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Research Article

Green Supply Chain Decision-Making considering Retailer's Fairness Concerns and Government Subsidy Policy

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Government's green subsidy and retailer's fairness concerns have great implications for enterprise's operation strategy in the green supply chain (GSC). With the continuous deepening of retailer's participation in supply chain management, the green services they provided by retailer have become a crucial role in promoting the terminal sales of green products. To further research the government subsidies and retailer's fairness concerns on the optimal decisions of product pricing, green R&D, and service level, we construct four two-stage GSC models: no subsidy and fairness concerns, subsidizes manufacturer without retailer's fairness concerns, subsidizes manufacturer with retailer's fairness concerns, and subsidizes all members with retailer's fairness concerns. The results show that subsidizes to manufacturers has significantly improved supply chain performance and environmental governance, but it exacerbates the unfair distribution of profits among members, and retailers' fairness concerns drive them to offer lower green service level. With the green demand of consumers being unable to be fully satisfied, the consumer surplus and effectiveness of government environmental governance decrease accordingly. To eliminate the adverse effect caused by unfair distribution of profits, it is necessary to subsidize retailers so as to share their green service costs and increase their share of profits.

1. Introduction

In recent decades, the rapid development of global economy has greatly improved the peoples' living standard, but mass production and consumption of products exacerbate the greenhouse gas emissions. According to a press release by the International Energy Agency (IEA) in Global Energy reviews 2021, global energy demand will grow by 4.6 percent in 2021, and global energy-related carbon dioxide emissions will increase by 4.8 percent, which will reach 33 billion tons. To reduce carbon emission from the consumption of oil, coal, and other mineral resources, some countries have formulated a series of environmental protection laws and strengthened international cooperation [1]. Back in November 2015, leaders from 20 countries announced an initiative in Paris aimed at dramatically accelerating global clean energy innovation, the initiative required participating countries commit to double their state-directed investment in clean energy within five years, and the consensus also spur government subsidies the development of clean energy technology. As a manufacturing powerhouse, China has been working hard to promote the green transformation of manufacturing industry and focus on the implementation of green manufacturing system construction. During the 13th Five-Year Plan period, China issued a serious of guidelines, including promulgates corresponding subsidy policies to encourage enterprises to participate in the practice of GSC. According to the Ministry of Ecology and Environment (http://www.scio.gov.cn/ztk/dtzt/44689/47315/index.html), China's carbon intensity in 2020 dropped 18.8 percent from 2015, exceeding the binding target for the 13th Five-Year Plan, while nonfossil energy accounted for 15.9 percent of China's energy consumption, both exceeding the 2020 target China had promised to the international community.

Recently in September 2020, China's top leader Xi Jinping announced China's initiative to scale up the nationally determined contributions to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060.

In addition to the guiding role of the government in promoting green manufacturing construction, the behavior of channel members and consumers' green preference also have a significant impact on the supply chain operation. Encouraged by the government's green subsidy policy, manufacturers have incentive to curb carbon emission and focus on promoting the environmental attributes of manufactured product. As the concept of green environmental protection and the healthy living is deeply rooted in the hearts of people, consumers are paying more and more attention to the environmental properties of products, such as the degradability of raw materials and the recyclability of products. The rapid economic development has also led to the improvement of residents' income level, and people are more likely to choose green products than traditional ones, even though the former are more expensive than the latter. Motived by shaping the green corporate image and expand the market size, manufacturers are more willing to produce environmentally friendly products; for example, as a leading enterprise of car industry, Toyota has introduced Corolla pure electric edition to expand the products category and satisfied the diversified needs of consumers.

As the main initiator of green innovation, manufacturers always make decisions in their own favor relying on technological advantages. Compared to traditional brown products, the performance of green products has not been fully realized by consumers, and the demand for green products is uncertain. Driven by green purchasing behavior in consumption, manufacturers need to choose between green product market expansion and green R&D costs increasing. As retailers directly face consumers, their service efforts are the main means to promote the sales of green products, such as environmental education and advertising investment [2]. As the leading institution to regulate the market, the government will provide subsidy or levying carbon tax in order to promote the improvement of environmental governance and social welfare [3, 4]; for example, to encourage consumers buy new energy vehicles, the Ministry of Finance of China issued a notice on financial support policies for the promotion and application of new energy vehicles from 2016 to 2020, providing subsidies to consumers who choose the new energy vehicles (http://jjs.mof.gov.cn/zhengcefagui/202004/t20200423_3502975.html). However, relevant government subsidies mainly focus on green manufacturing, and there are few studies on subsidies for green service. Actually, government subsidies only for manufacturer always cause retailer's unfair psychology and weaken the enthusiasm of retailer to participate in GSC management.

To research the implication of government subsidy and retailer's fairness concerns on GSC management, four dynamic game models have been established. The following problems are studied in this paper: (1) compared with the baseline scenario, what is the impact of government subsidies on product pricing, green R&D, and green service? (2) How government subsidies affect supply chain performance and environmental governance? (3) How the retailer's fairness concerns affect green R&D, green service levels, consumer surplus, and the effectiveness of government environmental governance? (4) Which subsidies strategy is the optimal choice in terms of economic and social benefits, and what changes have taken place from the perspective of enterprises, government, and consumers?

This article is arranged as follows. First, we review the previous research in Section 2. The problem presentation and assumptions are given in Section 3. In Section 4, by using game theory, we obtained equilibrium results for four models. The decision results under the four models are compared and the reasons for the results are analyzed in Section 5. Section 6 conducts numerical analysis to prove the previous conclusions. Section 7 summarizes this article and elaborates on future research.

2. Literature Review

The research of this article is primarily related to three steams of literature: (i) green R&D and green service, (ii) fairness concerns in supply chain, and (iii) government subsidy. A summary of the research gaps and the contribution of our work is given in the end of this section.

2.1. Green R&D and Green Service. Sustainable operation has become an important research field of business management and a major branch of operations research and management [5]. Most recent studies have shown that environmental sustainability should be introduced in the supply chain operational decisions [6, 7]. Ma et al. [2] researched the influence of different supply chain structure on product pricing and then further investigated the channel coordination, in which demand is influenced by quality improvement and service effort. Basiri and Heydari [8] investigate the green channel coordination issue with existing nongreen traditional product and green-type product. Bhattacharyya and Sana [9] consider the production inventory system model in green manufacturing industry, establish the object function of profit depends on service and the stochastic demand of green technology, and analyze the optimization decision of each variable. Yang et al. [10] research the cooperation and coordination in GSC with R&D uncertainty. Similar to their research, this paper also assumes that the market demand is a linear function, which is jointly influenced by product greenness and service effort and analyzes the price and service effort determination under the leadership of manufacturer. Taleizadeh et al. [11] study the optimal pricing and production strategy of a two-stage GSC, in which the demands combined are influenced by price, refund rate, and green quality and discuss the optimal decision variables under cooperative game and noncooperative game, finally constructing a cost sharing agreement to provide high quality products to purchasers. Ranjan and Jha [12] discuss the pricing strategy and coordination mechanism among members in dual-channel supply chain, in which the demand is a linear function of online/offline price, green quality level, and sales effort level. Similar to the researches of scholars above, we jointly discuss the optimal equilibrium results of manufacturer's green R&D and retailer's green service effort, and the impact on consumer surplus and environmental governance.

2.2. Fairness Concerns in Supply Chain. Numerous behavioral economics studies have point out that people always show great concerns about the fairness of income distribution in addition to pursuing the maximization interests [13], which is mainly caused by uneven profit allocations. To explore the impact of fairness concerns on the supply chain management, many scholars have conducted researches on the fairness concerns behavior, channel structure, contract design, etc. Zhou et al. [14] study the optimization of contract design of low-carbon supply chain channel and discuss the change of optimal decision and behavior when considering retailer's fairness concern behavior. Zhang et al. [15] discuss three decision-making scenarios, in which the manufacturer is the leader considered to explore the impact of consumer environmental awareness and retailer's fairness concerns on green product quality and product pricing. It is found that retailer's fairness concerns do not change the environmental quality of green products, and retailer's power and fairness concerns degree in the supply chain jointly determine whether the retailer can benefit from fairness concerns. Wang et al. [16] consider the common demand of product greenness and service level, the centralized model, the manufacturer's fairness concerns considered in the decentralized model, and the retailer's fairness concerns not considered in the decentralized model. Finally, the cost sharing joint commission contract is proposed to realize supply chain coordination. Jin et al. [17] discuss the influence of green optimism on GSC and find that green optimism is always bad for upstream manufacturers and may be good for downstream retailers. Zhang et al. [18] study how green retailers' fairness concerns affect greenness and profits of supply chain members and establish three coordination mechanisms to promote cooperation among supply chain members. Zhen et al. [19] research the influence of members' fairness concerns behavior on a retailer's dual-channel supply chain, and the results show that if the manufacturer has high fairness concerns level, the retailer should not pay attention to fairness. Sana [20] discusses the formulation of optimal price and green quality under two models, considering the influences of product substitution and corporate social responsibility, in order to realize the profit maximization of individual and integrated systems. Ma et al. [21] study the closed-loop supply chain with four reverse channel structures and analyze the optimal pricing decisions, marketing effort and collection rate under different structures, and then further discuss the influence mechanism of retailer's fairness concerns on marketing effort, recovery rate, and supply chain performance. Liu et al. [22] study the impact of retailer's fairness concerns on the three-party sustainable supply chain and reveal how retailer's fairness concerns affect the cooperation among supply chain members. Du and Zhao [23] investigate the comprehensive influence of fairness preference and channel preference on business strategy; if manufacturers take fairness preferences into account, they will lower wholesale prices to reduce retailers' losses, and as fairness preferences increase, manufacturers tend to establish online channels with low acceptance. Zhang et al. [24] introduce the vertical and horizontal fairness concerns of retailer and discuss the impact of retailer's fairness concerns on online channel strategy under direct selling and platform agency mode. The above studies show that fairness concerns have significant impact on the operation performance of supply chain management, and few studies have considered the impression of fairness concerns on green R&D and green service effort, and even on the consumer surplus and carbon emission. It is valuable to discuss the influence of members' fairness concerns on the operation of GSC.

