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Research article

Dynamic strategy for low-carbon supply chain considering retailers competition and technological innovation

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ABSTRACT

This paper discusses how managers adjust their strategies to allocate relevant resources more effectively and maximize economic benefits when major technological changes are predicted for the future. For a supply chain system consisting of a single manufacturer and two competing retailers as the research object. First, random stop model is applied to portray the impact of technological innovation on the decision-making of supply chain members. On this basis, differential game models for supply chain members are constructed based on different cooperation modes, including centralized, decentralized, and retailers alliance. Second, we solve and compare the optimal decision-making, emissions reduction, low-carbon goodwill, and profit levels before and after technological innovation in different modes. Finally, we design a bilateral cost-sharing contract to achieve coordination. Results demonstrate that: (1) Before the success of technological innovation, when a higher probability of success and uplift rate is predicted can incentivize supply chain members' emissions reduction and low-carbon promotion inputs; (2) In the presuccess period of technological innovation, members' independent decision-making (decentralized decision-making) can optimize the retailer's low-carbon promotional inputs under certain conditions. In contrast, the optimality of decentralized decision-making after technological innovation depends only on the influence of competition intensity. (3) The bilateral cost-sharing contract designed in this paper can optimize supply chain-related inputs and performance levels to achieve perfect coordination within the supply chain system, given that specific preconditions are satisfied.

1. Introduction

"Accelerating R&D (Research and Development), promotion, application of advanced energy-saving and carbon emission reduction technologies, encourage green consumption, promote green and low-carbon ways of production and life." is an important strategic deployment for China in the New Era [1]. It provides crucial guidance and fundamental principles for the transformation and upgrading of China's manufacturing enterprises. Nevertheless, during the actual process of R&D, significant uncertainties arise in various facets, including technology, market, and policies, the success and timing of technological innovation carry a high degree of uncertainty [2–4]. For instance, the electric vehicle batteries industry faces uncertainties associated with material technology upgrades [5], ambiguous market dynamics (electric or hydrogen energy) [6], and the reduction of subsidies for new energy vehicles

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[7]. The timing of achieving a technological breakthrough in performance remains uncertain [8]. At the theoretical level, random stop model effectively utilizes conditional probabilities to characterize the likelihood of technological innovation reaching realization at a certain uncertain time node [9]. This model provides an effective mathematical framework for studying the procedural nature and uncertainty involved in the temporal realization of the aforementioned technological innovation.

Furthermore, the low-carbon awareness of consumers also holds significant importance in the pursuit of energy conservation and emissions reduction [10,11]. According to the “2020 Research Report on Climate Awareness and Behavior of Chinese Youth” [12], the proportions of individuals expressing willingness to “Allocate additional financial resources towards environmental protection”, “Contribute higher taxes for environmental preservation”, and “Sacrifice living standards for the sake of environmental conservation” were recorded as 68%, 62%, and 57% correspondingly. The data mentioned above provide comprehensive evidence that contemporary youth cohorts possess a significant subjective consciousness regarding environmental preservation and value assessment. On the other hand, their inclination toward low-carbon practices is likely to translate into tangible consumer behavior to some degree. Driven by consumers’ low-carbon consumption concepts, higher emissions reduction often means more business opportunities, in which manufacturers’ emissions reduction inputs play a crucial role [13,14]. However, consumer awareness of product emissions reduction requires appropriate low-carbon promotion by retailers [15,16]. From the perspective of the entire supply chain system, the emissions reduction efforts of manufacturers and the low-carbon promotion by all retailers collectively contribute to shaping the overall low-carbon goodwill of the entire supply chain [17]. In 2021, Gree Group developed a zero-carbon source air conditioning technology, reducing the environmental impact of air conditioning by 85.7%. This innovation led to the company winning the Global Refrigeration Technology Innovation Award, significantly enhancing the enterprise’s low-carbon goodwill. Therefore, from a practical perspective, it is necessary to concurrently examine the impact of emissions reduction and low-carbon goodwill on the decision-making of supply chain members. Notably, influenced by internal and external factors, both the aforementioned emissions reduction and low-carbon goodwill are dynamic processes [18,19]. Differential game theory, utilizing differential equations, effectively models and optimizes the strategic interactions of multiple parties in a dynamic environment [20], providing a theoretical foundation for characterizing the dynamics of emissions reduction and low-carbon goodwill.

In reality, a single manufacturer often provides products to multiple retailers. For instance, the well-known soft drink brand Coca-Cola has over 1,300,000 distribution points globally, resulting in evident competition among these distribution outlets [21,22]. In this context, businesses within the supply chain frequently enhance their competitiveness and expand their market share through various forms of collaboration and mergers [23,24]. For example, Wangfujing and Bailian Group engaged in horizontal mergers to consolidate the market, weaken competition, and enhance bargaining power [25]. Retail giant Walmart, on the other hand, made significant emissions reductions in product manufacturing, transportation, and operations through vertical cooperation, thereby improving its corporate image and social competitiveness [26]. Therefore, studying decision-making regarding R&D investments in technology innovation between the manufacturer and competitive retailers, along with cooperation agreements, holds significant importance in achieving sustainable development in the supply chain.

In light of the aforementioned background, the following issues are worthy of researchers’ attention:

(1) Under the competitive environment among retailers, do various modes of collaboration within the supply chain impact the manufacturer’s willingness to reduce emissions and the optimal decisions of retailers?

(2) Are the relationships between decisions made by supply chain members and the intensity of competition different under different collaboration modes?

(3) If managers can anticipate the occurrence of future technological innovations and their impact on business operations, how should they make decisions to rapidly and effectively apply new technologies, thereby enhancing the economic benefits of the supply chain?

These issues hold paramount significance in advancing the green transformation of manufacturing enterprises and promoting social sustainability, and are the primary focus of this paper. Specifically, this research aims to explore and quantify the impact of technological innovation on the emissions reduction and promotional decisions of low-carbon supply chain members under different competitive and cooperative modes. On the practical level, the research conclusions are intended to serve as a reference for decision-making by supply chain members in the context of the contemporary economy characterized by high-quality development and continuous technological innovation.

To analyze the above issues, we consider the competitive factors of low-carbon promotion by retailers, introducing the process of technological innovation into a supply chain system consisting of a single manufacturer and two retailers. This research explores how upstream and downstream members of the supply chain can adjust their strategies when predicting significant technological changes in the future to allocate relevant resources more reasonably, ultimately maximizing economic benefits. Additionally, we consider the dynamic nature of emissions reduction and goodwill both before and after the technological innovation. The low-carbon promotional inputs, competition in low-carbon promotions, and goodwill levels are collectively considered decisive factors for market demand. Utilizing differential game theory, we formulate three models: centralized decision-making, decentralized decision-making, and retailers alliance. Furthermore, we design a bilateral cost-sharing contract to achieve coordination. The primary goal is to provide a reference basis for supply chain member decisions in the context of current high-quality economic development and the ever-evolving technological background. Specifically, this paper contributes theoretically and practically in the following ways:

(1) On the theoretical level, we consider the competitive environment of retailers. On this basis, we utilize the random stop model to effectively characterize the uncertainty in the realization of technological innovation and its impact on the decision-making of supply chain members. This represents a methodological attempt to apply the random stop model in the competitive environment.

(2) On the practical level, we confirm that the predicted success rate, improvement rate, and competition intensity before and after technological innovation have positive impacts on the emissions reduction and low-carbon promotional decisions of supply chain members. These findings can provide guidance and reference for relevant practitioners.

2. Literature review

2.1. Supply chain emissions reduction

In terms of supply chain emissions reduction, the most representative study is that of Benjaafar et al. [27], which, for the first time, integrated emissions reduction into supply chain members' decision-making and analyzed the impact of carbon emissions on the overall profitability of the supply chain. Subsequently, scholarly investigations of reducing emissions in supply chains can be classified into two distinct categories: static and dynamic viewpoints.

A significant body of related research focuses on supply chain emissions reduction from the static perspective. For instance, Li et al. [28] explored the impact of incentives for professional managers on supply chain R&D for emissions reduction within the context of existing carbon trading policies. The findings suggested that, under specific circumstances, a cooperative R&D approach and sharing strategy could be considered the most effective strategies for the supply chain system. In contrast, He et al. [29] conducted a study on the influence of government subsidies and corporate social responsibility (CSR) practices on emissions reduction efforts and the profitability of the supply chain system. Their research substantiated that both government subsidies and CSR behaviors contribute to mitigating carbon emissions and enhancing the financial performance of supply chain systems.

However, in reality, the production processes of enterprises are often long-term, thus, from a practical perspective, it is necessary to study the emission reduction issues of the supply chain system from a dynamic viewpoint. One of the most representative works in this regard is by Xu et al. [15]. For the first time, they utilized differential game theory to study the joint emissions reduction and low-carbon promotion issues between upstream and downstream from a dynamic perspective. Furthermore, they explored the impact of a cost-sharing contract on the emissions reduction and profits of the supply chain system, indicating that under certain conditions, this contract can enhance the retailer's level of low-carbon promotional investment and further achieve Pareto improvement in supply chain profits. Due to the dynamic optimization and optimal control theory used by Xu et al. [15], which can express complex evolutionary processes very clearly and concisely, it is possible to further solve the analytical expression of the optimal strategy. Building on this, Liang et al. [30], by constructing a differential game model of a two-tier supply chain consisting of a manufacturer and retailer, investigated the impact of consumer low-carbon preferences on emissions reduction in the supply chain system. Xia et al. [31] incorporated consumer low-carbon awareness and social preferences into the emissions reduction problem of the supply chain and introduced the cost-sharing contract for coordination, studying its impact on carbon reduction in the supply chain. The above studies ingeniously use differential game theory to vividly depict the dynamics of enterprise emissions reduction, laying a foundation for subsequent research on supply chain emission reduction.

2.2. Supply chain goodwill

From an economic standpoint, goodwill refers to the prospective economic value that can yield surplus profits for a company and is considered a significant factor in shaping consumer demand [32]. Similar to the emissions reduction, previous studies on goodwill are predominantly based on the static aspect. For instance, Pnevmatikos et al. [33] found that companies' investments in brand goodwill enhance supply chain performance and result in a certain degree of gain in consumer surplus. Wang et al. [34] concluded that institutional investors could enhance the extent of corporate goodwill by implementing strategies such as augmenting corporate disclosure practices and mitigating corporate agency costs.

However, goodwill is also a dynamic process and is bound to be affected by other state variables during the long-term operation of companies [35,36]. Guan et al. [37] assumed that the evolution of goodwill is influenced by a combination of product quality and market promotion and investigated the issue of bargaining fairness among upstream and downstream members of the supply chain. On the other hand, Liu et al. [17] considered the impact of corporate emissions reduction on supply chain goodwill, studied the investment decision problem of the supply chain system with differential game theory, and analyzed the dynamic trend of brand goodwill. In contrast to the literature on supply chain dynamic emissions reduction, the studies conducted by Guan et al. [37] and Liu et al. [17] considered the interdependent relationship between dual state variables in supply chain management, which is more in line with the supply chain management complexity.

2.3. Technological innovation

In the contemporary setting of the strategic objective of achieving the "carbon peak and carbon neutrality" and the advent of the green development period, enterprises need to attain green transformation through technical innovation [1]. In their study, Hajhashem et al. [9] noted that the time of realization of technological innovations is often uncertain, and the effective implementation of such innovations might result in substantial advancements in performance. Within the realm of supply chain management, numerous researchers have undertaken research on the technological innovation behaviors of supply chain members [38,39], investment strategies [40], and the influence of technological innovation on levels of supply chain profitability [41,42].

Nevertheless, the aforementioned research is grounded in a static framework that fails to consider the enduring and evolving nature of organizations' production and operations, as well as the unpredictability surrounding the timing of technical innovations.

Consequently, several scholars have sought to investigate the technical innovation of supply chain systems from a dynamic standpoint. For instance, Hu et al. [43] delved into the optimal decision-making of supply chain members before and after technological innovation using differential game theory. Their study indicated a significant correlation between the level of relevant inputs from supply chain members and the predicted probability of success in technological innovation. Wu et al. [44] explored the impact of the carbon trading mechanism and government subsidies on the decision-making of supply chain members, with the level of low-carbon technological innovation as the state variable. They demonstrated that under specific conditions, government subsidies can effectively optimize the overall technological innovation level and emission reduction within the supply chain. Unfortunately, their investigation was confined to a two-tier supply chain comprising a manufacturer and a retailer, presenting a discrepancy with the complex structure of practical supply chain settings. In contrast, Liu et al. [45] investigated the impact of technological innovation on green R&D investments among supply chain members in a three-tier supply chain. They concluded that the influence of green technological innovation on manufacturers' decisions regarding green R&D investments is contingent upon the level of their green competitive intensity. The research by Liu et al. [45], to a certain extent, expands upon the practical significance of the research objects in Hu et al. [43] and Wu et al. [43]. However, concerning the setting of the state variable, they only consider the dynamics of supply chain greenness and do not consider the existence of multiple state variables during the operational period or the interplay relationships among them.

2.4. Competitive scenario

In the context of the market economy, competition is a fundamental characteristic among enterprises, and even among different departments within the same enterprise during their operational processes. Through competition, entities seek to acquire more market resources while simultaneously achieving the survival of the fittest, thereby coordinating the allocation of production factors. In the field of supply chain management, existing research has predominantly focused on the competition among horizontal members, primarily analyzing the impact of competitive behavior on supply chain performance or profits from a static perspective. For example, Zhou et al. [46] argued that under conditions of manufacturer competition, government carbon tax policies can significantly promote energy conservation and emission reduction efforts within the supply chain system. Jahanbakhsh et al. [47] suggested that competitive advantages can positively impact organizational performance, confirming the mediating effect of competitive advantages between supply chain management and organizational performance.

Although there are several existing studies on supply chain competition, in recent years, only few scholars have attempted to study the impact of competitive relationships on supply chain decisions from the perspective of long-term business operations. Zhang et al. [48] applied differential game theory to analyze the relationship between travel agency competition intensity and scenic area profits within a supply chain system consisting of a low-carbon scenic area and two competing travel agencies. However, their focus was limited to the dynamics of low-carbon scenic emissions reduction and the reputation of travel agency service providers within the supply chain system. It is worth noting that external influences beyond these factors can significantly affect the decision-making processes and profitability of supply chain participants. In this context, Zhuo et al. [49] and Huang [50] made pioneering attempts to study retailers' competitive supply chain pricing decisions and emissions reduction decisions, respectively, considering the perspective of government subsidies. While commendable for integrating external environmental factors into the analysis of decision-making behavior within competitive supply chain systems, these studies assume that the government's objective is to maximize social welfare and the overall return of the supply chain [51,52]. However, constructing a realistic government objective function may be challenging due to the national conditions of each country, the nature of enterprises, and other contextual influences. Apart from government subsidies, technological innovation stands out as another significant external factor. As mentioned earlier, technological innovation differs from government subsidies in that its stochastic and processual nature can be visually depicted using the random stop model. Hu et al. [43] were pioneers in using this model to portray the technological innovation process and confirm its validity. In practical terms, portraying the technological innovation process appears to be more relevant than the often complex and rationally oriented nature of government subsidy decision-making.

2.5. Supply chain coordination

In the field of supply chain management, collaboration among supply chain members is often advantageous for the achievement of overall objectives, with the cost-sharing contract being a beneficial means of cooperation among these members. Tsao et al. [53] first applied the cost-sharing strategy to the field of supply chain management, considering the cost-sharing contract as a coordination mechanism for the supply chain system. Ghosh et al. [54] and Zhang et al. [55] introduced the cost-sharing contract to address emissions reduction issues in supply chain systems, finding that the cost-sharing contract can improve carbon emissions in the supply chain to some extent. Huang et al. [56], focusing on the coexistence of government subsidies and cost-sharing, studied the impact of government subsidies and the cost-sharing contract on the retailer's willingness to share information with suppliers. They suggested that the retailer's willingness to share information is positively correlated with the level of government subsidies and negatively correlated with the level of cost-sharing.

It is worth noting that, while the aforementioned cost-sharing contract can improve the decision-making of supply chain members to some extent, the complexity of the supply chain environment and the heterogeneity among members make it challenging to achieve full coordination within the supply chain system. Based on this foundation, Giannoccaro et al. [57] designed a revenue-sharing contract that achieves complete coordination within the supply chain. Similar studies have been conducted by Xu et al. [58]

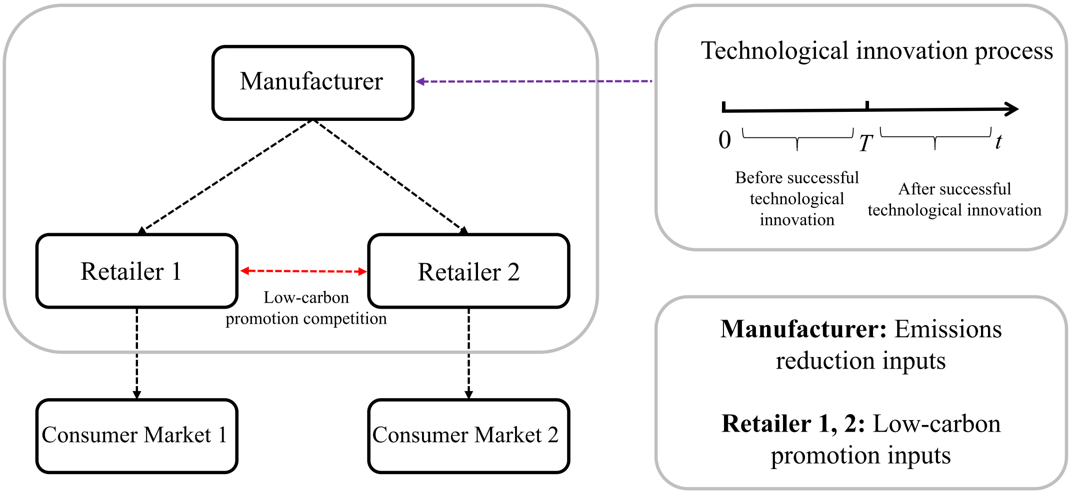

Fig. 1. Schematic diagram of supply chain members' decision-making considering retailers' competition and technological innovation.

and Bhuniya et al. [59]. This contract, building upon the cost-sharing contract, incorporates revenue-sharing mechanisms to incentivize the behavior of supply chain members. However, the implementation of the revenue-sharing contract often requires defining and calculating contributions from each party [60]. In practical management, different participants may have varying perspectives on how to measure and allocate contributions, thereby increasing the potential for disputes [61]. To address the aforementioned shortcomings, Feng et al. [62] devised a bilateral cost-sharing contract to incentivize all parties to prudently control and manage various production and operational costs. Subsequent extensive research indicates that providing incentives to supply chain members is more achievable through the mutual sharing of costs [63,64]. Considering that, in practical management, the bilateral cost-sharing contract is often easier to implement and manage, it has gradually become a favorable tool for coordinating supply chains.

2.6. *Summary*

In brief, the current research on emissions reduction in supply chain management primarily revolves around the static framework. While Xu et al. [15], Liang et al. [30], and Xia et al. [31] expanded on this research by incorporating a dynamic framework, Guan et al. [37] and Liu et al. [17] further investigated the influence of two state variables on supply chain decision-making within this context. However, these studies do not consider competitive factors, nor do they consider the effects of external technological advancements on the decision-making processes of supply chain participants. In the existing research on technological innovation, the majority tends to perceive it as a fixed scenario and does not account for its stochastic and process-oriented nature.

Building upon these gaps, we adopt the processing method proposed by Hu et al. [43], utilizing the random stop model to illustrate the influence of technological innovation on supply chain decision-making. First, we consider the competitive environment, supply chain emissions reduction, and low-carbon goodwill, by constructing centralized decision-making, retailers alliance, and decentralized decision-making models from both vertical and horizontal cooperation perspectives. Subsequently, we analyze optimal decisions, emissions reduction, low-carbon goodwill, and profits before and after technological innovation. On this basis, we design a contract to facilitate coordination.

3. Problem description and model assumptions

3.1. *Problem description*

This paper examines a supply chain system consisting of a single manufacturer M and two competing retailers $R_i, (i = 1, 2)$, where the manufacturer's main objective is to reduce the carbon emissions of the entire supply chain, and the retailers' primary objective is to promote the manufacturer's low-carbon products. In this process, the emergence of new technology will significantly change all aspects of the low-carbon supply chain industry. Therefore, this paper explores how supply chain members can optimize their decision-making to allocate resources to achieve sustainable development and increase profitability when significant technological changes are predicted. The specific game process comprises two stages: pre-technology innovation implementation and post-technology innovation implementation. In the pre-technology innovation stage, the manufacturer and retailers aim to maximize their profits throughout the entire operational period while determining their investments in emissions reduction and low-carbon promotional inputs. In the post-technology innovation stage, both the manufacturer and retailers shift their focus to maximizing profits in the post-technology innovation stage, with corresponding decisions on emissions reduction and low-carbon promotional investments during this phase. Fig. 1 shows the specific decision-making process and order.

Table 1
Symbols declaration.

