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Research Article

Optimal Decisions of a Green Supply Chain under the Joint Action of Fairness Preference and Subsidy to the Manufacturer

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Government subsidy promotes the development of green supply chain, and the influence of decision-makers' behavioral preferences becomes increasingly prominent in green supply chain management. In order to further enrich the research content of green supply chain, we first use Stackelberg game theory to construct game models by taking the product green degree, wholesale price and retail price as the decision variables, then we work out the equilibrium strategies of the manufacturer and the retailer under four decision scenarios, and reveal the impact differences between the two parties' fairness preference behaviors. Our research mainly has the following findings: Firstly, the government subsidy to the manufacturer can benefit these two parties and can have certain impact on the optimal decisions only by working with the green product market expansion efficiency. Secondly, these two parties' fairness preference behaviors can cause serious damage to the other party's profit and the overall profit of green supply chain, and increase the rate of their own profit in the overall profit of green supply chain, but the difference is that the retailer's fairness preference behavior can cause a greater decline in product green degree and wholesale price, and when certain conditions are met, its own profit may rise compared to its fairness neutral, while the manufacturer's fairness preference behavior can cause a greater damage to the overall profit of green supply chain and make its own profit always be lower than its fairness neutral. Thirdly, the government subsidy to the manufacturer and the fairness preference behaviors of both parties can cause a stack effect on the optimal solutions, which means that the subsidy government provides for the manufacturer can aggravate the negative influence caused by these two parties' fairness preference behaviors.

1. Introduction

With the industrialization constantly developing, the deterioration of the ecosystem and the shortage of resources are becoming more and more serious, therefore, more and more scholars start to focus on the researches of green supply chain management [1]. Moreover, the decline in environment quality promotes the increase in consumers' environmental awareness, consumers are becoming more and more willing to buy environment-friendly products [2]. For instance, a research about consumers revealed that approximately 80% of consumers in America would buy green products even if they need to pay an additional fee [3]. Given this finding, the core companies of a supply chain produce green products can not only enhance their environmental image, but also gain competitive advantage in market. However, there are still many constraints such as the lack of R&D funds and technical capabilities for companies to effectively establish green supply chain, which seriously influences manufacturers' enthusiasm for producing green products. To encourage manufacturers to develop and produce greener products, governments all over the world have implemented various legal regulations (e.g., hazardous substance ban) and financial assistance policies (e.g., subsidy for green products). Compared with other measures, subsidy policy is more common and effective in reality. For example, the Recovery and Reinvestment Act of America in 2009 offers a tax deduction of $2500 for every sold electric vehicle possessing at least 4 kWh battery capacity and an extra $417 for every supernumerary kWh of battery capacity surpassing 4 kWh [4]. Chinese government announced that it would provide ¥60,000 and ¥50,000, respectively, for consumers in five major cities who purchase new electric vehicles and plug-in hybrids in 2010 [5]. Besides, several similar subsidy policies are carried out to accelerate the development of environmental protection industries in Canada, Europe, and so on [6]. In short, these findings show that government subsidy is very important to promote green products' development, and one of the main purposes of our research is to study the optimal decisions including pricing, product green degree and green supply chain performance in the context of government subsidy policy.

However, in addition to considering government subsidy this external environmental factor, decision-maker's fairness preference is also an important internal factor considered in our research. Scholars represented by Nobel economist Kahnema found that decision makers often show great concern for fairness in reality [7]. Subsequently, many economic experiments and empirical studies confirmed the existence of fairness preference behavior [8, 9], which means that decision-makers not only focus on their own profit, but they also pay attention to the comparison of their own profit with other members' profit, and when they are treated unfairly, they may take actions at the cost of losing profit themselves to punish each other and achieve more fair results. To distinguish from the distributional fairness concern, which uses the other party's profit as a fair reference point to judge the gains and losses, and requires the absolute fairness of channel profit distribution, we will mainly discuss the fairness preference in this paper which fully considers the impact of the strength and contribution of all parties in the supply chain on channel profit distribution, supposes that Nash bargaining solutions are the fairness reference points and reflects relative fairness, because this kind of relative fairness is more consistent with the realistic environment.

