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Research Article

Dynamic Green Innovation Decision of the Supply Chain with Innovating and Free-Riding Manufacturers: Cooperation and Spillover

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Green innovation for supply chain has attracted much academic attention. Yet, there is no adequate understanding of how spillover and cooperation can impact the enterprises' green innovation decisions in the presence of free-rider. Besides, the dynamic impact of green innovation on emission is still lack of attention. We develop a differential game model that explicitly considers a supply chain with two types of manufacturers (i.e., green innovation and free-riding) to examine the dynamics of green innovation. The analysis reveals that under the noncooperation mode, the emissions and profits of free-riding manufacturers are found to be lower than that of innovating manufacturers, but technology spillovers will narrow the gap between them. Under the cooperation mode, there would be greater innovation efforts of green manufacturers and lesser efforts of green suppliers. Moreover, technology spillovers will have less impact on optimal decision changes. The profit of free-riding manufacturers is higher than that of innovating manufacturers, but the initial market power will affect the changes in their sales and profits. Meanwhile, cooperation will increase the total emission amount and long-term profits of the green supply chain, and technology spillovers of green manufacturers will help narrow the emission gap and broaden the profit gap, while that of the suppliers will have the opposite effect. The present study provides a new perspective for research on green innovation decisions for supply chain.

1. Introduction

With rapid industrialization, innumerable resources are leading to insurmountable pollution generated by human activities, in particular, fossil fuel combustion producing greenhouse gases, which leads to global warming and thus seriously threatening the global natural ecological balance [1]. Owing to the devastating effects of enterprise behavior on the environment, cleaner production has garnered much attention [2]. To reduce emissions arising from the production process, clean manufacturers will also compel upstream suppliers to reduce emissions by mandating disclosure of green development information and to organize green information for the full product life cycle. In this case, the entire supply chain has an incentive to implement the green strategy.

Evolution of green technology is vital for improving the enterprises' environmental performance without sacrificing economic benefits [3, 4]. Therefore, more and more enterprises invest in green technology to address the growing environmental needs. In addition, green technology innovation is more dependent than other types of technology innovation on external sources of knowledge and information [5]. Innovation cooperation [6, 7] and technology spillovers [8] are two important means of acquiring technical capacity (knowledge capital). The internal access to more knowledge draws out green innovation [9, 10], which can ease the vulnerability under the demands of new environmental regulations [11], as well as respond to the market's green demands [12]. Therefore, several researchers analyzed the impact of enterprises' green innovation [13, 14].

Supply chain enterprises recognize that the innovation cooperation between upstream and downstream enterprises favors integration of internal and external innovation resources to earn greater profit margins. As majority of enterprises are still without green innovation, technology spillovers will improve the influence of innovation within the green chain but would undermine the effect outside. In other words, when the free-riding enterprises suffer from both horizontal and vertical technology spillovers, they will also reduce pollution emission. So, we call these enterprises that do not innovate free-riders, whose existence severely hinders the reform of green management [15]. Cappelli [16] empirically analyzed the impact of the source of technology spillover on innovation and found that technology spillovers from companies in the same industry are easy to induce competitors to imitate, and the transfer of innovation advantages has a negative impact on the innovating manufacturers. Therefore, the free-riders' consequent on technology spillovers are very unfavorable to innovating enterprises.

However, the existing research shows that free-riding enterprises are rarely considered within the research framework. The research on technology spillover focuses on the bidirectional (or unidirectional) spillover of the participants in innovation decision-making, disregarding the free-ride behavior, and the spillover consequences for competitors are disregarded in the decision model. Therefore, the present study, assuming that technology spillovers (one-way flow) exist in free-riding manufacturers, complements the existing research by addressing the following issues:

(1) Whether the enterprise will transform from free-riding to innovation based on the impact on the optimal innovation decision of green manufacturers and green suppliers and by comparing the emissions and profits of the two types of manufacturers.

(2) Whether chain innovation cooperation will lead manufacturers to switch from free-riding to innovation when the green manufacturer and green supplier engage in innovation cooperation based on the impact on their optimal innovation decision and by comparing the emissions and profits of green innovation manufacturers before and after cooperation.

(3) Whether innovation cooperation in the green supply chain can improve supply chain profits and reduce emissions.

To address these issues, a supply chain model with two types of manufacturers (green innovation and free-riding) and a shared green supplier was established. The green manufacturer and the green supplier reduced emissions in the production process. The demand for products produced by these manufacturers is determined by the amount of emissions, and their products compete in the same product market. In the case of vertical innovation noncooperation and cooperation in the green supply chain, the impact of asymmetric technology spillover on the optimal innovation decision of the green manufacturer and the green supplier is considered. In the profit-maximizing decision, the cost of innovation as well as that of the emission treatment is considered in the present study, which makes it unique from other studies. Given that the long-term impact of corporate innovation input on emissions, the static analysis framework is extended to dynamic situations. We use differential game theory to describe the dynamic characteristic. The essence of this theory is to solve the optimal control problem of two or more participants, which can better address the dynamic game problem between supply chain members, such as supply chain cooperation advertising [17], the coordination mechanism of supply chain cooperation [18], and supply chain emission reduction strategy [19]. Using the emissions of supply chain enterprises as state variables to build a differential game model, the dynamic trend of emissions and corporate profits over time are examined, and conclusions are offered from a long-term steady-state perspective.

This study is presented as follows. Section 2 presents the literature, and Section 3 provides a differential game model as well as an explanation of some parameters and assumptions to examine the optimal innovation decision and steady-state equilibrium of green supply chain enterprises under noncooperation and cooperation. Section 4 indicates the impact of innovation cooperation and technology spillovers on enterprise innovation decisions, and Section 5 compares the two situations through numerical analysis. Finally, Section 6 presents the results and conclusions.

2. Literature Review

Green supply chain innovation has been extensively studied. This field is basically an intersection of two research fields: green supply chain management and technological innovation. Some empirical studies have found that green innovation has a favorable influence on the supply chain. For example, Lee et al. [20] used data from 133 Malaysian manufacturing enterprises to confirm that technological innovation not only improves the environment but also favors eco-design, investment recovery, and technological innovation. De Marchi [21] used the data of Spanish manufacturing enterprises to study the relationship between corporate innovation cooperation and green innovation and argued that the focus should be more on external cooperation, such as suppliers and universities, than on other innovations. It also found that there is a substitution effect between cooperation and internal R&D efforts. Green innovation cooperation with upstream suppliers can lead to higher environmental performance [22]. When enterprises need to change their inputs to create new products, establishing a strong cooperative relationship with suppliers may be the best strategic choice [23, 24]. Dai et al. [25] studied the R&D cooperation behavior of upstream and downstream enterprises in the green supply chain, compared the three scenarios of cartelization, cost-sharing contract, and a benchmark of noncooperation, and introduced the technical differences between the members of the supply chain and consumers' green awareness as well as the influence of government subsidy parameters on cooperative behavior. The results showed that upstream enterprises are always likely to adopt cartel rather than noncooperation models, which favors the cartel. The downstream enterprises generally prefer the cooperation model. However, if the market is more sensitive to green and government subsidies which are strong, downstream enterprises can earn more revenue through a cartel. From the perspective of the overall supply chain, cooperation has more benefits than noncooperation. Upstream suppliers are the best partners for green innovation in supply chain enterprises. However, majority of studies have focused on the cooperation problem of green innovation enterprises in the chain and rarely included innovative enterprises. Therefore, the present study addresses this gap and considers the enterprises that do not include green innovation into the decision-making framework.

Several studies have examined the impact of technology spillovers [26, 27]; D'Aspremont and Jacquemin [28] first studied the duopoly two-stage game model (AJ model). They highlighted that the spillover effect favors improved social welfare and increased research and development (R&D) investment of enterprises. Several other researchers extended the study on this model and applied it to multiple fields. Steurs [29] combined different technology spillover parameters within and between industries to achieve effective R&D investment levels. From the perspective of increasing sales, vertical spillovers between industries can increase product output more than horizontal spillovers within industries that can increase social welfare. From the technological innovation perspective, Ge et al. [9] discussed vertical innovation and cooperation behavior of supply chain enterprises that can reduce the production cost based on endogenizing technology spillover and cartelization as two means of cooperation. Considering the impact of spillovers on production costs, Shibata [30] studied the issue of innovation investment in different market structures and found that, in a duopoly market, noncooperation innovation investment, in contrast with innovation cooperation, is likely to exhibit less technology spillover. When the market tends to be perfectly competitive, technology spillover has no effect regardless of cooperation. Several studies contend that technology spillovers can improve supplier's reliability [31].

The common factor in the aforementioned studies is the positive externality to economic activities. However, the supply chain decisions resulting from various manifestations also differ. Green innovation results in emission reduction through technology spillovers, thereby increasing the demand in green-sensitive markets and increasing revenues. Besides, unlike other spillovers, owing to the external impact on the environment, the cost of emission treatment for enterprises reduces. Therefore, this spillover effect is affected by the type of market and the extent of environmental regulation. Therefore, the present study considers the two aspects of the spillover of green innovation technology, which provides an accurate reference for enterprises to make green innovation decisions.