Symbols	Description
α	The impact of the manufacturer's emissions reduction inputs on the emissions reduction, $\alpha^+ > \alpha^-$
ε	Decay factor for supply chain emissions reduction, $\varepsilon^+ < \varepsilon^-$
β, θ	The impact of the emissions reduction and low-carbon promotion inputs on low-carbon goodwill
σ	Decay factor for supply chain low-carbon goodwill
ξ, μ	The uplift rate of technological innovation on emissions reduction and low carbon goodwill
ς	Probability of realization of the technological innovation
Ω_i	Consumer market demand of retailer *i*
Π	Initial market demand
φ, ϖ	The impact of the low-carbon promotional inputs and low-carbon goodwill on consumer market
γ	The intensity of competition between two retailers
C_M, C_{Ri}	The costs of emissions reduction inputs and low-carbon promotion inputs
η_M, η_{Ri}	The cost factors for the manufacturer and retailer *i*
π_M, π_{Ri}	Marginal returns per unit for the manufacturer and retailer *i*, $\pi_M^+ > \pi_M^-$, $\pi_{Ri}^+ > \pi_{Ri}^-$
E_M, E_{Ri}	Emissions reduction and low-carbon promotion inputs by the manufacturer and retailers
τ, χ	Emissions reduction and low-carbon goodwill

3.2. *Symbols declaration*

To enhance the clarity of the paper's presentation, Table 1 shows the symbols declaration that have been utilized.

3.3. *Model assumptions*

Assumption 1. A considerable body of existing research indicates that carbon emissions within the supply chain system primarily occur during the manufacturing phase [15], [65,66]. Consequently, the manufacturer's inputs to reduce emissions positively impact the overall emissions reduction within the supply chain at moment t. Additionally, emissions naturally decay due to factors such as aging equipment and technological upgrades. Therefore, drawing from the study in reference [15], [17]. We employ the following differential equations to describe the dynamic changes in emissions reduction within the supply chain:

$$\dot{\tau}(t) = \alpha E_M(t) - \varepsilon\tau(t). \tag{1}$$

In equation (1), $\tau(0) = \tau_0 \geq 0$ represents the initial value of the emissions reduction.

Assumption 2. At the moment t, the low-carbon goodwill of the supply chain system is positively influenced by the combination of emissions reduction and low-carbon promotion inputs from retailers, with some decay occurring over time [17],[37]. Based on the Nerlove-Arrow classical goodwill model [67], the dynamic process of low-carbon goodwill in supply chain systems can be characterized as equation (2):

$$\dot{\chi}(t) = \beta\tau(t) + \theta\sum_{i=1}^{2} E_{Ri}(t) - \sigma\chi(t). \tag{2}$$

In equation (2), $\chi(0) = \chi_0 \geq 0$ represents the initial value of the low-carbon goodwill.

Assumption 3. Technological innovation in the manufacturing process has the potential to enhance emissions reduction in production. However, technical innovation is a complex and time-consuming endeavor with unpredictable timelines for its realization [2–4], [9]. Building on the research of Hu et al. [43], assume that technical innovation is accomplished at time node T with a probability $\varsigma, \varsigma \in (0,1)$. The entire production process can be divided into two stages: pre-technology innovation implementation and post-technology innovation implementation. Therefore, the process of technological innovation is jumpy, as: $\lim\limits_{\Delta\to 0}\frac{P\{t\leq T<t+\Delta|t\leq T\}}{\Delta} = \varsigma$. Where, the conditional probability $P\{t \leq T < t+\Delta|t \leq T\}$ represents the probability of achieving technical innovation at the time node $(t, t+\Delta)$. Considering that the realization of technological innovation will lead to an instantaneous increase in the level of emissions reduction in the supply chain system [42], the emissions reduction after technological innovation can be described as $\tau(T^+) = (1+\xi)\tau(T^-)$. Where $\xi > 0$ is the influence of the technological innovation on emissions reduction. Based on equation (1), we can derive the dynamic process of emissions reduction before and after the success of technological innovation as follows:

$$\begin{cases} \dot{\tau^-}(t) = \alpha^- E_M^-(t) - \varepsilon^-\tau^-(t) & \tau^-(0) = \tau_0, t \in [0,T) \\ \dot{\tau^+}(t) = \alpha^+ E_M^+(t) - \varepsilon^+\tau^+(t) & \tau^+(T^+) = (1+\xi)\tau^-(T^-), t \in [T,\infty) \end{cases} \tag{3}$$

To align with practical scenarios, let $\alpha^+ > \alpha^-$, $\varepsilon^- > \varepsilon^+$, show that the impact of the manufacturer's emissions reduction inputs on supply chain emissions reduction is more significant when technological innovations are successful and the rate of decay is reduced due to technological advances. As an illustration, the adoption of the Liquefied Petroleum Gas to Electricity Conversion technology has led to an annual reduction of approximately 26,000 tons of carbon dioxide emissions in the commercial catering sector of Beijing's central area.

Furthermore, as emissions reduction can impact the supply chain's low-carbon goodwill, similarly, the low-carbon goodwill after the realization of technological innovation can be inscribed as $\chi(T^+) = (1+\mu)\chi(T^-)$. Where $\mu > 0$ represents the influence of the technological innovation on low-carbon goodwill. According to equation (2), the dynamic process of the low-carbon goodwill before and after the success of technological innovation as follows:

$$\begin{cases} \dot{\chi^-}(t) = \beta\tau^-(t) + \theta\sum\limits_{i=1}^{2} E^-_{Ri}(t) - \sigma\chi^-(t) \quad \chi^-(0) = \chi_0, t \in [0, T) \\ \dot{\chi^+}(t) = \beta\tau^+(t) + \theta\sum\limits_{i=1}^{2} E^+_{Ri}(t) - \sigma\chi^+(t) \quad \chi^+(T^+) = (1+\mu)\chi^-(T^-), t \in [T, \infty)) \end{cases} \tag{4}$$

The main objective of technological innovation is to improve emissions reduction in the supply chain system. In accordance with practical considerations [38], we assume that the impact of emissions reduction and retailers' promotional inputs on low-carbon goodwill, as well as the decay coefficient of the supply chain's low-carbon goodwill, remains constant before and after technological innovation.

Assumption 4. In this paper, we consider the competitive relationship between the two retailers. According to the findings in reference [11], consumers can readily perceive the low-carbon promotions provided by retailers, and create a reference effect in competitive situations, further influencing the market demand. Furthermore, numerous studies have demonstrated a positive correlation between the low-carbon goodwill and market demand [56], [68,69]. Therefore, the consumer market demand of retailer i at t moment can be expressed as follows:

$$\Omega_i(t) = \Pi + \varphi E_{Ri}(t) + \gamma[E_{Ri}(t) - E_{R(3-i)}(t)] + \varpi\chi(t). \tag{5}$$

Assume that the two retailers have the same initial market demand, further, in conjunction with Assumption 3, the market demand of the retailer i before and after the achievement of the technical innovation can be expressed as:

$$\begin{cases} \Omega_i(t)^- = \Pi + \varphi E^-_{Ri}(t) + \gamma[E^-_{Ri}(t) - E^-_{R(3-i)}(t)] + \varpi\chi^-(t)) \quad t \in [0, T) \\ \Omega_i(t)^+ = \Pi + \varphi E^+_{Ri}(t) + \gamma[E^+_{Ri}(t) - E^+_{R(3-i)}(t)] + \varpi\chi^+(t)) \quad t \in [T, \infty) \end{cases} \tag{6}$$

Assumption 5. Following the commonly used principle of increasing marginal cost [70], the manufacturer's inputs for emissions reduction and retailer i's inputs for low-carbon promotion at time t are represented by quadratic convex functions with respect to their effort inputs, as follows:

$$C_M[E_M(t)] = \frac{\eta_M}{2}[E_M(t)]^2. \tag{7}$$

$$C_{Ri}[E_{Ri}(t)] = \frac{\eta_{Ri}}{2}[E_{Ri}(t)]^2. \tag{8}$$

Assumption 6. Assuming that all supply chain members share the same discount factor $\rho, \rho > 0$ and aim to maximize their interests during the game period $[0, \infty]$. Then the objective functions for the decisions of the manufacturer and retailer i before the implementation of technological innovation as follows:

$$J^-_M = \max_{E^-_M(t)} \int_0^T e^{-\rho t}\{\pi^-_M \sum_{i=1}^{2} \Omega^-_i(t) - \frac{\eta_M}{2}[E^-_M(t)]^2\}dt. \tag{9}$$

$$J^-_{Ri} = \max_{E^-_{Ri}(t)} \int_0^T e^{-\rho t}\{\pi^-_{Ri}\Omega^-_i(t) - \frac{\eta_{Ri}}{2}[E^-_{Ri}(t)]^2\}dt. \tag{10}$$

The objective functions of the manufacturer and retailer i decision after the successful technological innovation can be expressed as follows:

$$J^+_M = \max_{E^+_M(t)} \int_T^\infty e^{-\rho t}\{\pi^+_M \sum_{i=1}^{2} \Omega^+_i(t) - \frac{\eta_M}{2}[E^+_M(t)]^2\}dt. \tag{11}$$

$$J^+_{Ri} = \max_{E^+_{Ri}(t)} \int_T^\infty e^{-\rho t}\{\pi^-_{Ri}\Omega^-_i(t) - \frac{\eta_{Ri}}{2}[E^+_{Ri}(t)]^2\}dt. \tag{12}$$

Due to the stochastic nature of the technological innovation implementation point T, let $F(x)$ and $f(x)$ represent the distribution function and probability density of random time T, respectively. Based on Rubel et al. [71], assuming that $v(t)$ represents the entire process of the technological innovation. $v(t) = 0$ denotes that the technological innovation is not achieved at the t moment; $v(t) = 1$ denotes that the technological innovation is successfully achieved at the t moment. Therefore, $\lim\limits_{\Delta \to 0} \frac{P\{t \le T < t+\Delta | t \le T\}}{\Delta} = \lim\limits_{\Delta \to 0} \frac{P\{v(t+\delta)|v(t)=0\}}{\Delta}$, we get $F(t) = 1 - e^{-\varsigma t}$, $f(t) = e^{-\varsigma t}$. Further, by taking the expected value of the random time node T, the expected Net Present Value (NPV) of the overall long-term profits of the manufacturer and retailer i can be obtained as: $J_M = E[J_M^- + e^{-\rho T} J_M^+]$, $J_{Ri} = E[J_{Ri}^- + e^{-\rho T} J_{Ri}^+]$. Using $f(t)$ to solve for J_M and J_{Ri}, respectively, the NPV of the expected profits of the supply chain members for the entire game period (the objective function of the members' decision-making) as:

$$J_M^{=} \max_{E_M^-(t), E_M^+(t)} \int_0^\infty e^{-(\rho+\varsigma)t} \{\pi_M^- \sum_{i=1}^{2} \Omega_i^-(t) - \frac{\eta_M}{2}[E_M^-(t)]^2 + \varsigma J_M^+[E_M^+(t)]\} dt. \tag{13}$$

$$J_{Ri}^{=} \max_{E_{Ri}^-(t), E_{Ri}^+(t)} \int_0^\infty e^{-(\rho+\varsigma)t} \{\pi_{Ri}^- \Omega_{Ri}^-(t) - \frac{\eta_{Ri}}{2}[E_{Ri}^-(t)]^2 + \varsigma J_{Ri}^+[E_{Ri}^+(t)]\} dt. \tag{14}$$

To simplify the writing process, the following text omits the time t.

4. Model construction and analysis

In this section, we explore members' equilibrium strategies, emissions reduction, low-carbon goodwill, and profits before and after technological innovation under three models of decentralized decision-making, centralized decision-making, and retailers alliance, respectively. On this basis, we analyze the impact of various critical parameters on them.

The model construction is based on the following:

(1) Theoretical perspective: In the centralized decision-making, supply chain members form a single entity through vertical cooperation, making decisions with the common goal of maximizing joint profits [72]; In the decentralized decision-making, supply chain members are considered to be independent, without any dominance or follower relationships. Each member makes decisions based on maximizing individual profits [73,74]. In the retailers alliance, retailers form a collective entity through an alliance, making decisions with the goal of maximizing alliance profits [75].

(2) Realistic perspective: In the centralized decision-making, achieving the ideal scenario of centralized decision-making is challenging due to members' self-interest. However, decisions under this model are often considered optimal equilibriums in practice [45]; In the decentralized decision-making, departments operate independently to adapt to diverse market conditions and demands. For instance, companies like Procter & Gamble (P&G) and L'Oreal Paris, which have multiple brands, often make independent decisions to maximize brands' respective interests. In the retailers alliance, chain-operated supermarkets such as Walmart and Carrefour. Profit scenarios for the same product may differ across retail institutions due to regional variations, but the decision-making focus is on maximizing the alliance's benefits.

By analyzing and comparing these three models, our objective is to explore the influence of diverse collaboration approaches on supply chain performance. This exploration aids manufacturers and retailers gain a deeper understanding of their shared interests and relationships, facilitating the development of more effective strategies and decisions.

4.1. Decentralized decision-making model

In the decentralized decision-making model (denoted by the superscript N), all members of the supply chain (manufacturer and two retailers) make decisions simultaneously, forming a Nash non-cooperative game. Each member pursues the maximization of individual interests and independently formulates strategies for emissions reduction and low-carbon promotion inputs both before and after technological innovation. Therefore, the decision problems of the manufacturer and retailer i throughout the operation period in the decentralized decision-making model are, respectively:

$$J_M^N = \max_{E_M^-, E_M^+} \int_0^\infty e^{-(\rho+\varsigma)t} \{\pi_M^- \sum_{i=1}^{2} [\Pi + \varphi E_{Ri}^- + \gamma(E_{Ri}^- - E_{R(3-i)}^-) + \varpi \chi^{N-}] - \frac{\eta_M}{2}(E_M^-)^2 + \varsigma J_M^{N+}(E_M^+)\} dt. \tag{15}$$

$$J_{R1}^N = \max_{E_{R1}^-, E_{R1}^+} \int_0^\infty e^{-(\rho+\varsigma)t} \{\pi_{R1}^- [\Pi + \varphi E_{R1}^- + \gamma(E_{R1}^- - E_{R2}^-) + \varpi \chi^{N-}] - \frac{\eta_{R1}}{2}(E_{R1}^-)^2 + \varsigma J_{R1}^{N+}(E_{R1}^+)\} dt. \tag{16}$$

$$J_{R2}^N = \max_{E_{R2}^-, E_{R2}^+} \int_0^\infty e^{-(\rho+\varsigma)t} \{\pi_{R2}^- [\Pi + \varphi E_{R2}^- + \gamma(E_{R2}^- - E_{R1}^-) + \varpi \chi^{N-}] - \frac{\eta_{R2}}{2}(E_{R2}^-)^2 + \varsigma J_{R2}^{N+}(E_{R2}^+)\} dt. \tag{17}$$

Where J_M^N and J_{Ri}^N respectively represent the generalization functions of the decision objectives for the manufacturer and retailer i throughout the entire planning period.

Theorem 1a. *The optimal emissions reduction inputs and low-carbon promotion inputs for the manufacturer and two retailers before and after the realization of the technological innovation in the decentralized decision-making model are:*

$$\begin{cases} E_M^{N*-} = \frac{\alpha^-}{\eta_M}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ E_{R1}^{N*-} = \frac{\pi_{R1}^-(\varphi+\gamma)}{\eta_{R1}} + \frac{\theta}{\eta_{R1}}[\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \\ E_{R2}^{N*-} = \frac{\pi_{R2}^-(\varphi+\gamma)}{\eta_{R2}} + \frac{\theta}{\eta_{R2}}[\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \end{cases} \tag{18}$$

$$\begin{cases} E_M^{N*+} = \frac{2\alpha^+\beta\pi_M^+\varpi}{\eta_M(\rho+\sigma)(\rho+\varepsilon^+)} \\ E_{R1}^{N*+} = \frac{\pi_{R1}^+[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R1}(\rho+\sigma)} \\ E_{R2}^{N*+} = \frac{\pi_{R2}^+[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R2}(\rho+\sigma)} \end{cases} \tag{19}$$

Theorem 1b. *The dynamics of the emissions reduction before and after the realization of technological innovation in the decentralized decision-making model are:*

$$\begin{cases} \tau^{N*-} = \tau_\infty^{N*-} + (\tau_0 + \tau_\infty^{N*-})e^{-\varepsilon^- t} \\ \tau_\infty^{N*-} = \frac{(\alpha^-)^2}{\eta_M\varepsilon^-}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ t \in [0, T] \end{cases} \tag{20}$$

$$\begin{cases} \tau^{N*+} = \{[\tau_\infty^{N*-}(\tau_0 - \tau_\infty^{N*-})e^{-\varepsilon^- t}](1+\xi) - \tau_\infty^{N*+}\}e^{-\varepsilon^+(t-T)} + \tau_\infty^{N*+} \\ \tau_\infty^{N*+} = \frac{2(\alpha^+)^2\beta\pi_M\varpi}{\eta_M\varepsilon^+(\rho+\sigma)(\rho+\varepsilon^+)} \\ t \in (T, \infty) \end{cases} \tag{21}$$

Where τ_∞^{N*-} and τ_∞^{N*+} represent the steady state values of the emissions reduction before and after technological innovation in the decentralized decision-making model, respectively.

Theorem 1c. *The dynamics of low-carbon goodwill in the supply chain system before and after the realization of technological innovation in the decentralized decision-making model are:*

$$\begin{cases} \chi^{N*-} = [\chi_0 - \chi_\infty^{N*-} - \frac{\beta(\tau_0-\tau_\infty^{N*-})}{\varepsilon^- - \sigma}]e^{-\varepsilon^- t} + \frac{\beta(\tau_0-\tau_\infty^{N*-})}{\varepsilon^- - \sigma}e^{-\sigma t} + \chi_\infty^{N*-} \\ \chi_\infty^{N*-} = \frac{\pi_{R1}^-\theta(\varphi+\gamma)}{\sigma\eta_{R1}} + \frac{\theta^2}{\sigma\eta_{R1}}[\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^+\varsigma\varpi(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\pi_{R2}^-\theta(\varphi+\gamma)}{\sigma\eta_{R2}} + \frac{\theta^2}{\sigma\eta_{R2}}[\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\beta\tau_\infty^{N*-}}{\sigma} \\ t \in [T, \infty] \end{cases} \tag{22}$$

$$\begin{cases} \chi^{N*+} = \big(\{[\chi_0 - \chi_\infty^{N*-} - \frac{\beta(\tau_0-\tau^{N*-})}{\varepsilon^- - \sigma}]e^{-\varepsilon^- t} + \frac{\beta(\tau_0-\tau_\infty^{N*-})}{\varepsilon^- - \sigma}e^{-\sigma t} + \chi_\infty^{N*-}\}(1+\mu) - \chi_\infty^{N*+}\big)e^{\sigma(t-T)} + \chi_\infty^{N*+} \\ \chi_\infty^{N*+} = \frac{\pi_{R1}^+\theta[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R1}\sigma(\rho+\sigma)} + \frac{\pi_{R2}^+\theta[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R2}\sigma(\rho+\sigma)} + \frac{\beta\tau_\infty^{N*+}}{\sigma} \\ t \in (T, \infty) \end{cases} \tag{23}$$

Where χ_∞^{N*-} and χ_∞^{N*+} represent the steady state values of low-carbon goodwill before and after technological innovation in the decentralized decision-making model, respectively.

Theorem 1d. *The profit functions of the manufacturer, retailer 1 and retailer 2 after successful technological innovation in the decentralized decision-making model are:*

$$\begin{cases} G_M^{N*} = k_1\tau^{N*+} + k_2\chi^{N*+} + k_3 \\ G_{R1}^{N*} = k_4\tau^{N*+} + k_5\chi^{N*+} + k_6 \\ G_{R2}^{N*} = k_7\tau^{N*+} + k_8\chi^{N*+} + k_9 \end{cases} \tag{24}$$

The profit functions of the manufacturer, retailer 1 and retailer 2 for the entire period of operation are:

$$\begin{cases} W_M^{N*} = s_1\tau^{N*-} + s_2\chi^{N*-} + s_3 \\ W_{R1}^{N*} = s_4\tau^{N*-} + s_5\chi^{N*-} + s_6 \\ W_{R2}^{N*} = s_7\tau^{N*-} + s_8\chi^{N*-} + s_9 \end{cases} \tag{25}$$

Proof. Please see **Appendix** for detail. ☐

Proposition 1. *In the decentralized decision-making model, for the probability of technological innovation success ς, the uplift rate of emissions reduction ξ and low-carbon goodwill μ affect the manufacturer's emissions reduction inputs and retailers' low-carbon promotional* *inputs before and after technological innovation as:* $\frac{\partial E_M^{N*-}}{\partial \varsigma} > 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \varsigma} > 0$, $\frac{\partial E_M^{N*-}}{\partial \xi} > 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \xi} = 0$, $\frac{\partial E_M^{N*-}}{\partial \mu} > 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \mu} > 0$, $\frac{\partial E_M^{N*+}}{\partial \varsigma} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \varsigma} = 0$, $\frac{\partial E_M^{N*+}}{\partial \xi} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \xi} = 0$, $\frac{\partial E_M^{N*+}}{\partial \mu} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \mu} = 0$.

Proposition 1 suggests that: In anticipation of significant technological changes, managers' predictions regarding the probability of success and its impact on business operations are pivotal in decision-making. Specifically, when managers expect a high likelihood of technological success, they tend to increase corresponding investment levels. This is driven by a stronger motivation resulting from the higher success probability, directing managerial attention toward changes in the company's post-technological success and consequently leading to increased pre-implementation investments in technological innovation. Similarly, if managers predict that the emergence of new technology will substantially enhance emissions reduction and low-carbon goodwill, they are inclined to escalate investments in related initiatives. In this scenario, considering both the probability of technological success and the degree of improvement, a conducive environment for business operations is established, further boosting member motivation. Post-successful implementation of technological innovation, managers' earlier predictions about success probability and improvement degree no longer influence their decision-making, with the focus shifting to the product itself.