2.3. Government Subsidy Policy. In the process of GSC management, besides paying attention to the influence of members' attitude to fairness and invest cost enhances on the optimal decision of supply chain, we could not ignore the important role of government acting as the regulator of economic operation and environmental governance, promoting the sustainable development of economy and society. Ma et al. [25] research the decision-making with the implementation of the government subsidy and analyze the impact of consumer subsidies from the perspectives of consumers. Li et al. [26] consider two-stage supply chain consists of a fairness neutral retailer and a fairness concerns retailer, and the results show that when the cost of carbon emission is high, the retailers pay great concerns for fairness. In addition, in the case of retailers paying more attention to fairness, the government should reduce the carbon tax to induce manufacturer in reducing carbon emission. Nielsen et al. [27] investigate the optimal green level, members' profit, consumer surplus, and environmental improvement under two green technology incentive policies and consider the impact of single and two-period purchasing decisions on the sustainability goal of supply chain. Sharma et al. [28] study the role of option contract in realizing channel coordination and discuss the fairness of channel members when retailers purchase products from suppliers by option contract. Hadi et al. [4] consider the government uses economic incentives and penalties to manage the environmental effects of companies, and the results showed that the government's environmental protection strategy has a significant impact on the revenue and profit. Sana [29] discusses the product pricing under corporate social responsibility and researches the newsboy inventory model from the perspective of green product marketing. By comparing the green marketing and nongreen marketing, and considering the government subsidy and tax, the object expectation function is established, and the equilibrium solutions are obtained. Han et al. [30] study the decision-making behavior of manufacturers in an e-commerce supply chain and consider government subsidy policy and fairness concerns. Su et al. [31] discuss the optimal decision-making under government subsidy coefficient, where government has different subsidy strategies. Zhang et al. [32] study the WEEE closed-loop supply chain, in which the manufacturer can authorize the retailer to remanufacture the used products. Khosroshahi et al. [33] study different government subsidy strategies in the GSC, establish an interaction model between the degree of green and the level of transparency set by the manufacturer, and simulate how the market responds to the manufacturer's social responsibility decision. Wang et al. [34] discuss the fairness problem of three closed-loop supply chain models, using the proportion of government subsidies as a coordinating variable to design a joint contract of "government subsidy sharing and cost sharing." Han et al. [35] discuss the influence of carbon tax cost and consumer preference on low-carbon and design revenue sharing contract, which can significantly reduce carbon emission and improve supply chain operational efficiency. Liu et al. [36] introduce the deposit-refund policy and minimum recycling for used products, so as to solve the problem that the disposal cost of recycling is not enough to cover the recycling subsidy already paid. Kang et al. [37] show that reasonable government subsidies can enhance the effectiveness of market resource allocation and improve the corporate social responsibility, while the fairness concerns of farmers and enterprises aggravate the double marginalization and reduce the efficiency of supply chain, and social responsibility cost sharing mechanism helps realize Pareto improvement. All the above papers emphasize the great impression of government policies in GSC management, but there are few studies on the impact of government subsidies on green R&D and green service effort, especially when the retailer is concerned about the fairness of profit distribution. This paper attempts to explore the impact of government subsidies mechanism on members' optimal decision-making.

Different from the previous research, this paper considers that manufacturers are engaged in green R&D and retailers provide services to the market to improve the sales of green products, and it discusses the impact of government subsidy and retailers' fairness concerns on the operation of GSC. In the context of government subsidizes to manufacturer, retailers need to invest in the cost of sales, how retailers' fairness concerns affect the consumer surplus and environmental governance and how the government should adjust its subsidy strategy to reduce the adverse impact of fairness concerns. More specifically, considering manufacturer's green R&D, retailer's green service effort and fairness concerns, consumers' green preferences, and government subsidy, we introduce four subsidizes strategies of government and formulate four models: nongovernment subsidy without retailer's fairness concerns, subsidizes manufacturer without retailer's fairness concerns, subsidizes manufacturer with retailer's fairness concerns, and subsidizes all members with retailer's fairness concerns.

The main innovations of this paper are given as follows: firstly, it explores the impact mechanism of retailer's fairness on green R&D and service effort. Secondly, we research the effects of government subsidy on members' profits and supply chain performance. Finally, we study the impact mechanism of carbon subsidy and retailer's fairness concerns on the impact of service effort, consumer surplus, and environmental governance.

3. Problem Description and Model Assumptions

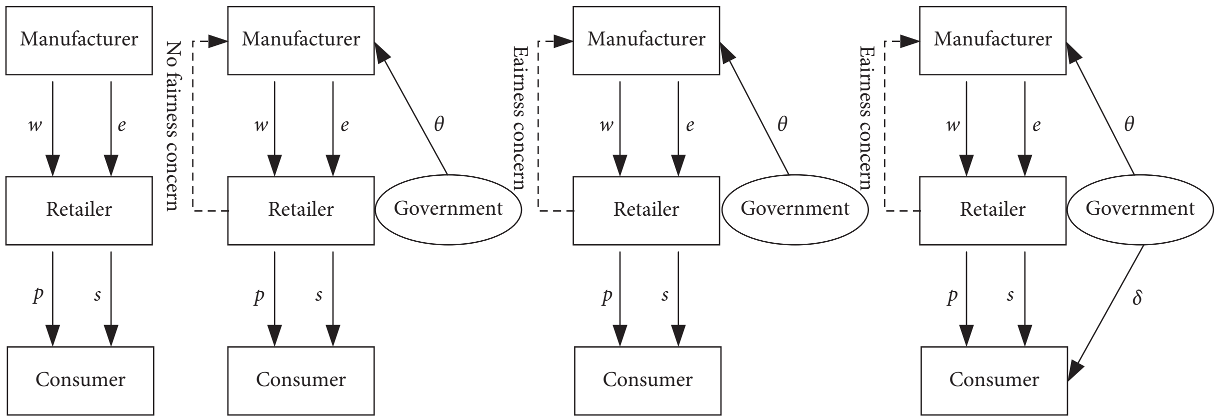
Consider that the supply chain consists of a manufacturer and a retailer, where the manufacturer invests the green R&D and produce green products, while the retailer sells green products to the market and providing service effort. Assume that the market demand is influenced by a combination of retail price, product greenness, and service effort.

The government plays an important role in promoting green manufacturing, and to improve the ecological environment, the government can reduce the risk of enterprises engaging in green manufacturing through green subsidy. Besides, to pursue utility maximization, channel member often shows great concerns to his share in the channel. As a key member, retailers play as important role due to their direct access to consumers. To research the operation of GSC consider government subsidy and retailer's fairness concerns, this paper establishes a two-stage GSC model dominated by manufacturer, and four GSC models are shown in Figure 1. Model NN is a benchmark model, model MN researches the situation with government subsidizes manufacturer without fairness concerns of retailer, model MY researches the situation of government subsidizes manufacturer and with retailer's fairness concerns, and model MRY researches the situation with government subsidizes both manufacturer and retailer with retailer's fairness concerns.

The symbols and meanings of this paper are given in Table 1.

Market demand is assumed to be $D = Q - \alpha p + \beta e + \gamma s$ [38–40]. The cost function of green R&D investment is assumed as $1/2 c_g e^2$ [41], and the cost function of service effort investment is assumed as $1/2 c_s s^2$ [42]. The unit cost of green product is c [43].

The consumer surplus is expressed as $\mathrm{CS} = \int_{Q-D+\beta e+\gamma s/\alpha}^{Q+\beta e+\gamma s/\alpha} \{Q - \alpha p + \beta e + \gamma s\} \mathrm{d}p = D^2/2\alpha$ [44, 45]. Assume that the total carbon emission reduction after green R&D investment is $e\ D$ [46]. Environmental improvement after green R&D investment is a linear expression of linear growth of carbon emission reduction $\mathrm{EI} = c_e e\ D$ [32, 39], without loss of generality, the value $c_e = 1$ [47]. Unlike the assumption of other scholars, we assume that the government distributes the governance cost saving from the reduction of carbon emission between manufacturer and retailer, and government carbon subsidy expenditure can be expressed as $\mathrm{GS} = (\theta + \delta) e\ D$, $0 < \theta < 1$, $0 < \delta < 1$, $0 < \theta + \delta < 1$.



(a) Model NN (b) Model MN (c) Model MY (d) Model MRY

Figure 1: Four models with government subsidy policy and retailer's fairness concerns. (a) Model NN. (b) Model MN. (c) Model MY. (d) Model MRY.

Table 1: Parameters and decision variables.

Notations	Definition
Q	Total market size
α	Coefficient of price elasticity of demand
β	Green prefers the elastic coefficient
γ	Elasticity coefficient of demand service
λ	Retailer's fairness concerns coefficient
c	Unit production cost of green product
c_g	Green R&D coefficient
c_s	Cost coefficient of service effort
c_e	Unit carbon emission
θ	Unit subsidy from the government to manufacturer
δ	Unit subsidy from the government to retailer
w	Wholesale price
p	Retail price
e	Greenness degree
s	Service effort
D	Market demand
$\prod_i^j$	Profit of supply chain member i in model j, $i \in \{m, r\}$ and $j \in \{NN, MN, MY, MRY\}$
$\prod_{sc}^j$	Whole supply chain profit of model j, $j \in \{NN, MN, MY, MRY\}$
CS^j	Consumer surplus of mode j, $j \in \{NN, MN, MY, MRY\}$
EI^j	Environmental improvement of mode j, $j \in \{NN, MN, MY, MRY\}$
GS^j	Government subsidy of mode j, $j \in \{NN, MN, MY, MRY\}$
SW^j	Social welfare in model j, $j \in \{NN, MN, MY, MRY\}$

Social welfare consists of the profits of supply chain members, consumer surplus and environmental improvement, and minus government subsidies and can be expressed as $\mathrm{SW} = \prod_m + \prod_r + \mathrm{CS} + \mathrm{EI} - \mathrm{GS}$ [39, 46, 48, 49].

