \begin{pmatrix}
F(x) = \frac{dx}{dt} = x(1-x)\{y[\beta(z\mu - 1)(Q_0 - Q_0) - a(Q_0 - Q_0) + W - S - z\mu P] + \beta(1-z\mu)(Q_0 - Q_0) - C_{g1} + C_{g2} - W + S + z\mu P \}

F(y) = \frac{dy}{dt} = y(1-y)\{x[a(Q_0 - Q_0) + (1-z\mu)\beta(Q_0 - Q_0)] + z\mu\beta(Q_0 - Q_0) + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M \}

F(z) = \frac{dz}{dt} = z(1-z)\{y[(x-1)P - M - L - H] - x\mu P - C_e + \mu(P + L) + H \}
\end{pmatrix}
$$

Let $A = 0$, eight pure strategy solutions $E_1 (0,0,0), E_2 (0,0,1), E_3 (0,1,0), E_4 (0,1,1), E_5 (1,0,0), E_6 (1,0,1), E_7 (1,1,0) \text{ and } E_8 (1,0,1)$ are derived. The Jacobian matrix formed according to the three-dimensional dynamic system $A$ is:

$$
J = \begin{pmatrix}
(1-2x)[y(\beta(z\mu - 1)(Q_0 - Q_0) - a(Q_0 - Q_0) + W - S - z\mu P) + \beta(1-z\mu)(Q_0 - Q_0)] + x(1-x)[\beta(z\mu - 1)(Q_0 - Q_0) - a(Q_0 - Q_0) + W - S - z\mu P] + x(1-x)(y - 1)\beta(Q_0 - Q_0) + (1-y)\mu L \\
(1-2y)[x[a(Q_0 - Q_0) + (1-z\mu)\beta(Q_0 - Q_0)] + z\mu\beta(Q_0 - Q_0)] + (1-x)[y(a(Q_0 - Q_0) + (1-z\mu)\beta(Q_0 - Q_0)] + x[\beta(Q_0 - Q_0) + \theta(Q_h - Q_l) - M] + z\mu L + R_l - R_h + \theta(Q_h - Q_l) - M \\
(y - 1)\mu P + z(1-z)[(x-1)P - M - L - H] - x\mu P - C_e + \mu(P + L) + H
\end{pmatrix}
$$

The above eight pure strategy solutions are respectively brought into the Jacobian matrix $J$. For example, when the strategy $E_1 (0,0,0)$ is selected, $x = 0$, $y = 0$, $z = 0$, then the Jacobian matrix $J_1$ is expressed as:

$$
J_1 = \begin{pmatrix}
\beta(Q_h - Q_0) - C_{g1} + C_{g2} - W + S & 0 & 0 \\
0 & R_l - R_h + \theta(Q_h - Q_l) - M & 0 \\
0 & 0 & -C_e + \mu(P + L) + H
\end{pmatrix}
$$

The three eigenvalues obtained from the matrix $J_1$ are respectively: $\lambda_1 = \beta(Q_h - Q_0) - C_{g1} + C_{g2} - W + S$, $\lambda_2 = R_l - R_h + \theta(Q_h - Q_l) - M$, and $\lambda_3 = -C_e + \mu(P + L) + H$. The remaining 7 equilibrium points are substituted into the Jacobian matrix $J$ in turn, and the local stability analysis of the equilibrium points will be obtained, as shown in Table 3.
5. Simulation of Evolutionary Game Model

5.1. System Dynamics (SD) Simulation Model

Vensim PLE software is used to simulate and analyze the evolutionary game between local governments, suppliers and downstream enterprises. Firstly, the system dynamics (SD) simulation model is built according to the Equations (1)–(2), (4)–(6), (8)–(10) and (12), as shown in Figure 6. This system involves 6 horizontal variables, 3 rate variables, 9 auxiliary variables and 18 exogenous variables.
When the initial conditions of the simulation are assigned, experts in low-carbon supply chains, system simulation and other related research fields are consulted [32, 33]. Meanwhile, parameters of this model are assigned in the existing literature. Finally, sensitivity analysis is carried out to ensure the accuracy of the data. The initial time is 0, the simulation cycle is 50 months, the simulation step size is 1 and the parameter settings in the model are shown in Table 4:

| $C_{g1}$ | $C_{g2}$ | $\alpha$ | $\beta$ | $\theta$ | $W$ | $R_I$ | $R_h$ | $Q_I$ | $Q_h$ | $Q_0$ | $M$ | $S$ | $L$ | $C_e$ | $\mu$ | $P$ | $H$ |
|---------|---------|----------|----------|----------|-----|-------|-------|-------|-------|-------|-----|-----|-----|-----|-----|-----|-----|
| 7       | 3       | 2        | 2        | 10       | 23  | 150   | 181.8 | 6     | 12     | 8     | 30  | 20  | 7   | 1   | 0.2 | 2   | 1.5 |

5.2. Simulation Analysis of Pure Strategy Equilibrium Solution

According to the local stability analysis of the equilibrium points in Table 3, it can be seen that the eigenvalues are affected by many factors, so it is difficult to judge the stability of each equilibrium point. Through the simulation of eight pure strategy equilibrium solutions, it is found that among the eight pure strategy equilibrium solutions, if the strategies of the three parties in the game do not change, the game is in an equilibrium state. However, this equilibrium state is not stable, as long as there is a slight change in the will of either party, the equilibrium state will be broken. For example, in the pure strategy equilibrium solution $E_1 (0,0,0)$, when the willingness of the local government to adopt strict supervision suddenly changes from 0 to 0.01, as time evolves, the willingness of the local government to take strict supervision will gradually increase. Until the 9th month, it will completely become 1, at which time the strategy of the game system will evolve into $E_5 (1,0,0)$, as shown in Figure 7a. Similarly, when the initial state is the pure strategy equilibrium solution $E_6 (1,0,1)$, if the willingness of the local government to strictly supervise changes from 1 to 0.99, the local government found that even if the supplier’s strategy is the production of ordinary products but due to factors such as the
cost of supervision, the overall economic benefits as well as the downstream enterprises adopting supervision strategies and other factors, the probability of local governments choosing strict supervision will gradually decrease and will eventually tend to 0, as shown in Figure 7b, that is, the strategy will evolve into $E_2(0,0,1)$.

Figure 7. Cont.
As for the pure strategy equilibrium solution \( E_2 (0,0,1) \), if the supplier’s willingness to produce low-carbon products suddenly changes from 0 to 0.01, the supplier will have to compensate the downstream enterprises for the supervision of the downstream enterprises. In order to avoid this expenditure, suppliers’ willingness to produce low-carbon products will gradually increase, will stabilize at 1 in the eighth month and the evolutionary strategy will become \( E_4 (0,1,1) \), as shown in Figure 7c. In the pure strategic equilibrium solution \( E_3 (0,1,0) \), the supplier’s willingness to produce low-carbon products is initially 1 and, if it suddenly changes to 0.99, when it finds that both the willingness of local government and the supervision of downstream enterprises are 0, and the supplier’s willingness to produce low-carbon products will decrease rapidly, as shown in Figure 7d. It will drop to 0 in the 6th month and then small fluctuations will happen in July and September, then will stabilize at 0, reaching the pure strategy equilibrium solution \( E_1 (0,0,0) \).

In the pure strategy equilibrium solution \( E_4 (0,1,1) \), the downstream enterprise initially adopts the strategy of participating in supervision. If its willingness to participate in supervision changes from 1 to 0.99, its willingness will become smaller and smaller until it decreases to 0 in the ninth month, as shown in Figure 7e. That is, when downstream enterprises find that their suppliers are adopting strategies of producing low-carbon products, they will take the initiative to give up supervision. For the pure strategy equilibrium solution \( E_5 (1,0,0) \), when the willingness of downstream enterprises to participate in super-
vision changes from 0 to 0.01, their willingness will increase rapidly and will rise to 1 in the fifth month. Between 6–12 months, there will be slight fluctuations and it will then stabilize at 1, as shown in Figure 7f. This phenomenon can be explained as downstream enterprises; in order to ensure consumers’ reliance on their brands and reputation, they would rather spend a small amount of supervision costs to monitor the carbon emission reduction issues of their upstream suppliers, but also to achieve the quality of their products sold.