Management Insights: Managers should adjust their investment levels in emissions reduction, low-carbon promotion, and other aspects based on their predictions regarding the probability of technological innovation success and the anticipated degree of improvement in the current operational conditions. This adaptation aims to better align with the new environment brought about by technological changes.

Proposition 2. *In the decentralized decision-making model, the effects of parameter* γ *before and after technological innovation on manufacturer's decisions to reduce emissions and retailers' decisions to promote low-carbon products are:* $\frac{\partial E_M^{N*-}}{\partial \gamma} = 0$, $\frac{\partial E_M^{N*+}}{\partial \gamma} = 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \gamma} > 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \gamma} > 0$.

Proposition 2 suggests that: Before and after the success of technological innovation, the extent of the manufacturer's emissions reduction investment and the retailer's low-carbon promotional investment are to some degree dependent on the impact of low-carbon promotion, competition, and low-carbon goodwill on market demand. With the increasing influence of low-carbon goodwill on market demand, the manufacturer will increase their investment levels in emissions reduction. This is because the level of supply chain low-carbon goodwill is partly dependent on the emissions reduction level of the supply chain system. In this scenario, manufacturers will increase their corresponding investments. For retailers, when predicting an increase in their own low-carbon promotional investments can stimulate market demand, they will also increase their corresponding investment levels. Moreover, competition among retailers can also motivate their low-carbon promotional investments.

Management Insights: Competition is conducive to mobilizing the proactive efforts of members. Coupled with the impact of competition on market demand, it is necessary for members to judiciously increase their respective investment levels to better respond to the competitive environment.

Proposition 3. *In the decentralized decision-making model, the effect of marginal returns per unit of each member before and after the technological innovation on their decisions are:* $\frac{\partial E_M^{N*-}}{\partial \pi_M^-} > 0$, $\frac{\partial E_M^{N*-}}{\partial \pi_{Ri}^-} = 0$, $\frac{\partial E_M^{N*-}}{\partial \pi_M^+} > 0$, $\frac{\partial E_M^{N*-}}{\partial \pi_{Ri}^+} = 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \pi_{R(3-i)}^-} = 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \pi_{R(3-i)}^+} = 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \pi_M^+} = 0$, $\frac{\partial E_{Ri}^{N*-}}{\partial \pi_M^-} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_M^-} > 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_{Ri}^+} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_{Ri}^+} > 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_M^+} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_M^-} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_{R(3-i)}^-} = 0$, $\frac{\partial E_{Ri}^{N*+}}{\partial \pi_{R(3-i)}^+} = 0$.

Proposition 3 suggests that: In the decentralized decision-making model, only the individual marginal revenue situation influences the decision-making behavior. This is due to the dual marginal effects resulting from independent decision-making among members, leading to relatively closed information exchange between members. Such a situation often hinders the achievement of overall objectives, and in practical management, corresponding collaboration is often necessary to eliminate this effect. Additionally, in the pre-technology innovation success stage, managers need to simultaneously consider the marginal revenue situations in both stages of technology innovation success. Specifically, when formulating decisions before the success of technological innovation, managers should consider both the current revenue situation and the anticipated revenue situation after the success of technological innovation.

Management Insights: Significant marginal benefits serve as a crucial motivating factor for managerial behavior. In practical management, it is imperative for managers to possess a certain level of foresight.

4.2. Centralized decision-making model

In the centralized decision-making model (denoted as superscript C), all supply chain members as a whole, to maximize the overall benefits. While achieving centralized management among supply chain members is challenging in practice, centralized decision-making serves as the theoretical foundation for supply chain coordination research. It also constitutes a crucial approach for analyzing the relevant decisions of supply chain members under collaborative situations. Thus, the decision-making problem of supply chain members in the centralized decision-making model during the whole operation period can be expressed as follows:

$$J^{C}=\max_{E_M^-,E_M^+,E_{R1}^-,E_{R1}^+,E_{R2}^-,E_{R2}^+}\int_0^\infty e^{-(\rho+\varsigma)t}\{\sum_{i=1}^{2}\{\pi_{Ri}^-[\Pi+\varphi E_{Ri}^-+\gamma(E_{Ri}^- -E_{R(3-i)}^-)+\varpi\chi^{C-}]-\sum_{i=1}^{2}\frac{\eta_{Ri}}{2}(E_{Ri}^-)^2+\pi_M^-(2\Pi+\varphi\sum_{i=1}^{2}E_{Ri}^- \\ +2\varpi\chi^{C-})-\frac{\eta_M}{2}(E_M^-)^2+\varsigma J^{C+}(E_M^+,E_{R1}^+,E_{R2}^+)\}dt. \tag{26}$$

Theorem 2a. *The optimal emissions reduction inputs and low-carbon promotion inputs for the manufacturer and the two retailers before and after the realization of the technological innovation in the centralized decision-making model are:*

$$\left\{\begin{array}{l} E_M^{C*-}=\frac{\alpha^-}{\eta_M}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ E_{R1}^{C*-}=\frac{(\pi_{R1}^- -\pi_{R2}^-)\gamma+(\pi_{R1}^- -\pi_M^-)\varphi}{\eta_{R1}}+\frac{\theta}{\eta_{R1}}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \\ E_{R2}^{C*-}=\frac{(\pi_{R2}^- -\pi_{R1}^-)\gamma+(\pi_{R2}^- -\pi_M^-)\varphi}{\eta_{R2}}+\frac{\theta}{\eta_{R2}}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)^-\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \end{array}\right. \tag{27}$$

$$\left\{\begin{array}{l} E_M^{C*+}=\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\alpha^+\beta\varpi}{\eta_M(\rho+\sigma)(\rho+\varepsilon^+)} \\ E_{R1}^{C*+}=\frac{(\pi_{R1}^+-\pi_{R2}^+)\gamma+(\pi_{R1}^+-\pi_M^+)\varphi}{\eta_{R1}}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\theta\varpi}{\eta_{R1}(\rho+\sigma)} \\ E_{R2}^{C*+}=\frac{(\pi_{R2}^+-\pi_{R1}^+)\gamma+(\pi_{R2}^+-\pi_M^+)\varphi}{\eta_{R2}}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\theta\varpi}{\eta_{R2}(\rho+\sigma)} \end{array}\right. \tag{28}$$

Theorem 2b. *The dynamics of the emissions reduction before and after the realization of technological innovation in the centralized decision-making model are:*

$$\left\{\begin{array}{c} \tau^{C*-}=\tau_\infty^{C*-}+(\tau_0+\tau_\infty^{C*-})e^{-\varepsilon^- t} \\ \tau_\infty^{C*-}=\frac{(\alpha^-)^2}{\eta_M\varepsilon^-}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ t\in[0,T] \end{array}\right. \tag{29}$$

$$\left\{\begin{array}{c} \tau^{C*+}=\{[\tau_\infty^{C*-}(\tau_0-\tau_\infty^{C*-})e^{-\varepsilon^- t}](1+\xi)-\tau_\infty^{C*+}\}e^{-\varepsilon^+(t-T)}+\tau_\infty^{C*+} \\ \tau_\infty^{C*+}=\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)(\alpha^+)^2\beta\varpi}{\eta_M\varepsilon^+(\rho+\sigma)(\rho+\varepsilon^+)} \\ t\in(T,\infty) \end{array}\right. \tag{30}$$

Where τ_∞^{C*-} and τ_∞^{C*+} represent the steady state values of the emissions reduction before and after technological innovation in the centralized decision-making model, respectively.

Theorem 2c. *The dynamics of low-carbon goodwill in the supply chain system before and after the realization of technological innovation in the centralized decision-making model are:*

$$\left\{\begin{array}{c} \chi^{C*-}=[\chi_0-\chi_\infty^{C*-}-\frac{\beta(\tau_0-\tau_\infty^{C*-})}{\varepsilon^- -\sigma}]e^{-\varepsilon^- t}+\frac{\beta(\tau_0-\tau_\infty^{C*-})}{\varepsilon^- -\sigma}e^{-\sigma t}+\chi_\infty^{C*-} \\ \chi_\infty^{C*-}=\frac{\theta[(\pi_{R1}^- -\pi_{R2}^-)\gamma+(\pi_{R1}^-+\pi_M^-)\varphi]}{\sigma\eta_{R1}}+\frac{\theta^2}{\sigma\eta_{R1}}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varsigma\varpi(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \\ +\frac{\theta[(\pi_{R2}^- -\pi_{R1}^-)\gamma+(\pi_{R2}^-+\pi_M^-)\varphi]}{\sigma\eta_{R2}}+\frac{\theta^2}{\sigma\eta_{R2}}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma}+\frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{\beta\tau_\infty^{C*-}}{\sigma} \\ t\in[T,\infty] \end{array}\right. \tag{31}$$

$$\left\{\begin{array}{c} \chi^{C*+}=\left(\{[\chi_0-\chi_\infty^{C*-}-\frac{\beta(\tau_0-\tau^{C*-})}{\varepsilon^- -\sigma}]e^{-\varepsilon^- t}+\frac{\beta(\tau_0-\tau_\infty^{C*-})}{\varepsilon^- -\sigma}e^{-\sigma t}+\chi_\infty^{C*-}\}(1+\mu)-\chi_\infty^{C*+}\right)e^{\sigma(t-T)}+\chi_\infty^{C*+} \\ \chi_\infty^{C*+}=\frac{\theta[(\pi_{R1}^+-\pi_{R2}^+)\gamma+(\pi_{R1}^++\pi_M^+)\varphi]}{\sigma\eta_{R1}}+\frac{\theta^2(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi}{(\rho+\sigma)\sigma\eta_{R1}}+\frac{\theta[(\pi_{R2}^+-\pi_{R1}^+)\gamma+(\pi_{R2}^++\pi_M^+)\varphi]}{\sigma\eta_{R2}}+\frac{\theta^2(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi}{(\rho+\sigma)\sigma\eta_{R2}}+\frac{\beta\tau_\infty^{C*+}}{\sigma} \\ t\in(T,\infty) \end{array}\right. \tag{32}$$

Where χ_∞^{C*-} and χ_∞^{C*+} represent the steady state values of low-carbon goodwill before and after technological innovation in the centralized decision-making model, respectively.

Theorem 2d. *The profit function of the whole supply chain after successful technological innovation in the centralized decision-making model is:*

$$G^{C*+}=e_1\tau^{C*+}+e_2\chi^{C*+}+e_3. \tag{33}$$

The profit function of the whole supply chain for the entire period of operation is:

$$W^{C*}=l_1\tau^{C*-}+l_2\chi^{C*-}+l_3. \tag{34}$$

Proof. Please see **Appendix** for detail. ☐

Proposition 4. *In the centralized decision-making model, the effects of parameter γ before and after technological innovation on manufacturer's decisions to reduce emissions and retailers' decisions to promote low-carbon products are* $\frac{\partial E_M^{C*-}}{\partial\gamma} = 0$, $\frac{\partial E_M^{C*-}}{\partial\gamma} = 0$; *When* $\pi_{Ri} - \pi_{R(3-i)} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\gamma} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\gamma} > 0$.

Proposition 4 shows that: In the centralized decision-making model, the impact of parameters *varpi* and *varphi* on managerial decisions is similar to that in the decentralized decision-making model. The difference lies in the context of low-carbon promotional investment by retailers. Only when the retailer's own marginal revenue exceeds that of competitors will an increase in parameter γ stimulate a corresponding increase in the investment level for the side with higher marginal revenue. The rationale behind this is that the decision objective in centralized decision-making is the maximization of overall benefits. Consequently, the party with higher marginal revenue willingly takes on a greater share of the low-carbon promotional investment as part of the collective effort to maximize overall benefits.

Management Insights: From the perspective of coordinating resource allocation, the central manager should make informed decisions based on the actual revenue situation of the subordinate departments. On the one hand, this involves incentivizing the party with higher marginal revenue to increase its corresponding investment level. On the other hand, it also requires the manager to appropriately concede to the party with lower marginal revenue.

Proposition 5. *In the centralized decision-making model, the effect of marginal returns per unit of each member before and after the technological innovation on their decisions are:* $\frac{\partial E_M^{C*-}}{\partial\pi_M^-} > 0$, $\frac{\partial E_M^{C*-}}{\partial\pi_{Ri}^-} > 0$, $\frac{\partial E_M^{C*-}}{\partial\pi_M^+} > 0$, $\frac{\partial E_M^{C*-}}{\partial\pi_{Ri}^+} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\pi_{R(3-i)}^-} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\pi_{R(3-i)}^+} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\pi_M^+} > 0$, $\frac{\partial E_{Ri}^{C*-}}{\partial\pi_M^-} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_M^-} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_{Ri}^+} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_{Ri}^+} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_M^+} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_M^-} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_{R(3-i)}^-} > 0$, $\frac{\partial E_{Ri}^{C*+}}{\partial\pi_{R(3-i)}^+} > 0$.

Proposition 5 shows that: In the centralized decision-making model, the marginal revenue situation of partners similarly influences managerial decisions. This is because, in this case, the supply chain system operates as a whole. In contrast to the self-interest behavior of decision-makers in the decentralized decision-making model mentioned earlier, the decision point for members in the centralized model is to maximize overall profits. When anticipating that partners have higher marginal revenue, the manager will also increase their relevant investment level.

Management Insights: In enterprises operating under the centralized mode, it is crucial for long-term sustainable development to have a timely and comprehensive understanding of the profitability of each department and to make decisions based on this scientific assessment.

4.3. Retailers alliance model

In the retailers alliance model (superscript S represents this decision model), the two retailers have formed an alliance to share information, negotiate, and make decisions to maximize mutual benefits. It is important to note that, with the establishment of the alliance between the two retailers, the sharing of information and negotiations enables alliance members to better adapt to market changes, collectively address challenges, and ensure the overall maximization of the alliance's interests. Thereby, the decision problem of the manufacturer and retailers alliance A during the whole operational period can be expressed as follows:

$$J_M^S = \max_{E_M^-, E_M^+} \int_0^\infty e^{-(\rho+\varsigma)t}\{\pi_M^- \sum_{i=1}^2 [\Pi + \varphi E_{Ri}^- + \gamma(E_{Ri}^- - E_{R(3-i)}^-) + \varpi\chi^{S-}] - \frac{\eta_M}{2}(E_M^-)^2 + \varsigma J_M^{S+}(E_M^+)\}dt. \tag{35}$$

$$J_A^S = \max_{E_{R1}^-, E_{R1}^+, E_{R2}^-, E_{R2}^+} \int_0^\infty e^{-(\rho+\varsigma)t}\{\sum_{i=1}^2 \pi_{Ri}^- [\Pi + \varphi E_{Ri}^- + \gamma(E_{Ri}^- - E_{R(3-i)}^-) + \varpi\chi^{S-}] - \sum_{i=1}^2 \frac{\eta_{Ri}}{2}(E_{Ri}^-)^2 + \varsigma J_A^{S+}(E_{R1}^+, E_{R2}^+)\}dt. \tag{36}$$

Theorem 3a. *The optimal emissions reduction inputs and low-carbon promotion inputs for the manufacturer and the two retailers before and after the realization of the technological innovation in the retailers alliance are:*

$$\begin{cases} E_M^{S*-} = \frac{\alpha^-}{\eta_M}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ E_{R1}^{S*-} = \frac{(\pi_{R1}^- - \pi_{R2}^-)\gamma + \pi_{R1}^-\varphi}{\eta_{R1}} + \frac{\theta}{\eta_{R1}}[\frac{(\pi_{R1}^- + \pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \\ E_{R2}^{S*-} = \frac{(\pi_{R2}^- - \pi_{R1}^-)\gamma + \pi_{R2}^-\varphi}{\eta_{R2}} + \frac{\theta}{\eta_{R2}}[\frac{(\pi_{R1}^- + \pi_{R2}^-)^-\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \end{cases} \tag{37}$$

$$\begin{cases} E_M^{S*+} = \frac{2\pi_M^+ \alpha^+ \beta \varpi}{\eta_M(\rho+\sigma)(\rho+\varepsilon^+)} \\ E_{R1}^{S*+} = \frac{(\pi_{R1}^+ - \pi_{R2}^+)\gamma + \pi_{R1}^+ \varphi}{\eta_{R1}} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\theta\varpi}{\eta_{R1}(\rho+\sigma)} \\ E_{R2}^{S*+} = \frac{(\pi_{R2}^+ - \pi_{R1}^+)\gamma + \pi_{R2}^+ \varphi}{\eta_{R2}} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\theta\varpi}{\eta_{R2}(\rho+\sigma)} \end{cases} \tag{38}$$

Theorem 3b. *The dynamics of the emissions reduction before and after the realization of technological innovation in the retailers alliance model are:*

$$\begin{cases} \tau^{S*-} = \tau_\infty^{S*-} + (\tau_0 + \tau_\infty^{S*-})e^{-\varepsilon^- t} \\ \tau_\infty^{S*-} = \frac{(\alpha^-)^2}{\eta_M \varepsilon^-}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^- \varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+ \varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+ \beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ t \in [0, T] \end{cases} \tag{39}$$

$$\begin{cases} \tau^{S*+} = \{[\tau_\infty^{S*-}(\tau_0 - \tau_\infty^{S*-})e^{-\varepsilon^- t}](1+\xi) - \tau_\infty^{S*+}\}e^{-\varepsilon^+(t-T)} + \tau_\infty^{S*+} \\ \tau_\infty^{S*+} = \frac{2\pi_M^+ (\alpha^+)^2 \beta\varpi}{\eta_M \varepsilon^+(\rho+\sigma)(\rho+\varepsilon^+)} \\ t \in (T, \infty) \end{cases} \tag{40}$$

Where τ_∞^{S*-} and τ_∞^{S*+} represent the steady state values of the emissions reduction before and after technological innovation in the retailers alliance model, respectively.

Theorem 3c. *The dynamics of low-carbon goodwill in the supply chain system before and after the realization of technological innovation in the retailers alliance model are:*

$$\begin{cases} \chi^{S*-} = [\chi_0 - \chi_\infty^{S*-} - \frac{\beta(\tau_0 - \tau_\infty^{S*-})}{\varepsilon^- - \sigma}]e^{-\varepsilon^- t} + \frac{\beta(\tau_0 - \tau_\infty^{S*-})}{\varepsilon^- - \sigma}e^{-\sigma t} + \chi_\infty^{S*-} \\ \chi_\infty^{S*-} = \frac{\theta[(\pi_{R1}^- - \pi_{R2}^-)\gamma + \pi_{R1}^- \varphi]}{\sigma\eta_{R1}} + \frac{\theta^2}{\sigma\eta_{R1}}[\frac{(\pi_{R1}^- + \pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\varsigma\varpi(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\theta[(\pi_{R2}^- - \pi_{R1}^-)\gamma + \pi_{R2}^- \varphi]}{\sigma\eta_{R2}} \\ \quad + \frac{\theta^2}{\sigma\eta_{R2}}[\frac{(\pi_{R1}^- + \pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\beta\tau_\infty^{S*-}}{\sigma} \\ t \in [T, \infty] \end{cases} \tag{41}$$

$$\begin{cases} \chi^{S*+} = \left(\{[\chi_0 - \chi_\infty^{S*-} - \frac{\beta(\tau_0 - \tau^{S*-})}{\varepsilon^- - \sigma}]e^{-\varepsilon^- t} + \frac{\beta(\tau_0 - \tau_\infty^{S*-})}{\varepsilon^- - \sigma}e^{-\sigma t} + \chi_\infty^{S*-}\}(1+\mu) - \chi_\infty^{S*+}\right)e^{\sigma(t-T)} + \chi_\infty^{S*+} \\ \chi_\infty^{S*+} = \frac{\theta[(\pi_{R1}^+ - \pi_{R2}^+)\gamma + \pi_{R1}^+ \varphi]}{\sigma\eta_{R1}} + \frac{\theta^2(\pi_{R1}^+ + \pi_{R2}^+)\varpi}{(\rho+\sigma)\sigma\eta_{R1}} + \frac{\theta[(\pi_{R2}^+ - \pi_{R1}^+)\gamma + \pi_{R2}^+ \varphi]}{\sigma\eta_{R2}} + \frac{\theta^2(\pi_{R1}^+ + \pi_{R2}^+)\varpi}{(\rho+\sigma)\sigma\eta_{R2}} + \frac{\beta\tau_\infty^{S*+}}{\sigma} \\ t \in (T, \infty) \end{cases} \tag{42}$$

Where χ_∞^{S*-} and χ_∞^{S*+} represent the steady state values of low-carbon goodwill before and after technological innovation in the centralized decision-making model, respectively.