According to previous studies, both government subsidy and fairness preference behavior can affect the manufacturer's and retailer's optimal strategies, but when government subsidy, fairness preference these two factors are considered simultaneously, what kind of state these two parties' optimal strategies and green supply chain performance will be remains unknown. Therefore, it is very necessary to explore the green supply chain optimal decision problem with consideration of the internal factor (decision makers' fairness preference behaviors) and the external factor (government subsidy).

Specifically, we will mainly investigate the following questions in this paper:

(1) How do the manufacturer's and retailer's fairness preference behaviors affect these two parties' optimal decisions when there is a government subsidy?
(2) How do the manufacturer's and retailer's fairness preference behaviors affect these two parties' optimal profit and green supply chain total profit when there is a government subsidy?
(3) What is the difference between the impacts of the two parties' fairness preference behaviors on equilibrium solutions when there is a government subsidy?

The theoretical significance of our research is mainly embodied in the following aspects: (1) Since there is little literature that introduces the manufacturer's and the retailer's fairness preference into the decision-making research of green supply chain with government subsidy, and explores the joint impact of government subsidy, manufacturer's and retailer's fairness preference behaviors on the optimal decisions and green supply chain performance in depth, so our study enriches the research content about green supply chain optimal decision problem. (2) Our study reveals the impact mechanism of government subsidy, the manufacturer's fairness preference behavior and retailer's fairness preference behavior on the optimal pricing decisions, product green degree decision and green supply chain performance, and reveals the impacted difference between manufacturer's fairness preference behavior and retailer's fairness preference behavior on equilibrium solutions in the context of government subsidy.

The practical value of our research is mainly embodied in the following aspects: (1) Our study explores the impact of the two factors (government subsidy and fairness preference) which are real existence and significant on the optimal strategies and green supply chain members' profit, the subject of this paper is closely related to the real background and has practical significance. (2) The research conclusions can not only provide reference for the companies in a green supply chain to adopt reasonable strategies when dealing with each other's fairness preference behaviors, but can also provide government with some theoretical support to determine appropriate subsidy intensity when the companies in a green supply chain have fairness preference behaviors.

This paper is arranged as follows. In Section 2, a review of literature relevant to our research is provided. Research assumptions and basic model are provided in Section 3. Section 4 presents optimal decisions under four decision-making scenarios. Section 5 provides the analysis and discussion, which presents some research conclusions by comparing the equilibrium solutions obtained from Section 4. Some numerical analyses are given in Section 6 to test and verify our conclusions. Finally, some conclusions and limitations of our study are summed up in Section 7. Some important proofs are provided in Appendices A and B.

2. Literature Review

In this section, we mainly comb out two categories literature about supply chain according to the research content of this paper. One stream is the study about green supply chain optimal decision problem; another one is the study about supply chain optimal decision problem considering fairness preference.

2.1. Green Supply Chain Optimal Decision. As mentioned in the introduction Section, with the ecological environment problem becoming increasingly serious, more and more researchers gradually pay close attention to GSCM. The previous literature relevant to GSCM can be roughly divided into two types depending on the study method, one category is empirical researches, another is mathematical researches which usually adopt game theory. Here, we denote the latter as optimal decision researches, and we will mainly summarize such literature in this subsection.