Extant literature analyzes the horizontal and vertical technology spillovers of supply chain enterprises, and it is inevitably associated with innovation cooperation to examine the impact of technology spillovers on the cooperation model. However, from the supply chain structure perspective, majority of extant literature focuses on a "one-to-one" type supply chain, and a "one-to-many" or "many-to-one" type supply chain is more consistent with the real situation. Results of past research are combined to examine the "one-to-two" (i.e., one supplier and two manufacturers) supply chain, of which, two manufacturers (green innovation and free-riding) constitute a duopoly market. For a green manufacturer, the technology spillover with suppliers is bidirectional and that with free-riding manufacturers is unidirectional. A free-riding manufacturer enjoys both vertical and horizontal technology spillovers. In this case, technology spillovers are asymmetrical. Therefore, it is important to analyze the green innovation decisions and cooperation strategies of enterprises.

3. The Model

A model that contains a green manufacturer (H), a free-riding manufacturer (L), and a shared green supplier (S) which is considered in the present study. The green manufacturer and the green supplier reduce pollutant emissions in the production process through green innovation activities. At the same time, the green supplier has provided green raw materials or components for undertaking technology spillovers to the downstream, assuming similarities between the manufacturers. The green manufacturer also spills over technology to the supplier and the free-riding manufacturer. For convenience, it is also assumed that there is no difference in the extent of spillovers. Because of the technology spillover, the pollutant emissions from the free-riding manufacturer will also be impacted by the innovation activities of the upstream supplier and the green manufacturer. The game participants (i.e., the green manufacturer and the green supplier) make green innovation decisions in time $t \in [0, +\infty)$; $z(t)$ and $u(t)$ are the degree of green innovation efforts at the moment t, assuming the green innovation efforts are all positive. The amount of pollutant emissions can be altered periodically by adjusting the degree of green innovation efforts $e_i(t)$ [32] at the moment t, where $i = H, L, S$, $e_i(0) = e_{i0}$:

$$\frac{de_H(t)}{dt} = q_H(t) - z(t) - \beta u(t) - \eta e_H(t), \quad (1)$$

$$\frac{de_L(t)}{dt} = q_L(t) - \alpha z(t) - \beta u(t) - \eta e_L(t), \quad (2)$$

$$\frac{de_S(t)}{dt} = Q - \alpha z(t) - u(t) - \eta e_S(t), \quad (3)$$

where $\alpha \in [0,1]$ and $\beta \in [0,1]$ are the technology spillovers of the green manufacturer and the supplier. $\eta > 0$ denotes the natural mitigation rate, which implies that when there is no green innovation, the emission is reduced because of the technological progress, assuming that the three enterprises are at the same level of technological progress. q_H and q_L are denoted as the manufacturer's production volume, assuming that one unit of parts can produce one unit of final products; therefore, the total number of components ordered from retailers is $Q = q_H + q_L$. Assuming that the total market to maintain a certain Q is given constant, the manufacturer does not have inventory, that is, sell as much as you produce. The products by both the green and the free-riding manufacturer are homogeneous and can be partially substituted. Given that the production process of both the products yield varying pollutant emissions, consumers could identify them through green labels, etc., which will affect the demand for green products. Therefore, the production volume of the two manufacturers can be assumed to be

$$\begin{aligned} q_H &= \theta Q + s[e_L(t) - e_H(t)], \\ q_L &= (1-\theta)Q + s[e_H(t) - e_L(t)], \end{aligned} \quad (4)$$

where $\theta \in (0,1)$ is the initial market share of green manufacturers. $s \in (0,1)$ denotes the green-sensitive coefficient. In the perfectly competitive market, the total sales volume of an enterprise often depends on its market share and the sales scale of similar products in the market. Therefore, under a duopoly game model, we propose that the sales of two types of manufacturers are affected by market share and competitor emissions, and the green sensitivity coefficient regulates the relationship between market demand and product emissions differences.

Through the aforementioned assumption, the profit margin of the green supply chain members $\rho_i > 0$ is given, $i = H, L, S$, and the instantaneous profit is given by

$$\pi_H(t) = \rho_H q_H(t) - \frac{\varphi_H z(t)^2}{2} - g e_H(t),$$

$$\pi_L(t) = \rho_L q_L(t) - g e_L(t), \quad (5)$$

$$\pi_S(t) = \rho_S Q - \frac{\varphi_S u(t)^2}{2} - g e_S(t).$$

Among them, the square of the green innovation effort is the cost of innovation [28], g is the processing cost per unit of emissions, considering the processing costs of pollutant emissions, which implies that enterprises must examine the targets of minimizing impact on the environment as well when making a green innovation decision.

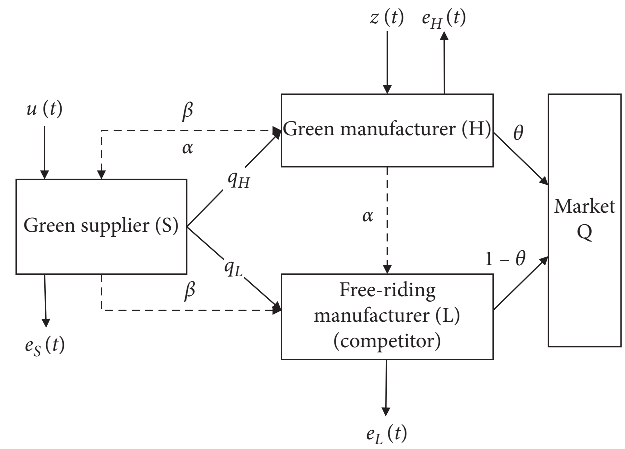


Figure 1: Supply chain structure.

Within an unlimited time frame, the manufacturer and the supplier have the same discount factor $r > 0$ at any time. The long-term profits of the green manufacturers, the free-riding manufacturer, and the green supplier are as follows:

$$\begin{aligned} J_H &= \int_0^\infty e^{-rt} \pi_H(t) dt, \\ J_L &= \int_0^\infty e^{-rt} \pi_L(t) dt, \\ J_S &= \int_0^\infty e^{-rt} \pi_S(t) dt. \end{aligned} \quad (6)$$

Figure 1 illustrates the logic framework of this study. The parameters in the model are independent of time and are constant. For the convenience of writing, the time t is not listed below.

Notations and definitions are explained in Table 1.

4. Equilibrium Analysis

4.1. Noncooperation Innovation Mode (N). In this model, the green manufacturer and the green supplier make decisions on optimal green innovation efforts to maximize long-term profits, and the decision process is distinguished by superscript N. Therefore, the decision-making problems of the green manufacturer and the green supplier are as follows:

$$\max_z J_H^N = \int_0^\infty e^{-rt} \left[\rho_H (\theta Q + s e_L - s e_H) - \frac{\varphi_H z^2}{2} - g e_H \right] dt, \quad (7)$$

$$\max_u J_S^N = \int_0^\infty e^{-rt} \left[\rho_S Q - \frac{\varphi_S u^2}{2} - g e_S \right] dt. \quad (8)$$

In order to have unique continuous solutions $e_H(t)$ and $e_S(t)$ for (1) and (3), a set of bounded, continuous, and differentiable value functions $V_H^N(e_H, e_L)$ and $V_S^N(e_S)$ should be constructed first to maximize (7) and (8), that is, to solve the equilibrium solution of the noncooperation innovation game. Then, Proposition 1 can be obtained.

Table 1: Notations and definitions.

