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GREEN DESIGN STRATEGIES FOR SUSTAINABLE SUPPLY CHAIN CONSIDERING CHANNEL LEADERSHIP

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Abstract. We have observed from practice that to create new economic and environmental values, both the upstream and downstream firms in sustainable supply chain are motivated to invest in green design. Channel leadership as an important factor affecting the channel profit distribution will reshape the investment motivation of enterprises. In this paper, we construct six kinds of pricing and green design decision models to explore the optimal green design strategies for sustainable supply chain consisting of one manufacturer and one retailer under different channel leadership, and investigate the interaction between channel leadership and green design strategy, and their impacts on sustainable supply chain performance, environment and consumer surplus. We find that regardless of the channel leadership, the wholesale and retail prices of products under different green design strategies are always affected by the cost effect of green design. In terms of boosting the green design level and market demand, increasing the consumer surplus and enterprises profits, only when the manufacturer is the channel leader and the green design cost effect is small, the retailer can implement green design better. Moreover, when the manufacturer implements green design, the better channel structure between the retailer-led and Nash equilibrium game depends on the green design cost effect, but both are better than the manufacturer-led. However, when the retailer implements green design, the channel structure of Nash equilibrium game is always better. We finally illustrate that under different channel leadership, which green design strategy is more conducive to reducing the total environment impact of products depends on the joint effect of green design cost effect and green design environment effect.

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1. Introduction

Facing the challenges of the global environmental crisis, many countries have raised the establishment of sustainable supply chains guided by environmental protection and resource conservation to a national strategic level [4,9,28]. The sustainable development of supply chain has become one of the most important research topics in the field of supply chain management and operation management in recent years [21, 52]. Green design, also known as environmental design or ecological design, as an effective means to improve the utilization of resources and reduce the emission of pollutants, has become one of the important ways for enterprises to realize the

Keywords. Sustainable supply chain, green design, channel leadership, pricing decision, environmental impact.

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sustainable development of supply chain [23, 38, 45]. It is estimated that 80% of the sustainability is determined in the product design stage [23]. Therefore, exploring the best green design strategy for sustainable supply chain can help enterprises use resources in the furthest economical and environmentally friendly manner, and help maximize economic, social and environmental benefits [45, 51].

As we known, green design has many obvious advantages, including helping enterprises reduce resource consumption and pollutant emissions in the production and operation process, meeting consumers' green preferences, and increasing corporate brand reputation [10, 38]. In practice, many enterprises have gradually realized the advantages of green design and started to achieve the goal of sustainable development through green design [37, 45]. For example, HUAWEI has established a sustainable development management system, integrating green design concepts into products development and manufacturing processes, effectively reducing products energy consumption and pollutant emissions, and improving resource utilization and operation performance [22]. HP, IBM, Apple and other enterprises are increasingly responding to the call for sustainable development by integrating green design into their products production systems to build a sustainable supply chain [19, 48].

Interestingly, with the increasing of consumers' environmental awareness (CEA), the growing retailers have begun to make green investments to win brand reputation and improve competitiveness [18, 39]. For example, IKEA invested 3 billion euros to establish the "Sustainable Investment Project", to invest in green technologies and to promote sustainable development [37]. Fast fashion retailer H&M has invested heavily in green technology to promote manufacturers to realize products greening [14]. Wal-Mart, Marks & Spencer and other well-known retail enterprises directly or indirectly invest in green production projects of manufacturers to master the decision-making power of green level [24, 39].

From the above business practice cases, it can be found that there are two main green design strategies in supply chain operation at present, that is, the manufacturer implements green design and the retailer implements green design. While green design investments can cater to increasing of CEA and increase market demand, both upstream and downstream enterprises in supply chain can benefit from it [46]. However, enterprises that implement green design need to bear a lot of investment costs [20, 48]. Different green design strategy significantly affects the balance between costs and benefits for enterprises in supply chain. So, from the perspective of enterprises and the entire supply chain, the environment and society (consumer surplus), who is more motivated to invest in green design? Which green design strategy is better?

In addition, there are always power differences among supply chain member enterprises, and the specific decision order of member enterprises in different channel leadership and the impact on the decisions of other members are also different [34, 47]. The dominant enterprises often have stronger bargaining power, enabling them to make decisions as leaders first, thus affecting the economic and environmental decisions of relatively weak enterprises [5, 7]. People are also increasingly worried about the impact of channel leadership on supply chain sustainability [27, 41]. Therefore, channel leadership has become an important factor that affects the green design motivation of enterprises and the sustainable development of supply chains [5, 34].

At present, under different channel leadership, what kind of green design strategy is more conducive to sustainable development of supply chain has not been fully investigated in the literature. In order to fill the research gaps, we mainly study the following questions:

(1) Under three kinds of channel leadership, which side of the manufacturer or retailer is more motivated to implement green design?
(2) How will the transformation of channel leadership and the change of green design strategy affect the green design level and the operation performance of sustainable supply chain?
(3) From the perspective of economy, environment and consumers, which green design strategy is better?

To solve the above problems, we construct six decision-making models for sustainable supply chain when the manufacturer/retailer to implement green design under three kinds of channel leadership. We solve and compare the optimal decisions of enterprises and analyze the difference of sustainable supply chain decision-making under different channel leadership and green design strategies. Moreover, we compare the profits of enterprises and the entire supply chain under different decision-making models, and investigate how they change with the power structure and green design strategies. We further discuss whether the green design strategy that is conducive to economic goals is also good for environment and society (consumer surplus).

Our research has made the following contributions. Firstly, we integrate the multiple impacts (cost, demand and environment) generated by green design into the enterprise decision-making models, and reveal the multiple impacts of green design on the selection of the best green design strategy of sustainable supply chain. Secondly, we derive the conditions under which the manufacturer and retailer tend to implement green design under different channel leadership, and clarify the interaction between these conditions and channel leadership. Finally, we illustrate the interaction between channel leadership and green design strategies, which are two key factors affecting the sustainability of supply chain. Especially, we give the optimal green design strategy under different channel leadership from the perspective of supply chain members and whole, consumers, and environment. To the best of our knowledge, there is no literature that integrates these two important factors in the framework of sustainable supply chain. Our research has filled this gap.

The remainder of the paper is organized as follows. In Section 2, we provide a related literature review. In Section 3, we introduce the problem. In Section 4, we construct and solve the decision-making models under different channel leadership. Section 5 makes a comparative study of the equilibrium results under different decision-making models. We illustrate the numerical simulation in Section 6, and finally in Section 7, conclusions and future research are suggested.

2. Literature review

This paper deals mainly with two research: Green design/green product development for sustainable supply chain and channel leadership of supply chain.

2.1. Green design/green investment for sustainable supply chain

As the core theme of sustainable supply chain management, green design/green investment has received extensive attention from scholars [12, 19, 23]. Considering that consumers pay more attention to environmental issues, many researches have incorporated CEA into the research framework of sustainable supply chain, and investigated the green investment of enterprises under CEA setting, such as Jin *et al.* [19], Zhang *et al.* [48] and Liu *et al.* [26]. Under this framework, some studies further investigated the greening and pricing decisions of sustainable supply chain when enterprises compete or cooperate, such as Heydari *et al.* [16] and Tao *et al.* [40]. On the other hand, some researches have discussed the green decision of sustainable supply chain under different government environmental regulation policies, such as Bian *et al.* [3], Li *et al.* [25] and Han *et al.* [15]. Meanwhile, some scholars have analyzed the impact of different carbon tax policies on sustainable supply chain operations [1, 2, 35, 36]. Barman *et al.* studied the impact of carbon tax and carbon cap-and-trade on supply chain emission reduction decisions for dual channel green supply chains [1]. Golmohammadi *et al.* [13] applied a mixed integer linear programming model to optimize production, inventory, location, and route in a multi-level sustainable supply chain. However, most of the existing studies assume that the manufacturer implements green investment or determines the optimal green level, ignoring that the retailer also has strong incentives to make green investment to master the decision-making power of green level.

Considering the green investment behavior of retailers, Dong *et al.* [10] investigated which manufacturer or retailer is more motivated to invest in green product in the two-cycle supply chain. Shi *et al.* [39] discussed the issue of cleaner technology investment between the manufacturer and retailers. They show that the manufacturer can always benefit from the investment behavior of retailers. Wang *et al.* [42] studied the impact of retailer's green investment behavior on the manufacturer's online sales mode selection, and pointed out that the manufacturer may not benefit from the retailer's green investment. Li *et al.* [24] compared and analyzed the supply chain pricing decisions and performance issues when the manufacturer or retailer conducts green product development. However, the above research still focuses on analyzing the impact of retailer's green investment behavior on market demand from an economic perspective, while ignoring the multiple impacts of green design on demand, cost and environment.

Since green design has more obvious advantages than other green behaviors of enterprises, including effectively improving resource utilization efficiency and reducing product environmental impact [23,38,45], it has attracted extensive attention of scholars in recent years. Raz *et al.* [38] introduced the concept of green design into the newsboy model earlier, and pointed out that manufacturer can reduce the production cost and environmental impact of unit product through green design. Yenipazarli [46] compared the difference of manufacturer's green design level under the cost sharing contract and revenue sharing contract. Du *et al.* [11] considered the green design problem between two competing manufacturers and discussed the impact of different manufacturers input green design on the pricing decision of sustainable supply chain. Cai *et al.* [4] further discussed the green design decision-making of manufacturer under different environmental tax settings. Zheng and Li [50] used cooperative and non cooperative game theory to analyze the green design strategies of competing manufacturers.