4. Equilibrium Analysis

In this section, we use reverse solution method to analyze the optimal decision in two-stage GSC composed of a manufacturer and a retailer and explore the government subsidy and retailer's fairness on the operation of GSC. Furthermore, we compare the whole supply chain profit, consumer surplus, environmental improvement, and social welfare in different models. To simplify formulas, we denote $\phi_1 = Q - \alpha c$, $\phi_2 = -\gamma^2 + 2\alpha c_s$, $\phi_3 = \beta + \alpha\theta$.

4.1. Model NN: Nongovernment Subsidy without Retailer's Fairness Concerns. In order to facilitate comparison with the optimal decision results of other models, we first establish a benchmark model, that is, considering the case of nongovernment subsidy without retailer's fairness concerns. In this case, a manufacturer and a retailer play a two-stage Stackelberg game aiming at maximizing their respective profit. In the first stage, the manufacturer determines the wholesale price and greenness of their products; in the second stage, the retailer determines the retail price and green service level. At this point, the objective functions of the manufacturer and the retailer are as follows:

$$\max_{w^{NN},e^{NN}} \prod_m^{NN} = \left(w^{NN} - c\right)\left(Q - \alpha p^{NN} + \beta e^{NN} + \gamma s^{NN}\right) - \frac{1}{2}c_g e^{NN2}$$
$$\text{s.t.} \max_{p^{NN},s^{NN}} \prod_r^{NN} = \left(p^{NN} - w^{NN}\right)\left(Q - \alpha p^{NN} + \beta e^{NN} + \gamma s^{NN}\right) - \frac{1}{2}c_s s^{NN2}. \tag{1}$$

Proposition 1. *If $0 < \beta < \sqrt{2c_g\phi_2/c_s}$, the optimal decision variables of model NN have the following values: $w^{NN*} = c + c_g\phi_2\phi_1/\alpha(2c_g\phi_2 - c_s\beta^2)$, $e^{NN*} = \beta c_s\phi_1/2c_g\phi_2 - c_s\beta^2$, $p^{NN*} = c + c_g(3\alpha c_s - \gamma^2)\phi_1/\alpha(2c_g\phi_2 - c_s\beta^2)$, $s^{NN*} = \gamma c_g\phi_1/2c_g\phi_2 - c_s\beta^2$, and $D^{NN*} = \alpha c_g c_s\phi_1/2c_g\phi_2 - c_s\beta^2$.*

The proof can be found in Appendix 1.

Substituting the optimal values of decision variables in Proposition 1 into formula (1), we can obtain the optimal values of members' profit: $\prod_m^{NN*} = c_g c_s\phi_1^2/2(2c_g\phi_2 - c_s\beta^2)$, $\prod_r^{NN*} = c_g^2 c_s\phi_1^2\phi_2/2(2c_g\phi_2 - c_s\beta^2)^2$.

Furthermore, the optimal supply chain profit, consumer surplus, environment improvement, and social welfare are shown as follows:

$$\prod_{sc}^{NN*} = \frac{c_g c_s\phi_1^2\left(3c_g\phi_2 - c_s\beta^2\right)}{2\left(2c_g\phi_2 - c_s\beta^2\right)^2},$$
$$\text{CS}^{NN*} = \frac{\alpha c_g^2 c_s^2\phi_1^2}{2\left(2c_g\phi_2 - c_s\beta^2\right)^2},$$
$$\text{EI}^{NN*} = \frac{\beta c_s^2\phi_1^2\alpha c_g}{\left(2c_g\phi_2 - c_s\beta^2\right)^2} \text{ and } \text{SW}^{NN*} = \frac{c_g c_s\phi_1^2\left(3c_g\phi_2 - c_s\beta^2\right) + \alpha c_g c_s^2\phi_1^2\left(2\beta + c_g\right)}{2\left(2c_g\phi_2 - c_s\beta^2\right)^2}. \tag{2}$$

4.2. Model MN: Subsidizes Manufacturer without Retailer's Fairness Concerns. To investigate the impacts of government subsidizes manufacturer on the operation of GSC, we suppose that the unit subsidy for green R&D is a fixed constant and analyze the variation of product pricing, greenness, and green service level with unit subsidy θ. At this point, the object functions of the manufacturer and the retailer are as follows:

$$\max_{w^{MN},e^{MN}} \prod_m^{MN} = \left(w^{MN} - c + \theta e^{MN}\right)\left(Q - \alpha p^{MN} + \beta e^{MN} + \gamma s^{MN}\right) - \frac{1}{2}c_g e^{MN2}$$
$$\text{s.t.} \max_{p^{MN},s^{MN}} \prod_r^{MN} = \left(p^{MN} - w^{MN}\right)\left(Q - \alpha p^{MN} + \beta e^{MN} + \gamma s^{MN}\right) - \frac{1}{2}c_s s^{MN2}. \tag{3}$$

Proposition 2. *If $0 < \phi_3 < \sqrt{2c_g\phi_2/c_s}$, the optimal decision variables of model MN have the following values: $w^{MN*} = c + (\phi_2 c_g - \alpha c_s\theta\phi_3)\phi_1/\alpha(2\phi_2 c_g - c_s\phi_3^2)$, $e^{MN*} = c_s\phi_1\phi_3/2\phi_2 c_g - c_s\phi_3^2$, $p^{MN*} = c + (c_g(\phi_2 + \alpha c_s) - \alpha c_s\theta\phi_3)\phi_1/\alpha(2\phi_2 c_g - c_s\phi_3^2)$, $s^{MN*} = c_g\gamma\phi_1/2\phi_2 c_g - c_s\phi_3^2$, and $D^{MN*} = \alpha c_g c_s\phi_1/2\phi_2 c_g - c_s\phi_3^2$.*

The proof can be found in Appendix 2.

Substituting the optimal values of decision variables in Proposition 2 into formula (3), we can obtain the optimal values of members' profit: $\prod_m^{MN*} = c_g c_s\phi_1^2/2(2\phi_2 c_g - c_s\phi_3^2)$, $\prod_r^{MN*} = c_g^2 c_s\phi_1^2\phi_2/2(2\phi_2 c_g - c_s\phi_3^2)^2$.

Furthermore, the optimal supply chain profit, consumer surplus, environment improvement, and social welfare are shown as follows:

$$\prod_{sc}^{MN*}=\frac{c_g c_s \phi_1^2\left(3\phi_2 c_g-c_s\phi_3^2\right)}{2\left(2\phi_2 c_g-c_s\phi_3^2\right)^2},$$
$$\mathrm{CS}^{MN*}=\frac{\alpha c_g^2 c_s^2 \phi_1^2}{2\left(2\phi_2 c_g-c_s\phi_3^2\right)^2},$$
$$\mathrm{EI}^{MN*}=\frac{\alpha c_g c_s^2 \phi_1^2 \phi_3}{\left(2\phi_2 c_g-c_s\phi_3^2\right)^2}, \tag{4}$$
$$\mathrm{GS}^{MN*}=\frac{\theta\alpha c_g c_s^2 \phi_1^2 \phi_3}{\left(2\phi_2 c_g-c_s\phi_3^2\right)^2}\ \text{and}\ \mathrm{SW}^{MN*}=\frac{c_g c_s \phi_1^2\left(3\phi_2 c_g-c_s\phi_3^2\right)+\alpha c_g^2 c_s^2\phi_1^2+2\alpha c_g c_s^2\phi_1^2\phi_3}{2\left(2\phi_2 c_g-c_s\phi_3^2\right)^2}.$$

4.3. Model MY: Subsidizes Manufacturer with Retailer's Fairness Concerns. Different form Section 4.2, this section considers that the case with retailer is concerned about the fairness of the distribution of channel profit. In this case, a manufacturer and a retailer play a Stackelberg game, where the manufacturer pursues the profit maximization, and the retailer pursues the utility maximization. At this point, the objective functions of the manufacturer and the retailer are as follows:

$$\max_{w^{MY},e^{MY}}\prod_{m}^{MY}=\left(w^{MY}-c+\theta e^{MY}\right)\left(Q-\alpha p^{MY}+\beta e^{MY}+\gamma s^{MY}\right)-\frac{1}{2}c_g e^{MY2}$$
$$\text{s.t.}\ \max_{p^{MY},s^{MY}} U_r^{MY}=\prod_{r}^{MY}-\lambda\left(\prod_{m}^{MY}-\prod_{r}^{MY}\right) \tag{5}$$
$$\text{where, }\prod_{r}^{MY}=\left(p^{MY}-w^{MY}\right)\left(Q-\alpha p^{MY}+\beta e^{MY}+\gamma s^{MY}\right)-\frac{1}{2}c_s s^{MY2}.$$

Proposition 3. *If* $0<\phi_3<\sqrt{2(2\lambda+1)\phi_2 c_g/c_s(\lambda+1)}$, *the optimal decision variables of model MY have the following values:* $w^{MY*}=c+(\lambda+1)(\phi_2 c_g-\alpha c_s\theta\phi_3)\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$, $e^{MY*}=(\lambda+1)c_s\phi_1\phi_3/2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1)$, $p^{MY*}=c+((2\lambda+1)c_g(\phi_2+\alpha c_s)-\alpha c_s\theta(\lambda+1)\phi_3)\,\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$, $s^{MY*}=c_g\gamma(2\lambda+1)\phi_1/2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1)$, *and* $D^{MY*}=\alpha c_g c_s(2\lambda+1)\phi_1/2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1)$.

The proof can be found in Appendix 3.