Notations	Definitions
Decision variables	
$z(t)$	Green innovation effort of the green manufacturer
$u(t)$	Green innovation effort of the green supplier
Parameters and other variables	
$e_H(t)$, $e_L(t)$, $e_S(t)$	Pollutant emissions of green manufacturer, free-rider, and green supplier at time t, with initial emissions $e_i(0) = e_{i0,}$ $i = H, L, S$
α, β	Technology spillovers of the green manufacturer and the supplier, $\alpha \in [0,1]$ and $\beta \in [0,1]$
η	Natural mitigation rate, $\eta > 0$
Q	Market capacity
q_H, q_L	Production volume
θ	Initial market share of green manufacturer, $\theta \in (0,1)$
s	Green -sensitive coefficient, $s \in (0,1)$
ρ_H, ρ_L, ρ_S	Profit margin of green manufacturer, free-rider, and green supplier
φ_H, φ_S	Cost parameter associated with green innovation efforts by green manufacturer and supplier, $\varphi_H > 0$ and $\varphi_S > 0$
g	Processing cost per unit of emissions
r	Discount factor, $r > 0$
$\pi_H(t)$, $\pi_L(t)$, $\pi_S(t)$	Instantaneous profit of green manufacturer, free-rider, and green supplier for $t \in [0, +\infty)$

Proposition 1. *Under the noncooperation innovation mode, the steady-state equilibrium of the green manufacturer and the green supplier is* $(z^{N*}, u^{N*}, e_H{}^{N*}, e_L{}^{N}, e_S{}^{N*})$:

$$\begin{cases} z^{N*} = \dfrac{g(\eta + r + s + \alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}, \\[2ex] u^{N*} = \dfrac{\eta + g}{\varphi_S r}, \\[2ex] e_H^{N*} = \dfrac{1}{\eta^2}\left\{(s - \eta - \alpha s)\left[\dfrac{g(\eta + r + s + \alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right] - \dfrac{\beta\eta(\eta + g)}{\varphi_S r} + Q(s + \eta\theta - 2s\theta)\right\}, \\[2ex] e_L^{N} = \dfrac{1}{\eta^2}\left\{(s - \alpha\eta - \alpha s)\left[\dfrac{g(\eta + r + s + \alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right] - \dfrac{\beta\eta(\eta + g)}{\varphi_S r} + Q(s + \eta - \eta\theta - 2s\theta)\right\}, \\[2ex] e_S^{N*} = \dfrac{1}{\eta}\left[Q - \dfrac{\eta + g}{\varphi_S r} - \dfrac{\alpha g(\eta + r + s + \alpha s) + \alpha\rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right]. \end{cases} \tag{9}$$

Proof. According to the optimal control theory, $V_H^N(e_H, e_L)$ and $V_S^N(e_S)$, for any $e_H \geq 0$, $e_L \geq 0$, and $e_S \geq 0$, would satisfy the Hamilton–Jacobi–Bellman (HJB) equation; let $V'_{ij} = \partial V_i / \partial e_j$, $i, j = H, L, S$,

$$rV_H^N(e_H, e_L) = \max_z\left[\rho_H(\theta Q + se_L - se_H) - \frac{\varphi_H z^2}{2} - ge_H + V_{HH}^{N'}\frac{\mathrm{d}e_H(t)}{\mathrm{d}t} + V_{HL}^{N'}\frac{\mathrm{d}e_L(t)}{\mathrm{d}t}\right], \tag{10}$$

$$rV_S^N(e_S) = \max_u\left[\rho_S Q - \frac{\varphi_S u^2}{2} - ge_S + V_{SS}^{N'}\frac{\mathrm{d}e_S(t)}{\mathrm{d}t}\right]. \tag{11}$$

Consider the first-order partial derivative of (10) and (11) with respect to z and u and make them equal to zero to derive

$$\begin{cases} z = -\dfrac{V_{HH}^{N'} + \alpha V_{HL}^{N'}}{\varphi_H}, \\ u = -\dfrac{V_{SS}^{N'}}{\varphi_S}. \end{cases} \tag{12}$$

Substitute (12) into (10) and (11) and simplify to derive

$$rV_H^N(e_H, e_L) = \left(-\rho_H s - g - sV_{HH}^{N'} - \eta V_{HH}^{N'} + sV_{HL}^{N'}\right)e_H + \left(\rho_H s + sV_{HH}^{N'} - sV_{HL}^{N'} - \eta V_{HL}^{N'}\right)e_L + Q\left(\rho_H\theta + V_{HL}^{N'} - \theta V_{HL}^{N'} + \theta V_{HH}^{N'}\right) + \frac{\left(V_{HH}^{N'} + \alpha V_{HL}^{N'}\right)^2}{2\varphi_H} + \frac{\beta V_{SS}^{N'}\left(V_{HH}^{N'} + V_{HL}^{N'}\right)}{\varphi_S}, \tag{13}$$

$$rV_S^N(e_S) = -(\eta + g)e_S + \rho_S Q + V_{SS}^{N'}Q + \frac{V_{SS}^{N'2}}{2\varphi_S} + \frac{\alpha V_{SS}^{N'}\left(V_{HH}^{N'} + \alpha V_{HL}^{N'}\right)}{\varphi_H}. \tag{14}$$

According to the structure of (13) and (14), it can be assumed that the linear analytical formulas of the optimal value function $rV_S^N(e_S) = -(\eta + g)e_S + \rho_S Q + V_{SS}^{N'}Q + (V_{SS}^{N'2}/2\varphi_S) + (\alpha V_{SS}^{N'}(V_{HH}^{N'} + \alpha V_{HL}^{N'})/\varphi_H)$, $V_S^N(e_S)$ with respect to e_H and e_L are, respectively,

$$\begin{cases} V_H^N(e_H, e_L) = a_1 e_H + a_2 e_L + a_3, \\ V_S^N(e_S) = b_1 e_S + b_2, \end{cases} \tag{15}$$

where a_1, a_2, a_3, b_1, and b_2 are the constants; substitute (20) and its first-order partial derivative with respect to e_H, e_L, and e_S into fd18(13) and (14)fd19 to obtain

$$\begin{cases} a_1^* = -\dfrac{\rho_H s + g + (gs/(r+\eta))}{r + \eta + 2s}, \\ a_2^* = \dfrac{s(\rho_H\eta - g + \rho_H r)}{(r+\eta)(r+\eta+2s)}, \\ a_3^* = \dfrac{1}{r}\left[Q(\rho_H\theta + a_2^* - \theta a_2^* + \theta a_1^*) + \dfrac{(a_1^* + \alpha a_2^*)^2}{2\varphi_H} - \dfrac{\beta(\eta+g)(a_1^* + a_2^*)}{\varphi_S r}\right], \end{cases} \tag{16}$$

$$\begin{cases} b_1^* = -\dfrac{\eta + g}{r}, \\ b_2^* = \dfrac{Q(\rho_S + b_1^*)}{r} + \dfrac{b_1^{*2}}{2r\varphi_S} + \dfrac{\alpha b_1^*(a_1^* + \alpha a_2^*)}{r\varphi_H}. \end{cases} \tag{17}$$

Substituting fd21(16) and (17)fd22 into (12) can derive the optimal innovation efforts of the green manufacturer and the supplier under the independent innovation model. Meanwhile, into fd1(2)–(3), invoking the steady-state conditions $(d/dt)\begin{pmatrix} e_H \\ e_L \\ e_S \end{pmatrix} = 0$, solve the linear equations to obtain the stable value of pollutant emissions, that is, $t \longrightarrow \infty$. Suppose the market capacity is very large to ensure that the stability of pollution emissions is positive, QED.

Furthermore, the optimal profit function of the green manufacturer and the green supplier under R&D noncooperation mode and the profit function of free-riding manufacturers are obtained: $J_H^{N*}(e_H, e_L) = e^{-rt}V_H^{N*}V(e_H, e_L)$, $J_S^{N*}(e_S) = e^{-rt}V_S^{N*}(e_S)$, and $J_L^N(e_H, e_L) = e^{-rt}V_L^N(e_H, e_L)$, where

$$
V_L^N(e_H, e_L) = l_1 e_L + l_2 e_H + l_3,
$$

$$
\begin{cases}
l_1 = \dfrac{(\eta + r)(g + \rho_L s) + gs}{(s+\eta)^2 + s^2 - r^2}, \\
l_2 = \dfrac{s(g + \rho_L \eta - \rho_L r + 2\rho_L s)}{(s+\eta)^2 + s^2 - r^2}, \\
l_3 = \dfrac{1}{r}\Big[Q(1-\theta)(\rho_L\theta + l_1) + Q\theta l_2 - (\alpha l_1 + l_2) z^{N*} \\
\quad - (l_1 + l_2)\beta u^{N*}\Big].
\end{cases}
\tag{18}
$$

The calculation of the profit function of the free-riding manufacturer is consistent with the proof derived earlier, and the profit under the situation of noncooperation innovation of the green manufacturer and the green supplier can be obtained by bringing in the optimal control variable. From the value function, a_1^*, a_2^*, and b_1^* are in fact the profit margins of the green manufacturer and the supplier in terms of pollution emissions. $a_1^* < 0$ explains that pollution emissions have a negative impact on the green manufacturer's profit, while the positive and negative judgments of a_2^* are related to $\rho_H(\eta + r) - g$. If $\rho_H(\eta + r) > g$, increasing emissions from the free-riding manufacturer can increase profits for the green manufacturer, while decreasing emissions can decrease the profits. a_3^* and b_2^* are the profits when the pollutant emissions are 0. The expression of green innovation efforts shows that optimal innovation efforts are guaranteed to be larger than zero. Static optimal control can be obtained by solving the HJB equation, which is the result of solving the linear value function. Such a strategy is more functional in enterprise innovation practice, and the optimal strategy in the continuous time range is not related to time, fairly demonstrating the management significance of the model.