For the pure strategy equilibrium solution $E_7 (1,1,0)$, when the initial willingness of the local government and the supplier do not change and the willingness of the downstream enterprises to participate in supervision suddenly changes from 0 to 0.01, the simulation finds that its participation in supervision will drop to 0 rapidly, as shown in Figure 7g. As a result, we continue to change the initial willingness of downstream enterprises to perform simulations. When their initial willingness to participate in supervision suddenly changes to 0.5, its value will drop rapidly as time evolves, and it will drop to 0 in the third month, as shown in Figure 7h. Then the simulation of $E_8 (1,1,1)$ is carried out, when the willingness of downstream enterprises to participate in supervision suddenly changes from 1 to 0.99, its value will gradually drop to 0. Therefore, when local governments strictly supervise and suppliers produce low-carbon products, regardless of the initial willingness of downstream enterprises to participate in supervision or not, downstream enterprises will eventually choose not to participate in supervision over time.

To sum up, through the simulation of eight pure strategy equilibrium solutions, it is found that the optimization path of each strategy is: $E_1 \rightarrow E_5, E_2 \rightarrow E_4, E_3 \rightarrow E_1, E_4 \rightarrow E_3, E_5 \rightarrow E_6, E_6 \rightarrow E_2, E_7 \rightarrow E_7, E_8 \rightarrow E_7$. Therefore, the strategy choice among local governments, suppliers and downstream enterprises always fluctuates repeatedly and the steady state will be broken if there is a slight change, and the evolutionary stability strategy does not exist. However, when the local government and the supplier’s strategy choices are both positive, that is, when the strategy is $(1, 1, z)$, the value of $z$ always tends to 0 eventually. This shows that when local governments choose “strict supervision” and suppliers choose “production of low-carbon products,” no matter which strategy downstream enterprises choose initially, the final strategy will evolve into “no participation in supervision”. The reason for this phenomenon is that the local government plays a leading role in the regulatory process. When the local government actively supervises the carbon emission reduction behavior of suppliers, the participation of downstream enterprises will not bring benefits to themselves. Therefore, the choice of downstream enterprises in this situation is not to participate in the supervision.

5.3. Parameter Sensitivity Analysis

5.3.1. Parameter Sensitivity Analysis of Influencing Local Government’s Strategy Choice

By simulating the local government’s strategic choices, it is found that there are some factors that have a significant impact on the local government’s strategic choice—the local government penalty coefficient ($\beta$), the success rate of downstream enterprise supervision ($\mu$), the difference between the carbon emissions of suppliers when producing ordinary products and the carbon emissions of low-carbon products specified by the government ($Q_h - Q_0$), the difference between the cost of strict government supervision and passive supervision ($C_{g1} - C_{g2}$), the reward from the government when the downstream company succeeds in supervision ($P$) and the difference between the environmental governance cost of the local government and the environmental loss caused by the supplier’s production of ordinary products ($W - S$). The above parameters are selected for sensitivity analysis, assuming that the parameter in the baseline scenario is 100% of the initial assignment, as shown in Figure 8. Taking $E_9 (1,0,1)$ as an example, the government’s initial strategy is strict supervision. That is assumed in the 0th month, and the government’s willingness to strictly supervise changes suddenly with a probability of 0.99.
Figure 8. Parameter sensitivity analysis of influencing local government’s strategy choice. (a): the effect of $\beta$ on $x$; (b): the effect of $\mu$ on $x$; (c): the effect of $Q_h$ on $x$; (d): the effect of $C_{g1}-C_{g2}$ on $x$; (e): the effect of $P$ on $x$; (f): the effect of $W$ on $x$.