Theorem 3d. *The profit functions of the manufacturer and retailers alliance after successful technological innovation in the retailers alliance model are:*

$$\begin{cases} G_M^{S*} = y_1\tau^{S*+} + y_2\chi^{S*+} + y_3 \\ G_A^{S*} = y_4\tau^{S*+} + y_5\chi^{S*+} + y_6 \end{cases} \tag{43}$$

The profit functions of the manufacturer and retailers alliance for the entire period of operation are:

$$\begin{cases} G_M^{S*} = q_1\tau^{S*-} + q_2\chi^{S*-} + q_3 \\ G_A^{S*} = q_4\tau^{S*-} + q_5\chi^{S*-} + q_6 \end{cases} \tag{44}$$

Proof. Please see **Appendix** for detail. ☐

Proposition 6. *In the retailers alliance model, the effect of marginal returns per unit of each member before and after the technological innovation on their decisions are:* $\frac{\partial E_M^{S*-}}{\partial \pi_M^-} > 0$, $\frac{\partial E_M^{S*-}}{\partial \pi_{Ri}^-} = 0$, $\frac{\partial E_M^{S*-}}{\partial \pi_M^+} > 0$, $\frac{\partial E_M^{S*-}}{\partial \pi_{Ri}^+} = 0$, $\frac{\partial E_{Ri}^{S*-}}{\partial \pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{S*-}}{\partial \pi_{R(3-i)}^-} > 0$, $\frac{\partial E_{Ri}^{S*-}}{\partial \pi_{R(3-i)}^+} > 0$, $\frac{\partial E_{Ri}^{S*-}}{\partial \pi_M^+} = 0$, $\frac{\partial E_{Ri}^{S*-}}{\partial \pi_M^-} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_M^-} > 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_{Ri}^+} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_{Ri}^-} > 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_{Ri}^+} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_M^+} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_M^-} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_{R(3-i)}^-} = 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \pi_{R(3-i)}^+} > 0$. *When* $\pi_{Ri} - \pi_{R(3-i)>0}$, $\frac{\partial E_{Ri}^{S*-}}{\partial \gamma} > 0$, $\frac{\partial E_{Ri}^{S*+}}{\partial \gamma} > 0$.

Proposition 6 suggests that: In the retails alliance, the manufacturer, functioning as an independent entity, is no longer affected by the marginal profits of individual retailers. Conversely, retailers, acting as a unified alliance, make decisions to maximize alliance benefits. Hence, the marginal profit situation of alliance partners becomes a factor considered by managers in the decision-making process.

Management Insights: The collaboration among retailers has also increased the sharing of information between departments, to some extent, mitigating the dual marginal effects arising from independent decision-making in each department.

4.4. Comparative analysis

This subsection compares the optimal decisions of supply chain members, emissions reduction, low-carbon goodwill, and profits before and after the technological innovation in the above three decision-making models and draws upon the following characteristics.

Characteristic 1. Before and after the realization of technological innovation, the optimal decision of the manufacturer to reduce emissions under the three decision models has the following relationship: $E_M^{N*-} = E_M^{S*-} < E_M^{C*-}$, $E_M^{N*+} = E_M^{S*+} < E_M^{C*+}$; Before the realization of technological innovation, the retailer *i*'s optimal decision for low-carbon promotion has the following relationship: $E_{Ri}^{S*-} < E_{Ri}^{C*-}$. When $\frac{\theta}{\eta_{Ri}}[\frac{(\pi_{R(3-i)}^- + 2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{\varsigma(1+\mu)(\pi_{R(3-i)}^+ + 2\pi_M^+)\varpi}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] < \frac{\pi_{R(3-i)}^-\gamma}{\eta_{Ri}}$, $E_{Ri}^{S*-} < E_{Ri}^{N*-}$. When $\frac{\theta}{\eta_{Ri}}[\frac{(\pi_{R(3-i)}^- + 2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{\varsigma(1+\mu)(\pi_{R(3-i)}^+ + 2\pi_M^+)\varpi}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] < \frac{\pi_{R(3-i)}^-\gamma - \pi_M^-\varphi}{\eta_{Ri}}$, $E_{Ri}^{C*-} < E_{Ri}^{N*-}$; After the realization of technological innovation, the retailer *i*'s optimal decision for low-carbon promotion has the following relationship: $E_{Ri}^{S*+} < E_{Ri}^{C*+}$. When $\frac{\theta\varpi}{\eta_{Ri}(\rho+\sigma)(\rho+\varepsilon^+)} < \frac{\gamma}{\eta_{Ri}}$, $E_{Ri}^{S*+} < E_{Ri}^{N*+}$. When $\frac{\theta(\pi_{R(3-i)}^+ + 2\pi_M^+)\varpi}{(\rho+\sigma)\eta_{Ri}} < \frac{\pi_{R(3-i)}^+\gamma - \pi_M^+\varphi}{\eta_{Ri}}$, $E_{Ri}^{C*+} < E_{Ri}^{N*+}$.

Characteristic 1 shows that: In the case of centralized decision-making, the manufacturer demonstrates a higher level of investment in emissions reduction compared to the scenarios of decentralized decision-making and the retail alliance. For competitive retailers, when the parameter γ falls below a specific threshold, the low-carbon promotion inputs for both retailers in the centralized decision-making model are maximized during post-technological innovation. It is noteworthy that, before the success of technological innovation, the low-carbon promotion investment of retailers in the three models is influenced by various factors. These factors include not only parameter γ but also considerations such as the probability of technological innovation success and the enhancement rate. In the subsequent sections, we will provide a detailed analysis of the pre-technological innovation investment levels of supply chain members with specific case examples. However, under the mentioned prerequisites, centralized decision-making can eliminate the dual marginal effects in the supply chain, allowing for a more rational allocation of resources among members and further enhancing supply chain efficiency.

Characteristic 2. The optimal trajectory of emissions reduction of the supply chain system under the three decision models before and after the success of technological innovation has the following relationship: $\tau^{N*-} = \tau^{S*-} < \tau^{C*-}$, $\tau^{N*+} = \tau^{S*+} < \tau^{C*+}$.

Characteristic 2 shows that: In the centralized decision-making model, the emissions reductions performance of the supply chain system surpasses that of both decentralized decision-making and the retails alliance scenarios. Combining Characteristic 1, it can be observed that in the centralized decision-making model, the manufacturer's emissions reduction investment is optimal, thereby further promoting an overall increase in the emissions reduction level of the supply chain.

Characteristic 3. Before the success of technological innovation, the optimal trajectory of low-carbon goodwill of the supply chain system under the three decision models has the following relationship: $\chi^{S*-} < \chi^{C*-}$. When $\frac{\theta^2}{\sigma\eta_{R1}}[\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] + \frac{\theta^2}{\sigma\eta_{R2}}[\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^+\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] < \frac{\theta\gamma\pi_{R2}^+}{\sigma\eta_{R1}} + \frac{\theta\gamma\pi_{R1}^+}{\sigma\eta_{R2}}$, $\chi^{S*-} < \chi^{N*-}$. When $\frac{\theta^2}{\sigma\eta_{R1}}[\frac{(\pi_{R2}^- + 2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R2}^+ + 2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] + \frac{\theta^2}{\sigma\eta_{R2}}[\frac{(\pi_{R1}^- + 2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + 2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] + \frac{(\alpha^-)^2\beta}{\eta_M\sigma\varepsilon^-}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{(\pi_{R1}^- + \pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] + \frac{(\pi_{R1}^+ + \pi_{R2}^+)\beta\varpi\varsigma(1+\xi)}{(\rho+\sigma)(\rho+\varsigma+\varepsilon^-)(\rho+\varepsilon^+} < \frac{\theta(\pi_{R2}^-\gamma - \pi_M^-\varphi)}{\sigma\eta_{R1}} + \frac{\theta(\pi_{R1}^-\gamma - \pi_M^-\varphi)}{\sigma\eta_{R2}}$, $\chi^{C*-} < \chi^{N*-}$; After the success of technological innovation, the optimal trajectory of low-carbon goodwill of the supply chain system under the three decision models has the following relationship: $\chi^{S*+} < \chi^{C*+}$. When $\frac{\eta^2\pi_{R2}^+\varpi}{\eta_{R1}(\rho+\sigma)(\rho+\varepsilon^+)} + \frac{\eta^2\pi_{R1}^+\varpi}{\eta_{R2}(\rho+\sigma)(\rho+\varepsilon^+)} < \frac{\gamma\theta\pi_{R2}^+}{\eta_{R1}} + \frac{\gamma\theta\pi_{R1}^+}{\eta_{R2}}$, $\chi^{S*+} < \chi^{N*+}$. When $\frac{\theta^2(\pi_{R2}^+ 2\pi_M^+)\varpi}{(\rho+\sigma)\sigma\eta_{R1}} + \frac{\theta^2(\pi_{R1}^+ 2\pi_M^+)\varpi}{(\rho+\sigma)\sigma\eta_{R2}} + \frac{(\alpha^+)^2\beta^2(\pi_{R1}^+ + \pi_{R2}^+)\varpi}{\eta_M\varepsilon^+\sigma(\rho+\varepsilon^+)(\rho+\sigma)} < \frac{\theta(\pi_{R2}^+\gamma - \pi_M^+\varphi)}{\sigma\eta_{R1}} + \frac{\theta(\pi_{R1}^+\gamma - \pi_M^+\varphi)}{\sigma\eta_{R2}}$, $\chi^{C*+} < \chi^{N*+}$.

Characteristic 3 shows that: When parameter γ is below a specific threshold, the low-carbon goodwill of the supply chain in the centralized decision-making model surpasses that of decentralized decision-making. Combining Characteristic 1, it can be observed that in the centralized decision-making model under such conditions, both retailers increase their respective low-carbon promotional investments, and the emissions reduction level of the supply chain system is optimal. Therefore, from the overall supply chain perspective, the resource allocation is more rational, and the corresponding investment levels of supply chain members are also at their optimum. Furthermore, considering the low-carbon promotional investments of the two retailers before the success of technological innovation, the low-carbon goodwill levels in the three models before technological innovation success are also influenced by factors such as the probability of technological innovation success and the enhancement rate.

Characteristic 4. In terms of the overall profitability of the supply chain system throughout the operation: $W^{S*} < W^{C*}$. When $\frac{\theta^2}{\sigma\eta_{R1}}[\frac{\pi_{R2}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^{+}\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] + \frac{\theta^2}{\sigma\eta_{R2}}[\frac{\pi_{R1}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^{+}\varpi\varsigma(1+\mu)}{(\rho+\sigma)(\rho+\varsigma+\sigma)}] < \frac{\theta\gamma\pi_{R2}^{+}}{\sigma\eta_{R1}} + \frac{\theta\gamma\pi_{R1}^{+}}{\sigma\eta_{R2}}$, $W^{S*} < W^{N*}$. When $\frac{\theta^2(\pi_{R2}^{+}2\pi_M^{+})\varpi}{(\rho+\sigma)\sigma\eta_{R1}} + \frac{\theta^2(\pi_{R1}^{+}2\pi_M^{+})\varpi}{(\rho+\sigma)\sigma\eta_{R2}} + \frac{(\alpha^{+})^2\beta^2(\pi_{R1}^{+}+\pi_{R2}^{+})\varpi}{\eta_M\varepsilon^{+}\sigma(\rho+\varepsilon^{+})(\rho+\sigma)} < \frac{\theta(\pi_{R2}^{+}\gamma-\pi_M^{+}\varphi)}{\sigma\eta_{R1}} + \frac{\theta(\pi_{R1}^{+}\gamma-\pi_M^{+}\varphi)}{\sigma\eta_{R2}}$, $W^{C*} < W^{N*}$; In terms of the overall profitability of the supply chain system after the success of the technological innovation: $G^{S*} < G^{C*}$. When $\frac{\theta^2\pi_{R2}^{+}\varphi}{\eta_{R1}(\rho+\sigma)(\rho+\varepsilon^{+})} + \frac{\theta^2\pi_{R1}^{+}\varphi}{\eta_{R2}(\rho+\sigma)(\rho+\varepsilon^{+})} < \frac{\pi_{R2}^{+}\gamma\theta}{\eta_{R1}} + \frac{\pi_{R1}^{+}\gamma\theta}{\eta_{R2}}$, $G^{S*} < G^{N*}$. When $\frac{\theta^2(\pi_{R2}^{+}2\pi_M^{+})\varpi}{(\rho+\sigma)\sigma\eta_{R1}} + \frac{\theta^2(\pi_{R1}^{+}2\pi_M^{+})\varpi}{(\rho+\sigma)\sigma\eta_{R2}} + \frac{(\alpha^{+})^2\beta^2(\pi_{R1}^{+}+\pi_{R2}^{+})\varpi}{\eta_M\varepsilon^{+}\sigma(\rho+\varepsilon^{+})(\rho+\sigma)} < \frac{\theta(\pi_{R2}^{+}\gamma-\pi_M^{+}\varphi)}{\sigma\eta_{R1}} + \frac{\theta(\pi_{R1}^{+}\gamma-\pi_M^{+}\varphi)}{\sigma\eta_{R2}}$, $G^{C*} < G^{N*}$.

Characteristic 4 shows that: When expected profits of the supply chain under centralized decision-making is higher than the decentralized decision-making and retailers alliance when the preconditions of Characteristic 3 are satisfied. This is due to the fact that supply chain low carbon goodwill can increase market demand, making centralized decision-making more economically efficient when other parameters are held constant. Similarly, under certain conditions, cooperation between retailers can bring higher benefits to the supply chain system than decentralized decision-making. Therefore, from a management practice point of view, the manufacturer and the two retailers should vertical for cooperation or an alliance between the horizontals when specific prerequisites are met, thus improving the overall profitability.

5. Bilateral cost-sharing contract

According to the analysis in Section 4, although the decentralized decision-making model can optimize the retailers' low-carbon promotion input, supply chain's low-carbon goodwill, and profits under certain conditions, it fails to improve the manufacturer's emissions reduction input and supply chain emissions reduction. The centralized decision-making model can optimize the manufacturer's emissions reduction input, retailers' low-carbon promotion input, emissions reductions, low-carbon goodwill, and profits under certain conditions. However, it is well known that decision-makers in real-world management practices are often driven by rationality, aiming to maximize their own interests. Therefore, this decision-making model is often challenging to implement in reality [76,77]. Based on this, this section designs a bilateral cost-sharing contract to coordinate for the following reasons:

(1) The bilateral cost-sharing contract can effectively mitigate risks arising from information asymmetry or environmental changes, thereby enhancing the stability of the supply chain [62].

(2) The bilateral cost-sharing contract helps optimize the allocation of resources in the supply chain system, encouraging members to use resources more efficiently and improving the overall efficiency of the supply chain [45].

(3) In practical management, the bilateral cost-sharing contract is typically relatively simple, making it easy to implement and manage [63,64].

Assuming the optimality of centralized decision-making across all metrics, as determined by the relevant parameters meeting the conditions outlined in Section 4. During both the pre- and post-successful stages of technological innovation, the manufacturer subsidizes the low-carbon promotion costs of the two retailers. The subsidy rates are denoted as Γ_i^{-} and Γ_i^{+}, respectively, aiming to incentivize their corresponding low-carbon promotion inputs. It's essential to note that the rationality principle is considered, assuming $0 < \Gamma_i^{-}, \Gamma_i^{+} < 1$. Meanwhile, the two retailers subsidize the cost of the manufacturer's emissions reduction inputs at rates of Φ_i^{-} and Φ_i^{+}, respectively, to incentivize their relevant emissions reduction inputs, and again, $0 < \Phi_i^{-}, \Phi_i^{+} < 1$. Further, under the bilateral cost contract (superscript Z represents it), the decision problem of the manufacturer and two retailers throughout the operation can be expressed as follows:

$$\begin{aligned} J_M^Z = \max_{E_M^{-},E_M^{+},\Gamma_1^{-},\Gamma_1^{+},\Gamma_2^{-},\Gamma_2^{+}} \int_0^{\infty} & e^{-(\rho+\varsigma)t}\{\pi_M^{-}\sum_{i=1}^{2}[\Pi + \varphi E_{Ri}^{-} + \gamma(E_{Ri}^{-} - E_{R(3-i)}^{-}) + \varpi\chi^{Z-}] \\ & - (1-\Phi_1^{-}-\Phi_2^{-})\frac{\eta_M}{2}(E_M^{-})^2 - \sum_{i=1}^{2}\frac{\Gamma_i^{-}\eta_{Ri}^{-}}{2}(E_{Ri}^{-})^2 + \varsigma J_M^{Z+}(E_M^{+},\Gamma_1^{+},\Gamma_2^{+})\}dt. \end{aligned} \tag{45}$$

$$\begin{aligned} J_{R1}^N = \max_{E_{R1}^{-},E_{R1}^{+},\Phi_1^{-},\Phi_1^{-}} \int_0^{\infty} & e^{-(\rho+\varsigma)t}\{\pi_{R1}^{-}[\Pi + \varphi E_{R1}^{-} + \gamma(E_{R1}^{-} - E_{R2}^{-}) + \varpi\chi^{Z-}] - (1-\Gamma_1^{-})\frac{\eta_{R1}}{2}(E_{R1}^{-})^2 \\ & - \Phi_1^{-}\frac{\eta_M}{2}(E_M^{-})^2 + \varsigma J_{R1}^{Z+}(E_{R1}^{+},\Phi_1^{+})\}dt. \end{aligned} \tag{46}$$

$$\begin{aligned} J_{R2}^N = \max_{E_{R2}^{-},E_{R2}^{+},\Phi_2^{-},\Phi_2^{-}} \int_0^{\infty} & e^{-(\rho+\varsigma)t}\{\pi_{R2}^{-}[\Pi + \varphi E_{R2}^{-} + \gamma(E_{R2}^{-} - E_{R1}^{-}) + \varpi\chi^{Z-}] - (1-\Gamma_2^{-})\frac{\eta_{R2}}{2}(E_{R2}^{-})^2 \\ & - \Phi_2^{-}\frac{\eta_M}{2}(E_M^{-})^2 + \varsigma J_{R2}^{N+}(E_{R2}^{+},\Phi_2^{+})\}dt. \end{aligned} \tag{47}$$

Theorem 4a. *The bilateral cost contract can fully coordinate the supply chain provided that the subsidy ratio before and after the technological innovation as:*

$$\begin{cases} \Phi_1^- + \Phi_2^- = \frac{\pi_{R1}^- + \pi_{R2}^-}{\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-} \\ \Gamma_1^- = \frac{\pi_M^- \varphi - \pi_{R2}^- \gamma + A\theta(\pi_{R2}^- + 2\pi_M^-) + B\theta(\pi_{R2}^+ + 2\pi_M^+)}{\pi_{R1}^-(\varphi+\gamma) + \pi_M^- \varphi - \pi_{R2}^- \gamma + A\theta(\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-) + B\theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)} \\ \Gamma_2^- = \frac{\pi_M^- \varphi - \pi_{R1}^- \gamma + A\theta(\pi_{R1}^- + 2\pi_M^-) + B\theta(\pi_{R1}^+ + 2\pi_M^+)}{\pi_{R2}^-(\varphi+\gamma) + \pi_M^- \varphi - \pi_{R1}^- \gamma + A\theta(\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-) + B\theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)} \end{cases} \tag{48}$$

$$\begin{cases} \Phi_1^+ + \Phi_2^+ = \frac{\pi_{R1}^+ + \pi_{R2}^+}{\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+} \\ \Gamma_1^+ = \frac{[(\pi_{R1}^+ - \pi_{R2}^+)\gamma + (\pi_{R1}^+ + \pi_M^+)\varphi](\rho+\sigma) + \theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varpi - \pi_{R1}^+[(\varphi+\gamma)(\rho+\sigma) + \theta\varpi]}{[(\pi_{R1}^+ - \pi_{R2}^+)\gamma + (\pi_{R1}^+ + \pi_M^+)\varphi](\rho+\sigma) + \theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varpi} \\ \Gamma_1^+ = \frac{[(\pi_{R2}^+ - \pi_{R1}^+)\gamma + (\pi_{R2}^+ + \pi_M^+)\varphi](\rho+\sigma) + \theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varpi - \pi_{R2}^+[(\varphi+\gamma)(\rho+\sigma) + \theta\varpi]}{[(\pi_{R2}^+ - \pi_{R1}^+)\gamma + (\pi_{R2}^+ + \pi_M^+)\varphi](\rho+\sigma) + \theta(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varpi} \end{cases} \tag{49}$$

Where, $A = \frac{\varpi}{\rho+\varsigma+\sigma}$, $B = \frac{\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$. *At this time,* $\tau^{Z*-} = \tau^{C*-}$, $\tau^{Z*+} = \tau^{C*+}$; $\chi^{Z*-} = \chi^{C*-}$, $\chi^{Z*+} = \chi^{C*+}$.

Theorem 4b. *The profit functions of the manufacturer, retailer 1 and retailer 2 after successful technological innovation under the bilateral cost-sharing contract are:*

$$\begin{cases} G_M^{Z*} = o_1\tau^{Z*+} + o_2\chi^{Z*+} + o_3 \\ G_{R1}^{Z*} = o_4\tau^{Z*+} + o_5\chi^{Z*+} + o_6 \\ G_{R2}^{Z*} = o_7\tau^{Z*+} + o_8\chi^{Z*+} + o_9 \end{cases} \tag{50}$$

The profit functions of the manufacturer retailer 1 and retailer 2 for the entire period of operation are:

$$\begin{cases} W_M^{Z*} = u_1\tau^{Z*-} + u_2\chi^{Z*-} + u_3 \\ W_{R1}^{Z*} = u_4\tau^{Z*-} + u_5\chi^{Z*-} + u_6 \\ W_{R2}^{N*} = u_7\tau^{Z*-} + u_8\chi^{Z*-} + u_9 \end{cases} \tag{51}$$

Proof. Please see **Appendix** for detail. ☐

Proposition 7. *By comparing the profits of supply chain members under the bilateral cost-sharing contract and decentralized decision-making model before and after technological innovation, the following relationship exists:* $W_M^{Z*} - W_M^{N*} > 0$, $W_{Ri}^{Z*} - W_{Ri}^{N*} > 0$, $G_M^{Z*} - G_M^{N*} > 0$, $G_{Ri}^{Z*} - G_{Ri}^{N*} > 0$.