According to Proposition 1, Propositions 2 and 3 can be obtained by analyzing the influence of related factors on the equilibrium strategy. □

Proposition 2

(1) *Under the noncooperation innovation mode, the optimal innovation efforts of green suppliers are positively related to the treatment cost per unit of emissions, negatively related to the cost coefficient and discount factor, and not related to technology spillovers.*

(2) *Under the noncooperation innovation mode, the optimal innovation efforts of green manufacturers is independent of the initial market share and are positively related to the marginal revenue per unit product and emission treatment cost per unit.*

(3) *Under the noncooperation innovation mode, when $\rho_H(\eta + r) > g$, $(\partial z^{N*}/\partial\alpha) < 0$ and $(\partial z^{N*}/\partial s) > 0$, and when $\rho_H(\eta + r) < g$, $(\partial z^{N*}/\partial\alpha) > 0$ and $(\partial z^{N*}/\partial s) < 0$.*

Proposition 2 (1) and (2) illustrate the relationship between optimal innovation efforts and parameters of green suppliers and manufacturers under the noncooperation innovation mode. Proposition 2 (3) explains that the impact of technology spillovers and green sensitivity coefficients on green manufacturers' innovation efforts is related to unit marginal revenue and unit emission process cost. The unit marginal revenue considering the natural emission reduction rate and the discount factor is still greater than the unit emission process cost; the greater the horizontal technological spillover of green manufacturers to free-riders is, the lower the innovation efforts would be. As technology spillover will weaken the difference between the emissions of the two types, it is not conducive to green manufacturers' exclusively extracting the high profits of innovation, due to lower motivation to innovation. In this case, most green manufacturers will file for patent application and other technical blockades to raise technical barriers and reduce technology spillovers as possible. Meanwhile, the greater the green sensitivity of the market is, the higher the innovation efforts would be because the increased sensitivity will increase the sales of innovation products, and consumers are willing to pay for low-emission products even for higher prices, which will stimulate green manufacturers increase the level of green innovation efforts, increase the green difference between alternatives, and thus increase revenue.

When the unit product revenue is lower than the unit emission process cost, the greater the horizontal technology spillover of green manufacturers to free riders is, the higher the innovation efforts would be. This is because the innovation result of green manufacturers is to be less economical than ecological. To reduce emissions and the cost of treatment, it is more likely to set new innovation standards in the same industry and encourage enterprises to become setters. From the government's point of view, the manufacturer's unit processing cost can be regarded as the government's environmental regulation measures. When the government promotes a certain green technology, it can promote the enterprise's technological exchange by increasing the regulation cost. Meanwhile, the greater the green sensitivity of the market is, the lower the innovation efforts would be. Because the profits of green products are smaller, consumers are reluctant to pay for green innovation. The increasing sales owing to the improvement of green sensitivity cannot compensate for the additional cost, so innovation efforts for green manufacturing cannot have a positive impact.

Proposition 3. *As the technological spillovers of green manufacturers increase, the gap between the steady emission of green manufacturers and free-riding manufacturers gradually narrows, and when $\rho_H(\eta + r) > g$, the rate of shrinkage slows down; when $\rho_H(\eta + r) < g$, the rate of shrinkage increases.*

Proposition 3 shows that when the margin revenue far outweighs the treatment cost of unit emissions, in the long term, a smaller technology spillover can reduce the eventual emissions of free-riding manufacturers significantly. However, when the margin revenue per unit product is significantly lesser than the treatment cost of unit emission, a large technology spillover can reduce the final emission of free-riding manufacturers. In contrast with the conclusion of Proposition 2, in the initial stage of the green technology innovation, the government can reduce the cost of emission treatment, such as relaxing regulations and encouraging green enterprises to strengthen innovation, while the lateral technology spillover to the competitors is small. However, in the long term, the amount of pollutants discharged by competitors will also significantly narrow the gap between green enterprises and competitors. When the green technology is in the mature stage, the government can enhance the treatment cost by imposing a more stringent environmental protection tax and encouraging enterprises to increase the spillover. After long-term stability, the amount of emission discharged by free-riding manufacturers will be almost similar to that of green manufacturers.

Proof. Let $f(\alpha) = e_L^{N*} - e_H^{N*}$ and $\partial f(\alpha)/\partial\alpha = -(\eta g + rg + 2\alpha gs + 2s\rho_H \quad (1-\alpha)(\eta + r))/(\eta\varphi_H(\eta + r)(r + \eta + 2s)) < 0$; $f(\alpha)$ is judged to be monotonically decreasing, and $(\partial^2 f(\alpha)/\partial\alpha^2) = ((2s(\rho_H\eta + \rho_H r - g))/(\eta\varphi_H(\eta + r)(r + \eta + 2s)))$; when $\rho_H(\eta + r) > g$, $f(\alpha)$ is convex; when $\rho_H(\eta + r) > g$, $f(\alpha)$ is concave.

The calculation of the trajectories of pollutant emissions of both the green and the free-riding manufacturer can refer to Proposition 1, take derivative of formula (1) with respect to time to obtain $(\mathrm{d}^2 e_H/\mathrm{d}t^2) = s(\mathrm{d}e_L/\mathrm{d}t) - (s + \eta)(\mathrm{d}e_H/\mathrm{d}t)$ and combine it with (2) to obtain $e_L(t)$, and then substitute (1) and resolve to obtain the second-order differential equation: $-(1/(s+\eta))(\mathrm{d}^2 e_H/\mathrm{d}t^2) + 2(\mathrm{d}e_H/\mathrm{d}t) + (s + \eta - (s^2/(s+\eta)))e_H = \theta Q - z_N^* - \beta u_N^*$; according to the boundary conditions $e_H(0) = e_0$ and $e_H(\infty) = e_H^{N*}$, the green manufacturer's optimal emission trajectory can be obtained:

$$e_H^N(t) = e_H^{N*} + (e_0 - A)e^{-(s+\eta)\left(\sqrt{2-\left(s^2/(s+\eta)^2\right)t}-1\right)} - \left(e_H^{N*} - A\right)e^{-2(s+\eta)\left(\sqrt{2-\left(s^2/(s+\eta)^2\right)t}\right)}, \tag{19}$$

where $A = ((s+\eta)(\theta Q - z_N^* - \beta u_N^*))/((s+\eta)^2 - s^2)$. Furthermore, the emission trajectory of the free-riding manufacturer can be solved as follows:

$$e_L^N(t) = \frac{B}{\eta+s} + e^{-(\eta+s)t}\left[e_0 - \frac{B}{\eta+s}\right] + \frac{s}{\eta+s}\left[e_H^{N*} + (e_0 - A)e^{-(s+\eta)\left(\sqrt{2-\left(s^2/(s+\eta)^2\right)}-1\right)t} - \left(e_H^{N*} - A\right)e^{-2(s+\eta)\left(\sqrt{2-\left(s^2/(s+\eta)^2\right)t}\right)}\right]\left(1 - e^{-(\eta+s)t}\right), \tag{20}$$

where $B = (1-\theta)Q - \alpha z_N^* - \beta u_N^*$. Similarly, the trajectory of pollutant emissions from the green supplier can be obtained as follows: $e_S^V(t) = e_S^{N*} + (e_0 - e_S^{N*})e^{-\eta t}$. □

4.2. Green Supply Chain Cooperation Mode (V). The green manufacturer and supplier cooperate in innovation and jointly determine the extent of green innovation efforts to maximize the profit of the green supply chain, which is indicated by the superscript V. At this time, the profit of the green supply chain at time t is $\pi_g(t) = \pi_H(t) + \pi_s(t)$, and the innovation decision of the green supply chain is

$$\max_{z,u} J_G^V = \int_0^\infty e^{-rt}\pi_G \mathrm{d}t. \tag{21}$$

Proposition 4. *Under the green supply chain cooperation mode, the steady-state equilibrium existing in the green supply chain is* $(z^{V*}, u^{V*}, e_H^{V*}, e_L^V, e_S^{V*})$:

$$\begin{cases} z^{V*} = \dfrac{g(\eta + r + s + \alpha\eta + \alpha r + 3\alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}, \\ u^{V*} = \dfrac{g(\alpha+\beta)}{\varphi_S(\eta + r)}, \\ e_H^{V*} = \dfrac{1}{\eta^2}\left\{(s - \eta - \alpha s)\left[\dfrac{g(\eta + r + s + \alpha\eta + \alpha r + 3\alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right] - \dfrac{\beta\eta g(\alpha+\beta)}{\varphi_S(\eta + r)} + Q(s + \eta\theta - 2s\theta)\right\}, \\ e_L^V = \dfrac{1}{\eta^2}\left\{(s - \alpha\eta - \alpha s)\left[\dfrac{g(\eta + r + s + \alpha\eta + \alpha r + 3\alpha s) + \rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right] - \dfrac{\beta\eta g(\alpha+\beta)}{\varphi_S(\eta + r)} + Q(s + \eta - \eta\theta - 2s\theta)\right\}, \\ e_S^{V*} = \dfrac{1}{\eta}\left[Q - \dfrac{g(\alpha+\beta)}{\varphi_S(\eta + r)} - \dfrac{\alpha g(\eta + r + s + \alpha\eta + \alpha r + 3\alpha s) + \alpha\rho_H s(1-\alpha)(\eta + r)}{\varphi_H(\eta + r)(\eta + r + 2s)}\right]. \end{cases} \tag{22}$$

The proof is the same as Proposition 1 and hence omitted.