Based on the above literature analysis, it can be found that the work of Li *et al.* [24] and Shi *et al.* [39] are similar to this study, and they also consider the green investment efforts of the manufacturer and retailer. But the difference is that we not only compare and analyze the differences between the manufacturer and retailer in green design behavior, but also consider the multiple impacts of green design, and investigate the impact of channel leadership transfer from the perspective of economy, environment and consumer surplus.

2.2. Channel leadership of supply chain

Channel leadership, as the ability of enterprises to influence supply chain decision-making through priority actions, has become an important factor affecting supply chain performance and sustainable development [5,34]. Many scholars have investigated the supply chain production, pricing and sales strategies under different channel leadership [5,8,29,49]. The common point of their research results is that the difference in channel leadership will change the operation decisions of supply chain enterprises, thus may lead to the difference in profits distribution.

In recent years, some scholars began to explore the pricing decisions of sustainable supply chain under different channel leadership [6,34]. Chen *et al.* [6] pointed out that a balanced channel leadership is more conducive to reducing supply chain emissions and improving overall profits. Xue and Zhang [44] pointed out that improving CEA can reduce the channel leadership conflict in the supply chain. Hong *et al.* [17] discussed the optimal green product design and pricing decision of supply chains with different channel leadership. Liu *et al.* [27] investigated the role of revenue sharing contract or cost sharing contract in improving the products green degree of supply chain under different channel leadership based on differential games. Xia *et al.* [43] discussed green supply chain pricing and emission reduction decision-making under different channel leadership and cross shareholding. Tang and Yang [41] analyzed the impact of channel leadership on carbon emission reduction and financing decisions of supply chain under carbon cap-and-trade mechanism. Niu *et al.* [34] studied the impact of channel leadership and innovation uncertainty on emission reduction investment decisions of manufacturer. Ma *et al.* [30] analyzed the impact of information advantage, green optimism, and power structure on the decision-making and performance of green supply chain. Different from the existing research that only focus on the impact of channel leadership on the manufacturer's green investment decisions, in this paper, we focus on the interaction between channel leadership and green design strategies from the perspective of economy, environment and consumer surplus, and consider the multiple impacts of green design on demand, cost and environment.

2.3. Research gaps

The analysis of relevant literature reveals two research gaps. On the one hand, most of the existing literature assume that the manufacturer makes green investment, and few literature consider the green investment motivation of the retailer. The comparative analysis of the differences between green design decisions of manufacturer and retailer from different perspectives is limited. On the other hand, only a small amount of literature considered the green investment of manufacturer and retailer [24,39]. However, they did not consider the multiple impacts of green design in combination with practice, nor did they involve the impact analysis of channel leadership transformation. As far as we know, it has not been found that there are studies that explore the interaction between channel leadership and green design strategies, and their joint impact on the optimal operation of sustainable supply chain from the perspective of economy, environment and consumer surplus.

Based on the above analysis, we construct six decision-making models for the sustainable supply chain when manufacturer/retailer implements green design under three kinds of channel leadership. Firstly, we analyze which side of the manufacturer and retailer is more motivated to implement green design under different channel leadership, and the impact of different green design strategies on pricing decisions, performance of sustainable supply chains members and the whole. Secondly, we discuss the interaction between the channel leadership and the green design strategies, as well as their impact on consumer surplus and environment. Finally, the main conclusions are verified and expanded by numerical simulation. Our research provides decision reference for upstream and downstream enterprises to select appropriate green design strategies, accelerate the construction of sustainable supply chain and realize green transformation.

3. Problem description and assumptions

3.1. Problem description

According to practical operation cases, there are two common green design strategies for sustainable supply chain: One is the manufacturer implements green design. For example, Lenovo, the world's largest PC manufacturer, has been committed to reducing resource and energy consumption in product production and use through green design for a long time, and won the title of "Green Design Demonstration Enterprise" in China. Another is the retailer implements green design. For example, Alibaba raised $987 million through the issuance of "Sustainable Development Bonds" to invest in multiple green development projects. At the same time, there are not only channel leadership structures dominated by manufacturers such as Lenovo and HUAWEI [7], but also channel leadership structures dominated by retailers such as Wal Mart and Home Depot [29], as well as the balanced channel leadership structures such as Gome and GREE [49].

Based on this, this paper aims at a sustainable supply chain consisting of one manufacturer and one retailer, in which both the manufacturer and retailer are motivated to implement green design in order to reduce resource consumption and environmental impact in production activities, and achieve sustainable development of supply chain. Consider the following six situations: manufacturer-led and implements green design, manufacturer-led and retailer implements green design, retailer-led and manufacturer implements green design, retailer-led and implements green design, Nash equilibrium game and manufacturer implements green design, Nash equilibrium game and retailer implements green design. Through comparative analysis, from the perspective of economy, environment and consumer surplus, we propose the optimal green design strategies for sustainable supply chain with different channel leadership.

Based on the problem description, for clarity, we define the model notations in Table 1. And reference related literature, we introduce the following assumptions.

Assumption 3.1. *As green design can effectively cater to the growing green consumption concept of consumers and help reduce the energy consumption of products, it can indirectly increase the market demand for products [40,46]. For example, in order to reduce the resource consumption of products, GREE, a Chinese electrical appliance manufacturer, insisted on integrating green design investment considering environmental factors, effectively reducing energy use and carbon emissions, and increasing market share. Referring to Yenipazarli [46], we assume that the market demand function is* $q(p,g) = a - bp + \theta g$.

Assumption 3.2. *The green design can effectively reduce the production cost and environmental impact of unit product [38]. For instance, in 2017, Apple invested about 1.657 billion dollars in implementing green design, which reduced about 454 200 metric tons of carbon emissions and greatly improved its energy efficiency and environmental performance. Therefore, when green design is implemented, the production cost of unit product is* $c(g) = (1 - dg)c$*, the environmental impact degree of unit product is* $\varphi(g) = (1 - \lambda g)\varphi$*, the total environmental impact of products is* $E = \varphi(g)q(p,g) = (1 - \lambda g)\varphi(a - bp + \theta g)$.

TABLE 1. Notation's description.

Notations	Description
w	Wholesale price
p	Retail price
v	The retailer's margin profit
g	The green design level, assume $0 < g \leq 1$ [17,51]
c	The production cost of unit product when does not implement green design
φ	Environment impact of unit product when does not implement green design
d	Green design cost effect, that is, the reduction degree of unit production cost caused by unit green design level [38], $0 < d < 1$
λ	Green design environmental effect, that is, the reduction degree of environmental impact of unit product caused by unit green design level
$c(g)$	The production cost of unit product when implementing green design
$\varphi(g)$	Environment impact of unit product when implementing green design
a	The potential market demand
b	Consumers' price sensitivity, $b > 0$
θ	Green design demand effect, that is, consumers' sensitivity to green design level (CEA level), $\theta > 0$
q	Market demand
$h(g)$	The investment cost for implementing green design. Refer to Yenipazarli [46] etc., assume $h(g) = kg^2$, where $k > 0$ represents the scale parameter of green design (also considered as green design investment cost coefficient)
CS	Consumer surplus. Refer to Niu *et al.* [34] etc., $\mathrm{CS} = \int_{p_{\min}}^{p_{\max}} q\,\mathrm{d}p = \frac{(a-bp+\theta g)^2}{2b}$
E	Total environmental impact of products, which is the aggregate lifetime impact of the products on the environment. Such impact may refer to the use of natural resources, emission of harmful gases, and generation of solid wastes. The total environmental impact E is the production quantity multiplied by the per-unit impact [38,50]
π_X^{ij}	The profits of supply chain members and whole, $i \in \{M, R, N\}$ represents the manufacturer-led, retailer-led and Nash equilibrium game respectively, $j \in \{M, R\}$ represents the manufacturer or retailer implements green design, $X \in \{M, R, S\}$ represents the manufacturer, retailer, and supply chain

Assumption 3.3. *In order to guarantee the concavity of all profit functions and the economic feasibility of related expressions, consistent with previous research [8, 40], the scale parameter should satisfy* $k > \max\left\{\frac{(a-bc)(bcd+\theta)+(bcd+\theta)^2}{6b}, \frac{(a-bc)(bcd+\theta)+2(bcd+\theta)^2}{8b}\right\}$.

4. MODELS CONSTRUCTION

4.1. Game model when manufacturer-led and implements green design (Model MM)

In the model MM, the decision-making sequence is: First, the dominant manufacturer determines the green design level and wholesale price. Next, the retailer determines the retail price. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{MM}}(w,g) = (w-(1-dg)c)(a-bp+\theta g)-kg^2 \tag{4.1}$$

$$\pi_R^{\mathrm{MM}}(p) = (p-w)(a-bp+\theta g). \tag{4.2}$$

TABLE 2. Equilibrium results under manufacturer-led.