Proposition 7 shows that: Before and after technological innovation, the profits of the supply chain members under the bilateral cost-sharing contract exceeds that of the decentralized decision-making model. Additionally, the bilateral cost-sharing contract can optimize the input levels, emissions reduction, and low-carbon goodwill of supply chain members both before and after the success of technological innovation, reaching the optimal scenario achieved by centralized decision-making. This indicates that the bilateral cost-sharing contract is universally acceptable to supply chain members from an economic perspective. In conclusion, under specific conditions, the bilateral cost-sharing contract can achieve perfect coordination within the supply chain system.

Management Insights: From a feasibility perspective, under certain conditions, the bilateral cost-sharing contract may be the optimal choice for decision-makers in low-carbon supply chains. The key lies in scientifically establishing the corresponding cost-sharing ratio.

6. Numerical analysis

This section uses Python for modeling and numerical simulations to validate the propositions and characteristics obtained earlier in the text, providing a visual representation of the results. Drawing on the studies of Hu et al. [43], Wu et al. [44], and Liu et al. [17], the relevant parameters are set as follows: $\alpha^- = 0.4$, $\alpha^+ = 0.6$, $\varepsilon^- = 0.3$, $\varepsilon^+ = 0.1$, $\beta = 0.5$, $\theta = 0.5$, $\varsigma = 0.6$, $\Pi = 15$, $\varphi = 0.9$, $\varpi = 0.6$, $\gamma = 1$, $\eta_M = 2$, $\eta_{R1} = 2$, $\eta_{R2} = 2$, $\pi_M^- = 3$, $\pi_M^+ = 7$, $\pi_{R1}^- = 1$, $\pi_{R1}^+ = 4$, $\pi_{R2}^- = 2$, $\pi_{R2}^+ = 3$, $\rho = 0.4$.

6.1. Supply chain members' decision-making

Fig. 2 illustrates the impact of the promotion parameters μ and ξ on the decisions of supply chain members under low technological success probability ($\varsigma = 0.2$) and high technological success probability ($\varsigma = 0.8$) before technological innovation.

It can be observed that predicting a higher probability of technological success can effectively motivate a higher level of effort among supply chain members, aligning with the conclusion of Proposition 1 in the previous section. The underlying reason is that a higher probability of technical success increases decision makers' confidence and alters their time preferences. For instance, since 2019, the Chinese government has issued more than 70 technical support policies for the development of new energy vehicles, which has significantly lowered the technical threshold for new energy vehicle research and development, promoting technological innovation. Presently, China has become one of the global leaders in the electric vehicle market.

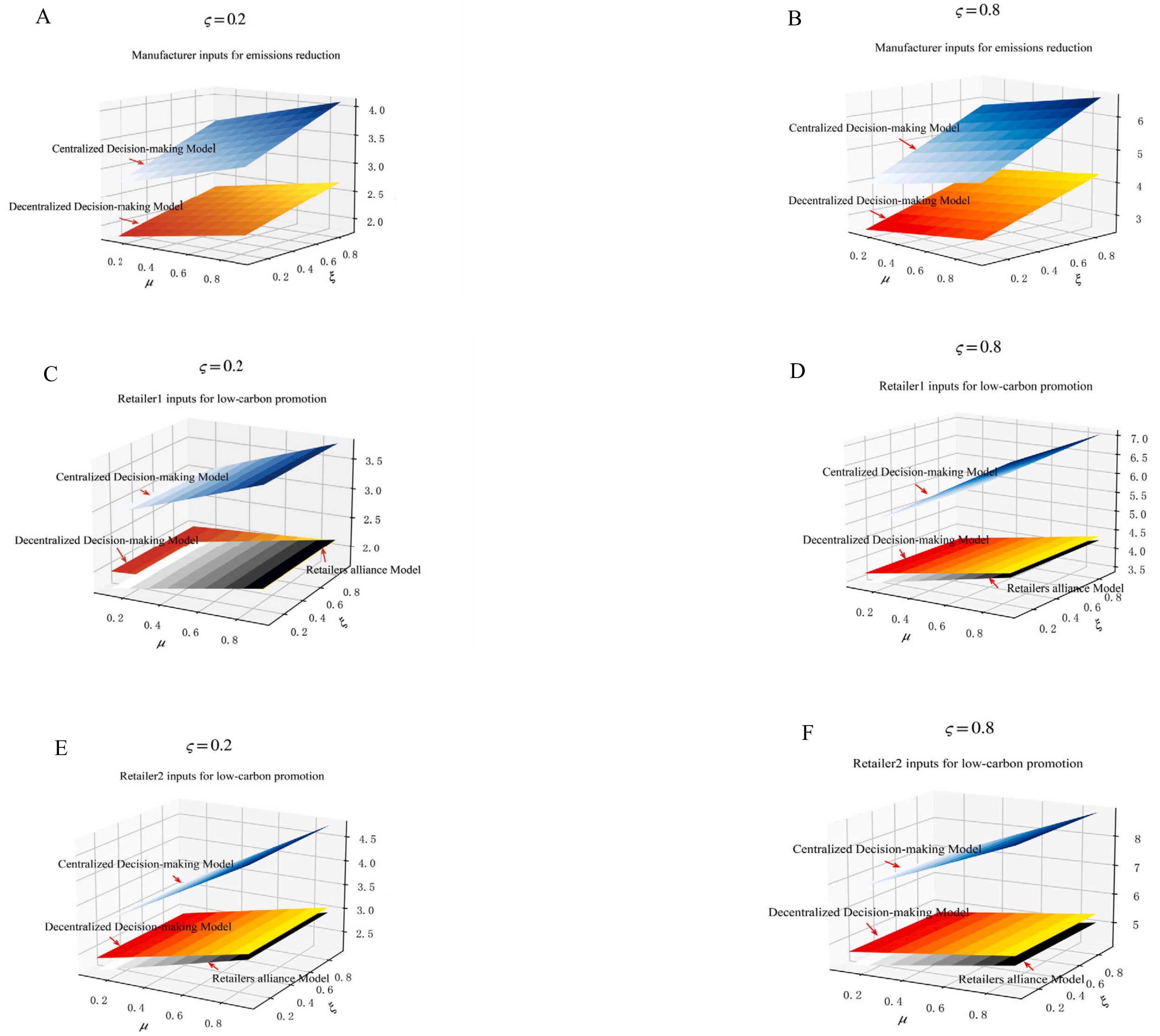

Fig. 2. The impact of parameters μ and ξ on the decisions of supply chain members before technological innovation.

Next, regarding the efforts invested by the manufacturer in emissions reduction, the centralized decision-making model is optimal. Moreover, with the increase in the values of parameters ξ and μ's values, the manufacturer will also increase their emissions reduction investments. In reality, the increase in parameters ξ and μ signifies that the emergence of new technology can result in corresponding improvements in both emission reduction and low-carbon reputation within the supply chain. This can foster a favorable operational environment for businesses, prompting members to increase their investments, thereby laying the groundwork for future development. For example, the introduction of Carbon Capture and Storage (CCS) technology by Beijing Huadian Group significantly enhanced the carbon dioxide capture rate, effectively incentivizing proactive efforts in carbon reduction technology research and development. Simultaneously, it helps the company establish a positive image of environmental sustainability.

Finally, concerning the efforts invested by the two retailers in low-carbon promotion, their decisions are no longer influenced by parameter ξ. The reason is that the emissions reduction occurs exclusively in the production phase of the enterprise, providing limited incentives for retailers to invest in promotional efforts. However, the increase in parameter μ effectively motivates their investments in low-carbon promotion. Moreover, under the alliance scenario, the relevant investment levels of retailer with lower marginal returns are further stimulated (Retailer 1). This reconfirms the conclusion drawn in the Characteristic 1, indicating that the alliance situation can to some extent mitigate the dual marginal effects resulting from independent decision-making by members. The underlying reason lies in the fact that retailers with lower marginal returns in the alliance benefit from resource sharing and joint promotional effects, making them more inclined to invest additional resources in low-carbon promotion to gain the benefits brought about by the alliance. Similar cases, such as the Ant Business Alliance, have significantly boosted member enthusiasm

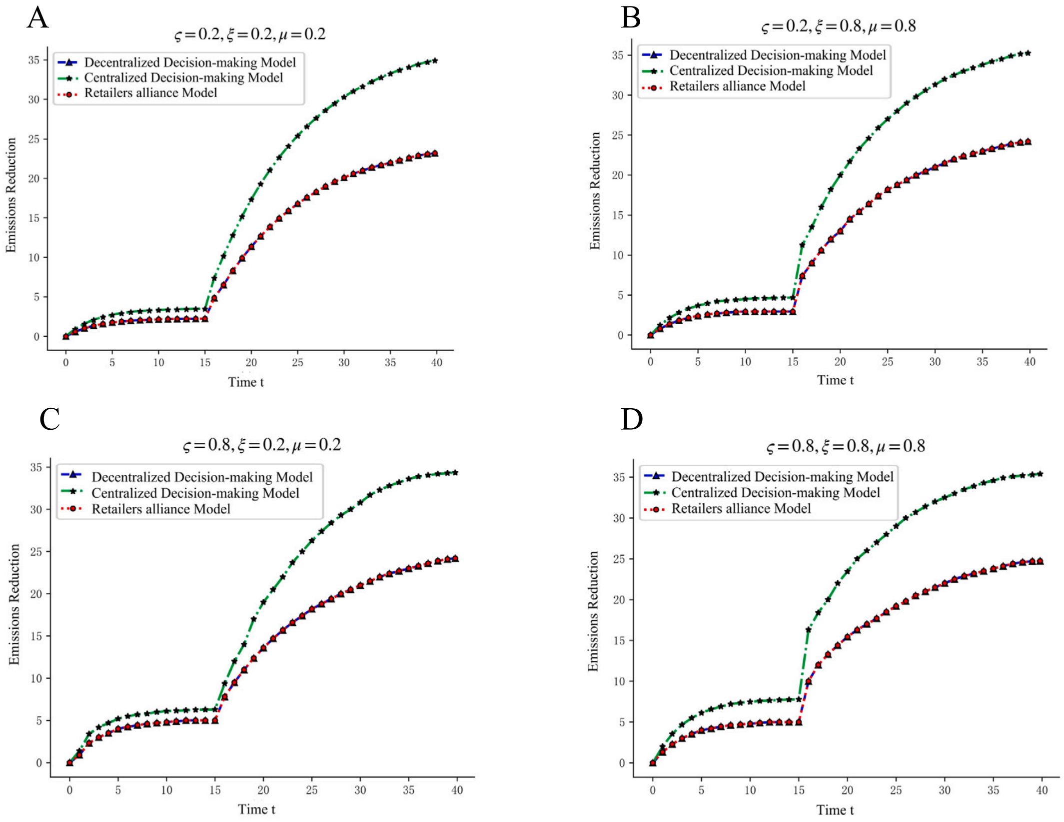

Fig. 3. Impact of technological innovation on supply chain emissions reduction.

through resource sharing and integration, achieving a turnover of 100 billion yuan in 2022 and becoming a nationwide voluntary alliance organization in the retail sector.

6.2. Emissions reduction

Fig. 3 illustrates the emissions reduction curves before and after technological innovation in four scenarios: low success probability and low enhancement rate ($\varsigma = 0.2, \mu = 0.2, \xi = 0.2$), low success probability and high enhancement rate ($\varsigma = 0.2, \mu = 0.8, \xi = 0.8$), high success probability and low enhancement rate ($\varsigma = 0.8, \mu = 0.2, \xi = 0.2$), and high success probability and high enhancement rate ($\varsigma = 0.8, \mu = 0.8, \xi = 0.8$). The moment of technological innovation success is assumed to be at time $T = 15$.

It can be observed that, both before and after technological innovation, the emissions reduction curves in all four scenarios show a “growth followed by stability” trend. Moreover, the emissions reduction levels after technological innovation are significantly higher than the levels before innovation across all scenarios. This aligns with many real-world cases, such as the Technology-Supported Carbon Peak and Carbon Neutrality Implementation Plan (2022-2030) issued in 2022, which indicates that future digital technology innovations are expected to increase carbon emissions by approximately 2% but result in a nearly 20% reduction in carbon emissions, contributing to an annual reduction of approximately 73 million tons of carbon emissions in China.

Additionally, the steady-state value of emissions reduction in four scenarios tends to increase with the improvement of success probability and enhancement rate in the early stages of successful technological innovation. However, after technological innovation success, the four scenarios converge to the same steady-state emissions reduction level. The reason for this lies in the impact of success probability and enhancement rate on the decisions of supply chain members before technological innovation, leading to increased corresponding investments. However, after technological innovation success, supply chain members focus on the product itself, and success probability and enhancement rate no longer influence their decisions.

6.3. Low-carbon goodwill

Fig. 4 depicts the low-carbon goodwill curves before and after technological innovation for four scenarios: low success probability and low enhancement rate, low success probability and high enhancement rate, high success probability and low enhancement rate, and high success probability and high enhancement rate. The assumption is that technological innovation succeeds at moment $T = 15$.

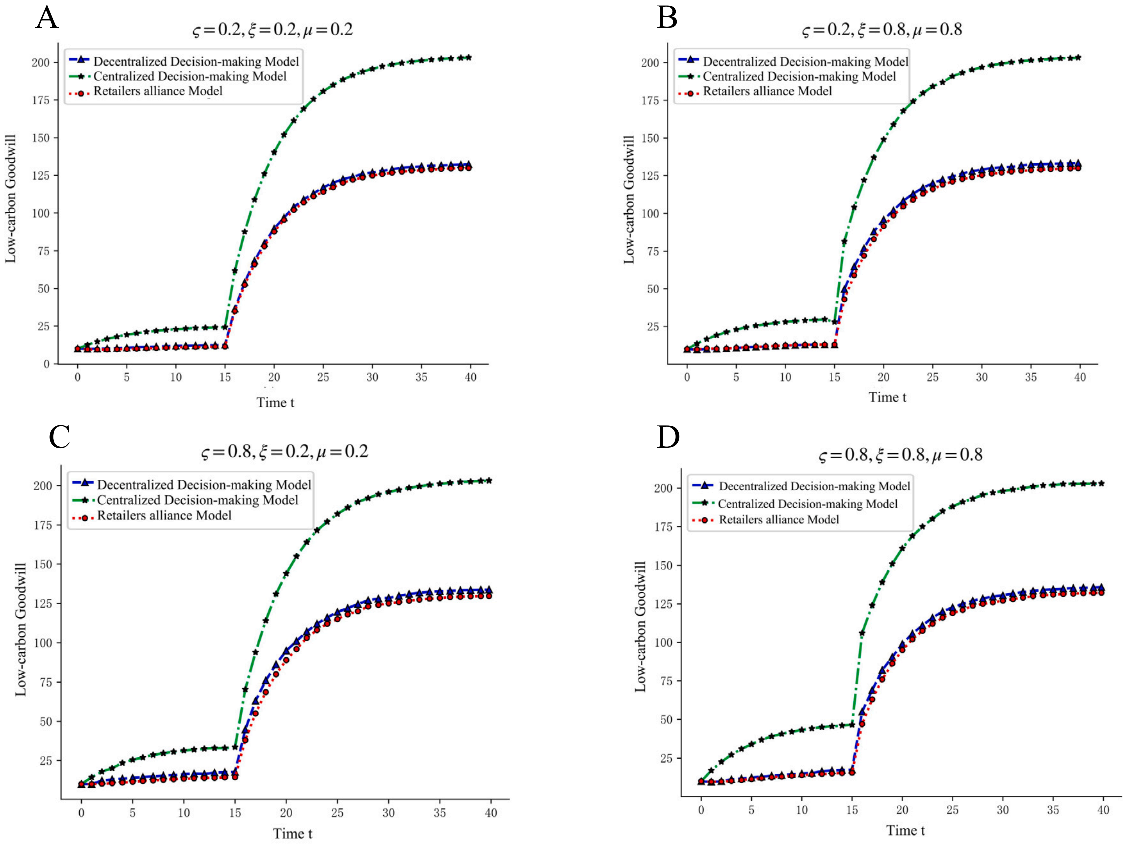

Fig. 4. Impact of technological innovation on supply chain low-carbon goodwill.

In the scenario of low success probability and high enhancement rate, the level of low-carbon goodwill under the retailers alliance is greater than that under the decentralized decision-making model during the pre-innovation period. In other scenarios, decentralized decision-making slightly surpasses the retailers alliance. As analyzed earlier, with the increasing of the parameter μ, the alliance situation is favorable for motivating the relevant investment level of the retailer with lower marginal returns. After technological innovation, low-carbon goodwill is highest in the centralized decision-making model, followed by that in the decentralized decision-making model, and the retailers alliance. In all scenarios, the models exhibit identical steady-state values, as after technological innovation, retailers' decisions are no longer influenced by the probability of technological success or the enhancement rate.

From a practical perspective, the application of new technology can attract more environmentally conscious consumers, positively impacting the brand image of businesses and further expanding market demand. The case of Apple Inc., adopting renewable energy globally, establishing low-carbon data centers and offices, resulted in significant increases in website sales, traffic, and customer retention rates, providing substantial evidence for this assertion.

6.4. Supply chain profits

Fig. 5 shows the profits situation before and after the success of technological innovation in four scenarios: low probability of innovation success-low enhancement, low probability of innovation success-high enhancement, high probability of innovation success-low enhancement, and high probability of innovation success-high enhancement.

It can be observed that, in all four scenarios, the profits situation is optimal under the centralized decision-making model. In the scenario of low probability of innovation success and high enhancement rate, the profits of the retailers alliance in the pre-innovation period are slightly higher than that of the decentralized decision-making model, while in the remaining scenarios, it falls below the profit of the decentralized decision-making model. This is because that the decentralized decision-making model and the retailers alliance have the same emissions reduction situation. Therefore, the profits in these two models primarily depend on the level of low-carbon goodwill. Additionally, regardless of the levels of technological success probability and enhancement rate, the supply chain's profits situation tends to improve over time and stabilize after technological innovation. The success of technological innovation leads to a substantial enhancement in the economic benefits of the enterprise.

From a management perspective, when predicting a high success probability of a new technological transformation or a significant enhancement rate for factors influencing market demand (such as emissions reduction and low-carbon goodwill), companies should increase early-stage research and development efforts to maximize the application value of their resources. For instance, the well-

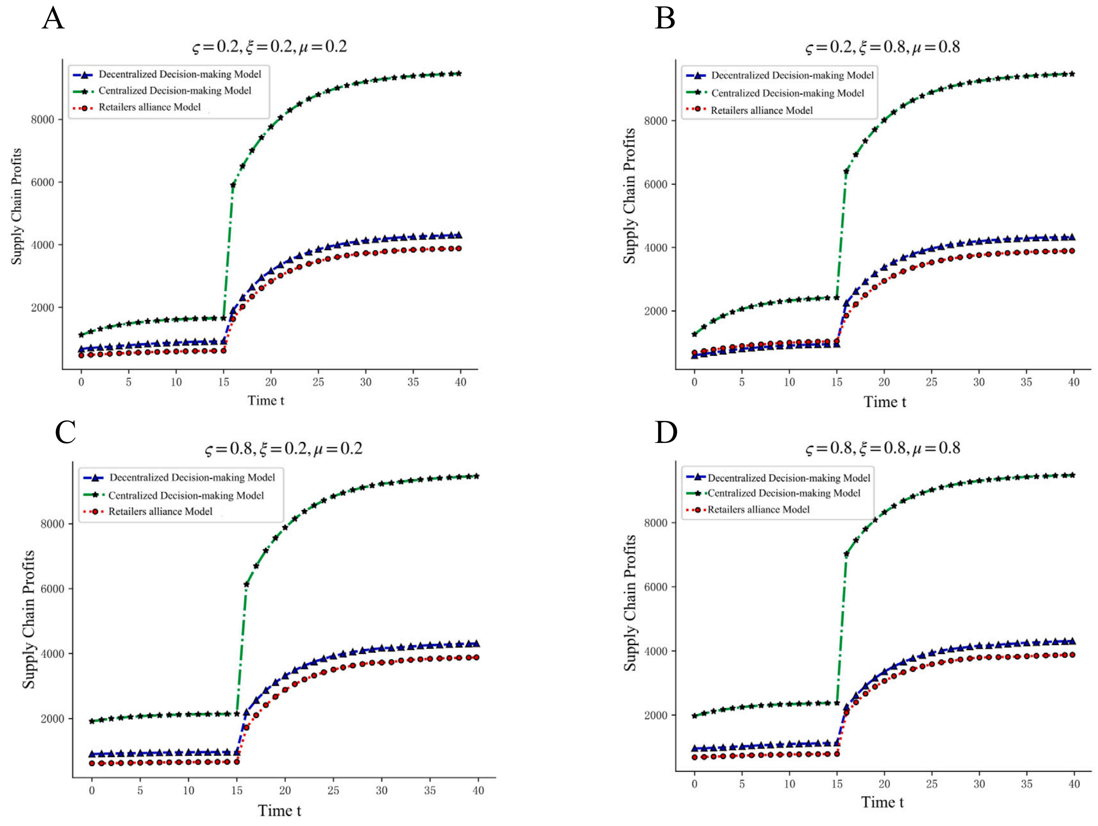

Fig. 5. Impact of technological innovation on supply chain profits.

known Chinese condiment company, JiaJia Group, expanded its visibility and broadened its sales channels by promoting soy sauce, vegetable oil, and other products. Later, with the upgrade of manufacturing technology, the traditional production model of existing foods broke through, new products were developed, and existing channels were utilized to promote these innovations. Through a forward-looking strategy, the company has experienced a remarkable increase in performance in recent years, reaching a historic high.