2.1.1. Without Government Subsidy. The researches relevant to the green supply chain optimal decision problem have achieved fruitful results. Some focus on the coordination and optimal pricing decision, for instance, Cao and Zhang [10] investigated the green supply chain coordination and pricing decision problem based on green product utility diversity. Some consider the competitive factors, for instance, Liu et al. [11] studied the impact of two competing factors consumers' environmental awareness on key players of a supply chain. Some focus on the channel coordination problem, for instance, Li et al. [12] studied a dual-channel green supply chain and assumed the product demand is influenced by retail price and greenness level, and discussed the optimal pricing the optimal greening problems under centralized and decentralized scenarios, then proposed a coordination contract. Zhang et al. [13] discussed how consumer environmental awareness influences order quantities, channel coordination considering the case that there are two products which is different from each other in retail price and environmental quality. Basiri and Heydari [14] investigated the green supply chain channel coordination problem based on the assumptions that there are two green products in the market and the product demand is influenced by products' price, green quality, retailer's sales efforts. Some then focus on the green supply chain contracts, for instance, Song and Gao [15] discussed how different contracts influence the members' decisions and the total profit of a green supply chain by establishing two revenue-sharing contracts models. Aslani and Heydari [16] investigated the optimal problem of pricing, product greenness and coordination in a dual channel supply chain under channel disruption.

2.1.2. With Government Subsidy. There are also many researches about green supply chain optimal decision problem considering government subsidy. Some consider government subsidy and competitive factors simultaneously, for instance, Sheu and Chen [17] studied how government financial policy influences green supply chains' competition. Considering government subsidy and green preference, Yu et al. [18] investigated green products' optimal levels and quantities in every green level under oligopolistic competition. Assuming that there are both green and common products in the market, Hafezalkotob et al. [19] studied the impact of government subsidy on the green supply chain members' optimal strategies. Some of them consider the uncertainties, for instance, Zhuo and Wei [20] explored green supply chain optimal decision problem in terms of demand uncertainty under government subsidies. Yang and Xiao [21] mainly investigated the impact of channel leadership, governmental interventions on retail price, green level, expected profit under fuzzy uncertainties. Heydari et al. [22] discussed the coordination of supply chain under the action of government in reverse and closed—loop supply chain respectively.

The researches mentioned above investigate the optimal decision problem and coordination problem of the green supply chain with different focus, but all of them assume that the manufacturer and the retailer are completely rational, none of them considers green supply chain members' fairness preference behaviors. Therefore, there are inevitably great limitations in their conclusions.

2.2. Supply Chain Optimal Decision with Fairness Preference. So far, there have been some literature which introduce fairness preference into supply chain optimal decision research. Fehr et al. [23] studied the impact of fairness concerns in supply chain on competition and cooperation. Subsequently, some scholars investigated the supply chain members' fairness concern behaviors in terms of different aspects. Under deterministic demand condition, Cui et al. [24] found that the manufacturers only need to set an appropriate price to achieve supply chain coordination if channel partners have fairness concern behaviors. Based on Cui et al. [24], Caliskan et al. [25] investigated the supply chain coordination problem with non-linear demand, and found that it needs less strict conditions for exponential demand function to realize supply chain coordination when only the retailer has fairness concern behavior. Du et al. [26] proposed a supply chain which the supplier and the retailer are fairness concern, they developed a fairness reference framework based on Nash bargaining theory and studied how these two parties' fairness concern behaviors influence both sides' optimal strategies under newsvendor model environment. Wu and Niederhoff [27] investigated how supply chain members' fairness concern behaviors influence supply chain members' performance in a two echelon newsvendor model. Li et al. [28] explored the retailer's fairness concern behavior in the encroachment problem. Nie and Du [29] investigated two sorts of fairness concerns including peer-induced and distributional fairness concerns at the same time, then provided a coordination framework combing quantity discount contracts with fixed fees. Considering channel competition, Li and Li [30] studied how value-added service and retailer's fairness concern behavior influence supply chain members' pricing decisions. Considering fairness concern behaviors of the supplier and manufacturer in the context of sustainable green technology innovation development, Du et al. [31] investigated the optimal decision problem in both with and without fairness concern. Considering retailer's fairness concern behavior and sales efforts, Liu et al. [32] studied the equilibrium solutions under two contracts: the wholesale price contract and the cost sharing contract, they found that both contracts can realize channel coordination under different contents.