	Model MM ($i=M, j=M$)	Model MR ($i=M, j=R$)
w^{ij^*}	$\frac{4k(a+bc)-c(ad+\theta)(bcd+\theta)}{8kb-(bcd+\theta)^2}$	$\frac{4kb(a+bc)-\theta(a\theta+2abcd+bc\theta)}{2b(4kb-\theta(bcd+\theta))}$
g^{ij^*}	$\frac{(a-bc)(bcd+\beta)}{8kb-(bcd+\theta)^2}$	$\frac{\theta(a-bc)}{2(4kb-\theta(bcd+\theta))}$
v^{ij^*}	$\frac{2k(a-bc)}{8kb-(bcd+\theta)^2}$	$\frac{k(a-bc)}{4kb-\theta(bcd+\theta)}$
p^{ij^*}	$\frac{2k(3a+bc)-c(ad+\theta)(bcd+\theta)}{8kb-(bcd+\theta)^2}$	$\frac{2kb(3a+bc)-\theta(a\theta+2abcd+bc\theta)}{2b(4kb-\theta(bcd+\theta))}$
q^{ij^*}	$\frac{2kb(a-bc)}{8kb-(bcd+\theta)^2}$	$\frac{kb(a-bc)}{4kb-\theta(bcd+\theta)}$
$\pi_M^{ij^*}$	$\frac{k(a-bc)^2}{8kb-(bcd+\theta)^2}$	$\frac{k(a-bc)^2}{2(4kb-\theta(bcd+\theta))}$
$\pi_R^{ij^*}$	$\frac{4k^2b(a-bc)^2}{(8kb-(bcd+\theta)^2)^2}$	$\frac{k(a-bc)^2(4kb-\theta^2)}{4(4kb-\theta(bcd+\theta))^2}$
$\pi_S^{ij^*}$	$\frac{k(a-bc)^2(12kb-(bcd+\theta)^2)}{(8kb-(bcd+\theta)^2)^2}$	$\frac{k(a-bc)^2(12kb-\theta(2bcd+3\theta))}{4(4kb-\theta(bcd+\theta))^2}$
CS^{ij^*}	$\frac{2k^2b(a-bc)^2}{(8kb-(bcd+\theta)^2)^2}$	$\frac{k^2b(a-bc)^2}{2(4kb-\theta(bcd+\theta))^2}$

According to the game order of the two-stage sustainable supply chain, the reverse recursion method is used to solve the problem. First, according to the retailer's profit function $\pi_R^{\mathrm{MM}}(p)$, we can easily get $\frac{\partial^2\pi_R^{\mathrm{MM}}(p)}{\partial p^2}=-2b<0$. Therefore, $\pi_R^{\mathrm{MM}}(p)$ is concave function about p. Then, according to the first order condition $\frac{\partial\pi_R^{\mathrm{ME}}(p)}{\partial p}=0$, the feedback function of retailer is $p^{\mathrm{MM}}=\frac{a+bw+\theta g}{2b}$. Furthermore, it will be substituted p^{MM} into the manufacturer's profit function $\pi_M^{\mathrm{MM}}(w,g)$, the Hessian matrix of $\pi_M^{\mathrm{MM}}(w,g)$ is $H^{\mathrm{MM}}=\begin{bmatrix}-b & \frac{\beta-bcr}{2}\\ \frac{\beta-bcr}{2} & \beta cr-2k\end{bmatrix}$, it is easy to verify when $k>\frac{(bcd+\theta)^2}{8b}$, the H^{MM} is negative definite, and $\pi_M^{\mathrm{MM}}(w,g)$ is concave function about w,g. According to the first order conditions, the optimal wholesale price w^{MM^*} and optimal green design level g^{MM^*} can be obtained. Then, by substituting w^{MM^*} and g^{MM^*} into p^{MM}, the optimal retail price p^{MM^*} can be obtained. Through $q(p,g)=a-bp+\theta g$, we can obtain the maximum market demand q^{MM^*}. Finally, by substituting the above optimal decision variables into formulas (4.1) and (4.2) respectively, we can obtain the maximum profits of manufacturer, retailer and whole system. The related equilibrium results are mathematically sorted out as shown in Table 2.

4.2. Game model when manufacturer-led and retailer implements green design (Model MR)

In the model MR, the decision-making sequence is: First, the dominant manufacturer determines the wholesale price. Then, the retailer determines the green design level and retail price. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{MR}}(w,g) = (w-(1-dg)c)(a-bp+\theta g) \tag{4.3}$$

$$\pi_R^{\mathrm{MR}}(p) = (p-w)(a-bp+\theta g) - kg^2. \tag{4.4}$$

The relevant solution method is similar to Section 4.1, the equilibrium results under the MR model can be obtained as shown in Table 2.

4.3. Game model when retailer-led and manufacturer implements green design (Model RM)

In the model RM, the decision-making sequence is: First, the dominant retailer determines the marginal profit. Then, the manufacturer determines the green design level and the wholesale price. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{RM}}(w,g) = (w-(1-dg)c)(a-bw-bv+\theta g) - kg^2 \tag{4.5}$$

$$\pi_R^{\mathrm{RM}}(v) = v(a-bw-bv+\theta g). \tag{4.6}$$

The relevant solution method is similar to Section 4.1, the equilibrium results under RM model can be obtained as shown in Table 3.

4.4. Game model when retailer-led and implements green design (Model RR)

In the model RR, the decision-making sequence is: First, the dominant retailer determines the green design level and the marginal profit, and then the manufacturer determines the wholesale price. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{RR}}(w,g) = (w-(1-dg)c)(a-bw-bv+\theta g) \tag{4.7}$$

$$\pi_R^{\mathrm{RR}}(v) = v(a-bw-bv+\theta g) - kg^2. \tag{4.8}$$

The relevant solution method is similar to Section 4.1, the equilibrium results under the RR model can be obtained as shown in Table 3.

4.5. Game model when Nash equilibrium Game and manufacturer implements green design (Model NM)

In the model NM, the decision-making sequence is: when the manufacturer determines the green design level and wholesale price, the retailer determines the marginal profit. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{NM}}(w,g) = (w-(1-dg)c)(a-bw-bv+\theta g) - kg^2 \tag{4.9}$$

$$\pi_R^{\mathrm{NM}}(v) = v(a-bw-bv+\theta g). \tag{4.10}$$

The relevant solution method is similar to Section 4.1, the equilibrium results under the NM model can be obtained as shown in Table 4.

4.6. Game model when Nash equilibrium game and retailer implements green design (Model NR)

In the model NR, the decision-making sequence is: when the manufacturer determines the wholesale price, the retailer determines the green design level and marginal profit. The profit functions of manufacturer and retailer are as follows

$$\pi_M^{\mathrm{NR}}(w,g) = (w-(1-dg)c)(a-bw-bv+\theta g) \tag{4.11}$$

TABLE 3. Equilibrium results under retailer-led.

	Model RM ($i=R, j=M$)	Model RR ($i=R, j=R$)
w^{ij^*}	$\frac{2k(a+3bc)-c(bcd+\theta)(ad+bcd+2\theta)}{2(4kb-(bcd+\theta)^2)}$	$\frac{2k(a+3bc)-c(ad+\theta)(bcd+\theta)}{8kb-(bcd+\theta)^2}$
g^{ij^*}	$\frac{(a-bc)(bcd+\theta)}{2(4kb-(bcd+\theta)^2)}$	$\frac{(a-bc)(bcd+\theta)}{8kb-(bcd+\theta)^2}$
v^{ij^*}	$\frac{a-bc}{2b}$	$\frac{4k(a-bc)}{8kb-(bcd+\theta)^2}$
p^{ij^*}	$\frac{2kb(3a+bc)-(bcd+\theta)(a\theta+2abcd+bc\theta)}{2(4kb-(bcd+\theta)^2)}$	$\frac{2k(3a+bc)-c(ad+\theta)(bcd+\theta)}{8kb-(bcd+\theta)^2}$
q^{ij^*}	$\frac{kb(a-bc)}{4kb-(bcd+\theta)^2}$	$\frac{2kb(a-bc)}{8kb-(bcd+\theta)^2}$
$\pi_M^{ij^*}$	$\frac{k(a-bc)^2}{4(4kb-(bcd+\theta)^2)}$	$\frac{4k^2b(a-bc)^2}{(8kb-(bcd+\theta)^2)^2}$
$\pi_R^{ij^*}$	$\frac{k(a-bc)^2}{2(4kb-(bcd+\theta)^2)}$	$\frac{k(a-bc)^2}{8kb-(bcd+\theta)^2}$
$\pi_S^{ij^*}$	$\frac{3k(a-bc)^2}{4(4kb-(bcd+\theta)^2)}$	$\frac{k(a-bc)^2(12kb-(bcd+\theta)^2)}{(8kb-(bcd+\theta)^2)^2}$
CS^{ij^*}	$\frac{k^2b(a-bc)^2}{2(4kb-(bcd+\theta)^2)^2}$	$\frac{2k^2b(a-bc)^2}{(8kb-(bcd+\theta)^2)^2}$

$$\pi_R^{\mathrm{NR}}(v) = v(a-bw-bv+\theta g)-kg^2. \tag{4.12}$$

The relevant solution method is similar to Section 4.1, the equilibrium results under NR model can be obtained as shown in Table 4.