Curves 1–7 in Figure 8a represent the rate of change corresponding to $x$ when $\beta$ is 1.8, 1.85, 1.9, 1.95, 2, 2.05 and 2.1, respectively. It can be seen that if the local government penalty coefficient increases within 2.5%, the local government tends to negatively regulate. At the same time, the change of $\beta$ makes the probability of strict government supervision gradually decrease. The smaller the $\beta$ is, the faster $x$ decreases and the larger the $\beta$ is, the more it promotes strict supervision by the local government, which shows that the increase in the value of the local government penalty coefficient can effectively stimulate the local government’s willingness to strictly supervise. In Figure 8b, $\mu_1-\mu_7$ are 0.15, 0.18, 0.19, 0.2, 0.25, 0.3 and 0.33, respectively. The simulation found that when the success rate of downstream enterprises’ supervision is reduced within 10%, it will prompt the local government to negatively supervise. When $\mu$ is 0.15, the local government will adopt strict supervision strategy and, when $\mu > 0.18$, the local government’s willingness to adopt a strict supervision strategy will become smaller and smaller. Where the larger $\mu$ is, the faster the rate of $x$ decreases. Figure 8c shows the change of $x$ when $Q_h = 8$ and $Q_h$ takes 7 values in 11.5–12.2 respectively. It can be seen from the figure that, when carbon emissions are controlled to increase below 2%, local governments will not strictly supervise them. As the carbon emissions of ordinary products produced by suppliers increase, local governments are more inclined to strictly supervise their carbon emission reduction activities. Among them, when $Q_h > 12.5$, the probability of strict supervision by the local government will rise to 1.

Figure 8d shows the influence of $C_{g1}-C_{g2}$ on $x$. Curves 1–7 are the corresponding changes in $x$ when $C_{g2}$ is equal to 3 and $C_{g1}$ is equal to 6.8, 6.9, 7, 7.2, 7.4, 7.6, and 7.8 respectively. Studies have shown that when the cost of strict supervision is reduced to less than 7%, local government will stabilize in strict supervision. By comparing curves 1 and 2, it can be seen that when the difference between $C_{g1}$ and $C_{g2}$ is 3.8, the local government adopts strict supervision strategy. When the difference is greater than 3.8, the local govern-
ment’s willingness to strictly supervise gradually decreases, as shown in curve 2–7. The greater the difference between the cost of strict supervision and passive supervision by local governments, the more they tend to adopt passive supervision strategies. In Figure 8e, $P_1$–$P_7$ are 1, 1.5, 2, 2.5, 3, 3.5 and 4, respectively. The higher the reward from the government when the downstream enterprise is successfully supervised, the stronger the willingness of the local government to strictly supervise. $W_1$–$W_7$ in Figure 8f are 22.8, 22.9, 23, 23.1, 23.2, 23.3 and 23.5, respectively. When $W$ is 22.8, the local government strictly supervises. When $W > 22.8$, the probability of local government strict supervision gradually decreases. The larger $W$ is, the faster $x$ decreases. This indicates that when environmental governance costs are controlled within a certain amount, local governments are acceptable and will choose strict supervision but when environmental governance costs exceed a certain amount, local governments will be more and more willing to ignore environmental losses and choose passive supervision.

5.3.2. Parameter Sensitivity Analysis of Influencing Supplier’s Strategy Choice

Through the simulation of the supplier’s strategic selection, it is found that the downstream enterprises’ supervision success rate ($\mu$), the supplier’s compensation to the downstream enterprises ($L$), the local government penalty coefficient ($\beta$), the supplier’s emission reduction input cost when producing low-carbon products ($M$), supplier’s market revenue when producing ordinary products ($R_s$), carbon tax rate ($\theta$) and other factors will have a certain impact on the supplier’s strategic selection. The above parameters are selected for sensitivity analysis, assuming that the parameter in the baseline scenario is 100% of the initial assignment, as shown in Figure 9. Taking $E_2$ (0,0,1) as an example, the supplier’s initial strategy is to produce ordinary products. Assuming that in the 0th month, the supplier’s willingness to produce low-carbon products has a mutation with a probability of 0.01.