The literature mentioned above discuss supply chain members' fairness concern behaviors in terms of different aspects, but there still exist some shortcomings to be complemented in their researches, these shortcomings are mainly embodied in the following aspects: (1) they only study fairness concern behavior in the traditional supply chain ,but they do not study fairness concern behavior in the green supply chain when government provides subsidy for the manufacturer, (2) most of them only discuss one member's fairness concern behavior in their papers, few of them investigate two members' fairness concern behaviors simultaneously and compare the impact difference between different members' fairness concern behaviors on equilibrium solutions.

Considering these shortcomings, we think there still exists some work to be done. Therefore, we will discuss how government subsidy, fairness preference jointly influence the supply chain members' optimal decisions and profit, and green supply chain total profit in this paper. Moreover, we will discuss

Table 1: Some literature most relevant to this paper.

Author	Green degree	Subsidy	Fairness preference (manufacturer)	Fairness preference (retailer)	Supply chain Coordination
Du et al. [33]				✓	✓
Zhou et al. [7]	✓			✓	✓
Zhang et al. [34]	✓	✓		✓	
Song and Gao [15]	✓				✓
Nie and Du [29]				✓	✓
Li et al. [35]			✓	✓	
Du et al. [31]	✓		✓	✓	
Shi et al. [36]	✓		✓		
Li et al. [37]	✓			✓	✓
Zhuo and Wei [20]	✓	✓			
This paper	✓	✓	✓	✓	

manufacturer's fairness preference behavior and retailer's fairness preference behavior at the same time, and meanwhile we will compare the impact difference between both two parties' fairness preference behaviors on equilibrium solutions in order to deeply study fairness preference behavior.

Based on combing relevant literature, in order to highlight the innovation of this paper and clearly show the difference between this paper and previous literature, we list some literature in Table 1 which are most relevant to this paper. In order to achieve the purpose of differentiation, we mainly use the product green degree, government subsidy, fairness preference and the coordination contract as the classification criteria according to our research content. It should be noted that we denote the green degree as the index of green products' environmental quality, since disparate literature may define disparate indexes on behalf of green products' environmental quality (e.g., carbon emission reduction rate), but their models are similar, therefore, if the paper involves green products' environmental quality, we also think that it involves green degree. In addition, what needs to be explained is that Table 1 is just a rough division about these papers, there still exists great differences between our research and them in model construction because of different research priorities.

3. Research Assumptions and Basic Model

3.1. Research Assumptions. In our research, there is a green supply chain including only one manufacturer and one retailer, the manufacturer produces a sort of green product and sells the green products to the market through the single retailer. To facilitate subsequent study, we put forward some assumptions presented as follows:

(1) The manufacturer as the leader of the game firstly determines the product green degree and wholesale price, then the retailer determines the retail price according to the manufacturer's decisions.

(2) Based on previous literature [38–40], we assume the demand for green products to be linear in the retail price, product green degree, and consumers tend to buy the product with higher green degree and lower retail price [41]. Therefore, the demand for green products is:

$$D = \alpha - \beta p + \gamma g. \tag{1}$$

There are $\alpha > 0, \beta > 0, \gamma > 0, \alpha - \beta p > 0$.

(3) In addition to pay the fixed cost of production, the manufacturer needs to pay extra R&D cost. Similar to the previous literature [38, 39], we assume there is a quadratic relationship between R&D cost and product green degree. Therefore, the R&D cost is $(1/2)\eta g^2$.

(4) Different from the research [34], we consider that government will offer the manufacturer certain subsidy to promote the manufacturer to produce green products, and meanwhile we assume that per unit product subsidy is directly proportional to the product green degree based on the previous literature [21, 42], therefore, the government subsidy for the unit product is θg, in which $\theta > 0$ represents Unit product subsidy coefficient.