5. Equilibrium result analysis

Proposition 5.1. *When the manufacturer and retailer implement green design respectively, (1) Under the manufacturer-led, (a)* $w^{\mathrm{MM}^*} \geq w^{\mathrm{MR}^*}$*, when* $0<d\leq d_1$*;* $w^{\mathrm{MR}^*} > w^{\mathrm{MM}^*}$*, when* $d_1<d<1$*; (b)* $p^{\mathrm{MM}^*} \geq p^{\mathrm{MR}^*}$*, when* $0<d\leq d_2$*;* $p^{\mathrm{MR}^*} > p^{\mathrm{MM}^*}$*, when* $d_2<d<1$*; (2) Under the retailer-led, (a)* $w^{\mathrm{RM}^*} \geq w^{\mathrm{RR}^*}$*, when* $0<d\leq d_3$*;* $w^{\mathrm{RR}^*} > w^{\mathrm{RM}^*}$*, when* $d_3<d<1$*; (b)* $p^{\mathrm{RR}^*} \geq p^{\mathrm{RM}^*}$*, when* $0<d\leq d_4$*;* $p^{\mathrm{RM}^*} > p^{\mathrm{RR}^*}$*, when* $d_4<d<1$*; (3) Under the Nash equilibrium game, (a)* $w^{\mathrm{NM}^*} \geq w^{\mathrm{NR}^*}$*, when* $0<d\leq d_5$*;* $w^{\mathrm{NR}^*} > w^{\mathrm{NM}^*}$*, when* $d_5<d<1$*; (b)* $p^{\mathrm{NM}^*} \geq p^{\mathrm{NR}^*}$*, when* $0<d\leq d_6$*;* $p^{\mathrm{NR}^*} > p^{\mathrm{NM}^*}$*, when* $d_6<d<1$*. Where,* $d_1=\frac{\theta(4kb-\theta^2+2\sqrt{2kb(4kb-\theta^2)})}{bc(4kb+\theta^2)}$, $d_2=\frac{\theta(4kb-\theta^2+2\sqrt{kb(5kb-2\theta^2)})}{bc(2kb+\theta^2)}$, $d_3=\frac{\sqrt{8kb+\theta^2}-\theta}{2bc}$, $d_4=\frac{2kb-\theta^2}{bc\theta}$, $d_5=\frac{\theta}{2bc}$, $d_6=\frac{2\theta}{bc}$.

Proposition 5.1 shows that, whatever the channel leadership, which green design strategy can reduce the wholesale and retail prices more effectively depends on the size of green design cost effect, and the change rules under three kinds of channel leadership are different. Specifically, under the manufacturer-led and Nash equilibrium game, when the green design cost effect is small, the wholesale and retail prices are lower when the retailer implements green design. On the contrary, it is lower when the manufacturer implements green design.

Table 4. Equilibrium results under Nash equilibrium game.

	Model NM ($i=N, j=M$)	Model NR ($i=N, j=R$)
w^{ij^*}	$\frac{2k(a+2bc)-c(ad+\theta)(bcd+\theta)}{6kb-(bcd+\theta)^2}$	$\frac{2k(a+2bc)-c\theta(ad+\theta)}{6kb-\theta(bcd+\theta)}$
g^{ij^*}	$\frac{(a-bc)(bcd+\theta)}{6kb-(bcd+\theta)^2}$	$\frac{\theta(a-bc)}{6kb-\theta(bcd+\theta)}$
v^{ij^*}	$\frac{2k(a-bc)}{6kb-(bcd+\theta)^2}$	$\frac{2k(a-bc)}{6kb-\theta(bcd+\theta)}$
p^{ij^*}	$\frac{2k(2a+bc)-c(ad+\theta)(bcd+\theta)}{6kb-(bcd+\theta)^2}$	$\frac{2k(2a+bc)-c\theta(ad+\theta)}{6kb-\theta(bcd+\theta)}$
q^{ij^*}	$\frac{2kb(a-bc)}{6kb-(bcd+\theta)^2}$	$\frac{2kb(a-bc)}{6kb-\theta(bcd+\theta)}$
$\pi_M^{ij^*}$	$\frac{k(a-bc)^2(4kb-(bcd+\theta)^2)}{(6kb-(bcd+\theta)^2)^2}$	$\frac{4k^2b(a-bc)^2}{(6kb-\theta(bcd+\theta))^2}$
$\pi_R^{ij^*}$	$\frac{4k^2b(a-bc)^2}{(6kb-(bcd+\theta)^2)^2}$	$\frac{k(a-bc)^2(4kb-\theta^2)}{(6kb-\theta(bcd+\theta))^2}$
$\pi_S^{ij^*}$	$\frac{k(a-bc)^2(8kb-(bcd+\theta)^2)}{(6kb-(bcd+\theta)^2)^2}$	$\frac{k(a-bc)^2(8kb-\theta^2)}{(6kb-\theta(bcd+\theta))^2}$
CS^{ij^*}	$\frac{2k^2b(a-bc)^2}{(6kb-(bcd+\theta)^2)^2}$	$\frac{2k^2b(a-bc)^2}{(6kb-\theta(bcd+\theta))^2}$

This is different from Shi *et al.*'s research, which is based on manufacturer-led scenario studies and suggests that the retailer making green investments are more conducive to reducing the wholesale price [39]. Under the retailer-led, when the green design cost effect is small, the wholesale price is lower when retailer implementing green design, while the retail price is lower when manufacturer implementing green design. On the contrary, the wholesale price is lower when manufacturer implementing green design, while the retail price is lower when retailer implementing green design.

In fact, the manufacturer as the production enterprise, pays more attention to the changes of production costs and generally benefits more from the green design cost effect. And the retailer, as the sales enterprise, pays more attention to the changes of the market and generally benefits more from the green design demand effect. When the green design cost effect is small, it means that manufacturer can only get less income from green design invest, and she will tend to set higher wholesale price to make up for the invest costs of green design when implementing green design. When retailer has no channel dominance, the formulation of retail price will be affected by wholesale price to a large extent. Therefore, under the manufacturer-led and Nash equilibrium game, the wholesale and retail prices show the same change trend. When retailer has the channel leadership (pricing priority), he will give priority to maximizing market demand when formulating retail price. Therefore, under the green design cost effect is small (the green design demand effect will be relatively more significant) and the manufacturer implements green design, the retailer will set lower retail prices to maximize market demand, makes the manufacturer can also benefit from the increase in market demand.

Proposition 5.1 reveals that channel leadership, green design strategies and green design cost effect will all affect the pricing decisions of enterprises, and higher wholesale price will not necessarily lead to higher retail price. Therefore, enterprises should take full account of the channel leadership of their sustainable supply chain and the impact of green design strategies when formulating product prices.

Proposition 5.2. *When the manufacturer and retailer implement green design respectively, (1) Under the manufacturer-led, (a)* $v^{\mathrm{MR}^*} \geq v^{\mathrm{MM}^*}$, $q^{\mathrm{MR}^*} \geq q^{\mathrm{MM}^*}$, $\mathrm{CS}^{\mathrm{MR}^*} \geq \mathrm{CS}^{\mathrm{MM}^*}$*, when* $0 < d \leq d_7$*;* $v^{\mathrm{MM}^*} > v^{\mathrm{MR}^*}$, $q^{\mathrm{MM}^*} > q^{\mathrm{MR}^*}$, $\mathrm{CS}^{\mathrm{MM}^*} > \mathrm{CS}^{\mathrm{MR}^*}$*, when* $d_7 < d < 1$*; (b)* $g^{\mathrm{MR}^*} \geq g^{\mathrm{MM}^*}$*, when* $0 < d \leq d_8$*;* $g^{\mathrm{MM}^*} > g^{\mathrm{MR}^*}$*, when* $d_8 < d < 1$*; (2) Under the retailer-led,* $v^{\mathrm{RM}^*} > v^{\mathrm{RR}^*}$, $q^{\mathrm{RM}^*} > q^{\mathrm{RR}^*}$, $g^{\mathrm{RM}^*} > g^{\mathrm{RR}^*}$, $\mathrm{CS}^{\mathrm{RM}^*} > \mathrm{CS}^{\mathrm{RR}^*}$*; (3) Under the Nash equilibrium game,* $v^{\mathrm{NM}^*} > v^{\mathrm{NR}^*}$, $q^{\mathrm{NM}^*} > q^{\mathrm{NR}^*}$, $g^{\mathrm{NM}^*} > g^{\mathrm{NR}^*}$, $\mathrm{CS}^{\mathrm{NM}^*} > \mathrm{CS}^{\mathrm{NR}^*}$*. Where,* $d_7 = \frac{\theta}{bc}$, $d_8 = \frac{4kb-\theta^2+2\sqrt{2kb(2kb-\theta^2)}}{bc\theta}$.

Proposition 5.2 shows that, which green design strategy is more conducive to improving the green design level, increasing market demand and consumer surplus depends on the channel leadership and green design cost effect. Specifically, under the manufacturer-led, when the green design cost effect is small, the retailer implements green design is better. This is different from Dong *et al.*'s research, which is based on manufacturer-led scenario studies and indicates that green investment by the manufacturer is always more conducive to improving the green level of products [10]. On the contrary, the manufacturer implements green design is better. Under the retailer-led and Nash equilibrium game, it is always better for the manufacturer to implement green design.

In fact, when the manufacturer has the leadership, it can always obtain a certain profit advantage through the priority pricing right. And the relatively low green design cost effect means that the manufacturer can only obtain limited benefits from green design. At this time, the manufacturer has no profit motive to compete with the retailer for the decision-making right of green design. Therefore, when the green design cost effect is small, the retailer has more profit motive to implements green design to improve his marginal income and increase market demand and consumer surplus. When the manufacturer gradually loses her power, she will need more decision-making power of green design to make up for her own shortcomings in pricing power. Because she can effectively reduce her own production cost and expand market demand by adjusting the green design level. Therefore, under the retailer-led and Nash equilibrium game, it is always better for manufacturer to implement green design.

Proposition 5.2 reveals that enterprises should choose the appropriate green design strategy according to the channel leadership of their sustainable supply chain and the characteristics of green design. This can not only effectively improve the green design level, but also better stimulate the purchasing power of consumers, and improve the market share and consumer surplus. Specifically, under the manufacturer-led, when the green design cost effect is small, the retailer should implement green design. Conversely, the manufacturer should implement green design. Under the retailer-led and Nash equilibrium game, the manufacturer should always be advised to implement green design.

