

Research Article

Differential Game Analysis of the Green Innovation Cooperation in Supply Chain under the Background of Dual-Driving

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Taking government environmental regulation and consumer's green preference into a unified analytical framework, this study constructed a differential game model. With the joint effect of supplier and manufacturer green innovation efforts on the dynamic change of the product's green level, it compared and analyzed the long-term dynamic equilibrium strategies of green innovation cooperation in a supply chain under decentralized and centralized decision-making situations. Accordingly, a scientific and reasonable profit-distribution contract was then proposed. On this basis, it further carried out a numerical simulation analysis on the dual-driving effects of the government and market. The results showed that the scientific and reasonable profit-distribution contract under the centralized decision-making situation, which was designed by using the Rubinstein bargaining game model, could effectively ensure that the supply chain members' sharing profits would realize "Dual Pareto Improvements." With the increase of the environmental regulation's intensity, the product's green level kept rising and tended to be stable. However, the overall equilibrium profit of the supply chain was characterized by "U" fluctuation, which first descended and then ascended. In addition, the product's green level, the green innovation investment and equilibrium (distributed) profits of supply chain members, and the overall profits of supply chain all increased with the consumers' green preference.

1. Introduction

The growing concern for environmental protection in recent years has forced countries to pursue low-carbon economics and sustainable development. At the 75th Session of the United Nations General Assembly (2020), China made a solemn commitment to the world that it would adopt more forceful policies and measures to peak its carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060. In China, strengthening environmental supervision will become an inevitable trend in the long term [1]. With the promulgation and implementation of a series of environmental regulations, enterprises have been subjected to increasingly serious administrative penalties for their pollution behaviors, and they have even been faced with the punishment of having their production limited or outright stopped for rectification. Meanwhile, with the continuously improving

social awareness of environmental protection [2], more and more consumers tend to choose green products and are willing to pay higher prices for them to a certain degree [3]. Thus, under the background of stringent environmental regulations and consumers' green preference, the competitiveness and even survival of enterprises increasingly depend on whether they can respond to the requirements of sustainable development [4]. Numerous studies have shown that compared with general innovation, which only emphasizes economic performance, green innovation focuses on saving energy consumption and reducing pollutant emission in the production process through innovation, product development, and process optimization, so as to maximally reduce the negative impact on the environment [5]. Enterprises that implement green innovation often have a stronger competitive advantage than their competitors due to increased eco-efficiency and environmental image [6].

Besides, there is a growing recognition that individual businesses no longer compete as solely autonomous entities but rather as supply chains, in which the enterprises are interdependent [7, 8]. In other words, problems in any part of the supply chain may have a serious negative impact on other participants and can even lead to the rupture and failure of the whole supply chain [9]. On September 14, 2017, Schaeffler Greater China issued an Emergency Help Letter stating that Jielong, the only supplier of needle rolling raw materials in use, was ordered to stop production and dismantle the equipment due to its environmental problems. The supply shortage of needle rolling would result in the suspension of more than 200 models from 49 auto manufacturers. Thus, in the context of strong environmental regulation and green consumption upgrading, it is far from sufficient for enterprises to simply conduct their own environmental management compliance work well. They also need to cooperate with upstream/downstream supply chain partners on green innovation to improve the environmental performance, especially ones in complex industrial chains [10]. Green innovation cooperation in a supply chain refers to the cooperation between upstream and downstream members to carry out green innovation with the purpose of reducing or eliminating the negative impact of products or services on the environment [11]. For example, in order to incentivize the supplier to invest more in green innovation and make the product more environment friendly, the manufacturer is willing to share some of the spending [12]. Compared with other types of cooperation in supply chain, green innovation cooperation is driven not only by market factors (consumers' green preference) but also by government factors (environmental regulation). In practice, more than 1000 big firms, such as Lenovo, Bosch, Dell, and Apple, emphasize the importance of green investment and also motivate the upstream/downstream partners to drive and facilitate green innovation [13].

This paper is relevant to the current literature from two perspectives. The first is that we conducted research into the characteristics and driving factors of green innovation. The addition of the environmental dimension brings green innovation remarkable characteristics, including the explicit demand for environmental benefits, the dual externalities of technology and environment, and the push/pull effect of environmental regulations [14, 15]. Furthermore, the characteristics of dual externalities have severely hindered enterprises from investing in green innovation. Thus, environmental regulation has become an extremely important driving factor for green innovation. For example, the famous Porter hypothesis proposed by Porter and Van der Linde [16] believed that scientific and reasonable environmental regulation can stimulate enterprises' innovative behavior and consequently achieve a win-win situation of economic and environmental benefits. Similar to general innovation, market demand or customer pressure is another important driver of green innovation [17, 18]. The research on the characteristics and driving factors of green innovation has achieved fruitful results, laying a solid theoretical foundation for our study.

Combining the characteristics of green innovation, many scholars investigated the optimal decision and the

influence of the driving factors on the equilibrium strategies in a green supply chain. This is the second part of our literature review. Benjaafar et al. [19] were the first to introduce different carbon emission policies (carbon tax, carbon cap-and-trade, carbon offsets, etc.) into a simple supply chain, providing a basic solution to carbon reduction. Du et al. [20] analyzed the possibility for manufacturers and suppliers to coordinate and cooperate in emission reduction under cap-and-trade emission policy. Chen et al. [21] endogenized government subsidy in a research joint venture and deduced the equilibrium strategies of the innovation effort level and cost sharing ratio. On this basis, many scholars have included market-driven effect into the analytical framework. For example, Zhang and Yousaf [22] and Meng et al. [23] analyzed the optimal innovation decisions in a supply chain by taking the comprehensive influence of government intervention and consumers' green preference into account. However, the above research studies on green innovation cooperation in a supply chain mainly focused on the analysis of static equilibrium strategies.

In fact, the supply chain environment management is a long-term dynamic process, and the effects of green innovation can be intertemporal. By constructing differential equations in which the variables evolve with time, differential game is usually used to analyze the conflict and cooperation problems in dynamic situations [24, 25]. In the recent research studies related to the green supply chain, scholars often use differential game theory to investigate the optimal decisions and the variation with time. Considering the impact of environmental regulation, Wang et al. [26] and Yu et al. [27] introduced carbon tax parameters when constructing the differential game models to explore the dynamic cooperation strategies of the low-carbon technology. Wei and Wang [28] analyzed the interaction between carbon reduction technology innovation and government intervention by using the differential game method. However, they did not take the consumers' green preference into account. Subsequently, Liu and Li [29] introduced low-carbon preference into the differential game models and analyzed the dynamic impacts of low-carbon reference on carbon reduction. Furthermore, Zu and Zeng [30] analyzed the dynamic optimization problem of energy-efficiency efforts and product pricing with considering the discontinuous market demand. However, they did not consider the impact of environmental regulation. Besides, differential game analysis has been well applied in analyzing dynamic equilibrium strategies of advertising investment, quality improvement, and so on [31, 32].

On the basis of the existing research results, we take government environmental regulation and consumers' green preference into a unified analysis framework, using the differential game model to study the cooperative innovation dynamic strategies. In addition, this study also proposes a scientific and rationale profit-distribution contract to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance.

Compared to existing research, the contribution of this paper is mainly reflected in three main aspects:

- (1) This study comprehensively considers the dual-driving effect of government and market on the green innovation cooperation in a supply chain. As far as we can determine, existing studies mainly concentrated on the impact of a single driving factor on green innovation decisions in a supply chain either in terms of consumers' green preference or environmental regulation. There is still little research on the superposed effects of two driving factors. However, government regulation and market demand are the two most important drivers of green innovation [18]. In this study, both government regulation and consumers' green preference are included into the analytical framework when constructing the game models. Moreover, we also analyze and compare the optimal cooperation strategies for green innovation between supply chain members under the decentralized and centralized decision situations.
- (2) This study analyses the optimal decisions dynamically rather than statically by using differential equations to describe the changes of product green level with the supply chain members' innovation efforts. To the best of our knowledge, research on the dynamic equilibrium strategies of the green innovation cooperation in a supply chain is very scarce, especially considering the dual-driving effects of the government and the market. In fact, green innovation, pollutant emissions, market demand, etc. are all dynamic phenomena [30, 33]. The investment of the members' innovation in the prior period will affect the products' green level and the relevant decisions in the next period. Thus, applying differential game theory to analyze the dynamic strategies in this study is closer to the reality of the situation. More importantly, the government and market dual-driving effect is also considered in this study when using differential game to analyze the dynamic strategies. This study will effectively extend the existing research.
- (3) A scientific and rational profit-distribution agreement under the centralized decision situations is proposed in this study. After analyzing the long-term dynamic equilibrium strategies of green innovation cooperation under decentralized and centralized decision situations, this study further designs a profit-distribution agreement by using the Rubinstein bargaining game model to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance. This study can provide a useful reference for the green innovation practice of supply chain members.