![Figure 9](image-url)

**Figure 9.** Parameter sensitivity analysis of influencing supplier’s strategy choice. (a), the effect of $\mu$ on $y$; (b), the effect of $L$ on $y$; (c), the effect of $\beta$ on $y$; (d), the effect of $M$ on $y$; (e), the effect of $R_s - R_l$ on $y$; (f), the effect of $\theta$ on $y$. 
As shown in Figure 9a, $\mu_1$–$\mu_7$ are 0.12, 0.13, 0.16, 0.18, 0.2, 0.21 and 0.22, respectively. It can be seen from the figure that, when the success rate of downstream companies’ supervision is reduced by less than 25%, suppliers will tend to choose to produce low-carbon products. When $\mu \leq 0.12$, the success rate of downstream enterprises’ supervision is too small to motivate suppliers to produce low-carbon products. When $\mu > 0.12$, the probability of suppliers producing low-carbon products gradually increases, and the larger $\mu$ is, the faster the probability of suppliers producing low-carbon products. It indicates that, within a certain range, the supervision of downstream enterprises plays a constraint role on the carbon emission reduction behavior of suppliers. Figure 9b shows the influence of $L$ on supplier strategy selection, and $L$ in curves 1–7 is 4, 5.5, 6, 6.5, 7, 7.5 and 8, respectively. By comparing the seven curves, it can be concluded that, when the supplier’s compensation control for downstream companies is reduced within 43%, the supplier will tend to choose to produce low-carbon products, otherwise the supply will produce ordinary products. The greater the compensation from suppliers to downstream enterprises, the faster the growth rate of the probability that suppliers tend to produce low-carbon products. Similar to the compensation fund, $\beta$ also has a restrictive effect on $\gamma$. In Figure 9c, curves 1–7 represent the cases where $\beta$ is 1.2, 1.4, 1.6, 1.8, 2, 2.1 and 2.2, respectively. It can be concluded that the local government penalty coefficient is reduced within 30% and downstream enterprises will choose to produce low-carbon products. The larger $\beta$ is, the more suppliers tend to produce low-carbon products. The impact of emission reduction input costs when suppliers produce low-carbon products is opposite to the former two.

$M_1$–$M_7$ in Figure 9d are 29.9, 30, 30.5, 30.8, 31, 31.3, and 31.5 respectively. The image shows that the cost of reducing emissions is controlled within 5% and suppliers will choose to produce low-carbon products. The trend of the curve in the figure indicates that the smaller $M$ is, the greater the probability of suppliers producing low-carbon products, indicating that within the controllable range, a smaller investment cost for emission reduction can provide an incentive for suppliers to produce low-carbon products. The smaller $M$ is, the greater the probability of suppliers producing low-carbon products. Figure 9e plots the impact of the difference in market revenue between suppliers producing low-carbon products and ordinary products on $\gamma$ and the seven curves are 7 values in 182.2–183.2 respectively when $R_l$ is fixed at 150. The simulation shows that the smaller the difference between $R_h$ and $R_l$ within a certain range, the more inclined suppliers are to produce low-carbon products. Figure 9f shows the impact of the carbon tax rate ($\theta$) on the supplier’s strategic choice, and curves 1–7 represent that $\theta$ is 9.7, 9.8, 9.9, 10, 10.1, 10.2 and 10.3 respectively. Suppliers tend to produce low-carbon products when the carbon tax rate is controlled to be reduced to less than 3%. When $\theta > 9.8$, the supplier tends to choose to produce low-carbon products. Every 0.1 change in $\theta$ will have a great impact on the probability of suppliers producing low-carbon products. The greater the $\theta$, the more sensitive the supplier’s response to product low-carbon products, which indicates that the carbon tax rate ($\theta$) has a more compulsory constraint on whether suppliers produce low-carbon products.