(5) Different from these researches [31, 34, 39] considering distribution fairness concern, we describe fairness preference by taking Nash bargaining solutions as fairness reference points according to previous literature [26, 43].

The decision variables and major parameters in our research are presented in Table 2.

Based on the assumptions above, the manufacturer's profit, retailer's profit, the total profit of green supply chain are presented as follows:

$$\pi_M = (w + \theta g - c)(\alpha - \beta p + \gamma g) - \frac{1}{2}\eta g^2, \tag{2}$$

$$\pi_R = (p - w)(\alpha - \beta p + \gamma g), \tag{3}$$

$$\pi_{SC} = (p + \theta g - c)(\alpha - \beta p + \gamma g) - \frac{1}{2}\eta g^2. \tag{4}$$

3.2. The Model of Fairness Preference with Nash Bargaining Reference. Whether the manufacturer or the retailer is fairness preference, they not only pay attention to their own profit, but they also focus on the fairness of channel profit distribution, that is, the decision-making objectives of these two parties

Table 2: Decision variables and major parameters.

Decision variables	The meaning of the decision variables
w	Wholesale price of unit green product
g	Product green degree
p	Retail price of unit green product
Parameters	The meaning of the parameters
α	Green products' potential demand
β	Demand sensitivity coefficient to price
γ	Consumer green preference coefficient
η	R&D cost coefficient
c	Fixed cost of production
π_M, π_R, π_{SC}	Manufacturer's profit retailer's profit and total profit of green supply chain
U_M, U_R	Manufacturer's and retailer's utility
λ_M, λ_R	Manufacturer's preference coefficient and retailer's fairness preference coefficient

are to maximize their own utilities considering fairness preference. Here, we will solve the utility function by taking the manufacturer's fairness preference as an example.

Assuming that manufacturer's and retailer's Nash bargaining fairness reference solutions are $(\bar{\pi_M}, \bar{\pi_R})$ and $\bar{\pi_M} + \bar{\pi_R} = \pi_{SC}$, we can obtain the utility function when only the manufacturer has fairness preference behavior:

$$\begin{aligned} U_M &= \pi_M - \lambda_M(\bar{\pi_M} - \pi_M), \\ U_R &= \pi_R. \end{aligned} \tag{5}$$

According to Nash axiomatization definition, the Nash bargaining fairness reference solution is the optimal solution for the following model:

$$\begin{aligned} &\max_{\pi_M,\pi_R} \psi = U_M U_R, \\ &s.t. \begin{cases} \pi_M + \pi_R = \pi_{SC}, \\ 0 \le \pi_M, \pi_R \le \pi_{SC}, \\ U_M > 0, U_R > 0. \end{cases} \end{aligned} \tag{6}$$

Here, we will solve the model above. By substituting $\bar{\pi_M} + \bar{\pi_R} = \pi_{SC}$ and $\pi_M + \pi_R = \pi_{SC}$ into formula $U_M = \pi_M - \lambda_M(\bar{\pi_M} - \pi_M)$, we can obtain:

$$U_M = (1 + \lambda_M)(\pi_{SC} - \pi_R) - \lambda_M(\pi_{SC} - \bar{\pi_R}). \tag{7}$$

By substituting formula (7) and formula $U_R = \pi_R$ into formula $\max_{\pi_M,\pi_R} \psi = U_M U_R$, we can obtain:

$$\begin{aligned} \psi(\pi_{SC}, \pi_R) &= U_M U_R \\ &= [(1 + \lambda_M)(\pi_{SC} - \pi_R) - \lambda_M(\pi_{SC} - \bar{\pi_R})]\pi_R. \end{aligned} \tag{8}$$