The remainder of the article is arranged as follows: Section 2 describes the problem and assumptions of the model. Section 3 discusses and compares the long-term dynamic equilibrium strategies under decentralized and centralized decision-making scenarios. Section 4 provides a profit-distribution contract for the supply chain. Some simulations and sensitivity analysis are given in Section 5. The conclusions and research prospects are given in Section 6.

2. Problem Description and Assumptions

2.1. Problem Description. This article assumes that the green supply chain consists of one large manufacturer (as leader) and one supplier (as follower). In order to meet the consumers' demand for green purchase, the supplier and manufacturer invest in green innovation by introducing new technologies, purchasing new equipment, and transforming existing technological processes, so as to reduce the energy consumption and pollutant emissions in the production process and improve the product's green level. In the context of sustainable development, more and more countries are actively implementing their carbon labeling plans, i.e., marking the carbon emissions of products in the production process with a quantified indicator and implementing the government regulations on the final products according to the carbon emission standards. Drawing from Zu et al. [34], the energy consumption standard and pollutant emissions constraints of the government only focus on the manufacturer without considering the emission cost or benefits incurred by the supplier. Meanwhile, Heydari et al. [35] found that it is more cost-effective for the government to provide subsidies or tax exemption for manufacturers rather than other members in the supply chain. Thus, we assume that the government rewards or punishes the manufacturer according to the product's green level. Besides, the large manufacturer, as the leader, is willing to bear part or all of the green innovation investment costs for supplier, in order to encourage the supplier to increase innovation investment and improve the greenness of their products. The research framework of this paper is shown in Figure 1.

2.2. Assumptions

Assumption 1. The supplier and the manufacturer will work together on green innovation to reduce energy consumption and pollutant discharge per unit product and improve the product's green level. With the passage of time, the product's green level will naturally decline due to the aging and backwardness of emission-reduction technologies, equipment, etc. Drawing from El Ouardighi [36], we modify the classic goodwill model of Nerlove-Arrow [37] according to the characteristics of green innovation to describe the change of product's green level.

$$\dot{E}(t) = \alpha S(t) + \beta M(t) - \sigma E(t), \quad (1)$$

where $E(t) \geq 0$ is the product's green level at time t , and the initial green level $E(0)$ is assumed to be 0. This indicates that the supplier and manufacturer have not invested in green innovation prior to the initial time. $S(t) \geq 0$ and $M(t) \geq 0$, respectively, represent the green innovation efforts of the supplier and manufacturer at time t . $\alpha > 0$ and $\beta > 0$, respectively, represent the marginal contribution rates of green innovation efforts of the supplier and manufacturer to the product's green level. $\sigma > 0$ is the natural decay rate of the product's green level.

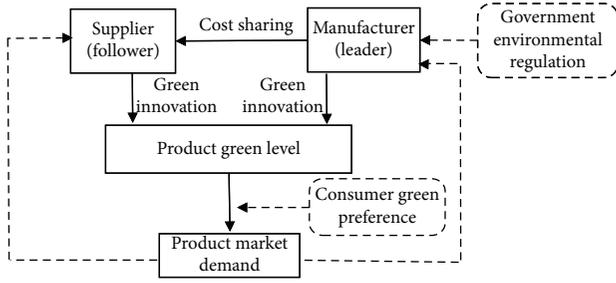


FIGURE 1: Framework of cooperative innovation in a green supply chain under the background of dual-driving.

Assumption 2. Like the method used by most scholars to deal with the green innovation cost, we assume that the green innovation cost of the supplier and manufacturer is a convex increasing function of green innovation efforts, namely,

$$C_S(t) = \frac{\eta_S}{2} S(t)^2, \quad (2)$$

$$C_M(t) = \frac{\eta_M}{2} M(t)^2,$$

where $C_S(t)$ and $C_M(t)$, respectively, represent the cost of green innovation efforts from the supplier and manufacturer at time t . The representation of innovation cost by the quadratic function is commonly used in the literature [29, 34] $\eta_S > 0$ and $\eta_M > 0$ respectively, represent the cost coefficients of green innovation efforts of the supplier and manufacturer.

Assumption 3. Regardless of the influence of green product prices, we assume that consumers with green preference will tend to buy products with higher green level [30, 38], namely,

$$D(t) = \bar{D} + \theta E(t), \quad (3)$$

where $D(t) \geq 0$ is the market demand for green products at time t and $\bar{D} > 0$ is the product market scale before green innovation from the supplier and manufacturer. $\theta > 0$ is the coefficient of consumer green preference, representing the positive impact of the product's green level on the market demand.

Assumption 4. In the context of the low-carbon economy, pollutant discharge behaviors of enterprises are regulated by the government environmental regulation, such as carbon tax, carbon trading, carbon cap, and innovation subsidies. Drawing from Wei and Wang [28], we assume that, in the context of low-carbon policies, the regulation cost or benefit of pollutant emission by enterprises is

$$T_g(t) = \varphi [(E_h - E(t) - E_g)D(t)], \quad (4)$$

where $T_g(t)$ is the regulation cost or benefit generated by pollutant emission of enterprises at time t under environmental regulation. $\varphi > 0$ is the intensity of government regulation, which can be expressed in various forms, such as government carbon tax rate, carbon trading price, and incentive/subsidy for unit emission reduction. $E_h \geq 0$ is the initial pollutant emission of unit product. $E_g \geq 0$ is the amount of pollution emitted per unit of product assigned by the government. Thus, $(E_h - E(t) - E_g)D(t) > 0$ indicates that the actual pollutant emission of the enterprise exceeds the carbon emission limit set by the government, so the enterprise needs to purchase the emission right or pay emission fee (tax). On the contrary, $(E_h - E(t) - E_g)D(t) < 0$ means that the enterprise can sell emission rights or obtain government subsidies. Without loss of generality, we assume $E_g = 0$, namely, $T_g(t) = \varphi (E_h - E(t))D(t)$.

Assumption 5. To encourage the supplier to increase innovation investment, the manufacturer that plays a dominant role in the supply chain will be willing to actively bear part or all of the green innovation costs for the supplier in order to improve the product's green level, expand the market scale, and reduce the costs required to comply with the environmental regulations. $\lambda(t) (0 \leq \lambda(t) \leq 1)$ is the proportion of green innovation cost shared by the manufacturer for the supplier at time t .

Assumption 6. This study aims to explore the optimal decision in green innovation cooperation between upstream and downstream enterprises in the green supply chain under the dual-driving of both government and market, while ignoring the influences of other factors such as product prices, inventory costs, and shortage costs. Without loss of generality, the inventory costs and shortage costs of the members in the supply chain are recorded as 0. π_S and π_M , respectively, represent the marginal profit of the supplier and the manufacturer. At any time, all members of the supply chain have the same discount factor, denoted as $\rho (\rho > 0)$. Supplier, manufacturer, and supply chain variables are, respectively, denoted by the subscripts S , M , and C . As a result, members of the supply chain and their overall long-term profits are as follows:

$$\begin{aligned} J_S &= \int_0^{\infty} e^{-\rho t} \left[\pi_S (\bar{D} + \theta E(t)) - \frac{\eta_S (1 - \lambda(t))}{2} S(t)^2 \right] dt, \\ J_M &= \int_0^{\infty} e^{-\rho t} \left[[\pi_M - \varphi (E_h - E(t))] (\bar{D} + \theta E(t)) - \frac{\eta_M}{2} M(t)^2 - \frac{\eta_S \lambda(t)}{2} S(t)^2 \right] dt, \\ J_C &= \int_0^{\infty} e^{-\rho t} \left[[\pi_S + \pi_M - \varphi (E_h - E(t))] (\bar{D} + \theta E(t)) - \frac{\eta_M}{2} M(t)^2 - \frac{\eta_S}{2} S(t)^2 \right] dt. \end{aligned} \quad (5)$$

In summary, compared with the existing literature, the model constructed in this study has the following differences: (1) using the differential equation to describe the dynamic change of the product's green level; (2) while considering the impact of consumers' green preference on the demands, the environmental regulation intensity is also introduced to describe the cost or benefit of enterprises' environmental behavior.

All of the parameters in this model are atemporal constants. For the convenience of writing, t will not be listed.