Furthermore, the optimal value function of the profit of the green manufacturer and the green supplier and the profit function of the free-riding manufacturer can be obtained:

$$
\begin{aligned}
&J_G^{V*}(e_H, e_L, e_S) = e^{-rt} V_G^{V*}(e_H, e_L, e_S),\\
&V_G^{V*}(e_H, e_L) = c_1 e_H + c_2 e_L + c_3 e_S + c_4,\\
&\begin{cases}
c_1 = -\dfrac{\eta g + gr + gs + \eta\rho_H s + r\rho_H s}{(\eta + r)(\eta + r + 2s)},\\[2ex]
c_2 = \dfrac{\rho_H s(\eta + r) - gs}{(\eta + r)(\eta + r + 2s)},\\[2ex]
c_3 = -\dfrac{g}{\eta + r},\\[2ex]
c_4 = \dfrac{1}{r}\Big[\rho_S Q + \rho_H \theta Q - \dfrac{\varphi_H}{2} z^{V*2} - \dfrac{\varphi_S}{2} u^{V*2}\\
\quad +(\theta Q - z^{V*} - \beta u^{V*}) c_1\\
\quad +(Q - \theta Q - \alpha z^{V*} - \beta u^{V*}) c_2\\
\quad +(Q - z^{V*} - u^{V*}) c_3\Big],
\end{cases}\\
&J_L^V(e_H, e_L) = e^{-rt} V_L^V(e_H, e_L),\\
&V_L^V(e_H, e_L) = m_1 e_L + m_2 e_H + m_3,
\end{aligned}
\tag{23}
$$

where the shadow price of the free-riding manufacturer's unit emissions is not impacted under these two innovation models; therefore, $m_1 = l_1$, $m_2 = l_2$, *and* $m_3 = (1/r)[Q(1-\theta)(\rho_L \theta + l_1) + Q\theta l_2 - (\alpha l_1 + l_2) z^{V*} - (l_1 + l_2)\beta u^{V*}]$; *substituting the steady-state equilibrium solution of Proposition 2 into the steady-state equation can also find the trajectory of pollution emissions under the cooperation innovation model,* $e_H^V(t)$, $e_L^V(t)$, *and* $e_S^V(t)$, *and the formula is identical, except that the best green innovation efforts are replaced, and so it is not repeated here.*

5. Comparison and Analysis

Based on the equilibrium analysis of the two models, three problems are solved through a comparative analysis: (1) whether competing in the homogeneous product market can encourage enterprises to change from free-riding to innovation; (2) whether the green supply chain members are willing to innovate and cooperate; and (3) the impact of technology spillover on the enterprise's green innovation decision and cooperation strategy. Owing to the high complexity of the earlier analytical solutions, numerical methods are preferred. The baseline values of parameters are shown in Table 2.

5.1. Green Innovation Decision of a Free-Riding Manufacturer. The impact on the free-riding manufacturer under the two models is analyzed from the perspective of dynamic emissions, demand, and dynamic profit. Figure 2 shows that, under the benchmark parameter setting, the emission trajectories in both the modes have a time-stable trend, which indicates that even if the emission amount deviates from the stable state because of the interference from factors such as green technology, it would return as time evolves. Meanwhile, the upward trend shows that the emissions of the free-riding manufacturer and the green manufacturer are greater than the initial emissions. A comparison of the emission trajectories of the two types of manufacturers shows that the green manufacturer's emissions are always greater than those of the free-riding manufacturer in the early stage, but quickly stabilize as time evolves, while that of the free-riding manufacturer gradually exceed those of the green manufacturer and gradually stabilize. When the free-riding manufacturer experiences vertical supply chain innovation cooperation, the emissions are higher than that in the noncooperation model. From the perspective of emissions, free-riding manufacturers are encouraged to enhance their issues of emission reduction through technological innovation. The innovative cooperation model of green supply chain is also attractive for innovation for free-riding manufacturers.

Figures 3(a) and 4(a) show that cooperation innovation will reduce sales of the free-riding manufacturer; Figures 3(b) and 4(b) show that cooperation innovation will increase profits. A comparison with the green manufacturer shows that when the free-riding manufacturer dominates the market; the innovation efforts of the green manufacturer is likely to increase the market share of new products, but the effect is insignificant, and they are still not the dominant products in the market. In this case, from the profit perspective, the free-riding manufacturer will choose green innovation when challenged by independent green innovation from competitors and not when confronted by green supply chain cooperation innovation. When the green manufacturer has the same market position as the free-riding manufacturer, the sales volume of the green manufacturer is lower than the latter at the initial stage, but after rapid growth, it eventually surpasses the free-riders. The green manufacturer's profit will be much higher than the free-riding manufacturer' profit to stay abreast with the market changes, and the free-riding manufacturer will choose green innovation. From another perspective, manufacturers who rely on green differences of a product would delay in opening the market, and many short-sighted manufacturers will disregard green production or product R&D activities to earn early profits, while farsighted manufacturers can choose to improve market influence in advance and then promote green innovation strategies to gain competitive advantage for green products.

5.2. Effects of Spillover and Cooperation on the Decision of Green Manufacturers. Calculate the difference between green innovation efforts in two modes:

Table 2: Baseline parameter values.

Q	r	η	s	φ_H	φ_S	ρ_H	ρ_S	ρ_L	e_0	g	β	θ	α
150	0.1	0.5	0.3	2	1	40	30	10	30	4	0.3	0.3	0.3

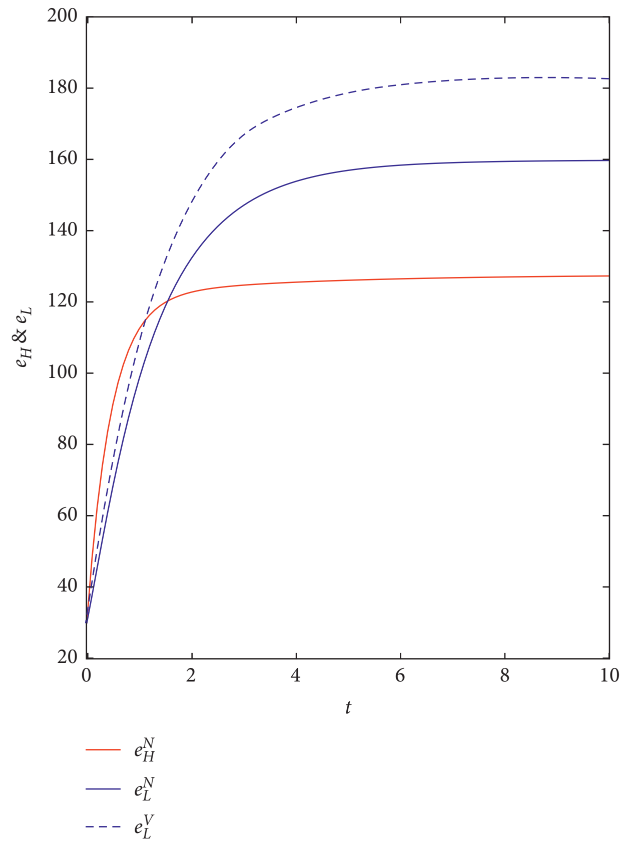


Figure 2: Comparison of the trajectories of the free-riding manufacturer and the green manufacturer.

$$\Delta z(t) = z^{V*}(t) - z^{N*}(t) = \frac{\alpha g}{\varphi_H(\eta + r)} > 0,$$
$$\Delta u(t) = u^{V*}(t) - u^{N*}(t) = \frac{gr(\alpha + \beta) - (\eta + r)(\eta + g)}{\varphi_S r(\eta + r)}. \quad (24)$$

The degree of innovation efforts of the green manufacturer in the cooperation mode is higher than that in the noncooperation mode because the discount factor is small, and it can be determined that $\Delta u(t) < 0$; the degree of innovation efforts of the green supplier in innovative cooperation is lesser than that in noncooperation. When maximizing innovation efforts for goal decision-making, the innovation efforts of manufacturers are higher than those of suppliers. Figures 5(a) and 5(b) show that the green manufacturer's innovation efforts decrease with the increase of their own technology spillovers, and the innovation cooperation with suppliers slows down this reduction rate, indicating that, under the cooperation model, if manufacturers are willing to actively share fully technical information (perfect knowledge share) and still maintain a high degree of innovation efforts and if the green manufacturer does not share technical information with suppliers and competitors, innovation cooperation does not affect the innovation efforts. Under the cooperation mode, green suppliers will increase their innovation efforts with the increase of technology spillovers (including outward spillovers β and inward spillovers α), but there is still a large gap compared with the noncooperation model. This indicates that as the only shared supplier in the product competition market, following innovative cooperation with green manufacturers, and it does not favor suppliers' innovation efforts. This is because suppliers do not need to reduce emissions to increase product sales. There are only two constraints: innovation cost and processing cost. Given the technology spillover from green manufacturers to suppliers, suppliers will pass on the pressure of innovation to manufacturing, which can reduce not only their own emissions but also the cost of innovation.