When the effectiveness or efficiency of the green design implementation by manufacturer is limited, the manufacturer should take measures to incentivize the retailer to implement green design. However, to improve the green design level and market demand more effectively, the retailer should also selectively implement green design based on the different channel structures and his own ability.

Proposition 5.3. *When the manufacturer and retailer implement green design respectively, (1) Under the manufacturer-led, (a)* $\pi_M^{\mathrm{MR}^*} \geq \pi_M^{\mathrm{MM}^*}$*, when* $0 < d \leq d_7$*;* $\pi_M^{\mathrm{MM}^*} > \pi_M^{\mathrm{MR}^*}$*, when* $d_7 < d < 1$*; (b)* $\pi_R^{\mathrm{MR}^*} \geq \pi_R^{\mathrm{MM}^*}$*, when* $0 < d \leq d_9$*;* $\pi_R^{\mathrm{MM}^*} > \pi_R^{\mathrm{MR}^*}$*, when* $d_9 < d < 1$*; (c)* $\pi_S^{\mathrm{MR}^*} \geq \pi_S^{\mathrm{MM}^*}$*, when* $0 < d \leq d_{10}$*;* $\pi_S^{\mathrm{MM}^*} > \pi_S^{\mathrm{MR}^*}$*, when* $d_{10} < d < 1$*; (2) Under the retailer-led,* $\pi_M^{\mathrm{RM}^*} > \pi_M^{\mathrm{RR}^*}$, $\pi_R^{\mathrm{RM}^*} > \pi_R^{\mathrm{RR}^*}$, $\pi_S^{\mathrm{RM}^*} > \pi_S^{\mathrm{RR}^*}$*; (3) Under the Nash equilibrium game,* $\pi_M^{\mathrm{NM}^*} > \pi_M^{\mathrm{NR}^*}$, $\pi_R^{\mathrm{NM}^*} > \pi_R^{\mathrm{NR}^*}$, $\pi_S^{\mathrm{NM}^*} > \pi_S^{\mathrm{NR}^*}$*. Where,* $d_9 = \frac{\theta^2(\theta(4kb-\theta^2)+8\sqrt{k^2b^2(4kb-\theta^2)})}{bc(4kb(16kb-\theta^2)+\theta^4)}$, $d_{10} = \frac{\theta(\theta^2(4kb-\theta^2)+\sqrt{k^2b^2(16kb(32kb+7\theta^2)-15\theta^4)})}{bc(kb(32kb-3\theta^2)+\theta^4)}$.

Proposition 5.3 shows that, which green design strategy is more conducive to improving the performance of sustainable supply chain members and the whole depends on the channel leadership and the green design cost effect. Specifically, under the manufacturer-led, when the green design cost effect is small, the retailer implements green design is better. Conversely, the manufacturer implements green design is better. Under the retailer-led and Nash equilibrium game, it is always better for manufacturer to implement green design.

Proposition 5.3 reveals that manufacturer may not have profit motive to implement green design when she has dominant advantages, but she is always more inclined to implement green design when she has no dominant advantages. However, retailer is more inclined to implement green design only when he has no dominant advantage and the green design cost effect is small.

Based on the channel leadership dominated by the manufacturer, Shi *et al.* [39] studied that both manufacturer and retailer have gained more profits when retailer makes green investments. However, we further show that only when the manufacturer dominates and the green design cost effect is small, can the retailer implement green design to make the member enterprises of supply chain gain more profits. Under the retailer-led and Nash equilibrium game, manufacturer and retailer will benefit more from the green design implemented by manufacturer.

At the same time, when implementing green design by the follower is more conducive to improving the green design level and profits of sustainable supply chain, follower should not be short-sighted, but should consider the impact of green behavior on the long-term development of the enterprise, and actively implement green design. And the leader should also take initiative to control and coordinate the overall sustainable supply chain, not only to encourage follower to actively implement green design, but also to ensure reasonable profits and development of follower, thereby effectively promoting the long-term development of sustainable supply chain.

Proposition 5.4. *When the manufacturer implements green design, under different channel leadership,* $g^{\mathrm{NM}^*} \geq g^{\mathrm{RM}^*} > g^{\mathrm{MM}^*}$, $w^{\mathrm{MM}^*} > w^{\mathrm{NM}^*} \geq w^{\mathrm{RM}^*}$, $p^{\mathrm{MM}^*} > p^{\mathrm{RM}^*} \geq p^{\mathrm{NM}^*}$, $q^{\mathrm{NM}^*} \geq q^{\mathrm{RM}^*} > q^{\mathrm{MM}^*}$, $S^{\mathrm{NM}^*} \geq \mathrm{CS}^{\mathrm{RM}^*} > \mathrm{CS}^{\mathrm{MM}^*}$, *when* $0 < d \leq d_{11}$; $g^{\mathrm{RM}^*} > g^{\mathrm{NM}^*} > g^{\mathrm{MM}^*}$, $w^{\mathrm{MM}^*} > w^{\mathrm{RM}^*} > w^{\mathrm{NM}^*}$, $p^{\mathrm{MM}^*} > p^{\mathrm{NM}^*} > p^{\mathrm{RM}^*}$, $q^{\mathrm{RM}^*} > q^{\mathrm{NM}^*} > q^{\mathrm{MM}^*}$, $\mathrm{CS}^{\mathrm{RM}^*} > \mathrm{CS}^{\mathrm{NM}^*} > \mathrm{CS}^{\mathrm{MM}^*}$, *when* $d_{11} < d < 1$. *Where,* $d_{11} = \frac{\sqrt{2kb}-\theta}{bc}$.

Proposition 5.4 shows that, when the manufacturer implements green design, in terms of reducing the wholesale and retail prices, improving the green design level, market demand and consumer surplus, the manufacturer-led is always worst. This result is consistent with that in Chen *et al.* [6], which pointed out that wholesale and retail prices are higher and green investment levels are lower when manufacturer is dominant. When the green design cost effect is small, the Nash equilibrium game is better. On the contrary, when the green design cost effect is large, the retailer-led is better. This result is different from the research conclusion of Chen *et al.* [6], which showed that wholesale and retail prices are always lower, and the level of green investment is higher under the Nash game. In fact, when the manufacturer implements green design, on the one hand, she always tends to increase profit by increasing wholesale price, and on the other hand, she balances green design investment costs and profit by adjusting the green design level. Under the manufacturer-led, the manufacturer has stronger bargaining power. Therefore, the wholesale price is always higher and the green design level is lower. Under the Nash equilibrium game, the manufacturer still has certain bargaining power, and can make up her own investment costs in green design by adjusting wholesale price. Therefore, even if the green design cost effect is small, the manufacturer will tend to reduce production costs and increase market demand by improving the green design level. However, under the retailer-led, the manufacturer has weak bargaining power, so only when the green design cost effect is large, can manufacturer be motivated to invest in green design at a high level.

Proposition 5.4 reveals that when the manufacturer implements green design, who has power is always not conducive to improving the green design level and market demand. Under the retailer-led and Nash equilibrium game, which is more conducive to improving the green design level and market demand depends on the green design cost effect.

Proposition 5.5. *When the retailer implements green design, under different channel leadership, (1)* $g^{\mathrm{NR}^*} > g^{\mathrm{RR}^*} > g^{\mathrm{MR}^*}$, $w^{\mathrm{MR}^*} > w^{\mathrm{NR}^*} > w^{\mathrm{RR}^*}$, $p^{\mathrm{RR}^*} > p^{\mathrm{MR}^*} > p^{\mathrm{NR}^*}$*; (2)* $q^{\mathrm{NR}^*} > q^{\mathrm{MR}^*} \geq q^{\mathrm{RR}^*}$, $\mathrm{CS}^{\mathrm{NR}^*} > \mathrm{CS}^{\mathrm{MR}^*} \geq \mathrm{CS}^{\mathrm{RR}^*}$*, when* $0 < d \leq d_7$*;* $q^{\mathrm{NR}^*} > q^{\mathrm{RR}^*} > q^{\mathrm{MR}^*}$, $\mathrm{CS}^{\mathrm{NR}^*} > \mathrm{CS}^{\mathrm{RR}^*} > \mathrm{CS}^{\mathrm{MR}^*}$*, when* $d_4 < d < 1$.

Proposition 5.5 shows that, when the retailer implements green design, in terms of reducing the wholesale and retail prices, improving the green design level, market demand and consumer surplus, the Nash equilibrium game is always optimal. Compared with the manufacturer-led, the retailer-led is more conducive to improving the green design level and reducing the wholesale price, but will lead to higher retail price, which may not lead to higher market demand and consumer surplus. In fact, enterprises always use their dominant advantages to set higher prices to benefit, so that the wholesale price is always higher when manufacturer dominates, and the retail price is always higher when retailer dominates. Higher wholesale price will squeeze the profit space of retailer. Therefore, under the manufacturer-led, retailer always tends to diminish the green design level to lessen the green design invest cost and increase his own profit. With the gradual transfer of power to retailer, on the one hand, the retailer will incentivize the manufacturer to reduce wholesale price by appropriately increasing the green design level to help manufacturer reduce production costs. On the other hand, he will also increase the retail price to further increase his own profit. Higher retail price will also affect consumers' purchasing enthusiasm to a certain extent, making the demand and consumer surplus lower than the manufacturer-led under certain circumstances.