3. Model Analysis

3.1. *Decentralized Decision-Making Model.* Under the decentralized decision-making situation, the manufacturer and the supplier have a two-stage Stackelberg game. In terms of the decision-making process, the manufacturer first determines its green innovation efforts and the proportion of green innovation costs to be borne by it for the supplier; then, the supplier further determines its optimal green innovation efforts. The decision-making model is (marked with a superscript D)

$$\begin{cases} \max_{M,\lambda} J_M^D = \int_0^\infty e^{-\rho t} \left[\pi_M - \varphi(E_h - E) \right] (\bar{D} + \theta E) - \frac{\eta_M}{2} M^2 - \frac{\eta_S \lambda}{2} S^2 \Big] dt, \\ \max_S J_S^D = \int_0^\infty e^{-\rho t} \left[\pi_S (\bar{D} + \theta E) - \frac{\eta_S (1-\lambda)}{2} S^2 \right] dt. \end{cases} \tag{6}$$

Theorem 1. *Under the decentralized decision-making situation, the long-term equilibrium strategies of the green innovation cooperation in the supply chain are as follows:*

- (1) *The optimal green innovation efforts of the supply chain members and the proportion of green innovation costs to be borne by the manufacturer for the supplier are*

$$\begin{cases} S^{D*} = \frac{2\alpha m_1^* E^D}{\eta_S} + \frac{\alpha(2m_2^* + s_1^*)}{2\eta_S}, \\ M^{D*} = \frac{2\beta m_1^* E^D}{\eta_M} + \frac{\beta(m_2^* + s_1^*)}{\eta_M}, \\ \lambda^* = \frac{4m_1^* E^D + 2m_2^* - s_1^*}{4m_1^* E^D + 2m_2^* + s_1^*}. \end{cases} \tag{7}$$

- (2) *The optimal trajectory of the products' green level is*

$$E^D(t) = E_{RSS}^D \left(1 - e^{-(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t} \right), \tag{8}$$

where $E_{RSS}^D = ((2m_2^* (\Delta_1 + \Delta_2) + s_1^* (\Delta_1 + 2\Delta_2)) / (2[\sigma - 2m_1^* (\Delta_1 + \Delta_2)]))$ is the stable value of the product's green level under the decentralized decision-making situation when the time factor approaches infinity ($t \rightarrow \infty$).

- (3) *The long-term profits of the supplier, manufacturer, and the whole supply chain are*

$$\begin{cases} J_S^{D*} = s_1^* E_{RSS}^D + s_2^* - s_1^* E_{RSS}^D e^{-(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t}, \\ J_M^{D*} = m_1^* (E_{RSS}^D)^2 e^{-2(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t} - (2m_1^* E_{RSS}^D + m_2^*) E_{RSS}^D e^{-(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t} + \\ m_1^* (E_{RSS}^D)^2 + m_2^* E_{RSS}^D + m_3^*, \\ J_C^{D*} = m_1^* (E_{RSS}^D)^2 e^{-2(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t} - (2m_1^* E_{RSS}^D + m_2^* + s_1^*) E_{RSS}^D e^{-(\sigma - 2m_1^* (\Delta_1 + \Delta_2))t} + \\ m_1^* (E_{RSS}^D)^2 + m_2^* E_{RSS}^D + s_1^* E_{RSS}^D + s_2^* + m_3^*, \end{cases} \tag{9}$$

where $m_1^*, m_2^*, m_3^*, s_1^*$, and s_2^* satisfy the following formula:

$$\left\{ \begin{array}{l} m_1^* = \frac{(\rho + 2\sigma) - \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}}{4(\Delta_1 + \Delta_2)}, \\ s_1^* = \frac{4\theta\pi_S(\Delta_1 + \Delta_2)}{\rho(3\Delta_1 + 2\Delta_2) + 2\sigma\Delta_1 + (\Delta_1 + 2\Delta_2)\sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}}, \\ m_2^* = \frac{2}{\rho + \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}} \{ \theta(\pi_M - \varphi E_h) + \bar{D}\varphi + \\ \frac{\Delta_1\theta\pi_S[\rho + 2\sigma - \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}]}{\rho(3\Delta_1 + 2\Delta_2) + 2\sigma\Delta_1 + (\Delta_1 + 2\Delta_2)\sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}} \}, \\ s_2^* = \frac{\bar{D}\pi_S}{\rho} + \frac{(\Delta_1 + 2\Delta_2)s_1^*m_2^*}{2\rho} + \frac{\Delta_1s_1^{*2}}{4\rho}, \\ m_3^* = \frac{\bar{D}(\pi_M - \varphi E_h)}{\rho} + \frac{m_2^{*2}(\Delta_1 + \Delta_2)}{2\rho} + \frac{\Delta_1s_1^*m_2^*}{2\rho} + \frac{\Delta_1s_1^{*2}}{8\rho}, \\ \Delta_1 = \frac{\alpha^2}{\eta_S}, \\ \Delta_2 = \frac{\beta^2}{\eta_M}. \end{array} \right. \quad (10)$$

Both $(\rho + 2\sigma)^2 \geq 8\theta\varphi(\Delta_1 + \Delta_2)$ and $\sigma \geq 2m_1^*(\Delta_1 + \Delta_1)$ need to be satisfied. For the sake of convenience, the subsequent research, analysis, and numerical simulation are conducted within this range.

Proof. Similar to many scholars, such as Liu and Li [29], Zu et al. [34], and Lu et al. [39], we try to seek a steady-state

feedback Stackelberg equilibrium because the game is played over an infinite time horizon. Backward induction is used to solve the model.

Assume that, after time t , the optimal value function of the supplier's long-term profit is $J_S^{D*}(S) = e^{-\rho t}V_S^D(E)$, and for any $E \geq 0$, $V_S^D(E)$ satisfies the Hamilton–Jacobi–Bellman (HJB) equation:

$$\rho V_S^D(E) = \max_S \left\{ \pi_S(\bar{D} + \theta E) - \frac{\eta_S(1-\lambda)}{2}S^2 + V_S^D(\alpha S + \beta M - \sigma E) \right\}. \quad (11)$$

Find the first-order partial derivative for the supplier's optimal green innovation effort (S) on the right side of formula (11) and make it equal to zero to obtain

$$S = \frac{\alpha V_S^D}{\eta_S(1-\lambda)}. \quad (12)$$

Similarly, assume that the optimal value function of the manufacturer's long-term profit after time t is $J_M^{D*}(M, \lambda) = e^{-\rho t}V_M^D(E)$, and for any $E \geq 0$, $V_M^D(E)$ satisfies the HJB equation:

$$\rho V_M^D(E) = \max_{M, \lambda} \left\{ [\pi_M - \varphi(E_h - E)](\bar{D} + \theta E) - \frac{\eta_M}{2}M^2 - \frac{\eta_S\lambda}{2}S^2 + V_M^D(\alpha S + \beta M - \sigma E) \right\}. \quad (13)$$

Find the first-order partial derivative for the manufacturer's optimal green innovation effort (M) and the optimal proportion on the right side of formula (13) and make them equal to zero to obtain

$$M = \frac{\beta V_M^D}{\eta_M},$$

$$\lambda = \frac{2V_M^D - V_S^D}{2V_M^D + V_S^D}. \quad (14)$$

Substituting formulas (12) and (14) into HJB equations (11) and (13), we can obtain

$$\begin{cases} \rho V_S^D(E) = \pi_S(\bar{D} + \theta E) - \sigma V_S^D E + \frac{\alpha^2 V_S^D (2V_M^D + V_S^D)}{4\eta_S} + \frac{\beta^2 V_S^D V_M^D}{\eta_M}, \\ \rho V_M^D(E) = [\pi_M - \varphi(E_h - E)](\bar{D} + \theta E) - \sigma V_M^D E + \frac{\alpha^2 (2V_M^D + V_S^D)^2}{8\eta_S} + \frac{\beta^2 V_M^{D/2}}{2\eta_M}. \end{cases} \quad (15)$$

Assume that the analytical expressions of optimal value functions $V_S^D(E)$ and $V_M^D(E)$ with E are, respectively, $V_S^D(E) = s_1 E + s_2$ and $V_M^D(E) = m_1 E^2 + m_2 E + m_3$, where

m_1, m_2, m_3, s_1 , and s_2 are constants, and combine this with the method of undetermined coefficients to obtain

$$\begin{cases} \rho s_1 = \theta \pi_S - \sigma s_1 + s_1 m_1 (\Delta_1 + 2\Delta_2), \\ \rho s_2 = \bar{D} \pi_S + \frac{(\Delta_1 + 2\Delta_2) s_1 m_2}{2} + \frac{\Delta_1 s_1^2}{4}, \\ \rho m_1 = \theta \varphi - 2\sigma m_1 + 2m_1^2 (\Delta_1 + \Delta_2), \\ \rho m_2 = \theta (\pi_M - \varphi E_h) + \bar{D} \varphi - \sigma m_2 + 2m_1 m_2 (\Delta_1 + \Delta_2) + \Delta_1 s_1 m_1, \\ \rho m_3 = \bar{D} (\pi_M - \varphi E_h) + \frac{m_2^2 (\Delta_1 + \Delta_2)}{2} + \frac{\Delta_1 s_1 m_2}{2} + \frac{\Delta_1 s_1^2}{8}. \end{cases} \quad (16)$$

Solve m_1, m_2, m_3, s_1 , and s_2 , and ensure that, for any $S^D, M^D, E^D, V_S^D(E)$, and $V_M^D(E)$, they are nonnegative. The expressions of $m_1^*, m_2^*, m_3^*, s_1^*$, and s_2^* that meet the conditions are shown in formula (10). Furthermore, we obtain the optimal green innovation efforts of the supplier and the manufacturer (S^{D*}, M^{D*}) and the proportion of green

innovation costs to be borne by the manufacturer for the supplier (λ^*) under the decentralized decision-making situation, as shown in Theorem 1 (1). In addition, the implicit condition of Theorem 1 is $(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2) \geq 0$.