It is worth noting that the result is the reduction of green innovation spillover on downstream free-riders, and the

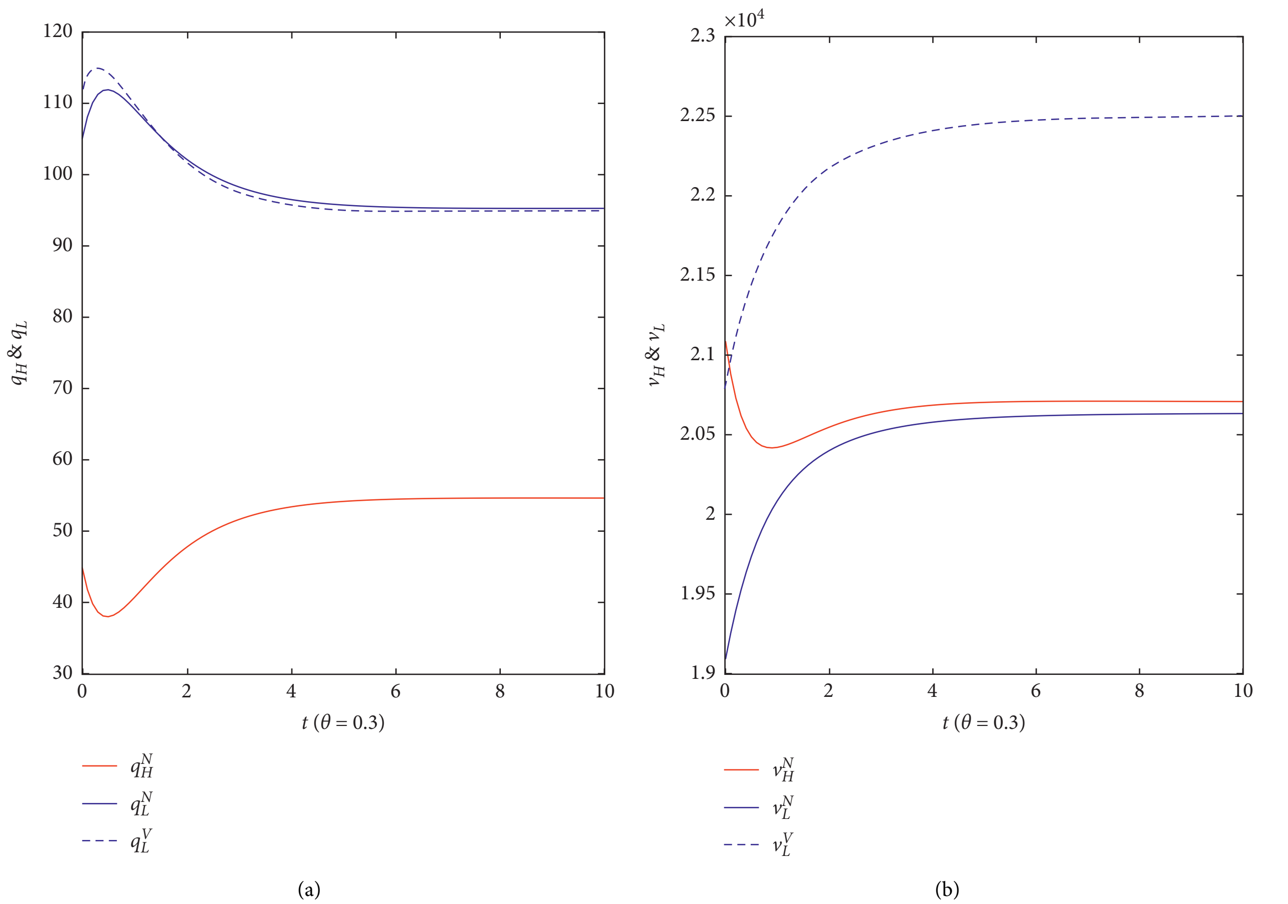


Figure 3: (a) Comparison of dynamic sales of the free-riding manufacturer and the green manufacturer under different modes ($\theta = 0.3$). (b) Comparison of dynamic profits of the free-riding manufacturer and the green manufacturer under different modes ($\theta = 0.3$).

emissions of free-riders are seriously affected, which is consistent with the conclusion of Section 5.1, that is, the emissions of free-riders in the cooperation mode are higher than those in the noncooperation mode.

5.3. Effects of Spillover and Cooperation on the Green Supply Chain Emission and Profit. The impact of cooperation on green supply chain emission reduction and profit is analyzed by comparing the trajectory of emissions and profits before and after the green supply chain cooperation. Let

$$\begin{aligned} \Delta e_G(t) &= e_H^V(t) + e_S^V(t) - e_H^N(t) - e_S^N(t), \\ \Delta V_G(t) &= V_G(t) - V_H^N(t) - V_S^N(t). \end{aligned} \quad (25)$$

Figure 6 shows that the emissions under the noncooperation model are higher than that under the cooperation model. It will stabilize gradually in about 10 periods, and green suppliers will increase their emissions after cooperation. Figure 7 shows that the degree of technology spillover of green manufacturers and the emissions of the green supply chain after cooperation are inversely proportional. This is the result obtained on the basic parameters set in Table 2, simplified and resolved:

$$\Delta e_G^* = \frac{\beta\eta^3\varphi_H g + \beta\eta\varphi_H(\eta g + \eta r - \alpha g r) + \alpha g\varphi_S r(1-\alpha)(\eta + s) + \beta\eta g\varphi_H r(1-\beta)}{\eta^2\varphi_H\varphi_S r(\eta + r)}. \quad (26)$$

$\Delta e_G^*(t) > 0$ and $\partial\Delta e_G^*/\partial\beta > 0$ can be intuitively judged, that is, the larger the extent of the technology spillover of green suppliers, the higher the green supply chain emissions after cooperation.

Based on an analysis, the stable emission reduction is closely related to the innovation efforts. Based on earlier conclusion, the innovation efforts of green suppliers under the cooperation mode are observed to have