Substituting the optimal values of decision variables in Proposition 3 into formula (5), we can obtain the optimal values of members' profit and retailer's utility: $\prod_m^{MY*}=c_g c_s\phi_1^2(\lambda+1)/2(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$, $\prod_r^{MY*}=c_g^2 c_s(2\lambda+1)(4\lambda+1)\phi_1^2\phi_2/2(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))^2$, and $U_r^{MY*}=\pi_r^{MY*}-\lambda(\pi_m^{MY*}-\pi_r^{MY*})$.

Furthermore, the optimal supply chain profit, consumer surplus, environment improvement, and social welfare are shown as follows:

$$\prod_{sc}^{MY*} = \frac{c_g c_s \phi_1^2 \left(3(2\lambda+1)^2 \phi_2 c_g - c_s(\lambda+1)^2 \phi_3^2\right)}{2\left(2(2\lambda+1)\phi_2 c_g - c_s \phi_3^2 (\lambda+1)\right)^2},$$

$$\mathrm{CS}^{MY*} = \frac{\alpha c_g^2 c_s^2 (2\lambda+1)^2 \phi_1^2}{2\left(2(2\lambda+1)\phi_2 c_g - c_s \phi_3^2 (\lambda+1)\right)^2},$$

$$\mathrm{EI}^{MY*} = \frac{\alpha c_g c_s^2 (2\lambda+1)(\lambda+1)\phi_1^2 \phi_3}{2\left(2(2\lambda+1)\phi_2 c_g - c_s \phi_3^2 (\lambda+1)\right)^2}, \tag{6}$$

$$\mathrm{GS}^{MY*} = \frac{\theta \alpha c_g c_s^2 (2\lambda+1)(\lambda+1)\phi_1^2 \phi_3}{2\left(2(2\lambda+1)\phi_2 c_g - c_s \phi_3^2 (\lambda+1)\right)^2},$$

$$\mathrm{SW}^{MY*} = \frac{c_g c_s \phi_1^2 \left(3(2\lambda+1)^2 \phi_2 c_g - c_s(\lambda+1)^2 \phi_3^2\right) + \alpha c_g^2 c_s^2 (2\lambda+1)^2 \phi_1^2 + 2\alpha c_g c_s^2 (2\lambda+1)(\lambda+1)\phi_1^2 \phi_3}{2\left(2(2\lambda+1)\phi_2 c_g - c_s \phi_3^2 (\lambda+1)\right)^2}.$$

4.4. Model MRY: Subsidizes All Members with Retailer's Fairness Concerns. One step further from Section 4.3, this section considers the case with government subsidies both manufacturer and retailer and explores the effect of government subsidizes retailer on alleviating the negative impact of retailer's fairness concerns. At this point, the objective functions of the manufacturer and the retailer are as follows:

$$\max_{w^{MRY}, e^{MRY}} \prod_m^{MRY} = \left(w^{MRY} - c + \theta e^{MRY}\right)\left(Q - \alpha p^{MRY} + \beta e^{MRY} + \gamma s^{MRY}\right) - \frac{1}{2} c_g e^{MRY2}$$

$$\text{s.t.} \max_{p^{MRY}, s^{MRY}} U_r^{MRY} = \prod_r^{MRY} - \lambda \left(\prod_m^{MRY} - \prod_r^{MRY}\right) \tag{7}$$

$$\text{where, } \prod_r^{MRY} = \left(p^{MRY} - w^{MRY} + \delta e^{MRY}\right)\left(Q - \alpha p^{MRY} + \beta e^{MRY} + \gamma s^{MRY}\right) - \frac{1}{2} c_s s^{MRY2}.$$

Proposition 4. *If* $0 < \phi_3 < \sqrt{2(2\lambda+1)\phi_2 c_g / c_s(\lambda+1)} - \alpha\delta$, *the optimal decision variables of model MRY have the following values:* $w^{MRY*} = c + (\lambda+1)(\phi_2 c_g - \alpha c_s \theta(\phi_3 + \alpha\delta))\phi_1 / \alpha(2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1))$, $e^{MRY*} = (\lambda+1)c_s(\phi_3+\alpha\delta)\phi_1 / 2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1)$, $p^{MRY*} = c + ((2\lambda+1)(3\alpha c_s - \gamma^2)c_g - \alpha c_s(\lambda+1)(\delta+\theta)(\phi_3+\alpha\delta))\phi_1 / \alpha(2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1))$, $s^{MRY*} = c_g \gamma(2\lambda+1)\phi_1 / 2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1)$, *and* $D^{MRY*} = \alpha c_g c_s(2\lambda+1)\phi_1 / 2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1)$.

The proof can be found in Appendix 4.

Substituting the optimal values of decision variables in Proposition 4 into formula (7), we can further obtain the optimal values of members' profit and retailer's utility: $\prod_m^{MRY*} = c_g c_s \phi_1^2 (\lambda+1)/2(2(2\lambda+1)\phi_2 c_g - c_s(\phi_3 + \alpha\delta)^2(\lambda+1))$, $\prod_r^{MRY*} = c_g^2 c_s (2\lambda+1)(4\lambda+1)\phi_1^2 \phi_2 / 2(2(2\lambda+1)\phi_2 c_g - c_s(\phi_3+\alpha\delta)^2(\lambda+1))^2$, and $U_r^{MRY*} = \pi_r^{MRY*} - \lambda(\pi_m^{MRY*} - \pi_r^{MRY*})$.

Furthermore, the optimal supply chain profit, consumer surplus, environment improvement, and social welfare are shown as follows:

$$\Pi_{sc}^{MRY*} = \frac{c_g c_s \phi_1^2 \left(3(2\lambda+1)^2 \phi_2 c_g - c_s (\lambda+1)^2 (\phi_3+\alpha\delta)^2\right)}{2\left(2(2\lambda+1)\phi_2 c_g - c_s (\phi_3+\alpha\delta)^2 (\lambda+1)\right)^2},$$

$$CS^{MRY*} = \frac{\alpha c_g^2 c_s^2 (2\lambda+1)^2 \phi_1^2}{2\left(2(2\lambda+1)\phi_2 c_g - c_s (\phi_3+\alpha\delta)^2 (\lambda+1)\right)^2},$$

$$EI^{MRY*} = \frac{(\lambda+1)\alpha c_g c_s^2 (2\lambda+1)\phi_1^2 (\phi_3+\alpha\delta)}{2\left(2(2\lambda+1)\phi_2 c_g - c_s (\phi_3+\alpha\delta)^2 (\lambda+1)\right)^2},$$

$$GS^{MRY*} = \frac{(\theta+\delta)(\lambda+1)\alpha c_g c_s^2 (2\lambda+1)\phi_1^2 (\phi_3+\alpha\delta)}{2\left(2(2\lambda+1)\phi_2 c_g - c_s (\phi_3+\alpha\delta)^2 (\lambda+1)\right)^2},$$

$$SW^{MRY*} = \frac{c_g c_s \phi_1^2 \left(3(2\lambda+1)^2 \phi_2 c_g - c_s (\lambda+1)^2 (\phi_3+\alpha\delta)^2\right) + \alpha c_g c_s^2 \phi_1^2 (2\lambda+1)\left((2\lambda+1)c_g + 2(\lambda+1)(1-\delta-\theta)(\phi_3+\alpha\delta)\right)}{2\left(2(2\lambda+1)\phi_2 c_g - c_s (\phi_3+\alpha\delta)^2 (\lambda+1)\right)^2}. \tag{8}$$

5. Comparative Analysis of Equilibrium Results

To analyze the effect of government subsidy policy and retailer's fairness concerns on operation of different GSC model, this part compares the optimal decision variables and objective functions. In order to make the comparison result more intuitive and better understand the change of variables with each parameter, we do simulation analysis in Section 6.

Proposition 5

(1) $e^{NN*} < e^{MN*}$, $e^{MY*} < e^{MN*}$, *and* $e^{MY*} < e^{MRY*}$;
(2) $s^{NN*} < s^{MN*}$, $s^{MY*} < s^{MN*}$, *and* $s^{MY*} < s^{MRY*}$.
(3) $D^{NN*} < D^{MN*}$, $D^{MY*} < D^{MN*}$, *and* $D^{MY*} < D^{MRY*}$.

The proof can be found in Appendix 5.

Proposition 5 (1) shows that government subsidy policy can effectively promote manufacturer to engage in green R&D, while the retailer's fairness concern behavior will reduce the positive effect of government green subsidy. As the government subsidies only for manufacturer witness the important role of retailer in promotion sales of green products and create an unfair mentality for retailer, to improve the retailer's fairness in the profit distribution, the retailer will raise the retail price of green products, so as to increase the retailer's expected utility. The higher price reduces the demand for green products and discourage the enthusiasm of manufacturer for green R&D. The government subsidizes both manufacturer and retailer according to the greenness of products can effectively alleviate the retailer's unfair psychology and decrease the retail price, and with the expansion of the market scale of green products, the manufacturer is willing to invest more in green manufacturing.

Proposition 5 (2)-(3) shows that the government subsidy policy also has a positive impact on encouraging retailer to engage in green service. Compared to the situation of government subsidizes manufacturer without retailer's fairness concerns, government subsidizes manufacturer causes the retailer to pay attention to the fairness of profit distribution. To eliminate the adverse effects of the uncertainty demand for green products and the increase of service cost, so as to improve the fairness of profit distribution, the retailer tends to reduce the green service level, thus reducing the market demand for green products, which has discouraged manufacturer's enthusiasm for green R&D. Under the premise of government subsidizes manufacturer and retailer concerns about the fairness, it is essential to provide a certain subsidy to retailer according the greenness of products, so as to enhance the fairness of profit distribution of supply chain.

Proposition 6

(1) $\Pi_m^{NN*} < \Pi_m^{MN*}$, $\Pi_m^{MY*} < \Pi_m^{MN*}$, *and* $\Pi_m^{MY*} < \Pi_m^{MRY*}$;
(2) $\Pi_r^{NN*} < \Pi_r^{MN*}$, $\Pi_r^{MY*} < \Pi_r^{MRY*}$;
(3) $\Pi_{sc}^{NN*} < \Pi_{sc}^{MN*}$, $\Pi_{sc}^{MY*} < \Pi_{sc}^{MN*}$, *and* $\Pi_{sc}^{MY*} < \Pi_{sc}^{MRY*}$.