Then, substitute S^{D*} and M^{D*} into equation (1) to obtain

$$\dot{E}^D(t) = m_2^* (\Delta_1 + \Delta_2) + s_1^* \left(\frac{\Delta_1}{2} + \Delta_2 \right) - [\sigma - 2m_1^* (\Delta_1 + \Delta_2)] E. \quad (17)$$

Solve the differential equation (17) to obtain the optimal trajectory of the product's green level under the decentralized decision-making situation, as shown in Theorem 1 (2).

If $\sigma - 2m_1^* (\Delta_1 + \Delta_2) < 0$, when the time factor approaches infinity, $E^D(t)$ will also approach infinity. This is inconsistent with the reality. If $\sigma - 2m_1^* (\Delta_1 + \Delta_2) \geq 0$, E_{RSS}^D is

the stable value of the product's green level when the time factor approaches infinity.

Furthermore, we obtain the long-term profits of supplier, manufacturer, and the whole green supply chain under the decentralized decision-making situation, as shown in Theorem 1 (3). \square

3.2. *Centralized Decision-Making Model.* In this situation, the manufacturer and the supplier should work together to determine their optimal green innovation efforts for the

purpose of maximizing supply chain profits. The strategic problem is (marked with a superscript C)

$$\max_{S,M} J_C^C = \int_0^\infty e^{-\rho t} \left\{ [\pi_S + \pi_M - \varphi(E_h - E)] (\bar{D} + \theta E) - \frac{\eta_M}{2} M^2 - \frac{\eta_S}{2} S^2 \right\} dt. \tag{18}$$

Theorem 2. Under the centralized decision-making situation, the long-term equilibrium strategies for the green innovation cooperation in the supply chain are as follows:

(1) The optimal green innovation efforts of the supply chain members are

$$\begin{cases} S^{C*} = \frac{2\alpha c_1^*}{\eta_S} E^C + \frac{\alpha c_2^*}{\eta_S}, \\ M^{C*} = \frac{2\beta c_1^*}{\eta_M} E^C + \frac{\beta c_2^*}{\eta_M}. \end{cases} \tag{19}$$

(2) The optimal trajectory of the product's green level is

$$E^C(t) = E_{RSS}^C \left(1 - e^{-(\sigma - 2c_1^*(\Delta_1 + \Delta_2))t} \right), \tag{20}$$

where $E_{RSS}^C = ((2c_2^*(\Delta_1 + \Delta_2))/(\sigma - 2c_1^*(\Delta_1 + \Delta_2)))$ is the stable value of the product's green level under centralized decision-making situation when the time factor approaches infinity ($t \rightarrow \infty$).

(3) The long-term equilibrium profit of the whole green supply chain is

$$J_C^{C*} = c_1^* (E_{RSS}^C)^2 e^{-2(\sigma - 2c_1^*(\Delta_1 + \Delta_2))t} - (2c_1^* E_{RSS}^C + c_2^*) E_{RSS}^C e^{-(\sigma - 2c_1^*(\Delta_1 + \Delta_2))t} + c_1^* (E_{RSS}^C)^2 + c_2^* E_{RSS}^C + c_3^*, \tag{21}$$

where c_1^* , c_2^* , and c_3^* satisfy the following formula:

$$\begin{cases} c_1^* = \frac{(\rho + 2\sigma) - \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}}{4(\Delta_1 + \Delta_2)}, \\ c_2^* = \frac{2\theta(\pi_S + \pi_M - \varphi E_h) + 2\bar{D}\varphi}{\rho + \sqrt{(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2)}}, \\ c_3^* = \frac{\bar{D}(\pi_S + \pi_M - \varphi E_h)}{\rho} + \frac{(\Delta_1 + \Delta_2)c_2^{*2}}{2\rho}. \end{cases} \tag{22}$$

Both $(\rho + 2\sigma)^2 - 8\theta\varphi(\Delta_1 + \Delta_2) \geq 0$ and $\sigma - 2c_1^*(\Delta_1 + \Delta_2) \geq 0$ need to be satisfied.

Proof. Similarly, we assume that the optimal value function of the supplier's long-term profit after time t is $J_C^{C*}(S, M) = e^{-\rho t} V_C^C(E)$, and for any $E \geq 0$, $V_C^C(E)$ satisfies the HJB equation:

$$\rho V_C^C(E) = \max_{S,M} \left\{ [\pi_S + \pi_M - \varphi(E_h - E)] (\bar{D} + \theta E) - \frac{\eta_M}{2} M^2 - \frac{\eta_S}{2} S^2 + V_C^C(\alpha S + \beta M - \sigma E) \right\}. \tag{23}$$

Find the first-order partial derivative for the supplier's green innovation effort (S) and manufacturer's green innovation effort (M) on the right side of formula (23) and make them equal to zero to obtain

$$\begin{aligned} S &= \frac{\alpha V_C^C}{\eta_S}, \\ M &= \frac{\beta V_C^C}{\eta_M}. \end{aligned} \tag{24}$$

Substitute formula (24) into formula (23) to obtain

$$\begin{aligned} \rho V_C^C(E) &= [\pi_S + \pi_M - \varphi(E_h - E)] (\bar{D} + \theta E) - \sigma V_C^C E \\ &\quad + \frac{\alpha^2 (V_C^C)^2}{2\eta_S} + \frac{\beta^2 (V_C^C)^2}{2\eta_M}. \end{aligned} \tag{25}$$

Similarly, assume $V_C^C(E) = c_1 E^2 + c_2 E + c_3$, where, c_1 , c_2 , and c_3 are constants, and combine this with the method of undetermined coefficients. We can obtain

$$\begin{cases} \rho c_1 = \theta\varphi - 2\sigma c_1 + 2c_1^2(\Delta_1 + \Delta_2), \\ \rho c_2 = \theta(\pi_S + \pi_M - \varphi E_h) + \bar{D}\varphi - \sigma c_2 + 2c_1 c_2(\Delta_1 + \Delta_2), \\ \rho c_3 = \bar{D}(\pi_S + \pi_M - \varphi E_h) + \frac{c_2^2}{2}(\Delta_1 + \Delta_2). \end{cases} \quad (26)$$

Solve c_1 , c_2 , and c_3 , and ensure that, for any S^C , M^C , E^C , and $V_C^C(E)$, they are nonnegative. The expressions of c_1^* , c_2^* , and c_3^* that meet the conditions are shown in formula (22). Furthermore, we obtain the optimal green innovation efforts of the supply chain members under the centralized decision-making situation, as shown in Theorem 2 (1).

Then, substitute the optimal green innovation strategy (formula (19)) into equation (1) to obtain

$$\dot{E}^C(t) = c_2^*(\Delta_1 + \Delta_2) - [\sigma - 2c_1^*(\Delta_1 + \Delta_2)]E. \quad (27)$$

Solve the differential equation (27), and obtain the optimal trajectory of the product's green level under the centralized decision-making situation, as shown in Theorem 2 (2). Similarly, if $\sigma - 2c_1^*(\Delta_1 + \Delta_2) \geq 0$, when the time factor approaches infinity, E_{RSS}^C is the stable value of the product's green level.