Under the assumption that manufacturer implements green investment, Hong *et al.* [17] found that compared to the retailer-led, the manufacturer-led is more unfavorable for improving greenness and market demand of products. This study further indicates that when the retailer implements green design, although the retailer-led is more conducive to improving the green design level than that the manufacturer-led, it may not necessarily be conducive to increasing market demand for products.

Proposition 5.6. *When the manufacturer implements green design, under different channel leadership, (1)* $\pi_R^{\mathrm{RM}^*} > \pi_R^{\mathrm{NM}^*} > \pi_R^{\mathrm{MM}^*}$*; (2)* $\pi_M^{\mathrm{MM}^*} > \pi_M^{\mathrm{NM}^*} \geq \pi_M^{\mathrm{RM}^*}$, $\pi_S^{\mathrm{NM}^*} \geq \pi_S^{\mathrm{RM}^*} > \pi_S^{\mathrm{MM}^*}$*, when* $0 < d \leq d_{11}$*;* $\pi_M^{\mathrm{MM}^*} > \pi_M^{\mathrm{RM}^*} > \pi_M^{\mathrm{NM}^*}$, $\pi_S^{\mathrm{RM}^*} > \pi_S^{\mathrm{NM}^*} > \pi_S^{\mathrm{MM}^*}$*, when* $d_{11} < d < 1$.

Proposition 5.6 shows that, when the manufacturer implements green design, under different channel leadership, the manufacturer and retailer can always obtain more profits when they are the channel leader. And retailer can always obtain less profit when he is channel follower, but only when the green design cost effect is small, the manufacturer can obtain less profit under she is channel follower. For the sustainable supply chain system, when the green design cost effect is small, the Nash equilibrium game is more conducive to improving the overall performance of sustainable supply chain. On the contrary, the retailer-led is better, and the manufacturer-led is always worst.

Proposition 5.7. *When the retailer implements green design, under different channel leadership,* $\pi_M^{\mathrm{MR}^*} > \pi_M^{\mathrm{NR}^*} > \pi_M^{\mathrm{RR}^*}$, $\pi_R^{\mathrm{RR}^*} > \pi_R^{\mathrm{NR}^*} > \pi_R^{\mathrm{MR}^*}$, $\pi_S^{\mathrm{NR}^*} > \pi_S^{\mathrm{RR}^*} > \pi_S^{\mathrm{MR}^*}$.

Proposition 5.7 shows that, when the retailer implements green design, under different channel leadership, manufacturer and retailer can always obtain more profits when they are the channel leaders, and less profits when they are the channel followers. The sustainable supply chain system has always gained more profits under the Nash equilibrium game, and has the least profits under the manufacturer-led.

Combined with Propositions 5.6 and 5.7, whether manufacturer or retailer implements green design, both manufacturer and retailer gain more profits when they are the channel leaders. For the overall profits of sustainable supply chain, when manufacturer implements green design and the green design cost effect is small, or when retailer implements green design, the Nash equilibrium game is better. When manufacturer implements green design and the green design cost effect is large, the retailer-led is better.

Combining Propositions 5.4–5.7, it can be found that regardless of whether the manufacturer or retailer implements green design, the level of green design and the overall profits of sustainable supply chains under manufacturer-led are always the lowest. This also reveals why in reality, the green transformation process of traditional large manufacturing enterprises (such as Volkswagen, Ford, etc.) is always relatively slow. Therefore, the dominant manufacturer should actively assume the environmental responsibilities, control and coordinate the supply chain, and choose the green design investment mode that is most conducive to the sustainable development of the supply chain.

Proposition 5.8. *When the manufacturer and retailer implement green design respectively, (1) Under the retailer-led,* $E^{\mathrm{RM}^*} \geq E^{\mathrm{RR}^*}$*, when* $0 < \lambda \leq \lambda_1$*;* $E^{\mathrm{RR}^*} > E^{\mathrm{RM}^*}$*, when* $\lambda_1 < \lambda < 1$*; (2) Under the Nash equilibrium game,* $E^{\mathrm{NM}^*} \geq E^{\mathrm{NR}^*}$*, when* $0 < \lambda \leq \lambda_2$*;* $E^{\mathrm{NR}^*} > E^{\mathrm{NM}^*}$*, when* $\lambda_2 < \lambda < 1$.

Proposition 5.8 shows that, under the retailer-led and Nash equilibrium game, when the green design environmental effect is small, compared with manufacturer implements green design, the retailer implements green design is more conducive to reducing the total environmental impact of products. On the contrary, when the green design environmental effect is large, the manufacturer implements green design is better. This is because the total environmental impact of products depends on two aspects, one is the sales volume of products (q), and the other is the environmental impact of unit product under green design ($(1-\lambda g)\varphi$, the greater the green design environmental impact λ, the smaller the environmental impact of unit product). Therefore, when λ is small, the effect of product sales on the total environmental impact of products is more significant. With the increase of λ, the environmental impact of unit product becomes smaller and smaller, and λ on the total environmental impact of products becomes more significant. As the relationship between the market demand and green design level under the manufacturer-led and other situations is also affected by the green design cost effect. As a result, the relationship between the total environment impact of products under other models will be affected by the green design cost effect and the green design environmental effect at the same time. This makes the comparative analysis of relevant analytic expressions more complicated. Therefore, we will make further analysis through numerical simulation later.

Proposition 5.8 reveals that whether the investment strategy conducive to improving the green design level can always effectively reduce the total environmental impact of products depends on the size of the green design environmental effect. Therefore, for enterprises, when implementing green design, they should pay attention to the multiple impacts brought by green design. While effectively improving the cost effect and demand effect of green design, they should also pay attention to enhancing the green design environmental effect, so as to reduce the total environmental impact of products while promoting the increase of demand. For the government, on the one hand, it can accelerate the improvement of green design and green manufacturing standard system, and accelerate the updating and upgrading of energy conservation standards (such as promoting the use of new energy efficiency). On the other hand, it can also increase the efforts to crack down on the behavior of falsely labeled green products, so as to regulate and guide enterprises to invest in green innovation in reducing the environment adverse impact of products, and effectively improve the green design environmental effect.

6. Numerical simulation analysis

In the section, we mainly analyze the impact of green design cost effect d on product pricing, green design level and performance of sustainable supply chain through numerical examples. And we also examine the green design cost effect and the green design environment effect on reducing the total environment impact of products. Refer to the parameter settings of Raj *et al.* [37] and Raz *et al.* [38], we assume $a = 100$, $b = 6$, $\theta = 8$, $c = 5$, $k = 60$, $\theta = 1$. We used Matlab 2018 and Excel 2019 software for numerical assignments and drew the following tables and graphs.

Table 5 shows that, with the increase of green design cost effect, it is conducive to reducing the wholesale and retail prices, and increasing the green design level and market demand. This is because as the increase of green design cost effect, the unit green design level can more effectively reduce the production cost of products, so that the manufacturer will also reduce the wholesale price, which will lead to a decline in retail price, as well as an increase of the green design level and market demand. Furthermore, under the different channel leadership,

TABLE 5. Equilibrium results under different models.

d		Model					
		MM	MR	RM	RR	NM	NR
w^{ij^*}	0.1	10.95	10.73	8.04	7.91	8.93	8.92
	0.3	10.80	10.51	7.87	7.55	8.54	8.74
	0.6	10.14	10.15	6.92	6.93	6.91	8.44
g^{ij^*}	0.1	0.19	0.20	0.29	0.19	0.38	0.27
	0.3	0.46	0.21	0.52	0.26	0.63	0.28
	0.6	0.68	0.22	0.78	0.28	0.71	0.29
p^{ij^*}	0.1	13.99	13.84	13.91	13.99	13.05	12.97
	0.3	13.89	13.73	13.88	13.89	13.02	12.88
	0.6	13.85	13.96	13.87	13.85	12.64	12.75
q^{ij^*}	0.1	18.27	18.64	19.11	18.27	24.72	24.32
	0.3	19.45	19.33	22.89	19.45	25.94	24.90
	0.6	22.87	20.45	26.98	22.87	26.56	25.81

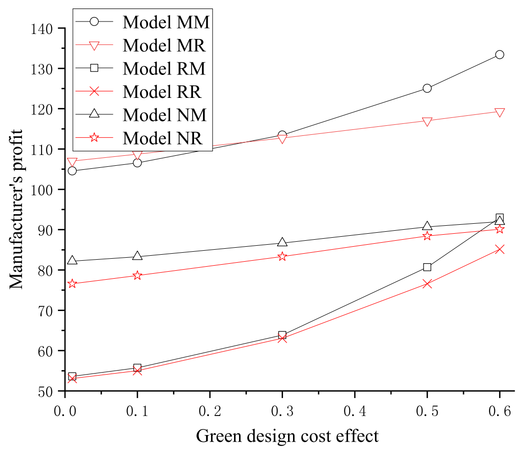

FIGURE 1. Manufacturer's profit under six models.

which green design strategy is more conducive to reducing the wholesale and retail prices depends on the size of green design cost effect. In terms of improving the green design level and market demand, under the retailer-led and Nash equilibrium game, the manufacturer implements green design is always better. However, under the manufacturer-led, only when the green design cost effect is large, can the manufacturer implement green design better than retailer. Therefore, sustainable supply chain enterprises should fully consider the influence of channel leadership and green design cost effect when choosing green design strategy, and then select the green design strategy that is most conducive to improving product green level and market demand.