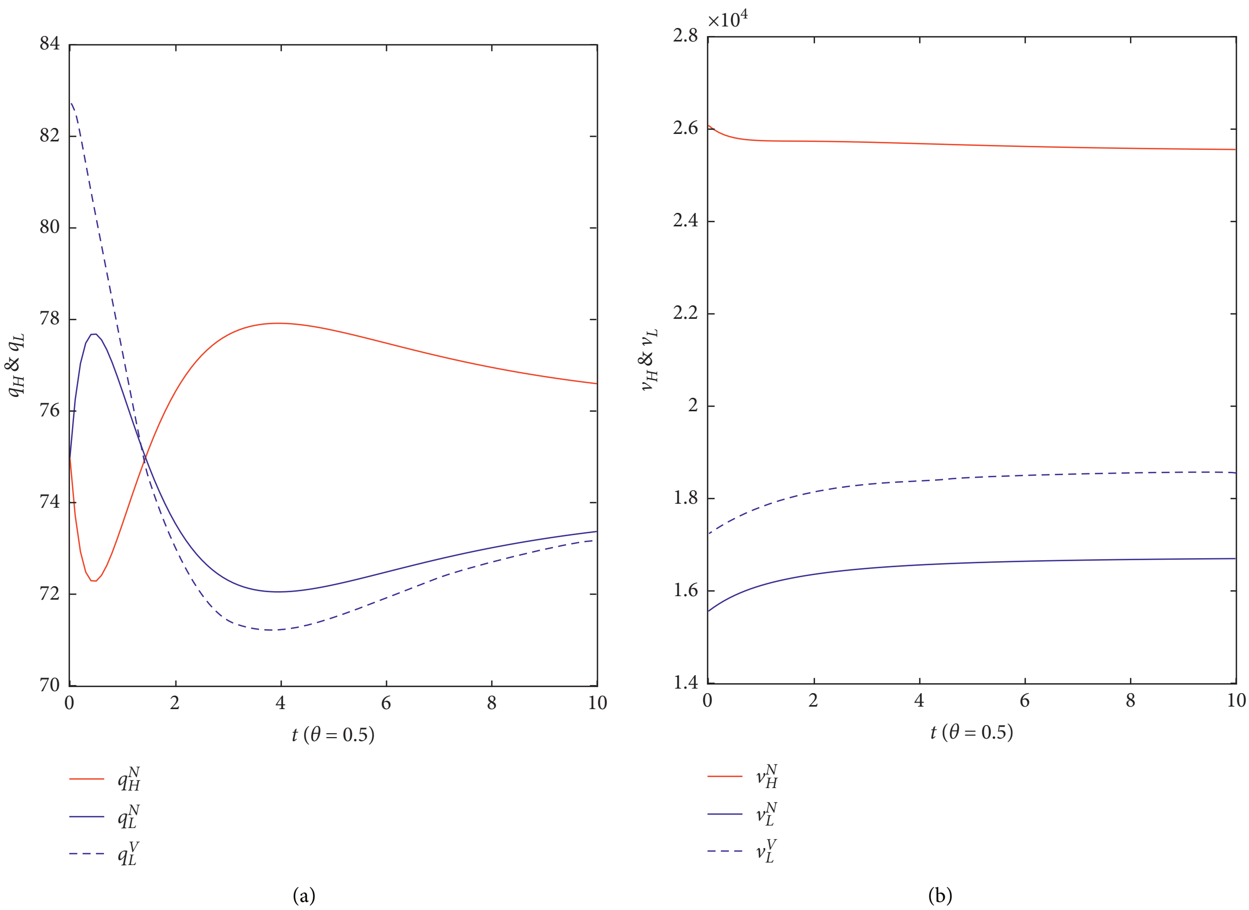
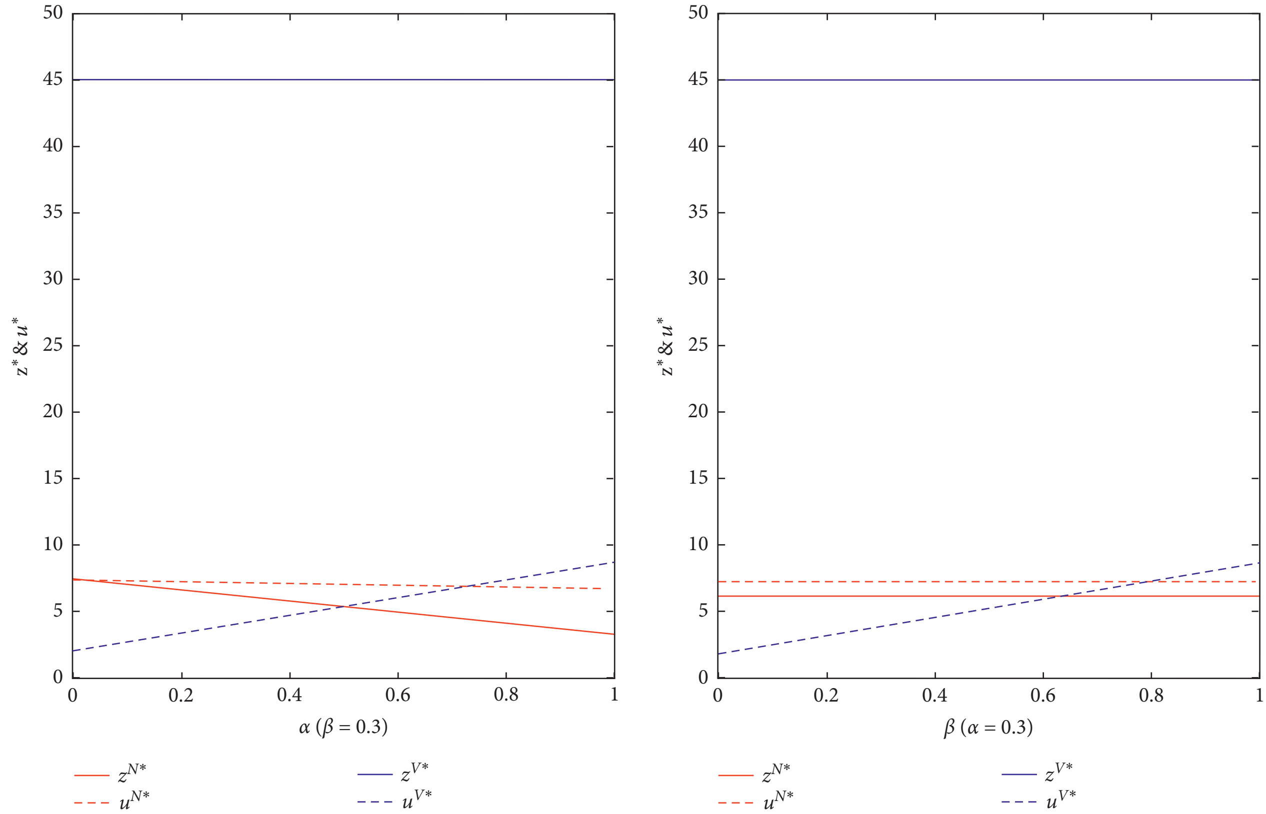


Figure 4: (a) Comparison of dynamic sales of the free-riding manufacturer and the green manufacturer under different modes ($\theta = 0.5$). (b) Comparison of dynamic profits of the free-riding manufacturer and the green manufacturer under different modes ($\theta = 0.5$).

dropped sharply, and the increased innovation efforts of green manufacturers are not enough to offset the impact of the sharp reduction of supplier innovation efforts, and the low level of technological spillovers does not favor green suppliers achieving innovation results from manufacturers, so it is reflected in the increase in emissions after cooperation innovation. It is concluded that the existence of green supply chain innovation cooperation with shared suppliers does not reduce emission, and technological spillovers can well compensate for the gap in emissions.

As shown in Figures 8(a) and 8(b), a comparison of the changes in profit of the green supply chain before and after cooperation shows that gradually the profit is greater than that in the noncooperation model and the gap is gradually widened, and finally stabilizes. Technology spillovers from green manufacturers will widen this gap, while that from green suppliers will narrow this gap. This indicates that, in the case of asymmetric technology spillovers, the innovative cooperation model is more inclined to green manufacturers with high technology spillovers and green suppliers with low technology spillovers. When $\alpha = 1$ and $\beta = 0$, a research cartel comprising green manufacturers was formed, that is, a green supply chain formed a cartel with perfect technology spillovers from manufacturers. This is the organizational form adopted by cooperation innovation trends, which is slightly different from the conclusions by Shibata [30] and Ge et al. [9] on symmetric vertical and horizontal technology spillovers. The research on innovation cooperation on the different roles of technology spillover is extensive.

A comparative analysis of the marginal profit of unit emissions shows that, in the two models of the optimal value function of the supply chain profit, the marginal profit of the emissions of green manufacturers and free-riding manufacturers is equal, while the margin profit of the green suppliers increases ($b_1 < c_3$). It shows that the effect of cooperation and noncooperation on the emissions of the two manufacturers remains unchanged, but under the innovative cooperation model, green suppliers have reduced the profit loss per unit of emissions under the innovative cooperation model. There are fewer constraints, which has reduced innovation efforts and used emissions in exchange for profits. Therefore, green suppliers are more inclined to adopt innovative cooperation models, which is consistent with the conclusion of Dai et al. [25].



(a) (b)

Figure 5: (a) The impact of cooperation models and technology spillovers α on optimal innovation decisions. (b) The impact of cooperation models and technology spillovers β on optimal innovation decisions.

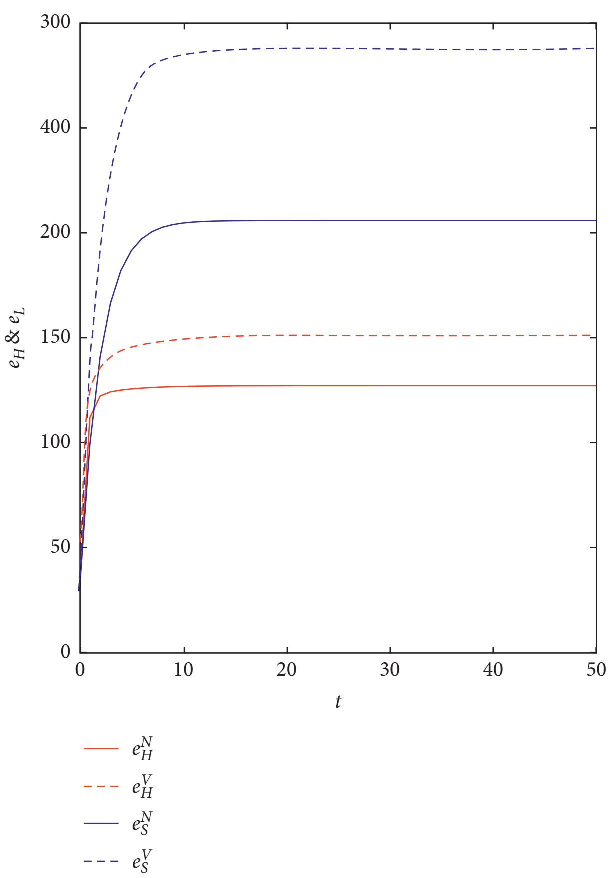


Figure 6: Emission trajectories of green manufacturers and suppliers in two modes.