Then, we can obtain the long-term profit of the whole green supply chain under the centralized decision-making situations, as shown in Theorem 2 (3). \square

3.3. Comparison and Analysis. Combining Theorems 1 and 2, we can draw the following corollaries.

Corollary 1. *Compared to the decentralized decision-making situations, the product's green level and its stable value under the centralized decision-making situations are relatively higher.*

Proof. According to equations (8) and (20), we can obtain $c_1^* = m_1^*$ and $c_2^* = m_2^* + s_1^*$. Because $E_{RSS}^C - E_{RSS}^D = ((2c_2^*(\Delta_1 + \Delta_2) - 2m_2^*(\Delta_1 + \Delta_2) - s_1^*(\Delta_1 + 2\Delta_2)) / (2[\sigma - 2c_1^*(\Delta_1 + \Delta_2)]))$, $E_{RSS}^C - E_{RSS}^D > 0$ can be obtained. In addition, $E^C(t) - E^D(t) = (E_{RSS}^C - E_{RSS}^D)(1 - e^{-(\sigma - 2c_1^*(\Delta_1 + \Delta_2))t})$, then $E^C(t) - E^D(t) > 0$ is obtained. \square

Corollary 2. *Compared to the decentralized decision-making situations, the green innovation efforts of the supply chain members under the centralized decision-making situations are relatively higher.*

Proof. A simple comparison of equations (19) and (7) can prove this. \square

Corollary 3. *Compared to the decentralized decision-making situations, the long-term profit of the whole green supply chain under the centralized decision-making situations is relatively higher. However, the amount of the profits obtained by the*

supply chain members, related to the profit-distribution agreement, is uncertain and variable.

Proof. $J_C^{C*} - J_C^{D*} > 0$ can be simply obtained according to formulas (10) and (22). However, under the centralized decision-making situation, the supplier and the manufacturer are regarded as a system, and they distribute their profits according to a pre-established mutual agreement. As emphasized by Liu and Papageorgiou [40], distributed profits of supply chain members may be higher or lower than those under the decentralized decision-making situation. \square

4. Profit-Distribution Contract Design

According to the previous analysis, the green innovation efforts of the supply chain members and the long-term profit of the whole supply chain under the centralized decision-making situations are higher relatively than those under the decentralized decision-making situations. A scientifically and reasonably designed profit-distribution agreement can effectively guarantee that the profits obtained by the supplier and the manufacturer are higher than their optimal profits under the decentralized decision-making situations. Moreover, it can also encourage the supply chain members to put more effort toward green innovation, improve the product's green level, and achieve the "Dual Pareto Improvements" in both economic and environmental performance [34, 39, 41]. Therefore, this section will focus on the design of the supply chain's profit-distribution agreement under the centralized decision-making situations.

Obviously, a profit-distribution agreement can be reached if and only if the supplier's and manufacturer's distributed profits under the centralized situations are not lower than their optimal profits under the decentralized situations. We assume that, under the centralized situations, the proportion of the profit distributed to the manufacturer in the whole supply chain is Φ ($0 \leq \Phi \leq 1$), and that of the supplier is $1 - \Phi$. Thus, the profit-distribution ratio (Φ) satisfies the following equation:

$$\begin{aligned} \Phi J_C^{C*} &\geq J_M^{D*}, \\ (1 - \Phi) J_C^{C*} &\geq J_S^{D*}. \end{aligned} \quad (28)$$

$\Phi \in [(J_M^{D*}/J_C^{C*}), ((J_C^{C*} - J_S^{D*})/J_C^{C*})]$ is obtained. For the sake of simplicity, note that $\Phi_{\min} = (J_M^{D*}/J_C^{C*})$ and $\Phi_{\max} = ((J_C^{C*} - J_S^{D*})/J_C^{C*})$.

Therefore, when $\Phi \in [\Phi_{\min}, \Phi_{\max}]$, the profit-distribution agreement can be reached; however, both the supplier and the manufacturer expect to obtain more profits, where the manufacturer expects a larger Φ while the supplier expects a smaller Φ . A reasonable profit-distribution plan can be designed based on the discount factor in the Rubinstein bargaining model [42]. It should be noted that the discount factor here is different from the discount rate in finance. It represents the "patience" or "bargaining power" of the participants and is generally related to the competitiveness, negotiation ability, and risk preference of the participants [43, 44]. We assume that the discount factors of the supplier and the manufacturer are σ_S and

$\sigma_M (0 \leq \sigma_S \leq 1, 0 \leq \sigma_M \leq 1)$. Drawing from Binmore et al. [45] and Zhang and Wang [46], we adopt the Rubinstein bargaining model by considering the manufacturer's dominant position to obtain the only subgame Nash equilibrium as follows:

$$K = \frac{1 - \sigma_S}{1 - \sigma_S \sigma_M}. \quad (29)$$

Therefore, the optimal profit-distribution ratio (Φ^*) under the centralized decision-making situation is

$$\begin{aligned} \Phi^* &= K(\Phi_{\max} - \Phi_{\min}) + \Phi_{\min} \\ &= \frac{1 - \sigma_S}{1 - \sigma_S \sigma_M} \Phi_{\max} + \frac{\sigma_S(1 - \sigma_M)}{1 - \sigma_S \sigma_M} \Phi_{\min}. \end{aligned} \quad (30)$$

Theorem 3. *Under the centralized decision-making situations, the optimal profits distributed to the supplier and the manufacturer are*

$$\begin{cases} J_S^{C*} = (1 - \Phi^*)J_C^{C*} = \frac{\sigma_S(1 - \sigma_M)}{1 - \sigma_S \sigma_M} (J_C^{C*} - J_C^{D*}) + J_S^{D*}, \\ J_M^{C*} = \Phi^* J_C^{C*} = \frac{1 - \sigma_S}{1 - \sigma_S \sigma_M} (J_C^{C*} - J_C^{D*}) + J_M^{D*}. \end{cases} \quad (31)$$

From formula (31), we can see that, under the centralized situation, using the Rubinstein bargaining model to formulate a scientific and reasonable profit-distribution plan can effectively ensure that the profits distributed to the supplier and the manufacturer are higher than their optimal profits under the decentralized situations.

5. Simulations and Sensitivity Analysis

Using exogenous variable assignment, this section will further analyze the impacts of the driving factors including the environmental regulations' intensity and the consumers' green preference, on the long-term dynamic equilibrium strategies of the green supply chain under the two different situations. We will also verify the scientificity and validity of the profit-distribution agreement. The following parameter value of simulations are set as benchmarks: $\alpha = 0.6$, $\beta = 0.7$, $\eta_S = 4$, $\eta_M = 3$, $\sigma = 0.8$, $\theta = 0.6$, $\bar{D} = 10$, $\varphi = 0.2$, $E_h = 3$, $E(0) = 0$, $\rho = 0.3$, $\pi_s = 0.8$, $\pi_m = 1$, $\sigma_s = 0.5$, and $\sigma_m = 0.7$. They are chosen from previous studies in green supply chain, such as Zhou and Ye [25], Wang et al. [26], Zu and Zeng [30], and Zu et al. [34].

5.1. Integrity Analysis. Under the case of benchmark parameters, we set $t \in [0, 10]$ and plot the change of the supply chain members' green innovation efforts and their equilibrium (distributed) profits and the profits of the whole supply chain under the two situations, as shown in Figures 2–3. In addition, when $t \in [0, 10]$ and increases by 1, the proportion of the green innovation investment borne by the manufacturer for the

supplier under the decentralized situations is continuously increasing and then tends to be stable with the passage of time. The values of λ^* are 0.8076, 0.8121, 0.8142, 0.8151, 0.8155, 0.8157, 0.8158, 0.8159, 0.8159, 0.8159, and 0.8159, respectively. Because of limited space, the changes of λ^* are expressed by numerical values instead of a separate drawing.

From Figure 2, it can be seen that the supply chain members' green innovation efforts under the centralized situations, including the supplier and manufacturer, are higher than the values of the relative variables under the decentralized situations. Because of the direct influence of the supply chain members' green innovation efforts, the products' green level under centralized situations is also higher than that under decentralized situations. This strongly verifies Corollaries 1 and 2. It shows that cooperation mechanism can motivate supply chain members to carry out green innovation and thus significantly improve the environmental performance of supply chain [47].

Similarly, from Figure 3(a), it can be seen that the dynamic equilibrium profit of the whole supply chain under the centralized situations is higher than that under decentralized situations. This indicates that green innovation cooperation among supply chain members can not only improve the environmental performance of supply chain but also increase the economic performance. However, whether the economic performance of supply chain members can be improved depends on the profit-distribution agreement. Furthermore, Figure 3(b) shows that the distributed profits of the supplier and the manufacturer under the centralized situations are higher than their equilibrium profits under the decentralized situations. In other words, a reasonable profit-distribution agreement designed by using the Rubinstein bargaining model can effectively promote both the economic performance and environmental performance of the supply chain members, i.e., $J_S^{C*} > J_S^{D*}$, $J_M^{C*} > J_M^{D*}$, and $E^C(t) > E^D(t)$. This strongly verifies Corollary 3. Therefore, in order to reduce pollutant emission and effectively improve the environment, the government should pay attention to the whole supply chain, including upstream and downstream enterprises. Moreover, the supply chain members should develop scientific and reasonable cooperation mechanism to improve the product's green level and obtain more economic profits, so as to achieve double Pareto improvement [34].