The proof can be found in Appendix 6.

Proposition 6 (1)-(2) shows that, with incentives from government's green subsidy, the manufacturer has increased the resistance to the risk of the uncertainty of green market demand and huge green R&D and better satisfies the consumers' green preference, who are willing to pay higher prices for green products. However, the fairness concerns of retailer intensify the competition among channel members, and in order to improve the fairness of profit distribution, the retailer tends to raise the retail price and reduce the green service effort. As a result, consumers are unable to fully understand the performance of green products and need to pay higher price for green products, thus decreasing the green market size and manufacturer's profit. To relieve the competitive pressure among channel members, the government could subsidy retailer for their contribution for product promotion, as long as the government subsidies to

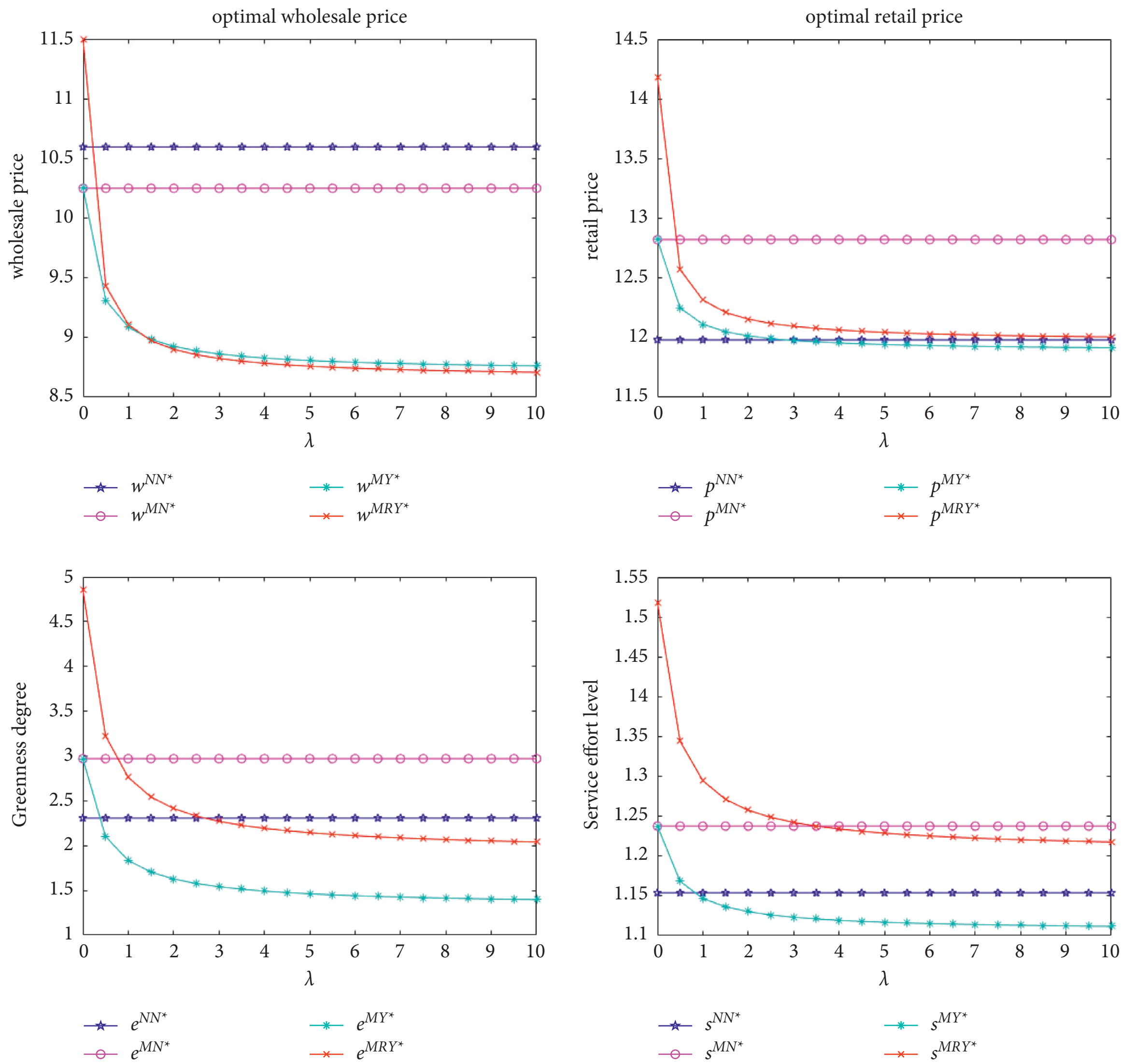


Figure 2: The impact of retailer's fairness concerns on pricing, greenness degree, and service effort.

manufacturer and retailer do not outweigh the saving in governance costs resulting from environmental improvements. Benefiting from government subsidies to manufacturer for green R&D, the retailer can order green products from manufacturer at lower wholesale price, and the product promotion strategy is more effective. The government subsidizes retailers according to the greenness of products, which increases the retailer's exposure to the uncertain market demand and huge green service costs, alleviates the competition among channel members and brings higher profit of retailer.

Proposition 6 (3) shows that, from the perspective of whole supply chain, the relationship of supply chain profit in different models is consistent with the relationship of manufacturer's profit. Due to the dominant position of manufacturer in GSC management, the manufacturer can even set up internal contracts to promote fairness in profit distribution.

Proposition 7

(1) $CS^{NN*} < CS^{MN*}$, $CS^{MY*} < CS^{MN*}$, $CS^{MY*} < CS^{MRY*}$;
(2) $EI^{NN*} < EI^{MN*}$, $EI^{MY*} < EI^{MN*}$, $EI^{MY*} < EI^{MRY*}$;
(3) $GS^{MY*} < GS^{MN*}$, $GS^{MY*} < GS^{MRY*}$;
(4) $SW^{NN*} < SW^{MN*}$, $SW^{MY*} < SW^{MN*}$, $SW^{MY*} < SW^{MRY*}$.

The proof can be found in Appendix 7.

Proposition 7 (1) show that, due to the positive effect of government's green subsidy policy, manufacturer and retailer

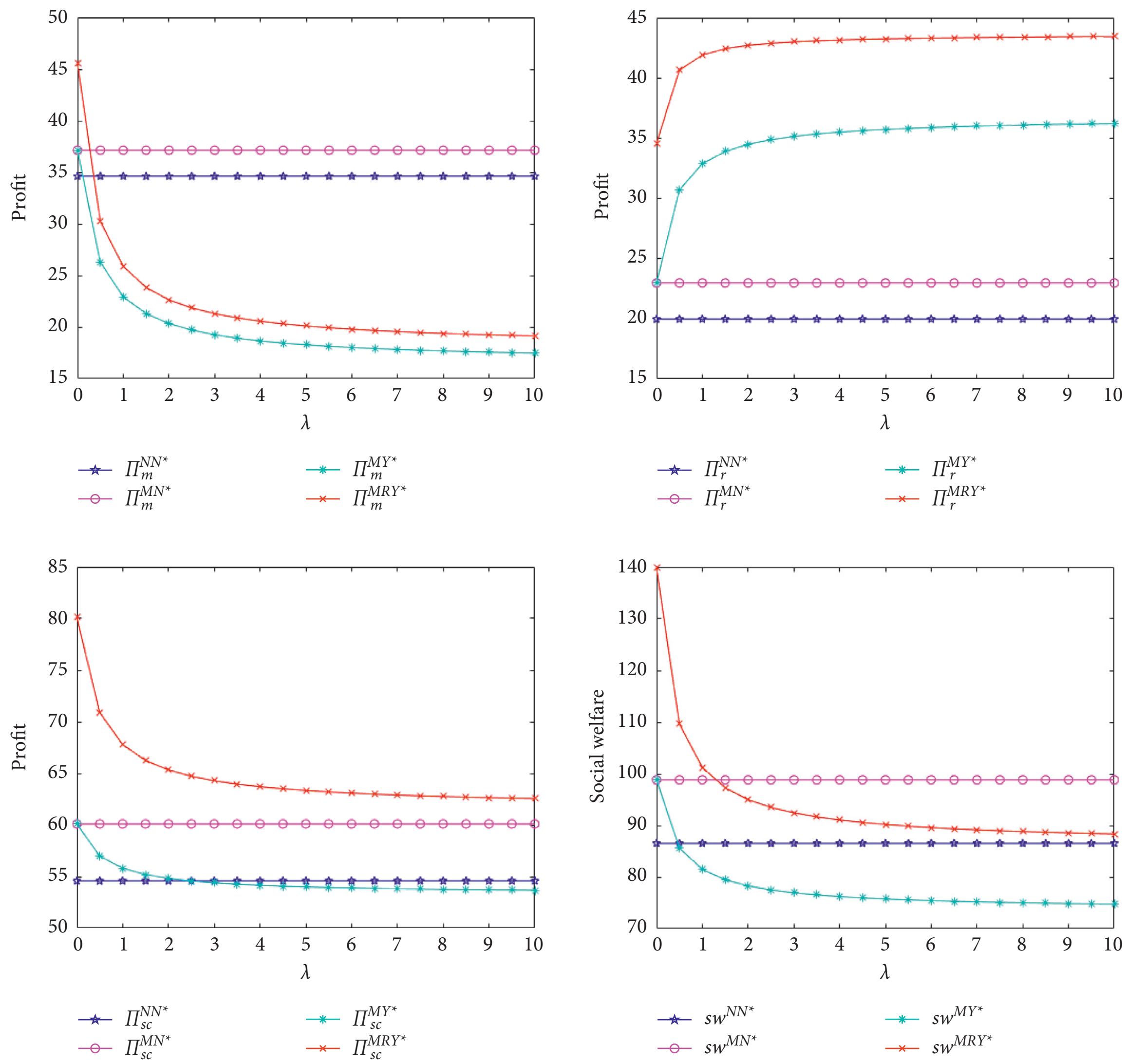


FIGURE 3: The impact of retailer's fairness concerns on members' profit and social welfare.

have improved the green quality of products, and consumers' green preferences for green products are satisfied with green products at a lower price. Retailer's fairness concerns have led to higher price for green products, the consumers' green preferences cannot be fully satisfied, and the consumer surplus has fallen. Proposition 7 (2)-(4) shows that the fairness concerns of retailer aggravate the competition between upstream and downstream members, with the conflict intensifying, which reduces the effect of government subsidy policy. Through government subsidy, the conflict between the manufacturer and retailer is alleviated, and the fairness of profit distribution is promoted. The level of consumer surplus, environmental improvement, and social welfare is higher than that of only subsidizes to manufacturer. When the retailer has no fairness concerns, the government expenditure is higher than that when retailer has fairness concerns. When the retailer has fairness concerns, the government expenditure when the government subsidizes both manufacturer and retailer is higher than that when only manufacturers are subsidized. With the situation manufacturer in different carbon subsidy situations having different levels of green R&D, corresponding government subsidy strategies should be adjusted accordingly, provided, of course, that the total cost of government subsidies should not exceed environmental improvements.