No matter the manufacturer or retailer implements green design, they can improve the cost effect of green design by introducing cutting-edge technology or optimizing the implementation process of green design, to better play the role of green design and truly help the supply chain achieve green development while reducing costs and increasing efficiency. In reality, Lenovo optimizes the green design implementation process comprehensively by utilizing advanced digital technology, resulting in annual savings of hundreds of millions of dollars.

Figures 1 and 2 show that, the increasing of green design cost effect, the profits of manufacturer and retailer are increasing. Furthermore, under the manufacturer-led, when the green design cost effect is small, both

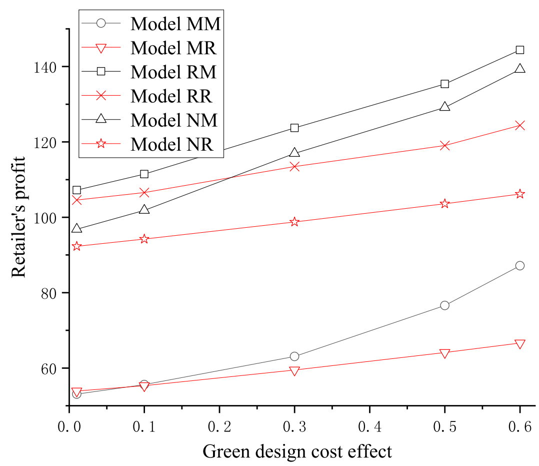

FIGURE 2. Retailer's profit under six models.

manufacturer and retailer gain more profits when retailer implements green design. On the contrary, they can obtain more profits when manufacturer implements green design. Under the retailer-led and Nash equilibrium game, the manufacturer and retailer can always obtain more profits when manufacturer implements green design. Therefore, from the practice, the manufacturer and retailer should choose appropriate green design strategy according to the channel leadership and the impact of green design cost effect to maximize their own profits.

Table 5, Figures 1 and 2 reveal that, when the manufacturer or retailer implement green design, they should reduce the use and consumption of raw materials of products without affecting product quality and performance as much as possible, so as to reduce the production cost of enterprises more efficiently through green design. This is not only conducive to improving the green level of products and market demand, but also to improving the performance of supply chain members and overall. For example, Chrysler saved hundreds of millions of dollars by reducing material consumption in the product manufacturing process through green design, and eliminating inefficient and redundant work processes in the production process.

Figures 3–5 show that, when the green design cost effect d is constant, the total environmental impact of products will decrease with the increase of green design environmental effect λ. Only when λ is large, the increase of d is conducive to reducing the total environment impact of products. Furthermore, under the manufacturer-led, when d is smaller and λ is larger or d is larger and λ is smaller, the retailer implements green design is more conducive to reducing the total environment impact of products. On the contrary, the manufacturer implements green design is more conducive to reducing the overall environmental impact of products. However, under the retailer-led and Nash equilibrium game, regardless the size of d, when λ is large, the manufacturer implements green design is more conducive to reducing the total environment impact of products. On the contrary, the retailer implements green design is more conducive to reducing the overall environment impact of products. In fact, the overall environment impact of products under different models is jointly affected by the market demand (affected by d) and the environmental impact degree of unit product (affected by λ). Therefore, the overall environmental impact of products under different channel leadership and green design strategy is also jointly affected by d and λ.

Figures 3–5 reveal that when implementing green design, the manufacturer or retailer should not only focus on improving the green design cost effect to increase demand and performance of sustainable supply chain, but they should also invest more in green innovation to diminish the environment adverse impact of products, and strive to enhance the green design environmental effect. Only in this way can truly promote the green development and diminish the adverse impact on the environment. For example, while reducing the energy

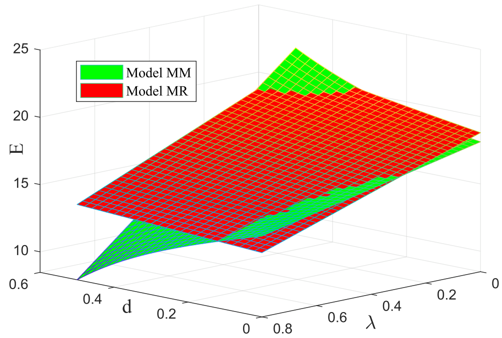

FIGURE 3. Impact of d, λ on the environment under manufacturer-led.

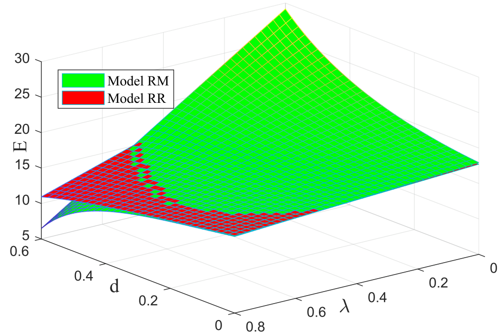

FIGURE 4. Impact of d, λ on the environment under retail-led.

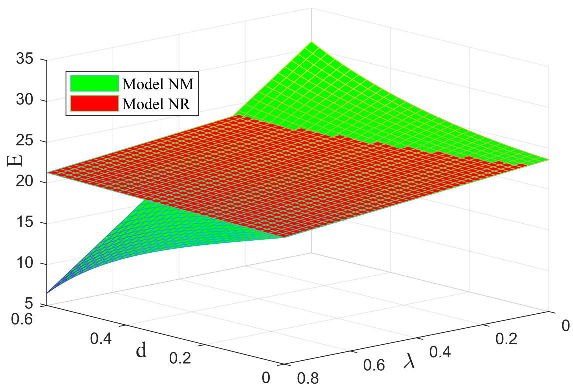

FIGURE 5. Impact of d, λ on the environment under Nash equilibrium game.

consumption of products through green design, Apple is also trying to reduce the carbon emissions of products. According to Apple's 2020 Environmental Progress Report, Apple has been improving resource and energy efficiency and reducing carbon emissions through green design, process and material innovation, and claims that it has achieved carbon neutrality in global operations.

Therefore, when implementing green design, the enterprises should strive to improve the environmental effect of green design, effectively increase the advantages of green products in energy conservation and environmental protection, and establish a good corporate reputation and brand image. Thus, while the green products are recognized by consumers, it also improves the profits and sustained competitiveness of green products. For the government, by collaborating with manufacturers, certification agencies, consumers and other social forces, it can promote the improvement of green product standards and certification, and promote green lifestyles and green products, further regulating the green production of enterprises. In reality, companies such as Gree and Haier have been actively engaged in green design research and development, and their energy-saving and environmentally friendly products (such as Gree variable frequency air conditioners, Haier fluorine free refrigerators, etc.) are highly recognized and supported by consumers.

7. Conclusion

As an effective strategy to reduce production costs and environmental impacts of products from the source, green design has become one of the most efficient means to practice sustainable supply chain. At present, there are two main green design strategy, namely, manufacturer implements green design and retailer implements green design. In addition, channel leadership as an important factor affecting enterprise decision-making and profits, but its impact on the selection of the best green design strategy for sustainable supply chain is still unclear. Based on this, we construct six decision-making models for sustainable supply chain considering two types of green design strategies under three kinds of channel leadership (manufacturer-led, retailer-led and Nash equilibrium game). We analyze the interaction between channel leadership and green design strategies, as well as their impact on pricing decisions, enterprise performance, consumer surplus and environment. Our research results are summarized as follows:

(1) Which green design strategy can reduce the wholesale and retail prices more effectively depends on the channel leadership and the size of green design cost effect, and the change laws of the two prices are not always consistent.
(2) Under the manufacturer-led, when the green design cost effect is small, the retailer implements green design is more conducive to improving the green design level, market demand, consumer surplus and overall profits of sustainable supply chain. However, under the retailer-led and Nash equilibrium game, it is always better for the manufacturer to implement green design.
(3) When the manufacturer implements green design and the green design cost effect is large, the retailer-led is more conducive to improving the green design level and the overall performance of sustainable supply chain. While, when the retailer implements green design, the Nash equilibrium game is always better.
(4) The increase of green design cost effect will always help to improve the green design level, expand market demand, and increase the overall profits of sustainable supply chain, but it may not always help to reduce the total environmental impact of products.
(5) In terms of reducing the total environmental impact of products, under the retailer-led and Nash equilibrium game, when the green design environmental effect is large, the manufacturer implements green design is better. Moreover, under the manufacturer-led, when the green design cost effect is small (large) and the green design environmental effect is large (small), the retailer implements green design is better.

According to the above conclusions, the management enlightenment as follows: Firstly, when implementing green design, enterprises should determine the best green design strategy for sustainable supply chain according to channel leadership and the characteristics of green design. In this way, they can more effectively implement green design, promote the development and circulation of green products, and improve their own performance. Secondly, whether the manufacturers or retailers implement green design, they should pay attention to strengthening the cost effect of green design to effectively improve the efficiency of green design. In this way, the green design investment can achieve the effect of "higher of efficiency investment, lower growth of investment level and higher growth of overall income". Finally, the government as a market regulator, can reduce the cost of enterprises engaging in green design innovation through green subsidies, green credit and other policies. Moreover, they can implement effective supervision on fake green products through strict environmental laws and regulations to encourage or regulate enterprises to increase investment in improving green design environmental effect, so as to promote enterprises to realize the balanced development of economy and environment.