5.3.3. Parameter Sensitivity Analysis of Influencing Downstream Enterprise’s Strategy Choice

By simulating the strategic choice of downstream enterprises, the results show that the cost of downstream company supervision ($C_e$), the supplier’s compensation to the downstream company ($L$), the consumer repeat customers lost when the downstream company buys ordinary products ($H$) and the success rate of downstream company supervision ($\mu$) will cause a certain impact versus the supplier’s strategic choice. The above parameters are selected for sensitivity analysis, assuming that the parameter in the baseline scenario is 100% of the initial assignment, as shown in Figure 10. Taking $E_5$ (1,0,0) as an example, the initial strategy of downstream enterprises is not to participate in supervision. Assume that the willingness of downstream enterprises to participate in supervision changes with a probability of 0.01 in the 0th month.
Figure 10. Parameter sensitivity analysis of influencing downstream enterprise’s strategy choice. (a) the effect of $C_e$ on $z$; (b) the effect of $L$ on $z$; (c) the effect of $H$ on $z$; (d) the effect of $\mu$ on $z$.

In Figure 10a, the supervision cost ($C_e$) of downstream enterprises is 0.5, 1, 1.5, 2, 2.5, 3 and 3.5, respectively. When the supervision cost increases by more than 50%, the downstream enterprises will choose not to participate in the supervision. With the increase of $C_e$, the enthusiasm of downstream enterprises to participate in supervision gradually decreases, and the rising speed of the curve slows down. Figure 10b shows the impact of compensation ($L$) from suppliers on downstream enterprises’ strategies, in which $L_1-L_7$ are 5.5, 6, 6.5, 7, 7.5, 8, and 8.5 respectively. When the supplier’s compensation to downstream enterprises increases by less than 7%, the willingness of downstream enterprises to participate in supervision will gradually decrease and eventually stabilize at 0. It can be seen from the figure that with the increase of $L$, the probability of downstream enterprises participating in supervision is gradually increasing, and the greater $L$ is, the stronger the willingness of downstream enterprises to choose to participate in supervision, so the compensation of suppliers plays a certain incentive role for downstream enterprises to participate in supervision.

$H_1-H_7$ in Figure 10c are 1, 1.2, 1.4, 1.5, 1.7, 1.9, and 2, respectively. When the supplier’s loss of consumer repeat customers is more than 20%, the willingness of downstream enterprises to participate in supervision will gradually rise and eventually stabilize 1. When $H$ is 1, the consumer repeat customers lost by downstream enterprises are not enough to attract the attention of downstream enterprises, so downstream enterprises choose not to participate in supervision. When $H > 1$, the loss is related to the fundamental interests
of downstream enterprises, which has attracted the attention of downstream enterprises. Therefore, the probability of downstream enterprises choosing to participate in supervision is gradually increasing, and the larger $H$ is, the faster $z$ will rise. In the same way, the success rate of downstream enterprises’ supervision has also played a certain role in motivating whether they participate in supervision. Curves 1–7 in Figure 10d represent $\mu$ as 0.14, 0.15, 0.16, 0.18, 0.2, 0.22 and 0.24, respectively. Figure 10d shows that when the success rate of supervision of downstream enterprises decreases by more than 25%, downstream enterprises will choose not to participate in supervision. When $\mu$ is 0.14, the success rate of supervision at this time is too small, and downstream enterprises will not take the risk of choosing to participate in supervision; but when $\mu > 0.14$, downstream enterprises may choose to pay a certain supervision cost to choose supervision, such as curve 2; as $\mu$ gradually increases, the probability of downstream enterprises choosing to participate in supervision is increasing, indicating that downstream enterprises are willing to pay for rewards or compensation to monitor suppliers’ carbon emission reduction behavior.

5.4. Result Discussion

Different from the differential game, the purpose of the evolutionary game method is not to solve the minimum cost and maximum benefit but to find a relatively stable strategy in the changing process with the evolution of time. By constructing the evolutionary game model, this paper draws a similar conclusion to Liu’s [24] research, but this paper also takes the supervision role of downstream enterprises into account, so the consideration is more comprehensive and closer to reality. Through the simulation analysis in the previous section, we can draw the following main conclusions:

(1) For local governments, from the perspective of parameter sensitivity analysis, the carbon emissions of ordinary products have the most sensitive impact on the choice of strict supervision by local governments. The local government penalty coefficient, the difference between the carbon emissions of ordinary products produced by suppliers and the carbon emissions of low-carbon products specified by the government, and the reward from the government when the downstream enterprises successfully supervise will all play a role in promoting strict supervision by local governments. However, the success rate of downstream enterprises’ supervision, the difference between local government’s strict supervision and passive supervision costs, and the difference between local government’s environmental control costs and environmental losses caused by suppliers’ production of ordinary products will play opposite roles. Therefore, the probability of strict supervision by local governments can be improved by appropriately increasing the value of local government penalty coefficient or increasing rewards for downstream enterprises participating in supervision.