6. Numerical Analysis

In this section, we perform numerical analysis examples to illustrate the value of two subsidy strategies and the influence of retailer's fairness concern coefficient on GSC performance, and the numerical analysis can further verify the previous research conclusions and analysis reasons and bring more management insights for enterprise managers. According to the previous constraints, we set the parameters value and range as $Q = 50$, $\alpha = 4$, $c = 5$, $\delta = 0.2$, $c_s = 2$, $c_g = 2$, $\beta = 2$, $\gamma = 1$, $\lambda = 0$: 0.5: 10 and $\theta = 0$: 0.05: 0.8.

6.1. The Variation of Equilibrium Results with the Coefficient of Fairness Concerns λ. Figure 2 shows that, with the retailer's

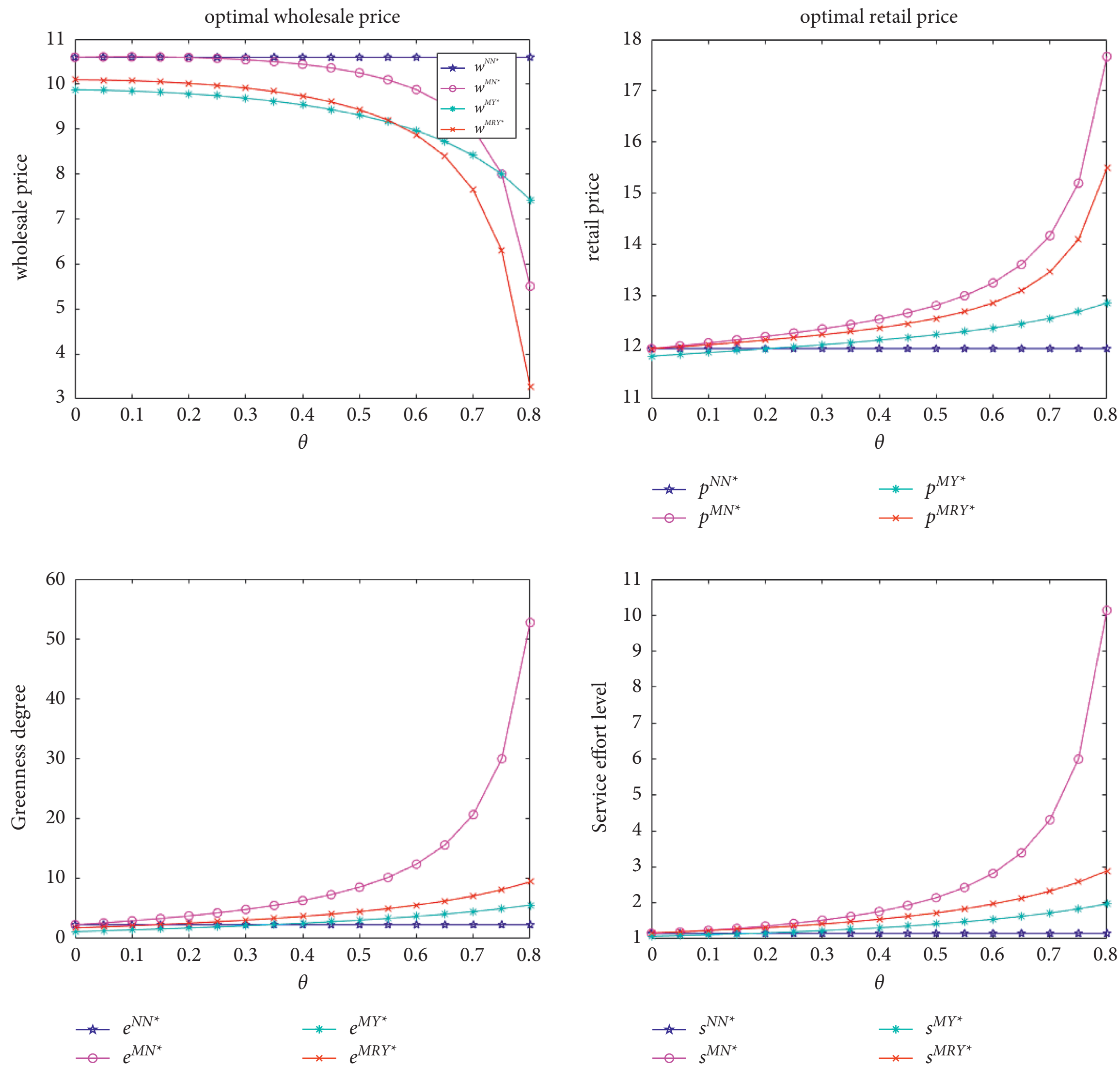


Figure 4: Unit government subsidy impact on greenness degree and service effort.

fairness concerns raising, the wholesale price, retail price, product greenness, and service effort are all decreasing. It means that manufacturer and retailer will lower product pricing due to the enhancement of retailer's concerns about fairness, but the marginal profit of manufacturer will decrease, which leads to the reduction of green invest and then decrease in the greenness of products. To promote the fairness of profit distribution, the retailer will reduce the level of green service.

Figure 3 shows that the manufacturer's profit, supply chain's profit, and social welfare are the subtraction functions of retailer's fairness concerns coefficient, while retailer's profit is the increment function of fairness concerns. There is a trade-off between manufacturer's profit and retailer's profit, and government subsidies both manufacturer and retailer benefit retailer and the supply chain to obtain the highest profit. When the retailer's fairness concerns fall below a certain threshold, the manufacturer's profit and the total social welfare are the highest among the four models under government subsidizes both manufacturer and retailer; at this point, the positive effect of government subsidies outweighs the negative effect of retailer's fairness concerns, and it is beneficial to supply chain members, environmental governance, and social benefits.

6.2. *The Variation of Equilibrium Results with the Unit Government Subsidy θ.*

It can be seen from Figures 4 and 5 that greenness degree, service effort, members' profit, and social welfare are the increasing functions of government subsidy. With the increase of government subsidy, the increasing trend of greenness degree, retailer service effort, members' profit, and social welfare is gradually increasing, which indicates that government subsidies stimulate the

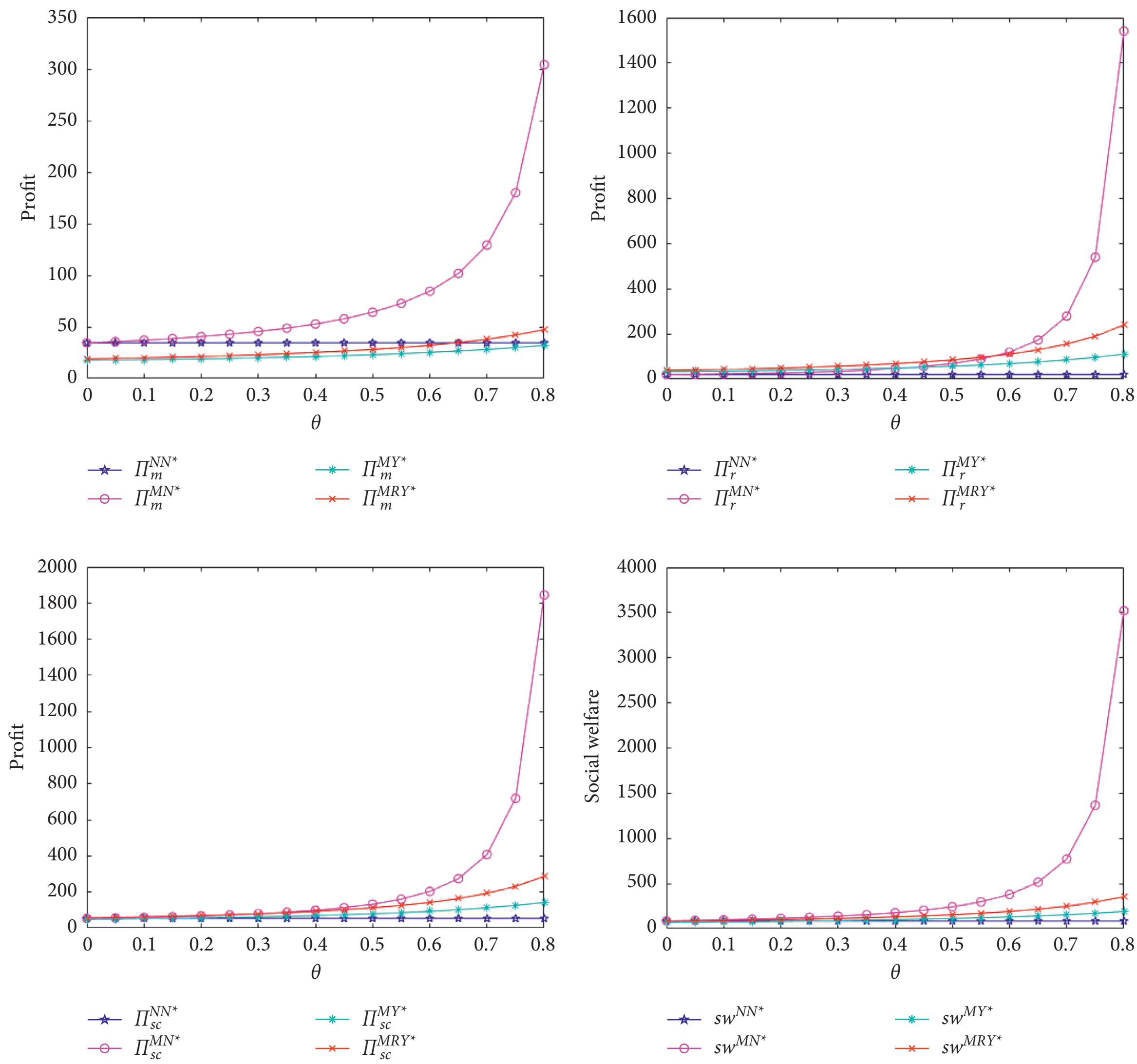


Figure 5: Unit government subsidy impact on members' profit and social welfare.