There are still some deficiencies and can be extended in future research. In this paper, in order to focus on the research issues, the sustainable supply chain system considered is relatively simple, and can be further studied in a more realistic competitive sustainable supply chain system in future. Furthermore, this paper does not consider the impact of external factors such as environmental regulations and government policies. Therefore, in the context of green economy, it is another direction worth studying to focus on the impact of different environmental regulations on green design decisions of sustainable supply chain. Finally, some model without uncertainty is adopted in our paper. Although this makes our analysis easier to handle and widely applied in similar studies [6, 10, 40]. However, uncertainty has always been an important practical issue in supply chain management [31–33]. Therefore, a future extension is to use other forms of models, including stochastic and probabilistic models, to explore how uncertainty affects the operation of sustainable supply chains.

Appendix A.

Proof of Proposition 5.1. Taking the relationship between w^{MM^*} and w^{MR^*} as an example, which can be obtained from the relevant equilibrium results in Table 2

$$w^{\mathrm{MM}^*} - w^{\mathrm{MR}^*} = \frac{(a-bc)\left(4kb^2cd(2\theta - bcd) + \theta^2\left(4kb - (bcd+\theta)^2\right)\right)}{2b\left(8kb - (bcd+\theta)^2\right)(4kb - \theta(bcd+\theta))}.$$

Let $f(d) = 4kb^2cd(2\theta - bcd) + \theta^2(4kb - (bcd+\theta)^2) = 0$, the only solution can be obtained is $d_1 = \frac{\theta(4kb-\theta^2+2\sqrt{2kb(4kb-\theta^2)})}{bc(4kb+\theta^2)}$. Therefore, $w^{\mathrm{MM}^*} \geq w^{\mathrm{MR}^*}$, when $0 < d \leq d_1$; $w^{\mathrm{MR}^*} > w^{\mathrm{MM}^*}$, when $d_1 < d < 1$. Other proof processes are similar, omitted here. □

Proof of Proposition 5.2. Since the process of proving Proposition 5.2 are similar to that of Proposition 5.1, it is omitted here. □

Proof of Proposition 5.3. Taking the relationship between $\pi_M^{\mathrm{MR}^*}$ and $\pi_M^{\mathrm{MM}^*}$ as an example, which can be obtained from the relevant equilibrium results in Table 2

$$\pi_M^{\mathrm{MR}^*} - \pi_M^{\mathrm{MM}^*} = \frac{k(a-bc)^2(bcd+\theta)(bcd-\theta)}{2(8kb-(bcd+\theta)^2)(4kb-\theta(bcd+\theta))}.$$

Let $f(d) = bcd - \theta = 0$, the only solution can be obtained is $d_7 = \frac{\theta}{bc}$. Therefore, $\pi_M^{\mathrm{MR}^*} \geq \pi_M^{\mathrm{MM}^*}$, when $0 < d \leq d_7$; $\pi_M^{\mathrm{MM}^*} > \pi_M^{\mathrm{MR}^*}$, when $d_7 < d < 1$. Other proof processes are similar, omitted here. □

Proof of Proposition 5.4. Taking the green design level under the three kinds of channel leadership as an example, it can be obtained from the relevant equilibrium results in Tables 2–4

$$g^{\mathrm{NM}^*} - g^{\mathrm{RM}^*} = \frac{(a-bc)(bcd+\theta)(2kb-(bcd+\theta)^2)}{2\left(4kb-(bcd+\theta)^2\right)\left(6kb-(bcd+\theta)^2\right)},$$

$$g^{\mathrm{RM}^*} - g^{\mathrm{MM}^*} = \frac{(a-bc)(bcd+\theta)^3}{2\left(4kb-(bcd+\theta)^2\right)\left(8kb-(bcd+\theta)^2\right)} > 0,$$

$$g^{\mathrm{NM}^*} - g^{\mathrm{MM}^*} = \frac{2kb(a-bc)(bcd+\theta)}{\left(6kb-(bcd+\theta)^2\right)\left(8kb-(bcd+\theta)^2\right)} > 0.$$

Let $F(d) = 2kb - (bcd+\theta)^2 = 0$, the only solution can be obtained is $d_{11} = \frac{\sqrt{2kb}-\theta}{bc}$. Therefore, $g^{\mathrm{NM}^*} \geq g^{\mathrm{RM}^*}$, when $0 < d \leq d_{11}$; $g^{\mathrm{RM}^*} > g^{\mathrm{NM}^*}$, when $d_{11} < d < 1$. Other proof processes are similar, omitted here. □

Proof of Proposition 5.5. Since the process of proving Proposition 5.5 are similar to that of Proposition 5.4, it is omitted here. □

Proof of Proposition 5.6. Taking the overall profits of the sustainable supply chain π_S under the three kinds of channel leadership as an example, it can be obtained from the relevant equilibrium results from Tables 2–4

$$\pi_S^{\mathrm{NM}^*} - \pi_S^{\mathrm{RM}^*} = \frac{k(a-bc)^2\left(2kb-(bcd+\theta)^2\right)\left(10kb-(bcd+\theta)^2\right)}{4\left(4kb-(bcd+\theta)^2\right)\left(6kb-(bcd+\theta)^2\right)^2},$$

$$\pi_S^{\mathrm{RM}^*} - \pi_S^{\mathrm{MM}^*} = \frac{k(a-bc)^2(bcd+\theta)^2\left(16kb-(bcd+\theta)^2\right)}{4\left(4kb-(bcd+\theta)^2\right)\left(8kb-(bcd+\theta)^2\right)^2} > 0,$$

$$\pi_S^{\mathrm{RE}^*} - \pi_S^{\mathrm{ME}^*} = \frac{4k^3b^2(a-bc)^2\left(20kb-3(bcd+\theta)^2\right)}{\left(6kb-(bcd+\theta)^2\right)^2\left(8kb-(bcd+\theta)^2\right)^2} > 0.$$

Let $F(d) = 2kb - (bcd+\theta)^2 = 0$, the only solution can be obtained is $d_{11} = \frac{\sqrt{2kb}-\theta}{bc}$. Therefore, $\pi_S^{\mathrm{NM}^*} \geq \pi_S^{\mathrm{RM}^*}$, when $0 < d \leq d_{11}$; $\pi_S^{\mathrm{RM}^*} > \pi_S^{\mathrm{NM}^*}$, when $d_{11} < d < 1$. Other proof processes are similar, omitted here. □

Proof of Proposition 5.7. Since the process of proving Proposition 5.7 are similar to that of Proposition 5.6, it is omitted here. □

Proof of Proposition 5.8. It can be obtained from the relevant equilibrium results in Tables 3 and 4

$$\begin{aligned}E^{\mathrm{RM}^*} - E^{\mathrm{RR}^*} &= \left(1-\lambda g^{\mathrm{RM}^*}\right)\varphi q^{\mathrm{RM}^*} - \left(1-\lambda g^{\mathrm{RR}^*}\right)\varphi q^{\mathrm{RR}^*} \\ &= \theta \frac{kb(a-bc)(bcd+\theta)^2\left(2\left(4kb-(bcd+\theta)^2\right)\left(8kb-(bcd+\theta)^2\right) - \lambda(a-bc)(bcd+\theta)\left(16kb-3(bcd+\theta)^2\right)\right)}{2\left(4kb-(bcd+\theta)^2\right)^2\left(8kb-(bcd+\theta)^2\right)^2},\end{aligned}$$

$$\begin{aligned}E^{\mathrm{NM}^*} - E^{\mathrm{NR}^*} &= \left(1-\lambda g^{\mathrm{NM}^*}\right)\varphi q^{\mathrm{NM}^*} - \left(1-\lambda g^{\mathrm{NR}^*}\right)\varphi q^{\mathrm{NR}^*} \\ &= \theta \frac{2kb^2cd(a-bc)\left((bcd+\theta)\left(6kb-(bcd+\theta)^2\right)(6kb-\theta(bcd+\theta)) - \lambda(a-bc)\left(36k^2b^2-\theta(bcd+\theta)^3\right)\right)}{\left(6kb-(bcd+\theta)^2\right)^2(6kb-\theta(bcd+\theta))^2}.\end{aligned}$$

Let $F_1(\lambda) = 2(4kb - (bcd+\theta)^2)(8kb - (bcd+\theta)^2) - \lambda(a-bc)(bcd+\theta)(16kb - 3(bcd+\theta)^2) = 0$, $F_2(\lambda) = (bcd+\theta)(6kb-(bcd+\theta)^2)(6kb-\theta(bcd+\theta)) - \lambda(a-bc)(36k^2b^2 - \theta(bcd+\theta)^3) = 0$, the only solution can be obtained is $\lambda_1 = \frac{2(4kb-(bcd+\theta)^2)(8kb-(bcd+\theta)^2)}{(a-bc)(bcd+\theta)(16kb-3(bcd+\theta)^2)}$, $\lambda_2 = \frac{(bcd+\theta)(6kb-(bcd+\theta)^2)(6kb-\theta(bcd+\theta))}{(a-bc)(36k^2b^2-\theta(bcd+\theta)^3)}$. Therefore, when $0 < \lambda \leq \lambda_1$, $E^{\mathrm{RM}^*} \geq E^{\mathrm{RR}^*}$, $\lambda_1 < \lambda < 1$, $E^{\mathrm{RR}^*} > E^{\mathrm{RM}^*}$. So, $E^{\mathrm{NM}^*} \geq E^{\mathrm{NR}^*}$, when $0 < \lambda \leq \lambda_2$; $E^{\mathrm{NR}^*} > E^{\mathrm{NM}^*}$, when $\lambda_2 < \lambda < 1$. □

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