5.2. Sensitivity Analysis

5.2.1. The Impact of the Consumer's Green Preference. In order to analyze the market driving effect, we keep the other parameters fixed and let the consumer's green preference θ take a random value in the range of $[0, 1]$. The relationship among S , M , J_S , J_M , and θ in different decision models is shown in Figure 4. Since the changes of relevant variables at different moments have been analyzed, for the sake of convenience, this section only analyzes the stability of relevant variables ($t \rightarrow \infty$).

Figures 4(a) and 4(b) show that, with the increase of the consumer's green preference θ , suppliers and manufacturers are increasing their investment in green innovation under

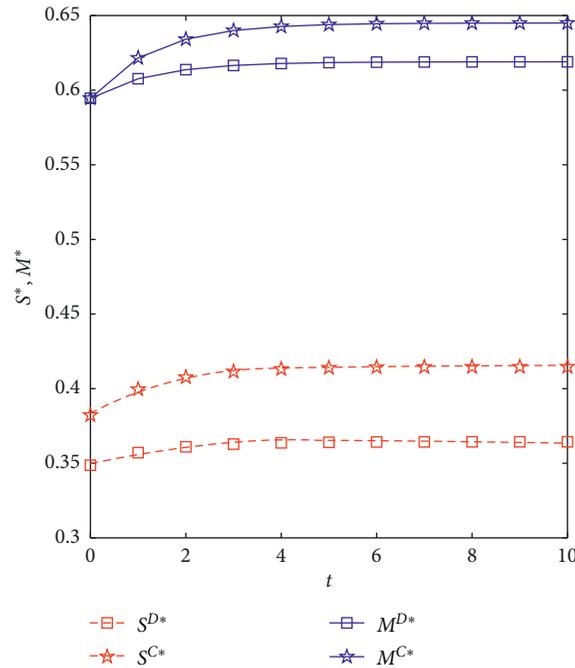


FIGURE 2: Comparison of green innovation efforts under different situations.

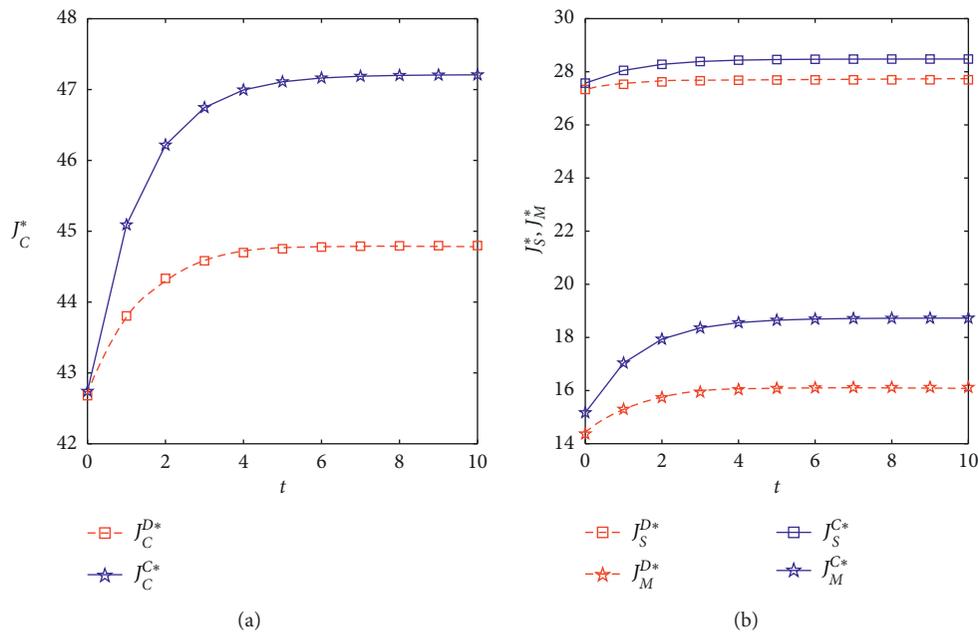


FIGURE 3: Comparison of the equilibrium (distributed) profits under different situations. (a) The equilibrium profit of the whole supply chain. (b) The equilibrium (distributed) profits of the supply chain members.

both the decentralized and centralized situations. Meanwhile, the benefits of the members' green innovation exceed the R&D costs with consumers' preference for green products. Moreover, the more consumers prefer green products, the more profits they will earn. However, under the decentralized situations, the proportion of the green innovation costs borne by the manufacturer for the supplier is decreasing. Specifically, when $\theta \in [0, 1]$ and increases by

0.1, the values of λ^* are 1.0000, 0.9618, 0.9271, 0.8954, 0.8665, 0.8400, 0.8159, 0.7938, 0.7736, 0.7552, and 0.7383, in turn.

This is because with the increasing preference of the consumer for green product, both the manufacturer and supplier are willing to actively increase their investment in green innovation and expand the market demands by increasing the product's green level to obtain more profits.

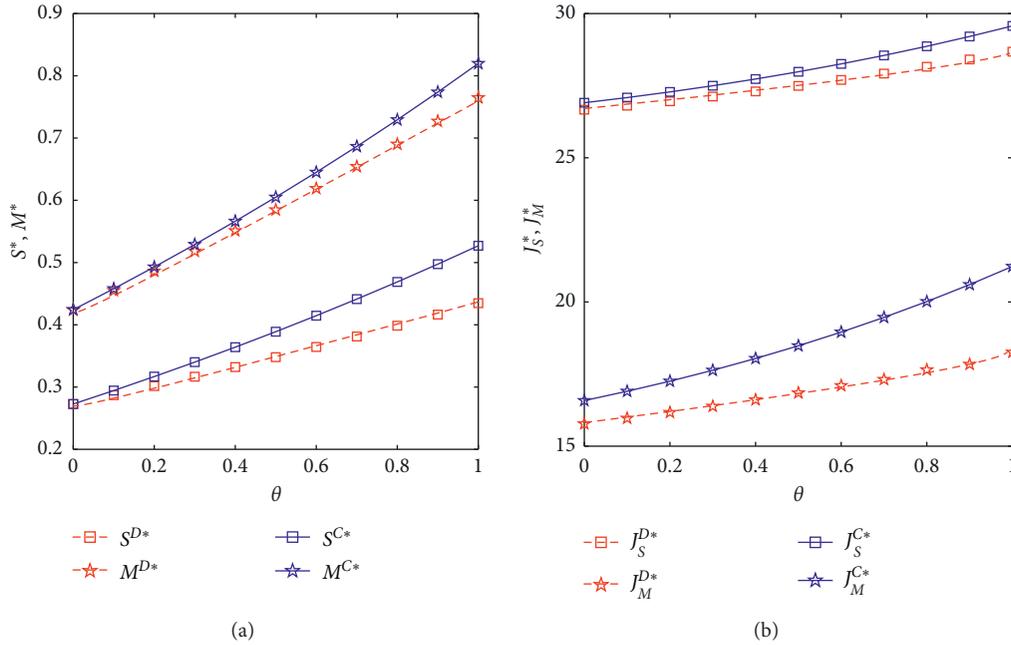


FIGURE 4: The impact of θ on the members' green innovation efforts and profits. (a) The changes of the green innovation efforts. (b) The changes of the members' profits.

Considering the direct driving effect of the consumer's green preference, the manufacturer will gradually reduce the proportion of innovation costs borne for the supplier to maximize its own profits. Particularly, when the consumers have no preference for green products (i.e., $\theta = 0$)—only the government driving effect is considered—the supplier is willing to invest in the green innovation only if the manufacturer bears all the innovation costs under the decentralized decision situations. Therefore, the government should—by making full use of the Internet, new media, and other platforms—strengthen the publicity of low-carbon technology and environmental protection and actively carry out public opinion guidance to raise the public's green consumption awareness and positively encourage enterprises to conduct green innovation.

5.2.2. The Impact of the Environmental Regulation Intensity.

Similarly, we keep the other parameters fixed and let environmental regulation intensity φ take a random value in the range of $[0, 1]$ to analyze the government driving effect. The relationship among S , M , J_S , J_M , and φ in different decision models is shown in Figure 5. For the sake of convenience, this section only analyzes the stability of relevant variables ($t \rightarrow \infty$).

From Figure 5(a), we can see that, with the continuous increase of φ , the manufacturer faces increasing pressure of emission reduction but is willing to bear a larger proportion of the green innovation costs for the supplier while increasing its own green innovation investment. Specifically, when $\varphi \in [0, 1]$ and increases by 0.1, the values of λ^* are 0.4286, 0.7181, 0.8159, 0.8651, 0.8947, 0.9146, 0.9288, 0.9395,

0.9479, 0.9546, and 0.9601, in turn. Although the environmental regulation has no direct effect on the supplier's green innovation, the supplier, under the indirect drive of the manufacturer's innovation participation and consumer's green preference, is also willing to continuously increase its green innovation investment. With the joint efforts of the manufacturer and the supplier in green innovation, the product's green level has been greatly improved. As we notice, this finding is consistent to the research of Yang and Lin [4] and Liao and Tsai [48]. The results show that the increase of customer's environmental pressure captivates firms to increase the enthusiasm to carry out green innovation; namely, effective supply chain management has a significant driving effect on green innovation performance.