(2) For suppliers, low-carbon emission reduction costs and carbon tax rates have the most intuitive impact on suppliers’ choice to produce low-carbon products. The success rate of supervision of downstream enterprises, the compensation of suppliers to downstream enterprises, the local government penalty coefficient and the carbon tax rate can restrain suppliers’ carbon reduction ranking to a certain extent, thus these factors will encourage them to produce low-carbon products. However, the input cost of emission reduction when suppliers produce low-carbon products, and the difference of income between ordinary products and low-carbon products will hinder the decision-making of suppliers to produce low-carbon products and promote them to develop in the direction of producing ordinary products.

(3) For downstream enterprises, the supplier’s compensation to downstream enterprises has the greatest impact on downstream enterprises’ choice to participate in supervision. The loss of consumers’ repeat customers when they buy ordinary products and the compensation from suppliers to downstream enterprises will give the downstream enterprises a certain amount of motivation, thus encouraging them to participate in the game of supervising upstream suppliers. However, in real life, the success rate of
supervision and the supervision cost and lower reaches enterprises will give a certain blow to their supervision behavior.

6. Conclusions

In this paper, the evolutionary game model among local governments, suppliers and downstream enterprises is constructed by using game theory method; the replication dynamic equation of the tripartite game subject is obtained and both its asymptotic stability and local stability are explored in detail. In addition to this, the system dynamics model is used to simulate the evolution path and analyze the sensitivity of the parameters that affect the strategy selection of each player. The results show that the success rate of downstream enterprises’ supervision is closely related to the decision-making of the three parties. Both local government decision-making and supplier decision-making will be affected by the local government’s penalty coefficient. The supplier’s compensation to the downstream enterprises not only encourages the suppliers to produce low-carbon products, but also promotes the downstream enterprises to participate in the decision-making of supervision. When the local government strictly supervises and the suppliers adopt the strategy of producing low-carbon products, the final evolutionary strategy is not to participate in the supervision, regardless of the initial willingness of downstream enterprises to participate in the supervision. Based on the analysis results, we give the following suggestions:

(a) For taxation policies, the government should collect actual emissions information as soon as possible, and formulate key values such as tax rates, subsidy coefficients and penalty coefficients, so that the taxation policies can be implemented.

(b) With regard to the “subsidy-punishment” system, local governments can increase subsidies and penalties, so that the enterprises of the supply chain members can really attract attention and at the same time strengthen the deterrence of local governments.

(c) Local governments can use various methods such as the Internet and the media to increase publicity on “low-carbon life,” increase consumers’ preference for low-carbon products and promote a lifestyle of energy saving and emission reduction.

(d) Local governments can collaborate with suppliers to improve the research and development of emission reduction technologies, generalize emission reduction technologies, reduce the suppliers’ emission reduction input costs, and truly apply them in the low-carbon supply chain.

(e) The low-carbon supply chain requires that carbon emissions should be minimized or not carbonized in the process of manufacturing and consumption, which should be extended to consumers at the end of the supply chain. We should also implement low-carbon life in our daily life, such as reducing travel, saving electricity and saving gas and recycling, especially reducing carbon dioxide emissions, thus reducing air pollution and slowing down ecological deterioration.

Moving towards low-carbon is the general trend, and the proposal of the Industrial Internet will help the structure of the supply chain to develop in a more environmentally friendly and low-carbon direction. This article provides some theoretical support for the emission reduction strategy in the low-carbon supply chain, but the selection of data in the simulation stage is still not objective enough, which is worthy of our next step to improve. In the future, our next research may consider consumers as one of the game subjects in the whole system, and we will take consumers’ preference for low-carbon products into consideration and form a joint force to create a situation of nationwide collaborative supervision.

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