enthusiasm of supply chain members to participate in green production. Green production not only meets the green preference of consumers, but also alleviates the contradiction of unfair profit distribution among channel members and further reduces the social production cost.

7. Managerial Insights

In the era of rapid update of information and technology, the income level and living standard of residents have been greatly improved and bring great burden on the environment. To realize the harmonious development of person and nature, we must carefully handle the relationship between economic activities and environment government. The reduction of carbon emission from economic activities is inseparable from the participation of enterprises management, consumers engagement, and the government macrocontrol.

To comprehensively describe the tripartite game behavior, we consider that the consumer demand is influenced by both product greenness and service effort, by introducing government subsidies and retailer's fairness concerns, to explore the interaction between government policy and retailer's behavior on the implement of green manufacturing and reducing carbon emission.

Most studies have emphasized the important role of manufacturers in green technology investment and retailers in green promotion and discuss the pricing and decision-making behavior by using game theory, so as to provide experience for GSC management; however, fewer studies focus on the retailer's fairness caused by government subsidies. Actually, retailers play an increasingly important role in supply chain operations due to their green product education and promotion. Green manufacturing enterprises implement green R&D conducive to reducing carbon emission and reducing the cost of environmental governance. How to distribute the environmental benefits reasonably among manufacturers, retailer, and consumers will become extremely meaningful. This paper considers government subsidies to retailers based on greenness and sales volume, and it is beneficial to eliminate the negative effects of retailer's fairness concerns and increase the social welfare.

8. Conclusions

Based on the GSC composed of M and R, from the perspective of greenness and service effort, this paper considers nongovernment subsidies, manufacturer subsidies to retailers, government subsidies to retailers, and government subsidies to both manufacturers and retailers. In the GSC, M is engaged in green R&D and production of green products and wholesales green products to R. R will sell green products to consumers and provide them with green efforts. This paper analyzes the impact of government subsidies and retailers' fairness concerns on consumers, environment, and society. The results show that (1) government subsidies to manufacturers can improve the overall profits of channel members' supply chain and enhance the level of consumer surplus and environmental improvement; (2) government subsidies to retailers are not conducive to the fairness of profit distribution in the supply chain. Retailers' fairness concerns reduce the role of government subsidies, and the demand for green products, the level of environmental improvement, and social welfare decrease; (3) the government subsidies manufacturers and retailers at the same time can reduce the adverse effects of retailers' fairness concerns and promote the effectiveness of environmental governance.

The management implications of this study are shown as follows: (1) from the manufacturer perspective, as the channel leader, the cooperation among members should be strengthened to enhance the GSC performance; (2) from the perspective of retailers, retailers can consider fairness concerns for more profit but should control their own when products have high green efficiency and flat concerns behavior; (3) from the perspective of GSC, improving the efficiency of green products is an important means to promote the performance of GSC, while the retailer's fairness concerns will reduce product green degree, which is an obstacle to green products market expansion, not conducive to the development of GSC; (4) from the government perspective, the government should subsidize both manufacturer and retailer to ease competition among members.

This paper only discusses the case of single channel and does not consider the competition between channels. In the future, it will include the case of multiple manufacturers and multiple retailers to compare the role of member alliances in eliminating the influence of fairness concerns under various circumstances. In addition, in the actual production process, manufacturers often have fair concerns. In the next step, the fairness concerns of both manufacturer and retailer should be considered to study the impact of their fairness concerns on the operation of multichannel GSC, and whether government subsidies can coordinate the impact of their fairness concerns on the supply chain.

Appendix

Proof. of Proposition 1. Π_r^{NN} strives for the partial derivatives of p^{NN} and s^{NN} is $H^{NN1} = \begin{bmatrix} -2\alpha & \gamma \\ \gamma & -c_s \end{bmatrix}$. Based on the assumption $2\alpha c_s - \gamma^2 > 0$, we can get $|H_1^{NN1}| = -2\alpha < 0$, $|H_2^{NN1}| = 2\alpha c_s - \gamma^2 > 0$. From $\partial\Pi_r^{NN}/\partial p^{NN} = 0$ and $\partial\Pi_r^{NN}/\partial s^{NN} = 0$ that $p^{NN} = (\alpha c_s - \gamma^2)w + (Q + \beta e)c_s/\phi_2$ and $s^{NN} = \gamma(Q + \beta e - \alpha w)/\phi_2$.

Substitute p^{NN} and s^{NN} into Π_m^{NN}, the Hessian matrix of Π_m^{NN} strives for the partial derivatives w^{NN} and e^{NN} is $H^{NN2} = \begin{bmatrix} -2\alpha^2 c_s/\phi_2 & \alpha\beta c_s/\phi_2 \\ \alpha\beta c_s/\phi_2 & -c_g \end{bmatrix}$. Based on the assumption $2c_g\phi_2 - \beta^2 c_s > 0$, we can get that $|H_1^{NN2}| = -2\alpha^2 c_s/\phi_2 < 0$, $|H_2^{NN2}| = \alpha^2 c_s(2c_g\phi_2 - \beta^2 c_s)/\phi_2^2 > 0$. Combine $\partial\Pi_m^{NN}/\partial w^{NN} = 0$ and $\partial\Pi_m^{NN}/\partial e^{NN} = 0$, it can obtain that $w^{NN*} = c + c_g\phi_2\phi_1/\alpha(2c_g\phi_2 - c_s\beta^2)$ and $e^{NN*} = \beta c_s\phi_1/2c_g\phi_2 - c_s\beta^2$.

Substitute w^{NN*} and e^{NN*} into previous optimal results p^{NN} and s^{NN}, we can get $p^{NN*} = c + c_g(3\alpha c_s - \gamma^2)\phi_1/\alpha(2c_g\phi_2 - c_s\beta^2)$, $s^{NN*} = \gamma c_g\phi_1/2c_g\phi_2 - c_s\beta^2$. □

Proof. of Proposition 2. Π_r^{MN} strives for the partial derivatives p^{MN} and s^{MN} is $H^{MN1} = \begin{bmatrix} -2\alpha & \gamma \\ \gamma & -c_s \end{bmatrix}$. Based on the assumption $2\alpha c_s - \gamma^2 > 0$, we can get $|H_1^{MN1}| = -2\alpha < 0$, $|H_2^{MN1}| = 2\alpha c_s - \gamma^2 > 0$. Combine $\partial\Pi_r^{MN}/\partial p^{MN} = 0$ and $\partial\Pi_r^{MN}/\partial s^{MN} = 0$, it can obtain that $p^{MN} = (\alpha c_s - \gamma^2)w + (Q + \beta e)c_s/\phi_2$ and $s^{MN} = \gamma(Q + \beta e - \alpha w)/\phi_2$.

Substitute p^{MN} and s^{MN} into Π_m^{MN}, the Hessian matrix of Π_m^{MN} strives for the partial derivatives w^{MN} and e^{MN} is $H^{MN2} = \begin{bmatrix} -2\alpha^2 c_s/\phi_2 & \alpha c_s(\beta - \alpha\theta)/\phi_2 \\ \alpha c_s(\beta - \alpha\theta)/\phi_2 & -c_g\phi_2 + 2\alpha\beta c_s\theta/\phi_2 \end{bmatrix}$. Based on the assumption $2c_g\phi_2 - \phi_3^2 c_s > 0$, we can get $|H_1^{MN2}| = -2\alpha^2 c_s/\phi_2 < 0$, $|H_2^{MN2}| = \alpha^2 c_s(2c_g\phi_2 - \phi_3^2 c_s)/\phi_2^2 > 0$. Combine $\partial\Pi_m^{MN}/\partial w^{MN} = 0$ and $\partial\Pi_m^{MN}/\partial e^{MN} = 0$, it can obtain that $w^{MN*} = c + (\phi_2 c_g - \alpha c_s\theta\phi_3)\phi_1/\alpha(2\phi_2 c_g - c_s\phi_3^2)$ and $e^{MN*} = c_s\phi_1\phi_3/2\phi_2 c_g - c_s\phi_3^2$.

Substitute w^{MN*} and e^{MN*} into previous optimal results p^{MN} and s^{MN}, we can get $p^{MN*} = c + (c_g(\phi_2 + \alpha c_s) - \alpha c_s\theta\phi_3)\phi_1/\alpha(2\phi_2 c_g - c_s\phi_3^2)$, $s^{MN*} = c_g\gamma\phi_1/2\phi_2 c_g - c_s\phi_3^2$. □

Proof. of Proposition 3. Π_r^{MY} strives for the partial derivatives p^{MY} and s^{MY} is $H^{MY1} = \begin{bmatrix} -2\alpha(\lambda + 1) & \gamma(\lambda + 1) \\ \gamma(\lambda + 1) & -c_s(\lambda + 1) \end{bmatrix}$. Based on the assumption $2\alpha c_s - \gamma^2 > 0$, we can get $|H_1^{MY1}| = -2\alpha(\lambda + 1) < 0$, $|H_2^{MY1}| = (2\alpha c_s - \gamma^2)(\lambda + 1)^2 > 0$.