Furthermore, from Figure 5(b), we can see that, with the continuous increase in the intensity of the environmental regulation (φ), both the supplier and manufacturer have increased their investment in green innovation; however, the equilibrium profit of the supplier only shows a slight increase, while the equilibrium profit of the manufacturer shows the U-shaped dynamic characteristic, i.e., decreasing and then increasing. This finding is different with the research of Deng and Li [49] and Pan et al. [50]. This is because this study integrates green innovation into the supply chain context, which leads to a different perspective from the previous two studies. When the intensity of the environmental regulation is relatively low, the manufacturer and supplier will make a low investment in green innovation and produce a large number of pollutant emissions, even exceeding the emission limits set by the government, thus incurring emission costs. With the gradual increase in the intensity of the environmental regulations, the manufacturer

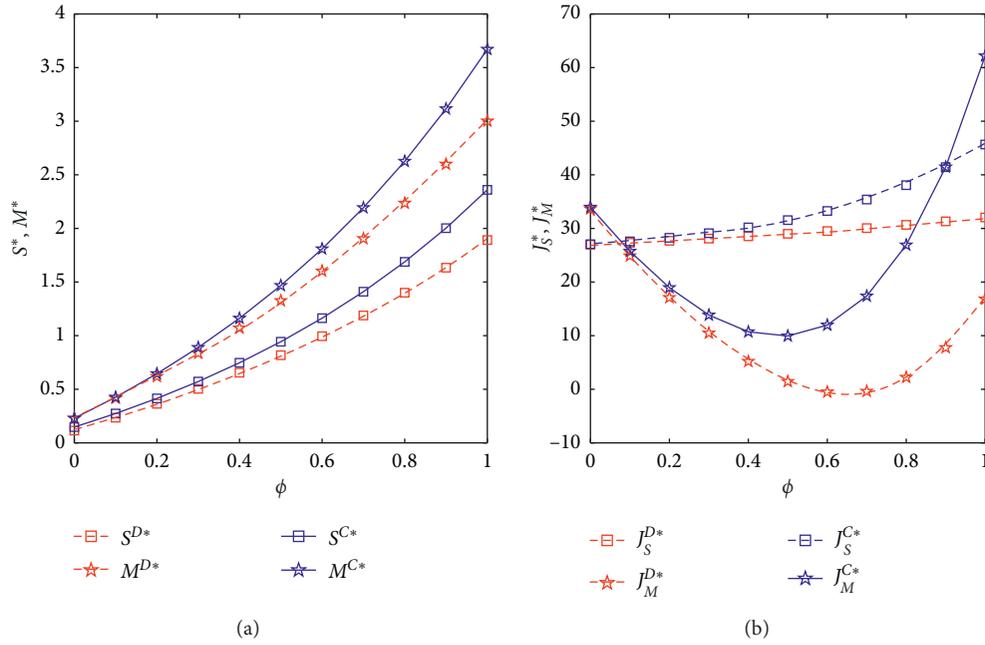


FIGURE 5: The impact of ϕ on the members' green innovation efforts and profits. (a) The changes of the green innovation efforts. (b) The changes of the members' profits.

needs to pay more and more emission costs while bearing increasing green innovation costs for the supplier, so the profit declines continuously. However, when the intensity of environmental regulation exceeds a given threshold, both the manufacturer and the supplier increase their investment in green innovation, the product's green level increases greatly, and the pollutant emission amount drops below the limit set by the government. The original emission cost then turns into benefits. In this case, with the gradual increase in the intensity of environmental regulation, the manufacturer obtains more and more benefits from emission reduction.

5.3. *Managerial Implications.* Through the above analysis, we can also obtain some managerial implications:

- (1) The government cannot blindly increase the intensity of the environmental regulations; rather, it should comprehensively consider the environmental performance and economic performance of the enterprises and the social welfare in a unified framework and then formulate scientific and reasonable environmental policies.
- (2) Considering the direct driving effect of market demand, while formulating environmental policies, the government should also actively carry out public opinion guidance to improve the public's awareness of green consumption.
- (3) Under the background of low-carbon economy, managers should transform their single-handed strategy into cooperation with the upstream and downstream firms for green innovation, so as to achieve the "Dual Pareto Improvements" in both economic and environmental performance.

6. Conclusions

Comprehensively considering the dual-driving effect of the environmental regulation and the consumer's green preference, this research studies the long-term dynamic equilibrium strategies of the green innovation cooperation in a supply chain by using differential game models. The green supply chain includes a manufacturer and a supplier, in which the members' green innovation positively affects the dynamic changes of the products' green level. A scientific and rational profit-distribution agreement under the centralized decision situations is designed to encourage the supply chain members invest more in the green innovation and achieve the "Dual Pareto Improvements" in both economic and environmental performance. The research results are as follows:

- (1) Compared with the decentralized decision situations, the green innovation efforts of the supply chain members, the optimal trajectory and stable value of the product's green level, and the long-term profit of the whole supply chain under the centralized situations are relatively higher. However, the amount of the profits obtained by the supply chain members is uncertain and related to the profit-distribution agreement.
- (2) Under the centralized situations, using the Rubinstein bargaining model to design a scientific and rational profit-distribution agreement can effectively ensure that the profits distributed to the supplier and the manufacturer achieve the "Dual Pareto Improvements".
- (3) With the increase of the environmental regulation's intensity, the optimal green innovation efforts of the

supply members continuously increase and the product's green level continues to rise and then tends to stabilize, but the equilibrium profit of the whole supply chain shows the U-shaped fluctuation characteristic, i.e., decreasing and then increasing.

- (4) With the increase of the consumer's green preference, the product's green level, the supply chain members' green innovation efforts and their equilibrium/distributed profits, and the equilibrium profits of the whole supply chain all keep increasing.

Nevertheless, this paper has some limitations. For example, this study does not consider the supply chain members' behavioral factors, including the risk preference, fair preference, and altruistic preference. In addition, this paper does not consider the competition between supply chains. In the future, the research can be further extended to the dynamic decision-making of the green innovation cooperation in multilevel green supply chains with competitive relationships and the influences of the fairness preference, risk preference, and other behavioral factors of the supply chain members.

Data Availability

The data are only based on an assumption of general market reality to verify the correctness of the model establishment and verification analysis.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