7. Conclusion and prospection

This paper focuses on a supply chain system consisting of a single manufacturer and two competitive retailers. It introduces the process of technological innovation and explores the optimal decisions, emissions reduction, low-carbon goodwill, and performance levels of supply chain members under three decision models: centralized decision-making, decentralized decision-making, and retailers alliance, based on differential game theory. On this basis, a comparative analysis is conducted. Furthermore, a bilateral cost-sharing contract is proposed to achieve coordination, and numerical examples are employed to analyze the impact of technological innovation on member decisions, emission reduction, and low-carbon goodwill. The main research conclusions are as follows:

(1) Managers' predictions of the probability of technological innovation success and the enhancement rate of emissions reduction and low-carbon goodwill after successful implementation are crucial for the decision-making in the early stages of technological innovation. Higher predictions of success probability and enhancement rate can incentivize supply chain members to invest more in emissions reduction and low-carbon promotional activities in the early stages of technological innovation, leading to increased levels of emission reduction and low-carbon goodwill in the supply chain and, consequently, higher profit levels. Additionally, in the early stages of technological innovation success, managerial decision-making is influenced by the marginal benefits after technological innovation success.

(2) The low-carbon promotional inputs of retailers are closely related to their competitive intensity but are also influenced by the level of cooperation among members. Specifically, when members make independent decisions, the retailer's low-carbon promotional decisions are positively correlated with their competitive intensity. As the cooperation among supply chain members increases, the party with higher marginal benefits will voluntarily bear a greater share of the low-carbon promotional inputs, providing concessions to the party with lower marginal benefits.

(3) Before the success of technological innovation, under certain conditions of competitive intensity, predicted success probability, or enhancement rate, independent decision-making can optimize the low-carbon promotional inputs of retailers. However, after the success of technological innovation, the optimality of retailers' promotional inputs is solely determined by their competitive intensity.

(4) Under certain conditions, centralized decision-making can optimize the related inputs, emissions reduction, low-carbon goodwill, and profit levels of supply chain members both before and after technological innovation. Additionally, the retailers alliance formed by supply chain members through horizontal collaboration can partly mitigate the dual marginal effect. This alliance contributes to improvements in retailer's low-carbon promotional decisions, low-carbon goodwill, and profits. On this basis, the bilateral cost-sharing contract can fully coordinate the supply chain both before and after the implementation of technological innovation.

Based on the above conclusions, the following managerial recommendations are proposed:

(1) Reducing resource consumption and emissions through technological innovation is a crucial approach for China to achieve its carbon peak and carbon neutrality goals. In this context, managers should conduct thorough research to predict both the probability of technological innovation success and the extent of improvement in current operational conditions. Based on these assessments, scientific decision-making should guide companies in allocating funds for emissions reduction and low-carbon promotional activities, enhancing the ability of enterprises to adapt to the new technological environment.

(2) For competitive retailers, maintaining healthy competition should be accompanied by active engagement in horizontal cooperation. On this basis, higher-profit retailers should take the initiative to assume a greater share of investments in low-carbon promotional activities, ensuring the overall long-term sustainability of the supply chain.

(3) Managers need to balance not only current profit levels but also comprehensively consider various potential factors, including marginal profit levels post-implementation, to determine current investment levels.

(4) In actual management practices, independent decision-making by individual departments or companies is not conducive to their own development. It is necessary to eliminate dual marginal effects through relevant contracts or collaborations to achieve the long-term sustainable development of a low-carbon supply chain system.

The current study still has certain limitations. Future research could consider expanding in the following areas:

(1) This paper only treats the marginal benefits of supply chain members as constants and does not account for the dynamic changes in prices. Future research could explore the impact of price dynamics by considering price factors as variables.

(2) The supply chain studied in this paper consists of a single manufacturer producing a single product and two competitive retailers. Future research could extend this study to investigate corresponding dynamics in three-tier or even multi-tier supply chains, involving multiple suppliers, manufacturers, and retailers, through the production of multiple products and mutual competition among them.

(3) This paper only considers the competition between retailers in low-carbon promotion. However, there may be price competition and advertisement competition between retailers, which can be considered to be introduced in the future for a more in-depth study.

CRediT authorship contribution statement

Wenqiang Guo: Supervision. **Yunze Liang:** Writing – original draft. **Ming Lei:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Proof of Theorem 1a-Theorem 1d

In order to maximize profits for all parties during the plan period, the manufacturer and retailer i need to maximize their profits in the two stages before and after the success of the technological innovation, respectively. Employing the backward induction for resolution, the first step is to determine the optimal strategies for the manufacturer and retailer i after the implementation of technological innovation. According to Bellman's continuous dynamic optimization theory, for any $\tau^{N+}, \chi^{N+} \geq 0$ the decision problem of the manufacturer and retailer i after the technological innovation satisfies the following Hamilton-Jacobi-Bellman (HJB) equations:

$$\begin{aligned}\rho G_M^N(\tau^{N+},\chi^{N+}) = & \max_{E_M^+}\{\pi_M^+\sum_{i=1}^{2}[\Pi+\varphi E_{Ri}^+ + \gamma(E_{Ri}^+ - E_{R(3-i)}^+) + \varpi\chi^{N+}] - \frac{\eta_M}{2}(E_M^+)^2 + G_M^{N'}(\tau^{N+})(\alpha^+E_M^+ - \varepsilon^+\tau^{N+}) \\ & + G_M^{N'}(\chi^{N+})(\beta\tau^{N+} + \theta\sum_{i=1}^{2}E_{Ri}^+ - \sigma\chi^{N+})\}.\end{aligned} \tag{A.1}$$

$$\begin{aligned}\rho G_{R1}^N(\tau^{N+},\chi^{N+}) = & \max_{E_{R1}^+}\{\pi_{R1}^+[\Pi+\varphi E_{R1}^+ + \gamma(E_{R1}^+ - E_{R2}^+) + \varpi\chi^{N+}] - \frac{\eta_{R1}}{2}(E_{R1}^+)^2 + G_{R1}^{N'}(\tau^{N+})(\alpha^+E_M^+ - \varepsilon^+\tau^{N+}) + \\ & G_{R1}^{N'}(\chi^{N+})(\beta\tau^{N+} + \theta\sum_{i=1}^{2}E_{Ri}^+ - \sigma\chi^{N+})\}.\end{aligned} \tag{A.2}$$

$$\begin{aligned}G_{R2}^N(\tau^{N+},\chi^{N+}) = & \max_{E_{R2}^+}\{\pi_{R2}^+[\Pi+\varphi E_{R2}^+ + \gamma(E_{R2}^+ - E_{R1}^+) + \varpi\chi^{N+}] - \frac{\eta_{R2}}{2}(E_{R2}^+)^2 + G_{R2}^{N'}(\tau^{N+})(\alpha^+E_M^+ - \varepsilon^+\tau^{N+}) + \\ & G_{R2}^{N'}(\chi^{N+})(\beta\tau^{N+} + \theta\sum_{i=1}^{2}E_{Ri}^+ - \sigma\chi^{N+})\}.\end{aligned} \tag{A.3}$$

Where G_M^N, G_{R1}^N, and G_{R2}^N are the optimal value functions of the manufacturer and retailer 1 and 2, respectively, in the post-successful stage of technological innovation. According to the first-order condition, we get the following: $E_M^{N*} = \frac{\alpha^+G_M^{N'}(\tau^+)}{\eta_M}$, $E_{R1}^{N+} = \frac{[\pi_{R1}^+(\varphi+\gamma)+\theta G_{R1}^{N'}(\chi^+)]}{\eta_{R1}}$, $E_{R2}^{N+} = \frac{[\pi_{R2}^+(\varphi+\gamma)+\theta G_{R2}^{N'}(\chi^+)]}{\eta_{R2}}$. Substituting into the corresponding HJB equation collapses to give:

$$\begin{aligned}\rho G_M^N(\tau^{N+},\chi^{N+}) = & [G_M^{N'}(\chi^{N+})\beta - G_M^{N'}(\tau^{N+})\varepsilon^+]\tau^{N+} + [2\pi_M^+\varpi - G_M^{N'}(\chi^{N+})\sigma]\chi^{N+} + \frac{[\alpha^+G_M^{N'}(\tau^{N+})]^2}{2\eta_M} + 2\pi_M^+\Pi \\ & + \frac{[\pi_M^+\varphi + \theta G_M^{N'}(\chi^{N+})][\pi_{R1}^+(\varphi+\gamma)+\theta G_{R1}^{N'}(\chi^{N+})]}{\eta_{R1}} + \frac{[\pi_M^+\varphi + \theta G_M^{N'}(\chi^{N+})][\pi_{R2}^+(\varphi+\gamma)+\theta G_{R2}^{N'}(\chi^{N+})]}{\eta_{R2}}.\end{aligned} \tag{A.4}$$

$$\begin{aligned}\rho G_{R1}^N(\tau^{N+},\chi^{N+}) = & [G_{R1}^{N'}(\chi^{N+})\beta - G_{R1}^{N'}(\tau^{N+})\varepsilon^+]\tau^{N+} + [\pi_{R1}^+\varpi - G_{R1}^{N'}(\chi^{N+})\sigma]\chi^{N+} + \frac{(\alpha^+)^2G_M^{N'}(\tau^{N+})G_{R1}^{N'}(\tau^{N+})}{\eta_M} + \pi_{R1}^+\Pi \\ & + \frac{[\pi_{R1}^+(\varphi+\gamma)+\theta G_{R1}^{N'}(\chi^{N+})]^2}{2\eta_{R1}} + \frac{[\pi_{R2}^+(\varphi+\gamma)+\theta G_{R2}^{N'}(\chi^{N+})][\theta G_{R1}^{N'}(\chi^{N+} - \gamma\pi_{R1}^+)]}{\eta_{R2}}.\end{aligned} \tag{A.5}$$

$$\begin{aligned}\rho G_{R2}^N(\tau^{N+},\chi^{N+}) = & [G_{R2}^{N'}(\chi^{N+})\beta - G_{R2}^{N'}(\tau^{N+})\varepsilon^+]\tau^{N+} + [\pi_{R2}^+\varpi - G_{R2}^{N'}(\chi^{N+})\sigma]\chi^{N+} + \frac{(\alpha^+)^2G_M^{N'}(\tau^{N+})G_{R2}^{N'}(\tau^{N+})}{\eta_M} + \pi_{R2}^+\Pi \\ & + \frac{[\pi_{R2}^+(\varphi+\gamma)+\theta G_{R2}^{N'}(\chi^{N+})]^2}{2\eta_{R2}} + \frac{[\pi_{R1}^+(\varphi+\gamma)+\theta G_{R1}^{N'}(\chi^{N+})][\theta G_{R2}^{N'}(\chi^{N+} - \gamma\pi_{R2}^+)]}{\eta_{R1}}.\end{aligned} \tag{A.6}$$

According to the equation (A.4)–(A.6) differential equations characteristics, can assume that $\rho G_M^N(\tau^{N*+},\chi^{N*+}) = k_1\tau^{N*+} + k_2\chi^{N*+} + k_3$, $\rho G_{R1}^N(\tau^{N*+},\chi^{N*+}) = k_4\tau^{N*+} + k_5\chi^{N*+} + k_6$, $\rho G_{R2}^N(\tau^{N+*},\chi^{N*+}) = k_7\tau^{N*+} + k_8\chi^{N*+} + k_9$. Where k_i, $i = 1,2,\ldots 9$ are the constant coefficients to be determined, it is easy to know that $G_M^N(\tau^{N*+}) = k_1$, $G_M^N(\chi^{N*+}) = k_2$, $G_{R1}^N(\tau^{N*+}) = k_4$, $G_{R1}^N(\chi^{N*+}) = k_5$, $G_{R2}^N(\tau^{N*+}) = k_7$, $G_{R2}^N(\chi^{N*+}) = k_8$. Where $k_1 = \frac{2\beta\pi_M^+\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $k_2 = \frac{2\pi_M^+\varpi}{\rho+\sigma}$, $k_3 = \frac{(\alpha^+k_1)^2}{2\rho\eta_M} + \frac{(\pi_M^+\varphi+\theta K_2)[\pi_{R1}^+(\varphi+\gamma)+\theta k_5]}{\rho\eta_{R1}} + \frac{(\pi_M^+\varphi+\theta K_2)[\pi_{R2}^+(\varphi+\gamma)+\theta k_8]}{\rho\eta_{R2}} + \frac{2\pi_M^+\Pi}{\rho}$, $k_4 = \frac{\beta\pi_{R1}^+\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $k_5 = \frac{\pi_{R1}^+\varpi}{\rho+\sigma}$, $k_6 = \frac{(\alpha^+)^2k_1k_4}{\rho\eta_M} + \frac{[\pi_{R1}^+(\varphi+\gamma)+\theta k_5]^2}{2\rho\eta_{R1}} + \frac{(\theta K_5-\gamma\pi_{R1}^+)[\pi_{R2}^+(\varphi+\gamma)+\theta k_8]}{\rho\eta_{R2}} + \frac{\pi_{R1}^+\Pi}{\rho}$, $k_7 = \frac{\beta\pi_{R2}^+\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $k_8 = \frac{\pi_{R2}^+\varpi}{\rho+\sigma}$, $k_9 = \frac{(\alpha^+)^2k_1k_7}{\rho\eta_M} + \frac{(\theta K_8-\gamma\pi_{R2}^+)[\pi_{R1}^+(\varphi+\gamma)+\theta k_5]}{\rho\eta_{R1}} + \frac{[\pi_{R2}^+(\varphi+\gamma)+\theta k_8]^2}{2\rho\eta_{R2}} + \frac{\pi_{R2}^+\Pi}{\rho}$. According to the constant relationship can be obtained k_i, $i = 1,2,\ldots 9$ respectively, substituting into the first-order conditions of the manufacturer and retailer 1,2's strategy can be obtained after the success of the technology and their equilibrium strategy. Secondly, substituting into G_M^N, G_{R1}^N and G_{R2}^N respectively, the optimal equilibrium decision and the optimal value function after the technological innovation of the supply chain members can be obtained according to the first-order condition and the expression.

Further, according to $\tau(T^+) = (1+\xi)\tau(T^-)$, $\chi(T^+) = (1+\mu)\tau(T^+)$ and equation (15)–(17), the HJB equations of the supply chain members during the whole operation process can be obtained as:

$$\begin{aligned}(\rho+\varsigma)W_M^N = & \max_{E_M^-}\{\pi_M^-\sum_{i=1}^{2}[\Pi+\varphi E_{Ri}^- + \gamma(E_{Ri}^- - E_{R(3-i)}^-) + \varpi\chi^{N-}] - \frac{\eta_M}{2}(E_M^-)^2 + \varsigma G_M^N[(1+\xi)\tau^{N-},(1+\mu)\chi^{N-}] \\ & + W_M^{N'}(\tau^{N-})(\alpha^-E_M^- - \varepsilon^-\tau^{N-}) + W_M^{N'}(\chi^{N-})(\beta\tau^{N-} + \theta\sum_{i=1}^{2}E_{Ri}^- - \sigma\chi^{N-})\}.\end{aligned} \tag{A.7}$$

$$(\rho+\varsigma)W_{R1}^{N}=\max_{E_{R1}^{-}}\{\pi_{R1}^{-}[\Pi+\varphi E_{R1}^{-}+\gamma(E_{R1}^{-}-E_{R2}^{-})+\varpi\chi^{N-}]-\frac{\eta_{R1}}{2}(E_{R1}^{-})^{2}+\varsigma G_{R1}^{N}[(1+\xi)\tau^{N-},(1+\mu)\chi^{N-}] + W_{R1}^{N'}(\tau^{N-})(\alpha^{-}E_{M}^{-}-\varepsilon^{-}\tau^{N-})+W_{R1}^{N'}(\chi^{N-})(\beta\tau^{N-}+\theta\sum_{i=1}^{2}E_{Ri}^{-}-\sigma\chi^{N-})\}. \tag{A.8}$$

$$(\rho+\varsigma)W_{R2}^{N}=\max_{E_{R2}^{-}}\{\pi_{R2}^{-}[\Pi+\varphi E_{R2}^{-}+\gamma(E_{R2}^{-}-E_{R1}^{-})+\varpi\chi^{N-}]-\frac{\eta_{R2}}{2}(E_{R2}^{-})^{2}+\varsigma G_{R2}^{N}[(1+\xi)\tau^{N-},(1+\mu)\chi^{N-}] + W_{R2}^{N'}(\tau^{N-})(\alpha^{-}E_{M}^{-}-\varepsilon^{-}\tau^{N-})+W_{R2}^{N'}(\chi^{N-})(\beta\tau^{N-}+\theta\sum_{i=1}^{2}E_{Ri}^{-}-\sigma\chi^{N-})\}. \tag{A.9}$$

Where W_M^N, W_{R1}^N, and W_{R2}^N are the optimal value functions of the manufacturer and retailers 1 and 2 over the entire period of operation. According to the first-order condition, we get the following: $E_M^{N-}=\frac{\alpha^{-}W_M^{N'}(\tau^{-})}{\eta_M}$, $E_{R1}^{N-}=\frac{[\pi_{R1}^{-}(\varphi+\gamma)+\theta W_{R1}^{N'}(\chi^{-})]}{\eta_{R1}}$, $E_{R2}^{N-}=\frac{[\pi_{R2}^{-}(\varphi+\gamma)+\theta W_{R2}^{N'}(\chi^{-})]}{\eta_{R2}}$. By substituting into the corresponding HJB equation collapses to give:

$$(\rho+\varsigma)W_{M}^{N}=[W_{M}^{N'}(\chi^{N-})\beta+\varsigma(1+\xi)k_{1}-W_{M}^{N'}(\tau^{N-})\varepsilon^{-}]\tau^{N-}+[2\pi_{M}^{-}\varpi+\varsigma(1+\mu)k_{2}-W_{M}^{N'}(\chi^{N-})\sigma]\chi^{N-}+\frac{[\alpha^{-}W_{M}^{N'}(\tau^{N-})]^{2}}{2\eta_{M}} +\frac{[\pi_{M}^{-}\varphi+\theta W_{M}^{N'}(\chi^{N-})][\pi_{R1}^{-}(\varphi+\gamma)+\theta W_{R1}^{N'}(\chi^{N-})]}{\eta_{R1}}+\frac{[\pi_{M}^{-}\varphi+\theta W_{M}^{N'}(\chi^{N-})][\pi_{R2}^{-}(\varphi+\gamma)+\theta W_{R2}^{N'}(\chi^{N-})]}{\eta_{R2}} +2\pi_{M}^{-}\Pi+\varsigma k_{3}. \tag{A.10}$$

$$(\rho+\varsigma)W_{R1}^{N}=[W_{R1}^{N'}(\chi^{N-})\beta+\varsigma(1+\xi)k_{4}-W_{R1}^{N'}(\tau^{N-})\varepsilon^{+}]\tau^{N-}+[\pi_{R1}^{-}\varpi+\varsigma(1+\mu)k_{5}-W_{R1}^{N'}(\chi^{N-})\sigma]\chi^{N-} +\frac{(\alpha^{-})^{2}W_{M}^{N'}(\tau^{N-})W_{R1}^{N'}(\tau^{N-})}{\eta_{M}}+\frac{[\pi_{R1}^{-}(\varphi+\gamma)+\theta W_{R1}^{N'}(\chi^{N-})]^{2}}{2\eta_{R1}}+\frac{[\pi_{R2}^{-}(\varphi+\gamma)+\theta W_{R2}^{N'}(\chi^{N-})][\theta W_{R1}^{N'}(\chi^{N-})-\gamma\pi_{R1}^{-}]}{\eta_{R2}} +\pi_{R1}^{-}\Pi+\varsigma k_{6}. \tag{A.11}$$

$$(\rho+\varsigma)W_{R2}^{N}=[W_{R2}^{N'}(\chi^{N-})\beta+\varsigma(1+\xi)k_{7}-W_{R2}^{N'}(\tau^{N-})\varepsilon^{+}]\tau^{N-}+[\pi_{R2}^{-}\varpi+\varsigma(1+\mu)k_{8}-W_{R2}^{N'}(\chi^{N-})\sigma]\chi^{N-} +\frac{(\alpha^{-})^{2}W_{M}^{N'}(\tau^{N-})W_{R2}^{N'}(\tau^{N-})}{\eta_{M}}+\frac{[\pi_{R2}^{-}(\varphi+\gamma)+\theta W_{R2}^{N'}(\chi^{N-})]^{2}}{2\eta_{R2}}+\frac{[\pi_{R1}^{-}(\varphi+\gamma)+\theta W_{R1}^{N'}(\chi^{N-})][\theta W_{R2}^{N'}(\chi^{N-)}-\gamma\pi_{R2}^{-})]}{\eta_{R1}} +\pi_{R2}^{-}\Pi+\varsigma k_{9}. \tag{A.12}$$

Similarly, assuming that $(\rho+\varsigma)W_M^N=s_1\tau^{N*+}+s_2\chi^{N*+}+s_3$, $(\rho+\varsigma)W_{R1}^N=s_4\tau^{N*+}+s_5\chi^{N*+}+s_6$, $(\rho+\varsigma)W_{R2}^N=s_7\tau^{N*+}+s_8\chi^{N*+}+s_9$. Where $s_i,\quad i=1,2,\ldots 9$ are the constant coefficients to be determined, it is easy to know that $W_M^N(\tau^{N-*})=s_1$, $W_M^N(\chi^{N-*})=s_2$, $W_{R1}^N(\tau^{N-*})=s_4$, $W_{R1}^N(\chi^{N-*})=s_5$, $W_{R2}^N(\tau^{N-*})=s_7$, $W_{R2}^N(\chi^{N-*})=s_8$. Where $s_1=\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma}+\frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $s_2=\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma}+\frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $s_3=\frac{(\alpha^-s_1)^2}{2(\rho+\varsigma)\eta_M}+\frac{(\pi_M^-\varphi+\theta s_2)[\pi_{R1}^+(\varphi+\gamma)+\theta s_5]}{(\rho+\varsigma)\eta_{R1}}+\frac{(\pi_M^-\varphi+\theta s_2)[\pi_{R2}^+(\varphi+\gamma)+\theta s_8]}{(\rho+\varsigma)\eta_{R2}}+\frac{2\pi_M^-\Pi+\varsigma k_3}{\rho+\varsigma}$, $s_4=\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma}+\frac{\pi_{R1}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{\pi_{R1}^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $s_5=\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma}+\frac{\pi_{R1}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $s_6=\frac{(\alpha^-)^2s_1s_4}{(\rho+\varsigma)\eta_M}+\frac{[\pi_{R1}^-(\varphi+\gamma)+\theta s_5]^2}{2(\rho+\varsigma)\eta_{R1}}+\frac{(\theta s_5-\gamma\pi_{R1}^-)[\pi_{R2}^+(\varphi+\gamma)+\theta s_8]}{(\rho+\varsigma)\eta_{R2}}+\frac{\pi_{R1}^-\Pi+\varsigma k_6}{\rho+\varsigma}$, $s_7=\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma}+\frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}]+\frac{\pi_{R2}^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $s_8=\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma}+\frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $s_9=\frac{(\alpha^-)^2s_1s_8}{(\rho+\varsigma)\eta_M}+\frac{(\theta s_8-\gamma\pi_{R2}^-)[\pi_{R1}^+(\varphi+\gamma)+\theta s_5]}{(\rho+\varsigma)\eta_{R1}}+\frac{[\pi_{R2}^-(\varphi+\gamma)+\theta s_8]^2}{2(\rho+\varsigma)\eta_{R2}}+\frac{\pi_{R2}^-\Pi+\varsigma k_9}{\rho+\varsigma}$. Further, we can get the equilibrium strategies of the manufacturer and the retailer 1, 2 before the success of the technology.