We can obtain p^{MY} and s^{MY} from simultaneous equations $\partial\Pi_r^{MY}/\partial p^{MY}=0$ and $\partial\Pi_r^{MY}/\partial s^{MY}=0$.

Substitute p^{MY} and s^{MY} into Π_m^{MY}, the Hessian matrix of Π_m^{MY} strives for the partial derivatives w^{MY} and e^{MY}. Combine $\partial\Pi_m^{MY}/\partial w^{MY}=0$ and $\partial\Pi_m^{MY}/\partial e^{MY}=0$, it can obtain that $w^{MY*}=c+(\lambda+1)(\phi_2 c_g-\alpha c_s\theta\phi_3)\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$ and $e^{MY*}=(\lambda+1)c_s\phi_1\phi_3/2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1)$.

Substitute w^{MY*} and e^{MY*} into previous optimal results p^{MY} and s^{MY}, we can get $p^{MY*}=c+((2\lambda+1)c_g(\phi_2+\alpha c_s)-\alpha c_s\theta(\lambda+1)\phi_3)\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$, $s^{MY*}=c_g\gamma(2\lambda+1)\phi_1/2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1)$. □

Proof. of Proposition 4. Π_r^{MRY} strives for the partial derivatives p^{MRY} and s^{MRY} is $H^{MRY1}=\begin{bmatrix}-2\alpha(\lambda+1) & \gamma(\lambda+1)\\ \gamma(\lambda+1) & -c_s(\lambda+1)\end{bmatrix}$. Based on the assumption $2\alpha c_s-\gamma^2>0$, we can get $|H_1^{MRY1}|=-2\alpha(\lambda+1)<0$, $|H_2^{MRY1}|=(2\alpha c_s-\gamma^2)(\lambda+1)^2>0$. It can obtain p^{MRY} and s^{MRY} from simultaneous equations $\partial\Pi_r^{MRY}/\partial p^{MRY}=0$ and $\partial\Pi_r^{MRY}/\partial s^{MRY}=0$.

Substitute p^{MRY} and s^{MRY} into Π_m^{MRY}, the Hessian matrix of Π_m^{MRY} strives for the partial derivatives w^{MRY} and e^{MRY}. Combine $\partial\Pi_m^{MRY}/\partial w^{MRY}=0$ and $\partial\Pi_m^{MRY}/\partial e^{MRY}=0$, it can obtain that $w^{MRY*}=c+(\lambda+1)(\phi_2 c_g-\alpha c_s\theta(\phi_3+\alpha\delta))\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))$ and $e^{MRY*}=(\lambda+1)c_s(\phi_3+\alpha\delta)\phi_1/2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1)$.

Substitute w^{MRY*} and e^{MRY*} into previous results p^{MRY} and s^{MRY}, we can get that $p^{MRY*}=c+((2\lambda+1)(3\alpha c_s-\gamma^2)c_g-\alpha c_s(\lambda+1)(\delta+\theta)(\phi_3+\alpha\delta))\phi_1/\alpha(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))$, $s^{MRY*}=c_g\gamma(2\lambda+1)\phi_1/2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1)$. □

Proof. of Proposition 5.

(1) $e^{MN*}-e^{NN*}=\alpha c_s\theta(2c_g\phi_2+\beta c_s\phi_3)\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2c_g\phi_2-c_s\beta^2)>0$, $e^{MN*}-e^{MY*}=2c_g c_s\lambda\phi_2\phi_3\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, $e^{MRY*}-e^{MY*}=\alpha c_s\delta(\lambda+1)(2(2\lambda+1)\phi_2 c_g+c_s(\lambda+1)\phi_3(\phi_3+\alpha\delta))\phi_1/(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$;

(2) $s^{MN*}-s^{NN*}=\alpha c_g c_s\gamma\theta(2\beta+\alpha\theta)\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2c_g\phi_2-c_s\beta^2)>0$, $s^{MN*}-s^{MY*}=c_g c_s\gamma\lambda\phi_3^2\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, $s^{MRY*}-s^{MY*}=\alpha c_g c_s\delta\gamma(\lambda+1)(2\lambda+1)(2\phi_3+\alpha\delta)\phi_1/(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$;

(3) $D^{MN*}-D^{NN*}=\alpha^2 c_g c_s^2\theta(2\beta+\alpha\theta)\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2c_g\phi_2-c_s\beta^2)>0$, $D^{MN*}-D^{MY*}=\alpha c_g c_s^2\lambda\phi_3^2\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, $D^{MRY*}-D^{MY*}=\alpha^2 c_g c_s^2\delta(\lambda+1)(2\lambda+1)(2\beta+\alpha\delta+2\alpha\theta)\phi_1/(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$. □

Proof. of Proposition 6.

(1) $\Pi_m^{MN*}-\Pi_m^{NN*}=\alpha c_g c_s^2\theta\phi_1^2(2\beta+\alpha\theta)/2(2\phi_2 c_g-c_s\phi_3^2)(2c_g\phi_2-c_s\beta^2)>0$, $\Pi_m^{MN*}-\Pi_m^{MY*}=c_g^2 c_s\lambda\phi_1^2\phi_2/(2\phi_2 c_g-c_s\phi_3^2)(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, $\Pi_m^{MRY*}-\Pi_m^{MY*}=\alpha c_g c_s^2\delta(\lambda+1)^2\phi_1^2(2\phi_3+\alpha\delta)/2(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))$;

(2) $\Pi_r^{MN*}-\Pi_r^{NN*}=\alpha c_g^2 c_s^2\theta\phi_1^2\phi_2(2\beta+\alpha\theta)(4\phi_2 c_g-c_s(\phi_3^2+\beta^2))/2(2\phi_2 c_g-c_s\phi_3^2)^2(2c_g\phi_2-c_s\beta^2)^2>0$, $\Pi_r^{MRY*}-\Pi_r^{MY*}=\alpha c_g^2 c_s^2\delta(4\lambda+1)(2\lambda+1)(\lambda+1)\phi_1^2\phi_2(2\phi_3+\alpha\delta)(4(2\lambda+1)\phi_2 c_g-c_s((\alpha\delta+\phi_3)^2+\phi_3^2)(\lambda+1))/2(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))^2(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))^2>0$;

(3) $\Pi_{sc}^{MN*}-\Pi_{sc}^{NN*}=\Pi_m^{MN*}-\Pi_m^{NN*}+\Pi_r^{MN*}-\Pi_r^{NN*}>0$, $\Pi_{sc}^{MN*}-\Pi_{sc}^{MY*}=c_g^2 c_s^2\lambda\phi_3^2\phi_1^2\phi_2(4(3\lambda+1)\phi_2 c_g-c_s\phi_3^2(5\lambda+2))/2(2\phi_2 c_g-c_s\phi_3^2)^2(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))^2>0$, $\Pi_{sc}^{MRY*}-\Pi_{sc}^{MY*}=\Pi_m^{MRY*}-\Pi_m^{MY*}+\Pi_r^{MRY*}-\Pi_r^{MY*}>0$. □

Proof. of Proposition 7.

(1) Comparing the demand, $D^{MN*}-D^{NN*}=\alpha^2 c_g c_s^2\theta(2\beta+\alpha\theta)\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2c_g\phi_2-c_s\beta^2)>0$, $D^{MN*}-D^{MY*}=\alpha c_g c_s^2\lambda\phi_3^2\phi_1/(2\phi_2 c_g-c_s\phi_3^2)(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, $D^{MRY*}-D^{MY*}=\alpha^2 c_g c_s^2\delta(\lambda+1)(2\lambda+1)(2\phi_3+\alpha\delta)\phi_1/(2(2\lambda+1)\phi_2 c_g-c_s(\phi_3+\alpha\delta)^2(\lambda+1))(2(2\lambda+1)\phi_2 c_g-c_s\phi_3^2(\lambda+1))>0$, so we get $D^{NN*}<D^{MN*}$, $D^{MY*}<D^{MN*}$, $D^{MY*}<D^{MRY*}$, and according to the hypothesis $CS=D^2/2\alpha$, so we get $CS^{NN*}<CS^{MN*}$, $CS^{MY*}<CS^{MN*}$, $CS^{MY*}<CS^{MRY*}$;

(2) It has been proved $e^{NN*}<e^{MN*}$, $e^{MY*}<e^{MN*}$, $e^{MY*}<e^{MRY*}$ and $D^{NN*}<D^{MN*}$, $D^{MY*}<D^{MN*}$, $D^{MY*}<D^{MRY*}$ in the previous section, and according to the hypothesis $EI=e\,D$, so we get $EI^{NN*}<EI^{MN*}$, $EI^{MY*}<EI^{MN*}$, $EI^{MY*}<EI^{MRY*}$;

(3) It has been proved $EI^{NN*}<EI^{MN*}$, $EI^{MY*}<EI^{MN*}$, $EI^{MYv}<EI^{MRY*}$ in the previous section, and according to the hypothesis $GS^{MN*}=\theta EI^{MN*}$, $GS^{MY*}=\theta EI^{MY*}$, $GS^{MRY*}=(\theta+\delta)EI^{MRY*}$, so we get $GS^{MY*}<GS^{MN*}$, $GS^{MY*}<GS^{MRY*}$;

(4) According to the hypothesis $SW=\prod_m+\prod_r+CS+EI-GS$, easy to prove $SW^{NN*}<SW^{MN*}$, $SW^{MY*}<SW^{MN*}$, $SW^{MY*}<SW^{MRY*}$. □

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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