- [1] B. Peng, Y. Tu, and G. Wei, "Can environmental regulations promote corporate environmental responsibility? Evidence from the moderated mediating effect model and an empirical study in China," *Sustainability*, vol. 10, no. 3, Article ID 641, 2018.
- [2] H. Fazlollahtabar, "Operations and inspection cost minimization for a reverse supply chain," *Operational Research in Engineering Sciences: Theory and Applications*, vol. 1, no. 1, pp. 91–107, 2018.
- [3] C. Su, X. Liu, and W. Du, "Green supply chain decisions considering consumers' low-carbon awareness under different government subsidies," *Sustainability*, vol. 12, no. 6, Article ID 2281, 2020.
- [4] Z. Yang and Y. Lin, "The effects of supply chain collaboration on green innovation performance: An interpretive structural modeling analysis," *Sustainable Production and Consumption*, vol. 23, pp. 1–10, 2020.
- [5] Q. Guo, M. Zhou, N. Liu, and Y. Wang, "Spatial effects of environmental regulation and green credits on green technology innovation under low-carbon economy background conditions," *International Journal of Environmental Research and Public Health*, vol. 16, no. 17, Article ID 3027, 2019.
- [6] F. Testa, F. Iraldo, and M. Frey, "The effect of environmental regulation on firms' competitive performance: the case of the building & construction sector in some EU regions," *Journal of Environmental Management*, vol. 92, no. 9, pp. 2136–2144, 2011.
- [7] M. Christopher, *Logistics and Supply Chain Management: Strategies for Reducing Cost and Improving Service*, Pitman Publishing, London, UK, 1998.
- [8] M. A. Lejeune and N. Yakova, "On characterizing the 4 C's in supply chain management," *Journal of Operations Management*, vol. 23, no. 1, pp. 81–100, 2005.
- [9] J. Gong, J. E. Mitchell, A. Krishnamurthy, and W. A. Wallace, "An interdependent layered network model for a resilient supply chain," *Omega*, vol. 46, pp. 104–116, 2014.
- [10] S.-Y. Lee, "The effects of green supply chain management on the supplier's performance through social capital accumulation," *Supply Chain Management: An International Journal*, vol. 20, no. 1, pp. 42–55, 2015.
- [11] S. Vachon and R. D. Klassen, "Environmental management and manufacturing performance: the role of collaboration in the supply chain," *International Journal of Production Economics*, vol. 111, no. 2, pp. 299–315, 2008.
- [12] J. Zhang, Q. Gou, S. Li, and Z. Huang, "Cooperative advertising with accrual rate in a dynamic supply chain," *Dynamic Games and Applications*, vol. 7, no. 1, pp. 112–130, 2017.
- [13] X. Chen, X. Wang, and M. Zhou, "Firms' green R&D cooperation behaviour in a supply chain: technological spillover, power and coordination," *International Journal of Production Economics*, vol. 218, pp. 118–134, 2019.
- [14] J. Carrillo-Hermosilla, P. Del Río, and T. Könnölä, "Diversity of eco-innovations: reflections from selected case studies," *Journal of Cleaner Production*, vol. 18, no. 10–11, pp. 1073–1083, 2010.
- [15] K. Rennings and C. Rammer, "The impact of regulation-driven environmental innovation on innovation success and firm performance," *Industry & Innovation*, vol. 18, no. 3, pp. 255–283, 2011.
- [16] M. E. Porter and C. Van der Linde, "Green and comparative: ending the stalemate," *Harvard Business Review*, vol. 73, pp. 120–134, 1995.
- [17] J. Hojnik and M. Ruzzier, "What drives eco-innovation? A review of an emerging literature," *Environmental Innovation and Societal Transitions*, vol. 19, pp. 31–41, 2016.
- [18] E. Kesidou and P. Demirel, "On the drivers of eco-innovations: empirical evidence from the UK," *Research Policy*, vol. 41, no. 5, pp. 862–870, 2012.
- [19] S. Benjaafar, Y. Li, and M. Daskin, "Carbon footprint and the management of supply chains: insights from simple models," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 1, pp. 99–116, 2012.
- [20] S. Du, F. Ma, Z. Fu, L. Zhu, and J. Zhang, "Game-theoretic analysis for an emission-dependent supply chain in a 'cap-and-trade' system," *Annals of Operations Research*, vol. 228, no. 1, pp. 135–149, 2015.
- [21] J.-Y. Chen, S. Dimitrov, and H. Pun, "The impact of government subsidy on supply chains' sustainability innovation," *Omega*, vol. 86, pp. 42–58, 2019.

- [22] X. Zhang and H. M. A. U. Yousaf, "Green supply chain coordination considering government intervention, green investment, and customer green preferences in the petroleum industry," *Journal of Cleaner Production*, vol. 246, Article ID 118984, 2020.
- [23] Q. Meng, Y. Wang, Z. Zhang, and Y. He, "Supply chain green innovation subsidy strategy considering consumer heterogeneity," *Journal of Cleaner Production*, vol. 281, Article ID 125199, 2021.
- [24] G. Feichtinger and S. Jørgensen, "Differential game models in management science," *European Journal of Operational Research*, vol. 14, no. 2, pp. 137–155, 1983.
- [25] Y. Zhou and X. Ye, "Differential game model of joint emission reduction strategies and contract design in a dual-channel supply chain," *Journal of Cleaner Production*, vol. 190, pp. 592–607, 2018.
- [26] M. Wang, Y. Li, M. Li, W. Shi, and S. Quan, "Will carbon tax affect the strategy and performance of low-carbon technology sharing between enterprises?" *Journal of Cleaner Production*, vol. 210, pp. 724–737, 2019.
- [27] B. Yu, J. Wang, X. Lu, and H. Yang, "Collaboration in a low-carbon supply chain with reference emission and cost learning effects: cost sharing versus revenue sharing strategies," *Journal of Cleaner Production*, vol. 250, Article ID 119460, 2020.
- [28] J. Wei and C. Wang, "Improving interaction mechanism of carbon reduction technology innovation between supply chain enterprises and government by means of differential game," *Journal of Cleaner Production*, vol. 296, Article ID 126578, 2021.
- [29] L. Liu and F. Li, "Differential game modelling of joint carbon reduction strategy and contract coordination based on low-carbon reference of consumers," *Journal of Cleaner Production*, vol. 277, Article ID 123798, 2020.
- [30] Y. Zu and X. Zeng, "Research on energy efficiency improvement in a supply chain with discontinuous market demand," *Environmental Science and Pollution Research*, vol. 27, no. 13, pp. 15537–15551, 2020.
- [31] S. Jørgensen and E. Gromova, "Sustaining cooperation in a differential game of advertising goodwill accumulation," *European Journal of Operational Research*, vol. 254, no. 1, pp. 294–303, 2016.
- [32] L. Lu and J. Navas, "Advertising and quality improving strategies in a supply chain when facing potential crises," *European Journal of Operational Research*, vol. 288, no. 3, pp. 839–851, 2021.
- [33] K. Adhikary, J. Roy, and S. Kar, "Newsboy problem with birandom demand," *Decision Making: Applications in Management and Engineering*, vol. 2, no. 1, pp. 1–12, 2019.
- [34] Y. Zu, L. Chen, and Y. Fan, "Research on low-carbon strategies in supply chain with environmental regulations based on differential game," *Journal of Cleaner Production*, vol. 177, pp. 527–546, 2018.
- [35] J. Heydari, K. Govindan, and A. Jafari, "Reverse and closed loop supply chain coordination by considering government role," *Transportation Research Part D: Transport and Environment*, vol. 52, pp. 379–398, 2017.
- [36] F. El Ouardighi, "Supply quality management with optimal wholesale price and revenue sharing contracts: a two-stage game approach," *International Journal of Production Economics*, vol. 156, pp. 260–268, 2014.
- [37] M. Nerlove and K. J. Arrow, "Optimal advertising policy under dynamic conditions," *Economica*, vol. 29, no. 114, pp. 129–142, 1962.
- [38] P. He, Y. He, C. Shi, H. Xu, and L. Zhou, "Cost-sharing contract design in a low-carbon service supply chain," *Computers & Industrial Engineering*, vol. 139, Article ID 106160, 2020.
- [39] L. Lu, J. Marín-Solano, and J. Navas, "An analysis of efficiency of time-consistent coordination mechanisms in a model of supply chain management," *European Journal of Operational Research*, vol. 279, no. 1, pp. 211–224, 2019.
- [40] S. Liu and L. G. Papageorgiou, "Fair profit distribution in multi-echelon supply chains via transfer prices," *Omega*, vol. 80, pp. 77–94, 2018.
- [41] W. Ma, Z. Cheng, and S. Xu, "A game theoretic approach for improving environmental and economic performance in a dual-channel green supply chain," *Sustainability*, vol. 10, no. 6, Article ID 1918, 2018.
- [42] A. Rubinstein, "Perfect equilibrium in bargaining model," *Econometrica*, no. 50, pp. 97–109, 1982.
- [43] J. Liu and X. Wang, "A dynamic multi-player bargaining game with veto players," *Journal of Systems Science and Complexity*, vol. 34, no. 2, pp. 673–691, 2021.
- [44] Z. Feng, C. Tan, J. Zhang et al., "Bargaining game with altruistic and spiteful preferences," *Group Decision and Negotiation*, no. 30, pp. 277–300, 2021.
- [45] K. Binmore, A. Rubinstein, and A. Wolinsky, "The Nash bargaining solution in economic modelling," *The RAND Journal of Economics*, vol. 17, no. 2, pp. 176–188, 1986.
- [46] C.-T. Zhang and Z. Wang, "Production mode and pricing coordination strategy of sustainable products considering consumers' preference," *Journal of Cleaner Production*, vol. 296, Article ID 126476, 2021.
- [47] S. Yin, N. Zhang, B. Li, and H. Dong, "Enhancing the effectiveness of multi-agent cooperation for green manufacturing: dynamic co-evolution mechanism of a green technology innovation system based on the innovation value chain," *Environmental Impact Assessment Review*, vol. 86, Article ID 106475, 2021.
- [48] Y.-C. Liao and K.-H. Tsai, "Innovation intensity, creativity enhancement, and eco-innovation strategy: the roles of customer demand and environmental regulation," *Business Strategy and the Environment*, vol. 28, no. 2, pp. 316–326, 2019.
- [49] X. Deng and L. Li, "Promoting or inhibiting? The impact of environmental regulation on corporate financial performance—an empirical analysis based on China," *International Journal of Environmental Research and Public Health*, vol. 17, no. 11, Article ID 3828, 2020.
- [50] X. Pan, W. Cheng, Y. Gao, T. Balezantis, and Z. Shen, "Is environmental regulation effective in promoting the quantity and quality of green innovation?" *Environmental Science and Pollution Research*, vol. 28, no. 5, pp. 6232–6241, 2021.