Theorem 1a can be proven.

Then, by substituting E_M^{N-*} into the state equation of emissions reduction, according to the boundary condition $\tau(0)=\tau_0\geq 0$ combined with the particular solution of $\tau(t)$, the optimal trajectory of emissions reduction before the success of technological innovation can be obtained, and similarly, the optimal trajectory of emissions reduction after the success of technological innovation can be obtained.

Theorem 1b can be proven.

Similarly, by substituting E_{R1}^{N*-}, E_{R2}^{N*-}, τ^{N*-} into the state equation of low-carbon goodwill, according to the boundary condition $\chi(0)=\chi_0\geq 0$ combined with the particular solution of, the optimal trajectory of low-carbon goodwill before the success of technological innovation can be obtained, and similarly, the optimal trajectory of low-carbon goodwill after the success of technological innovation can be obtained.

Theorem 1c can be proven.

Finally, by substituting $k_i, \quad i = 1, 2, \ldots 9$ and $s_i, \quad i = 1, 2, \ldots 9$ into G_M^N, G_{R1}^N, G_{R2}^N and W_M^N, W_{R1}^N, W_{R2}^N respectively, the optimal value function of the supply chain members after the success of technological innovation and during the whole operation period can be obtained according to their expressions.

Theorem 1d can be proven.

Appendix B. Proof of Theorem 2a-Theorem 2d

In the same way as the decentralized decision-making model. First, solve for the manufacturer and retailer i's optimal strategies after the technological innovation. According to Bellman's continuous dynamic optimization theory, the decision problem of the manufacturer and retailer i after technological innovation satisfies the following HJB equation:

$$\begin{aligned}\rho G^C(\tau^{C+}, \chi^{C+}) = \max_{E_M^+, E_{R1}^+, E_{R2}^+} \{ & \sum_{i=1}^{2} \{\pi_{Ri}^+[\Pi + \varphi E_{Ri}^+ + \gamma(E_{Ri}^+ - E_{R(3-i)}^+) + \varpi \chi^{C+}] - \sum_{i=1}^{2} \frac{\eta_{Ri}}{2}(E_{Ri}^+)^2 + \pi_M^+(2\Pi + \varphi \sum_{i=1}^{2} E_{Ri}^+ \\ & + 2\varpi \chi^{C+}) - \frac{\eta_M}{2}(E_M^+)^2 + G_M^{C'}(\tau^{C+})(\alpha^+ E_M^+ - \varepsilon^+ \tau^{C+}) + G_M^{C'}(\chi^{C+})(\beta \tau^{C+} + \theta \sum_{i=1}^{2} E_{Ri}^+ - \sigma \chi^{C+})\}.\end{aligned} \tag{B.1}$$

According to the first-order condition, we get the following: $E_M^{C+} = \frac{\alpha^+ G^{C'}(\tau^{C+})}{\eta_M}$, $E_{R1}^{C+} = \frac{(\pi_{R1}^+ - \pi_{R2}^+)\gamma + (\pi_{R1}^+ - \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})}{\eta_{R1}}$, $E_{R2}^{C+} = \frac{(\pi_{R2}^+ - \pi_{R1}^+)\gamma + (\pi_{R2}^+ - \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})}{\eta_{R2}}$. By substituting into equation (B.1) simplifies and collates to give:

$$\begin{aligned}\rho G^C(\tau^{C+}, \chi^{C+}) = {} & [G^{C'}(\chi^{C+})\beta - G^{C'}(\tau^{C+})\varepsilon^+]\tau^{C+} + [(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varphi - G^{C'}(\chi^{C+})\sigma]\chi^{C+} + \frac{[\alpha^+ G^{C'}(\tau^{C+})]^2}{2\eta_M} \\ & + \frac{[(\pi_{R1}^+ - \pi_{R2}^+)\gamma + 2(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varphi - (\pi_{R1}^+ + \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})][(\pi_{R1}^+ - \pi_{R2}^+)\gamma + (\pi_{R1}^+ + \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})}{2\eta_{R1}} \\ & + \frac{[(\pi_{R2}^+ - \pi_{R1}^+)\gamma + 2(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varphi - (\pi_{R2}^+ + \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})][(\pi_{R2}^+ - \pi_{R1}^+)\gamma + (\pi_{R2}^+ + \pi_M^+)\varphi + \theta G^{C'}(\chi^{C+})}{2\eta_{R2}} \\ & + (\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\Pi\end{aligned} \tag{B.2}$$

According to the equation (B.2), we can assume that $\rho G^C(\tau^{C*+}, \chi^{C*+}) = e_1 \tau^{C*+} + e_2 \chi^{C*+} + e_3$. Where $e_1 = \frac{(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\beta\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $e_2 = \frac{(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\varpi}{\rho+\sigma}$, $e_3 = \frac{[\gamma(\pi_{R1}^+ - \pi_{R2}^+) + 2\varphi(\pi_{R1}^+ + \pi_{R2}^+ + \pi_M^+) - (\pi_{R1}^+ + \pi_M^+)\varphi + \theta e_2][(\pi_{R1}^+ - \pi_{R2}^+)\gamma + (\pi_{R1}^+ + \pi_M^+)\varphi + \theta e_2]}{2\rho\eta_{R1}} + \frac{(\pi_{R1}^+ + \pi_{R2}^+ + 2\pi_M^+)\Pi}{\rho} + \frac{[\gamma(\pi_{R2}^+ - \pi_{R1}^+) + 2\varphi(\pi_{R1}^+ + \pi_{R2}^+ + \pi_M^+) - (\pi_{R2}^+ + \pi_M^+)\varphi + \theta e_2][(\pi_{R2}^+ - \pi_{R1}^+)\gamma + (\pi_{R2}^+ + \pi_M^+)\varphi + \theta e_2]}{2\rho\eta_{R2}} + \frac{(\alpha^+ e_1)^2}{2\rho\eta_M}+$. e_i, $i = 1, 2, 3$ are the constant coefficients to be determined, it is easy to know that $G^C(\tau^{C*+}) = e_1$, $G^C(\chi^{C*+}) = e_2$. After solving for e_i, $i = 1, 2, 3$, the optimal equilibrium decision and the optimal value function after the success of technological innovation of the supply chain members can be obtained according to the first-order condition and the expression.

Further, the HJB equation of the supply chain members during the whole operation process can be obtained as:

$$\begin{aligned}(\rho + \varsigma)W^C = \max_{E_M^-, E_{R1}^-, E_{R2}^-} \{ & \sum_{i=1}^{2} \{\pi_{Ri}^-[\Pi + \varphi E_{Ri}^- + \gamma(E_{Ri}^- - E_{R(3-i)}^-) + \varpi \chi^{C-}] - \sum_{i=1}^{2} \frac{\eta_{Ri}}{2}(E_{Ri}^-)^2 + \pi_M^-(2\Pi + \varphi \sum_{i=1}^{2} E_{Ri}^- + 2\varpi \chi^{C-}) \\ & - \frac{\eta_M}{2}(E_M^-)^2 + \varsigma G^C[(1+\xi)\tau^{C-}, (1+\mu)\chi^{C-}] + W_M^{C'}(\tau^{C-})(\alpha^- E_M^- - \varepsilon^- \tau^{C-}) + W_M^{C'}(\chi^{C-})(\beta \tau^{C-} + \theta \sum_{i=1}^{2} E_{Ri}^- - \sigma \chi^{C-})\}.\end{aligned} \tag{B.3}$$

According to the first-order condition, we get the following: $E_M^{C-} = \frac{\alpha^- W^{C'}(\tau^{C-})}{\eta_M}$, $E_{R1}^{C-} = \frac{(\pi_{R1}^- - \pi_{R2}^-)\gamma + (\pi_{R1}^- - \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})}{\eta_{R1}}$, $E_{R2}^{C-} = \frac{(\pi_{R2}^- - \pi_{R1}^-)\gamma + (\pi_{R2}^- - \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})}{\eta_{R2}}$. By substituting into equation (B.3) simplifies and collates to give:

$$\begin{aligned}(\rho + \varsigma)W^C = {} & [W^{C'}(\chi^{C-})\beta + \varsigma(1+\xi)e_1 - W^{C'}(\tau^{C-})\varepsilon^-]\tau^{C-} + [(\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-)\varphi + \varsigma(1+\mu)e_2 - W^{C'}(\chi^{C-})\sigma]\chi^{C-} \\ & + \frac{[(\pi_{R1}^- - \pi_{R2}^-)\gamma + 2(\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-)\varphi - (\pi_{R1}^- + \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})][(\pi_{R1}^- - \pi_{R2}^-)\gamma + (\pi_{R1}^- + \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})}{2\eta_{R1}} \\ & + \frac{[(\pi_{R2}^- - \pi_{R1}^-)\gamma + 2(\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-)\varphi - (\pi_{R2}^- + \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})][(\pi_{R2}^- - \pi_{R1}^-)\gamma + (\pi_{R2}^- + \pi_M^-)\varphi + \theta W^{C'}(\chi^{C-})}{2\eta_{R2}} \\ & + (\pi_{R1}^- + \pi_{R2}^- + 2\pi_M^-)\Pi + \frac{[\alpha^- W^{C'}(\tau^{C-})]^2}{2\eta_M} + \varsigma e_3\end{aligned} \tag{B.4}$$

Similarly, assuming that $(\rho+\varsigma)W^C = l_1\tau^{C*+} + l_2\chi^{C*+} + l_3$. Where $l_1 = \frac{\beta}{(\rho+\varsigma+\varepsilon^-)}[\frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $l_2 = \frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^++\pi_{R2}^++2\pi_M^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $l_3 = \frac{(\pi_{R1}^-+\pi_{R2}^-+2\pi_M^-)\Pi}{(\rho+\varsigma)} + \frac{(\alpha^-l_1)^2}{2(\rho+\varsigma)\eta_M} + \frac{\varsigma e_3}{\rho+\varsigma} + \frac{[\gamma(\pi_{R1}^+-\pi_{R2}^-)+2\varphi(\pi_{R1}^-+\pi_{R2}^-+\pi_M^-)-(\pi_{R1}^-+\pi_M^-)\varphi+\theta l_2][(\pi_{R1}^--\pi_{R2}^-)\gamma+(\pi_{R1}^-+\pi_M^-)\varphi+\theta l_2]}{2(\rho+\varsigma)\eta_{R1}} + \frac{[\gamma(\pi_{R2}^--\pi_{R1}^-)+2\varphi(\pi_{R1}^-+\pi_{R2}^-+\pi_M^-)-(\pi_{R2}^++\pi_M^+)\varphi+\theta l_2][(\pi_{R2}^--\pi_{R1}^-)\gamma+(\pi_{R2}^-+\pi_M^-)\varphi+\theta l_2]}{2(\rho+\varsigma)\eta_{R2}}$.
$l_i, \quad i=1,2,3$ are the constant coefficients to be determined, it is easy to know that $W^C(\tau^{C-*})=l_1$, $W^C(\chi^{C-*})=l_2$.

Further, we can get the equilibrium strategies of the manufacturer and the retailer 1, 2 before the success of the technology.

Theorem 2a can be proven.

Then, by substituting E_M^{C-*} into the state equation of emissions reduction, according to the boundary condition $\tau(0)=\tau_0 \geq 0$ combined with the particular solution of $\tau(t)$, the optimal trajectory of emissions reduction before the success of technological innovation can be obtained, and similarly, the optimal trajectory of emissions reduction after the success of technological innovation can be obtained.

Theorem 2b can be proven.

Similarly, by substituting E_{R1}^{C*-}, E_{R2}^{C*-}, τ^{C*-} into the state equation of low-carbon goodwill, according to the boundary condition $\chi(0)=\chi_0 \geq 0$ combined with the particular solution of, the optimal trajectory of low-carbon goodwill before the success of technological innovation can be obtained, and similarly, the optimal trajectory of low-carbon goodwill after the success of technological innovation can be obtained.

Theorem 2c can be proven.

Finally, by substituting $e_i, \quad i=1,2,3$ and $l_i, \quad i=1,2,3$ into G^C and W^C respectively, the optimal value function of the supply chain members after the success of technological innovation and during the whole operation period can be obtained according to their expressions.

Theorem 2d can be proven.

Appendix C. Proof of Theorem 3a-Theorem 3d

The proof process is similar to the decentralized decision-making model discussed earlier, with the distinction being that in this decision model, retailers form an alliance as a collective. The details are not reiterated here. Where $y_1 = \frac{2\pi_M^+\beta\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $y_2 = \frac{2\pi_M^+\varpi}{\rho+\sigma}$, $y_3 = \frac{(\alpha^+y_1)^2}{2\rho\eta_M} + \frac{[\gamma(\pi_{R1}^+-\pi_{R2}^+)+\varphi\pi_{R1}^++\theta y_5](\pi_M^+\varphi+\theta y_2)}{\rho\eta_{R1}} + \frac{[\gamma(\pi_{R2}^+-\pi_{R1}^+)+\varphi\pi_{R2}^++\theta y_5](\pi_M^+\varphi+\theta y_2)}{\rho\eta_{R2}} + \frac{2\pi_M^+\Pi}{\rho}$, $y_4 = \frac{(\pi_{R1}^++\pi_{R2}^+)\beta\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $y_5 = \frac{(\pi_{R1}^++\pi_{R2}^+)\varpi}{\rho+\sigma}$, $y_6 = \frac{(\alpha^+)^2y_1y_4}{\rho\eta_M} + \frac{[\gamma(\pi_{R1}^+-\pi_{R2}^+)+\varphi\pi_{R1}^++\theta y_5]^2+2\varphi\pi_{R2}^+[(\pi_{R1}^+-\pi_{R2}^+)\gamma+\pi_{R1}^+\varphi+\theta y_5]}{2\rho\eta_{R1}} + \frac{[\gamma(\pi_{R2}^+-\pi_{R1}^+)+\varphi\pi_{R2}^++\theta y_5]^2+2\varphi\pi_{R1}^+[(\pi_{R2}^+-\pi_{R1}^+)\gamma+\pi_{R2}^+\varphi+\theta y_5]}{2\rho\eta_{R2}} + \frac{(\pi_{R1}^++\pi_{R2}^+)\Pi}{\rho}$, and $q_1 = \frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $q_2 = \frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $q_3 = \frac{2\pi_M^-\Pi}{\rho+\varsigma} + \frac{\varsigma y_3}{\rho+\varsigma} + \frac{(\alpha^-q_1)^2}{2(\rho+\varsigma)\eta_M} + \frac{[\gamma(\pi_{R1}^+-\pi_{R2}^-)+\varphi\pi_{R1}^-+\theta q_5][\pi_M^-\varphi+\theta q_2]}{(\rho+\varsigma)\eta_{R1}} + \frac{[\gamma(\pi_{R2}^--\pi_{R1}^-)+\varphi\pi_{R2}^-+\theta q_2][\pi_M^-\varphi+\theta q_2]}{(\rho+\varsigma)\eta_{R2}}$, $q_4 = \frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{(\pi_{R1}^-+\pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^++\pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{(\pi_{R1}^++\pi_{R2}^+)\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}$, $q_5 = \frac{(\pi_{R1}^-+\pi_{R2}^-)\varpi}{\rho+\varsigma+\sigma} + \frac{(\pi_{R1}^++\pi_{R2}^+)\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $q_6 = \frac{(\pi_{R1}^-+\pi_{R2}^-)\Pi}{\rho+\varsigma} + \frac{(\alpha^-)^2q_1q_4}{(\rho+\varsigma)\eta_M} + \frac{\varsigma y_6}{\rho+\varsigma} + \frac{[\gamma(\pi_{R1}^+-\pi_{R2}^-)+\varphi\pi_{R1}^-+\theta q_5]^2+2\varphi\pi+R2^-[(\pi_{R1}^--\pi_{R2}^-)\gamma+\pi_{R1}^-\varphi+\theta q_5]}{2(\rho+\varsigma)\eta_{R1}} + \frac{[\gamma(\pi_{R2}^--\pi_{R1}^-)+\varphi\pi_{R2}^-+\theta q_5]^2+2\varphi\pi+R2^-[(\pi_{R2}^--\pi_{R1}^-)\gamma+\pi_{R2}^-\varphi+\theta q_5]}{2(\rho+\varsigma)\eta_{R2}}$.