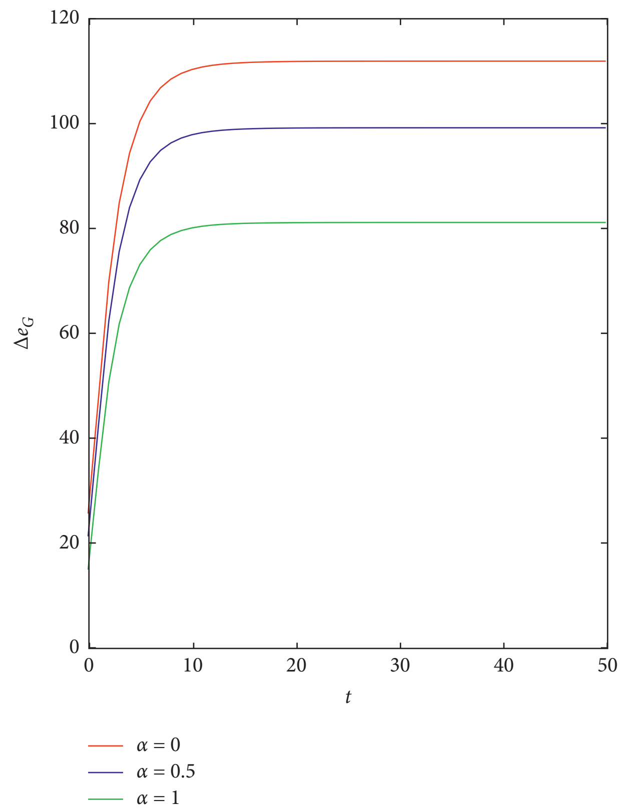


FIGURE 7: Trajectories of $\Delta e_G(t)$.

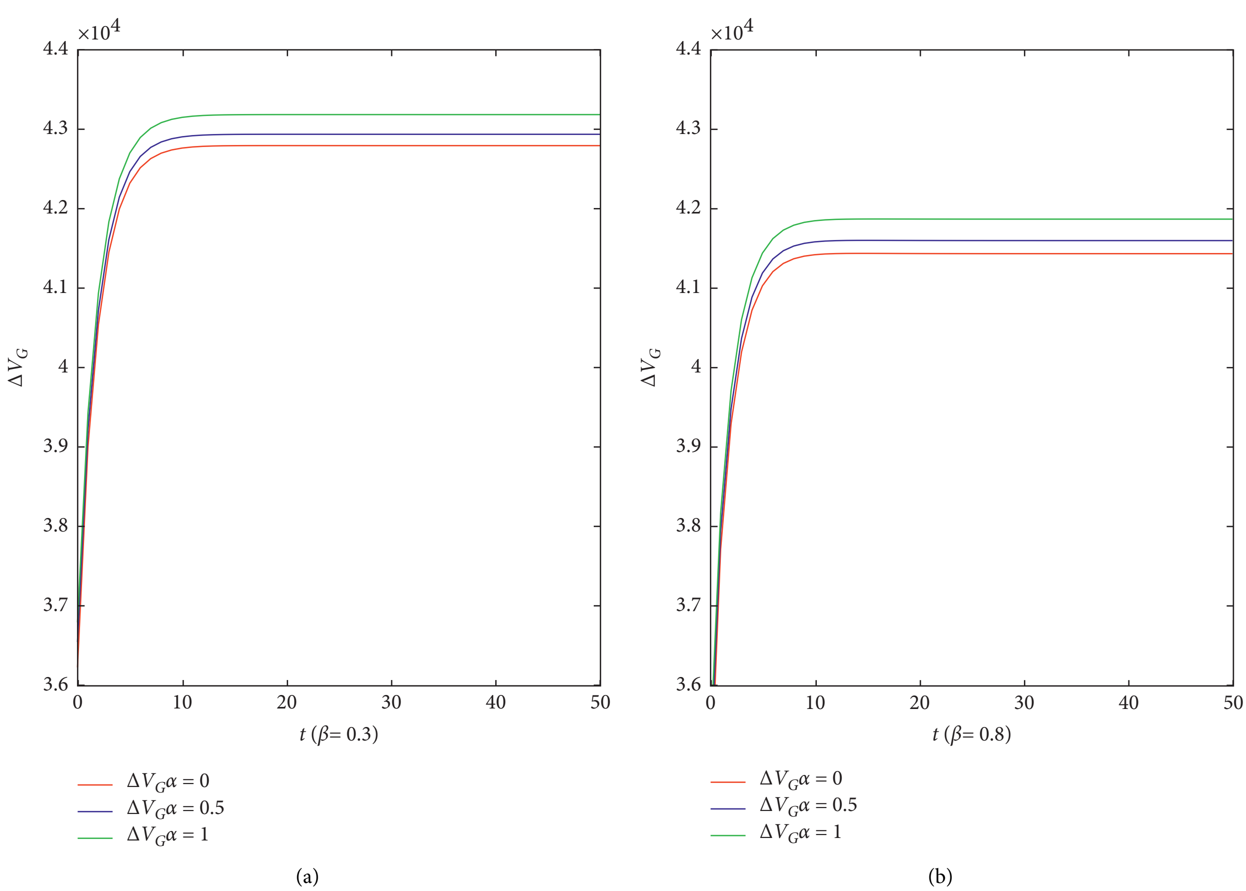


FIGURE 8: (a) Trajectories of $\Delta V_G(t)$ ($\beta = 0.3$). (b) Trajectories of $\Delta V_G(t)(\beta = 0.8)$.

6. Conclusion and Discussion

Given those market players that do not implement green strategies, technology spillovers allow such competitors to enjoy innovations at no cost, which will not only disincentive innovation but also weaken the green innovation effect of the enterprise. Meanwhile, the green innovation behavior of the upstream monopoly enterprises will also be passed on to the downstream enterprises, in which case the company's green innovation decision becomes particularly complicated. When enterprises attempt to reduce emissions in the production process through green innovation, two issues must be considered: (1) the impact of green innovation enterprise's technology spillovers on the emissions of different entities and (2) the impact of green innovation efforts on emissions is dynamic, and the innovation efforts the enterprise at various times have different adjustments to emissions. The present study examined the green innovation decision-making problem of green supply chain enterprises under the green innovation noncooperation and cooperation modes when there is an asymmetric technology spillover in the "one-to-two" supply chain structure and obtained the optimal solution and steady-state equilibrium by the differential game model.

The main conclusions are as follows:

(1) The optimal green innovation efforts of green suppliers and green manufacturers are independent of time. Under the noncooperation mode, the optimal innovation efforts of green suppliers ignore technology spillovers and that of green manufacturers are independent of their technology spillover; the greater the technology spillover, the smaller the gap between emissions from free-riding manufacturers.

(2) Under the noncooperation model, free-riding manufacturers have the incentive to change to green manufacturers, which cannot only reduce emissions but also increase profits. Under the cooperation model, different choices exist under different initial market forces. When free-riding manufacturers have market advantages, they still have greater profits and will not choose green innovation; when the initial market strengths of the two types of manufacturers are equal, nongreen manufacturers are motivated to change to green manufacturers.

(3) Under the cooperation model, green manufacturers will increase green innovation efforts, but green suppliers will significantly reduce green innovation efforts, resulting in increased emissions, and lower technological spillovers of green manufacturers will exacerbate this trend. However, the profit of the green supply chain has been greatly improved, and the technology spillovers of green manufacturers have a positive impact on profits, while that of green suppliers have a negative impact.

Existing literature on green innovation always considers profit as the only positive measure, and the impact on the direct results of innovation is always ignored. Yenipazarli [14] defines the role of eco-efficiency in improving the unit product environmental impact and reduction of production costs. The established objective function only reflects the environmental impact on the sales volume. Chen et al. [33] also only reflect the green innovation efforts on the sales volume. Such assumptions are generally that innovation cannot be distinguished. Therefore, when green innovation is examined, the effect of reducing emissions or the negative impact on the environment must also be considered. The present study draws on the practices of Feichtinger et al. [34] and Ni et al. [35], uses differential game models, and uses emissions as state variables to study the dynamic impact of green supply chain enterprises' innovation decisions and technology spillovers on them to be more targeted to provide green innovation suggestions for enterprises.

This study has certain limitations. It is assumed that green suppliers have the same technology spillovers for both types of manufacturers, and that green manufacturers have the same vertical and horizontal technical spillovers. In fact, the extent of spillover is affected by the company's technical strength, learning ability, or intellectual property protection policies. Therefore, it is necessary to examine the impact of different spillover levels on the stability of innovation cooperation and innovation decisions. In addition, from the perspective of green management in the entire life cycle of the supply chain, green innovation can also be manifested as cost savings (e.g., saving water and energy in green process innovation). However, considering the study focus and simplicity of the solution, the impact on cost is not considered separately. Our analytical framework can be generalized into investigating cooperation among the manufacturer and other stakeholders, such as the retailer, customer, or government. Also, the social welfare and other forms of green innovation should be considered with a holistic modeling framework in the future study.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

This article belongs to the Special section on "Complexity in Economics and Business."

Conflicts of Interest

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

Authors' Contributions

All authors contributed equally to this work.

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