Appendix D. Proof of Theorem 4a-Theorem 4b

Similar to the proof approach for the propositions in Section 4, we first determine the equilibrium strategies for the supply chain members both before and after the success of technological innovation:

$$\begin{cases} E_M^{Z*-} = \frac{\alpha^-}{\eta_M(1-\Phi_1^--\Phi_2^-)}\{\frac{\beta}{\rho+\varsigma+\varepsilon^-}[\frac{2\pi_M^-\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^+\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^-)(\rho+\sigma)(\rho+\varepsilon^+)}\} \\ E_{R1}^{Z*-} = \frac{\pi_{R1}^-(\varphi+\gamma)}{\eta_{R1}(1-\Gamma_1^-)} + \frac{\theta}{\eta_{R1}(1-\Gamma_1^-)}[\frac{\pi_{R1}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \\ E_{R2}^{N*-} = \frac{\pi_{R2}^-(\varphi+\gamma)}{\eta_{R2}(1-\Gamma_2^-)} + \frac{\theta}{\eta_{R2}(1-\Gamma_2^-)}[\frac{\pi_{R2}^-\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^+\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] \end{cases} \tag{D.1}$$

$$\begin{cases} E_M^{N*+} = \frac{2\alpha^+\beta\pi_M^+\varpi}{\eta_M(\rho+\sigma)(\rho+\varepsilon^+)(1-\Phi_1^+-\Phi_2^+)} \\ E_{R1}^{N*+} = \frac{\pi_{R1}^+[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R1}(\rho+\sigma)(1-\Gamma_1^+)} \\ E_{R2}^{N*+} = \frac{\pi_{R2}^+[(\varphi+\gamma)(\rho+\sigma)+\theta\varpi]}{\eta_{R2}(\rho+\sigma)(1-\Gamma_2^+)} \end{cases} \tag{D.2}$$

Letting $E_M^{Z*+} = E_M^{C*+}$, $E_{R1}^{Z*+} = E_{R1}^{C*+}$, $E_{R2}^{Z*+} = E_{R2}^{C*+}$, $E_M^{Z*-} = E_M^{C*-}$, $E_{R1}^{Z*-} = E_{R1}^{C*-}$, $E_{R2}^{Z*-} = E_{R2}^{C*-}$, we can derive the subsidy ratio for both before and after technological innovation that satisfies the above equation. Furthermore, we can solve for the emission reduction, low-carbon goodwill, and profits of the supply chain system under the bilateral cost-sharing contract. Where $o_1 = \frac{2\beta\pi_M^+\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $o_2 = \frac{2\pi_M^+\varpi}{\rho+\sigma}$, $o_3 = \frac{(\alpha^+o_1)^2}{2\rho(1-\Phi^+)\eta_M} + \frac{(\pi_M^+\varphi+\theta o_2)[\pi_{R1}^+(\varphi+\gamma)+\theta o_5]}{\rho(1-\Gamma_1^+)\eta_{R1}} - \frac{\Gamma_1^+[\pi_{R1}^+(\varphi+\gamma)+\theta o_5]^2}{2\rho(1-\Gamma_1^+)^2\eta_{R1}} + \frac{(\pi_M^+\varphi+\theta o_2)[\pi_{R2}^+(\varphi+\gamma)+\theta o_8]}{\rho(1-\Gamma_2^+)\eta_{R2}} - \frac{\Gamma_2^+[\pi_{R2}^+(\varphi+\gamma)+\theta o_8]^2}{2\rho(1-\Gamma_1^+)^2\eta_{R2}} + \frac{2\pi_M^+\Pi}{\rho}$, $o_4 = \frac{\beta\pi_{R1}^+\varpi}{(\rho+\sigma)(\rho+\varepsilon^+)}$, $o_5 = \frac{\pi_{R1}^+\varpi}{\rho+\sigma}$, $o_6 = \frac{(\alpha^+)^2o_1o_4}{(1-\Phi^+)\rho\eta_M} - \frac{\Phi_1^+(\alpha^+o_1)^2}{(1-\Phi^+)^2\rho\eta_M} + \frac{[\pi_{R1}^+(\varphi+\gamma)+\theta o_5]^2}{2(1-\Gamma_1^+)\rho\eta_{R1}} + \frac{(\theta o_5-\gamma\pi_{R1}^+)[\pi_{R2}^+(\varphi+\gamma)+\theta o_8]}{(1-\Gamma_2^+)\rho\eta_{R2}} + \frac{\pi_{R1}^+\Pi}{\rho}$,

$o_7 = \frac{\beta\pi_{R2}^{+}\varpi}{(\rho+\sigma)(\rho+\varepsilon^{+})}$, $o_8 = \frac{\pi_{R2}^{+}\varpi}{\rho+\sigma}$, $o_9 = \frac{(\alpha^{+})^2 o_1 o_4}{(1-\Phi^{+})\rho\eta_M} - \frac{\Phi_1^{+}(\alpha^{+}o_1)^2}{(1-\Phi^{+})^2\rho\eta_M} + \frac{[\pi_{R2}^{+}(\varphi+\gamma)+\theta o_8]^2}{2(1-\Gamma_2^{+})\rho\eta_{R2}} + \frac{(\theta o_8-\gamma\pi_{R2}^{+})[\pi_{R1}^{+}(\varphi+\gamma)+\theta o_5]}{(1-\Gamma_1^{+})\rho\eta_{R1}} + \frac{\pi_{R2}^{+}\Pi}{\rho}$. Let $\Phi^{-} = \Phi_1^{-} + \Phi_2^{-}$, $\Phi^{+} = \Phi_1^{+} + \Phi_2^{+}$. $u_1 = \frac{\beta}{\rho+\varsigma+\varepsilon^{-}}[\frac{2\pi_M^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{2\pi_M^{+}\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^{-})(\rho+\sigma)(\rho+\varepsilon^{+})}$, $u_2 = \frac{2\pi_M^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{2\pi_M^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $u_3 = \frac{(\alpha^{+}u_1)^2}{2\rho(1+\Phi^{-})\eta_M} + \frac{(\pi_M^{+}\varphi+\theta o_2)[\pi_{R2}^{+}(\varphi+\gamma)+\theta u_8]}{(1-\Gamma_2^{-})\rho\eta_{R2}} - \frac{\Gamma_2^{-}[\pi_{R2}^{+}(\varphi+\gamma)+\theta u_8]^2}{2\rho(1-\Gamma_2^{-})^2\eta_{R2}} + \frac{(\pi_M^{-}\varphi+\theta o_2)[\pi_{R1}^{+}(\varphi+\gamma)+\theta u_5]}{(1+\Gamma_1^{-})\rho\eta_{R1}} - \frac{\Gamma_1^{+}[\pi_{R1}^{+}(\varphi+\gamma)+\theta u_5]^2}{2\rho(1-\Gamma_1^{-})^2\eta_{R1}} + \frac{2\pi_M^{-}\Pi+o_3}{\rho}$, $u_4 = \frac{\beta}{\rho+\varsigma+\varepsilon^{-}}[\frac{\pi_{R1}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\pi_{R1}^{+}\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^{-})(\rho+\sigma)(\rho+\varepsilon^{+})}$, $u_5 = \frac{\pi_{R1}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R1}^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $u_6 = \frac{(\alpha^{+})^2u_1u_4}{\rho(1-\Phi^{-})\eta_M} - \frac{\Phi_1^{-}(\alpha^{+}u_1)^2}{(1-\Phi^{-})^2\rho\eta_M} + \frac{[\pi_{R1}^{+}(\varphi+\gamma)+\theta u_5]^2}{2\rho(1-\Gamma_1^{-})\eta_{R1}} + \frac{(\theta u_5-\gamma\pi_{R1}^{+})[\pi_{R2}^{+}(\varphi+\gamma)+\theta u_8]}{\rho(1-\Gamma_2^{-})\eta_{R2}} + \frac{\pi_{R1}^{+}\Pi+o_6}{\rho}$, $u_7 = \frac{\beta}{\rho+\varsigma+\varepsilon^{-}}[\frac{\pi_{R2}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}] + \frac{\pi_{R2}^{+}\beta\varpi\varsigma(1+\xi)}{(\rho+\varsigma+\varepsilon^{-})(\rho+\sigma)(\rho+\varepsilon^{+})}$, $u_8 = \frac{\pi_{R2}^{-}\varpi}{\rho+\varsigma+\sigma} + \frac{\pi_{R2}^{+}\varpi\varsigma(1+\mu)}{(\rho+\varsigma+\sigma)(\rho+\sigma)}$, $u_9 = \frac{(\alpha^{+})^2u_1u_4}{\rho(1-\Phi^{-})\eta_M} - \frac{\Phi_1^{-}(\alpha^{+}u_1)^2}{(1-\Phi^{-})^2\rho\eta_M} + \frac{[\pi_{R2}^{+}(\varphi+\gamma)+\theta u_8]^2}{2\rho(1-\Gamma_2^{-})\eta_{R2}} + \frac{(\theta u_8-\gamma\pi_{R2}^{+})[\pi_{R1}^{+}(\varphi+\gamma)+\theta u_5]}{\rho(1-\Gamma_1^{-})\eta_{R1}} + \frac{\pi_{R2}^{+}\Pi+o_9}{\rho}$.

Theorem 4a-Theorem 4b can be proven.

References

[1] X. Nie, J. Wu, H. Wang, W. Li, C. Huang, L. Li, Contributing to carbon peak: estimating the causal impact of eco-industrial parks on low-carbon development in China, J. Ind. Ecol. 26 (4) (2022) 1578–1593.

[2] B.K. Sovacool, P. Newell, S. Carley, J. Fanzo, Equity, technological innovation and sustainable behaviour in a low-carbon future, Nat. Hum. Behav. 6 (3) (2022) 326–337.

[3] B.K. Sovacool, C.M. Baum, S. Low, Risk–risk governance in a low-carbon future: exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways, Risk Anal. 43 (4) (2023) 838–859.

[4] J. Chen, X. Wang, W. Shen, Y. Tan, L.M. Matac, S. Samad, Environmental uncertainty, environmental regulation and enterprises' green technological innovation, Int. J. Environ. Res. Public Health 19 (16) (2022) 9781.

[5] L. Nojeem, M. Shun, M. Embouma, A. Inokon, I. Browndi, Technology forecasting and the Internet of things: accelerating electric vehicle adoption, Int. J. Basic Appl. Sci. 10 (05) (2023) 586–590.

[6] L. Bartolucci, E. Cennamo, S. Cordiner, V. Mulone, F. Pasqualini, M.A. Boot, Digital twin of a hydrogen fuel cell hybrid electric vehicle: effect of the control strategy on energy efficiency, Int. J. Hydrog. Energy 48 (54) (2023) 20971–20985.

[7] A. Nunes, L. Woodley, Governments should optimize electric vehicle subsidies, Nat. Hum. Behav. 7 (4) (2023) 470–471.

[8] K. Meng, G. Xu, X. Peng, K. Youcef-Toumi, J. Li, Intelligent disassembly of electric-vehicle batteries: a forward-looking overview, Resour. Conserv. Recycl. 182 (2022) 106207.

[9] M. Hajhashem, A. Khorasani, Demystifying the dynamic of disruptive innovations in markets with complex adoption networks: from encroachment to disruption, International Journal of Innovation and Technology Management 12 (05) (2015) 1550022.

[10] L. Xia, W. Hao, J. Qin, F. Ji, X. Yue, Carbon emission reduction and promotion policies considering social preferences and consumers' low-carbon awareness in the cap-and-trade system, J. Clean. Prod. 195 (2018) 1105–1124.

[11] J. Luo, M. Huang, Y. Bai, Promoting Green development of agriculture based on low-carbon policies and Green preferences: An evolutionary game analysis (2023), Environ. Dev. Sustain. 1–28.

[12] P. Han, Z. Tong, Y. Sun, X. Chen, Impact of climate change beliefs on Youths' engagement in energy-conservation behavior: the mediating mechanism of environmental concerns, Int. J. Environ. Res. Public Health 19 (12) (2022) 7222.

[13] J. Liu, H. Ke, Firms' preferences for retailing formats considering one manufacturer's emission reduction investment, Int. J. Prod. Res. 59 (10) (2021) 3062–3083.

[14] J. Bian, X. Guo, Policy analysis for emission-reduction with green technology investment in manufacturing, Ann. Oper. Res. 316 (1) (2022) 5–32.

[15] C. Xu, D. Zhao, B. Yuan, L. He, Differential game model on joint carbon emission reduction and low-carbon promotion in supply chains, J. Manag. Sci. China 19 (2) (2016) 53–65.

[16] H. Li, C. Wang, M. Shang, W. Ou, X. Qin, Cooperative decision in a closed-loop supply chain considering carbon emission reduction and low-carbon promotion, Environmental Progress & Sustainable Energy 38 (1) (2019) 143–153.

[17] L. Liu, T. Han, H. Jin, Differential game study of three-level green supply chain considering brand goodwill under cost sharing mechanism, Control Decis. 2023 (2023) 1–9.

[18] F. Ye, X. Xiong, L. Li, Y. Li, Measuring the effectiveness of the Chinese certified emission reduction scheme in mitigating CO2 emissions: a system dynamics approach, J. Clean. Prod. 294 (2021) 125355.

[19] S. Cheng, F. Zhang, X. Chen, Optimal contract design for a supply chain with information asymmetry under dual environmental responsibility constraints, Expert Syst. Appl. 237 (2024) 121466.

[20] R. Buckdahn, P. Cardaliaguet, M. Quincampoix, Some recent aspects of differential game theory, Dyn. Games Appl. 1 (2011) 74–114.

[21] F. Tang, Y. Dai, Z.J. Ma, T.M. Choi, Trade-in operations under retail competition: effects of brand loyalty, Eur. J. Oper. Res. 310 (1) (2023) 397–414.

[22] T.I. Khan, S.A. Raza, Revitalizing the retail: a case of the coca-cola company, Asian Journal of Management Cases 20 (2) (2023) 174–182.

[23] A.S. Thelisson, Coopetition in a merger process: regulators and management of coopetitive tensions, Int. Rev. Adm. Sci. 89 (2) (2023) 381–397.

[24] X. Guo, Y. Kuang, C.T. Ng, To centralize or decentralize: mergers under price and quality competition, Prod. Oper. Manag. 32 (3) (2023) 844–862.

[25] P. Mandal, T. Jain, When do competing retailers benefit from sourcing through an intermediary?, Int. J. Prod. Econ. 266 (2023) 109045.

[26] Q. Peng, C. Wang, M. Goh, Green innovation decision and coordination of supply chain under corporate social responsibility and risk preferences, Comput. Ind. Eng. 185 (2023) 109703.

[27] S. Benjaafar, Y. Li, M. Daskin, Carbon footprint and the management of supply chains: insights from simple models, IEEE Trans. Autom. Sci. Eng. 10 (1) (2012) 99–116.

[28] X. Li, J. Zhou, Incentive of professional manger and strategic selection of carbon emission reduction R&D in a two-echelon supply chain, Chinese Journal of Management 19 (07) (2022) 1071–1081.

[29] X. He, J. Jiang, W. Hu, Cross effects of government subsidies and corporate social responsibility on carbon emissions reductions in an omnichannel supply chain system, Comput. Ind. Eng. 175 (2023) 108872.

[30] L. Liang, L. Futou, Differential game modelling of joint carbon reduction strategy and contract coordination based on low-carbon reference of consumers, J. Clean. Prod. 277 (2020) 123798.

[31] L. Xia, Y. Bai, S. Ghose, J. Qin, Differential game analysis of carbon emissions reduction and promotion in a sustainable supply chain considering social preferences, Ann. Oper. Res. (2022) 1–36.

[32] A. Amel-Zadeh, M. Glaum, T. Sellhorn, Empirical goodwill research: insights, issues, and implications for standard setting and future research, Eur. Account. Rev. 32 (2) (2023) 415–446.

[33] N. Pnevmatikos, B. Vardar, G. Zaccour, When should a retailer invest in brand advertising?, Eur. J. Oper. Res. 267 (2) (2018) 754–764.

[34] J. Wang, Z. Yang, Whether field research by institutional investors can curb corporate goodwill bubble?, Journal of Central University of Finance & Economics 23 (06) (2023) 80–89.

[35] G. Guo, S. Li, Product innovation, process innovation and advertising-based goodwill: a dynamic analysis in a monopoly, J. Ind. Manag. Optim. 19 (2) (2023) 1152–1165.

[36] A. Amel-Zadeh, M. Glaum, T. Sellhorn, Empirical goodwill research: insights, issues, and implications for standard setting and future research, Eur. Account. Rev. 32 (2) (2023) 415–446.

[37] Z. Guan, T. Ye, R. Yin, Channel coordination under Nash bargaining fairness concerns in differential games of goodwill accumulation, Eur. J. Oper. Res. 285 (3) (2020) 916–930.

[38] Z. Li, Z. Huang, Y. Su, New media environment, environmental regulation and corporate green technology innovation: evidence from China, Energy Econ. 119 (2023) 106545.

[39] X. Xie, Y. Han, How can local manufacturing enterprises achieve luxuriant transformation in Green innovation? A multi-case study based on attention-based view, Journal of Management World 38 (03) (2022) 76–106.

[40] Z. Fang, Assessing the impact of renewable energy investment, green technology innovation, and industrialization on sustainable development: a case study of China, Renew. Energy 205 (2023) 772–782.

[41] A. Zhao, J. Wang, Z. Sun, H. Guan, Environmental taxes, technology innovation quality and firm performance in China—A test of effects based on the Porter hypothesis, Economic Analysis and Policy 74 (2022) 309–325.

[42] L. Qing, D. Chun, A.A. Dagestani, P. Li, Does proactive green technology innovation improve financial performance? Evidence from listed companies with semiconductor concepts stock in China, Sustainability 14 (8) (2022) 4600.

[43] J. Hu, Y. Liu, D. Ma, Dynamic strategy of food supply chain considering greenness and traceable goodwill under technological innovation, Soft Sci. (2020) 1–10.

[44] Q. Wu, X. Xu, Y. Tian, Research on enterprises emission reduction technology innovation strategies with government subsidy and carbon trading mechanism, Manag. Decis. Econ. 43 (6) (2022) 2083–2097.

[45] L. Liu, T. Han, H. Jin, Differential game study of green supply chain based on green technology innovation and manufacturer competition, Chinese Journal of Management 20 (01) (2023) 116–126.

[46] Y. Zhou, F. Hu, Z. Zhou, Pricing strategy and social welfare in supply chain with competing manufactures based on carbon tax policy, Chinese Journal of Management Science 27 (07) (2019) 94–105.

[47] N. Jahanbakhsh Javid, M. Amini, Evaluating the effect of supply chain management practice on implementation of halal agroindustry and competitive advantage for small and medium enterprises, International Journal of Computer Science and Information Technology 15 (2023) 8997–9008.

[48] R. Zhang, W. Zhao, Differential game analyses of low-carbon tourism supply chains considering competitions between travel agencies, J. Syst. Eng. 37 (05) (2022) 643–656.

[49] S. Zhuo, X. Han, Research on the differential game of supply chain cooperation under carbon subsidy and retailer competition, J. Ind. Eng. Manag. 37 (02) (2023) 80–89.

[50] X. Huang, Dynamic analysis of dual-market low-carbon supply chain: considering government intervention and joint promotion, J. Clean. Prod. 411 (2023) 137361.

[51] D. Wang, T. Wang, Gynamic optimization of coorperation on carbon emission reduction and promotion in supply chain under government subsidy, Journal of Systems & Management 30 (01) (2021) 14–27.

[52] O. Rubel, P.A. Naik, S. Srinivasan, Optimal advertising when envisioning a product-harm crisis, Mark. Sci. 30 (6) (2011) 1048–1065.

[53] Y.C. Tsao, G.J. Sheen, Effects of promotion cost sharing policy with the sales learning curve on supply chain coordination, Comput. Oper. Res. 39 (8) (2012) 1872–1878.

[54] D. Ghosh, J. Shah, Supply chain analysis under green sensitive consumer demand and cost sharing contract, Int. J. Prod. Econ. 164 (2015) 319–329.

[55] Q. Zhang, W. Tang, J. Zhang, Who should determine energy efficiency level in a green cost-sharing supply chain with learning effect?, Comput. Ind. Eng. 115 (2018) 226–239.

[56] H. Huang, W. Li, H. Xu, Research on information sharing of socially responsible retailers when government subsidies and cost sharing coexist, Chinese Journal of Management Science (2023) 1–12.

[57] I. Giannoccaro, P. Pontrandolfo, Supply chain coordination by revenue sharing contracts, Int. J. Prod. Econ. 89 (2) (2004) 131–139.

[58] S. Xu, H. Tang, Z. Lin, J. Lu, Pricing and sales-effort analysis of dual-channel supply chain with channel preference, cross-channel return and free riding behavior based on revenue-sharing contract, Int. J. Prod. Econ. 249 (2022) 108506.

[59] S. Bhuniya, S. Pareek, B. Sarkar, A sustainable game strategic supply chain model with multi-factor dependent demand and mark-up under revenue sharing contract, Complex Intell. Syst. 9 (2) (2023) 2101–2128.

[60] N. Koussis, F. Silaghi, Revenue-sharing and volume flexibility in the supply chain, Int. J. Prod. Econ. 261 (2023) 108845.

[61] E.K. Kuchesfehani, E.M. Parilina, G. Zaccour, Revenue and cost sharing contract in a dynamic closed-loop supply chain with uncertain parameters, Ann. Oper. Res. 322 (2) (2023) 851–877.

[62] Q. Feng, L.X. Lu, Supply chain contracting under competition: Bilateral bargaining vs. Stackelberg, Prod. Oper. Manag. 22 (3) (2013) 661–675.

[63] X. Tian, W. Chen, J. Hu, Game-theoretic modeling of power supply chain coordination under demand variation in China: a case study of Guangdong province, Energy 262 (2023) 125440.

[64] Z. Zhang, L. Yu, Dynamic decision-making and coordination of low-carbon closed-loop supply chain considering different power structures and government double subsidy, Clean Technol. Environ. Policy 25 (1) (2023) 143–171.

[65] M.L. Liu, Z.H. Li, S. Anwar, Y. Zhang, Supply chain carbon emission reductions and coordination when consumers have a strong preference for low-carbon products, Environ. Sci. Pollut. Res. 28 (2021) 19969–19983.

[66] B. Mridha, S. Pareek, A. Goswami, B. Sarkar, Joint effects of production quality improvement of biofuel and carbon emissions towards a smart sustainable supply chain management, J. Clean. Prod. 386 (2023) 135629.

[67] M. Nerlove, K.J. Arrow, Optimal advertising policy under dynamic conditions, Economica 29 (114) (1962) 129–142.

[68] Z. Zhang, L. Yu, Dynamic decision-making and coordination of low-carbon closed-loop supply chain considering different power structures and government double subsidy, Clean Technol. Environ. Policy 25 (1) (2023) 143–171.

[69] J. Cai, F. Jiang, Decision models of pricing and carbon emission reduction for low-carbon supply chain under cap-and-trade regulation, Int. J. Prod. Econ. 264 (2023) 108964.

[70] P.L. Joskow, Contributions to the theory of marginal cost pricing, Bell J. Econ. (1976) 197–206.

[71] O. Rubel, P.A. Naik, S. Srinivasan, Optimal advertising when envisioning a product-harm crisis, Mark. Sci. 30 (6) (2011) 1048–1065.

[72] Y. Han, H. Zheng, Y. Huang, X. Li, Considering consumers' green preferences and government subsidies in the decision making of the construction and demolition waste recycling supply chain: a Stackelberg game approach, Buildings 12 (6) (2022) 832.

[73] L.N. Boss, E.L. Gralla, Robustness of decentralized decision-making architectures in command and control systems, Syst. Eng. 26 (2) (2023) 149–161.

[74] S. Das, S. Pradhan, S. De, Multi criteria decision making for the most suitable combination of energy resources for a decentralized hybrid energy solution with green hydrogen as the storage option, Energy Convers. Manag. 285 (2023) 117028.

[75] T.Y. Wang, Z.S. Chen, P. He, K. Govindan, M.J. Skibniewski, Alliance strategy in an online retailing supply chain: motivation, choice, and equilibrium, Omega 115 (2023) 102791.

[76] I. Giannoccaro, Centralized vs. decentralized supply chains: the importance of decision maker's cognitive ability and resistance to change, Ind. Mark. Manage. 73 (2018) 59–69.

[77] D. Permitasari, I.D.A. Nurhaeni, R.H. Haryati, Is centralized decision-making better? A case study of decision-making in the internationalization of higher education institutions in Indonesia, International Journal of Educational Organization & Leadership 28 (2) (2021).