By solving the second-order partial derivative of formula (8) with respect to π_R, we can obtain: $\partial^2\psi/\partial\pi_R^2 = -2(1 + \lambda_M) < 0$, So there is a unique optimal value π_R^* that makes the objective function $\psi(\pi_{SC}, \pi_R)$ get the maximum value, and the optimal value π_R^* must satisfy the condition shown below:

$$\frac{\partial\psi}{\partial\pi_R} = \pi_{SC} - 2\pi_R^*(1 + \lambda_M) + \lambda_M \bar{\pi_R} = 0. \tag{9}$$

According to the fixed point theorem, Nash bargaining solution is the fairness reference solution, which is $\pi_R^* = \bar{\pi_R}$. Therefore, by substituting this formula $\pi_R^* = \bar{\pi_R}$ into the formula (9), we can obtain the retailer's Nash bargaining fairness reference solution as follows:

$$\bar{\pi_R} = \frac{\pi_{SC}}{2 + \lambda_M}. \tag{10}$$

According to $\bar{\pi_M} + \bar{\pi_R} = \pi_{SC}$, we can obtain the manufacturer's Nash bargaining fairness reference solution as follows:

$$\bar{\pi_M} = \frac{\pi_{SC}(1 + \lambda_M)}{2 + \lambda_M}. \tag{11}$$

By substituting formula (10) into formula $U_M = \pi_M - \lambda_M (\bar{\pi_M} - \pi_M)$, we can obtain the utility function when only the manufacturer has fairness preference behavior:

$$U_M = (1 + \lambda_M)\pi_M - \frac{(1 + \lambda_M)\lambda_M}{2 + \lambda_M}\pi_{SC}. \tag{12}$$

Similarly, we can obtain the utility function when only the retailer has fairness preference behavior:

$$U_R = (1 + \lambda_R)\pi_R - \frac{(1 + \lambda_R)\lambda_R}{2 + \lambda_R}\pi_{SC}. \tag{13}$$

4. The Optimal Decisions

Special explanation: because one of the main purposes of our research is to reveal the impact difference between both parties' fairness preference behaviors on the optimal decisions, it is necessary to avoid such scenario that both parties' fairness preference coefficients exist in the same model for the convenience of subsequent comparison. Therefore, we will mainly consider four decision-making scenarios in the context of government subsidy, and these scenarios are centralized decision-making scenario, decentralized decision-making scenario not considering both parties' fairness preference behaviors, decentralized decision-making scenario only considering the manufacturer's fairness preference behavior, decentralized decision-making scenario only considering the retailer's fairness preference behavior, and we do not consider such a scenario when both the manufacturer and the retailer have fairness preference behaviors.

4.1. Centralized Decision-Making Scenario. In this scenario, both the manufacturer and the retailer belong to the same company, we can take the solutions of this scenario as a benchmark to facilitate the subsequent comparison and analysis. In this scenario, the manufacturer and the retailer are committed to maximizing the total profit of green supply chain whether they are fairness preference or not.

Theorem 1. *The optimal retail price and product green degree are as follows (see Appendix A for the specific solution process):*

$$p_1 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(\alpha + \beta c)}{(\gamma + \beta\theta)^2 - 2\beta\eta}, \tag{14}$$

$$g_1 = \frac{(\gamma + \beta\theta)(\beta c - \alpha)}{(\gamma + \beta\theta)^2 - 2\beta\eta}. \tag{15}$$

The optimal total profit of green supply chain is as follows:

$$\pi_{SC1} = \frac{\eta(\beta c - \alpha)^2}{2\left[2\beta\eta - (\gamma + \beta\theta)^2\right]}. \quad (16)$$

4.2. Decentralized Decision-Making Scenario Not Considering Both Parties' Fairness Preference Behaviors. In this scenario, we assume that both parties are fairness neutral, therefore, both parties will make their own optimal strategies respectively in order to maximize their own profit. The decision-making process is presented as follows: Firstly, the manufacturer determines the product green degree and wholesale price, the retailer then determines the retail price according to the manufacturer's optimal strategies. We will adopt the backward method to solve such Stackelberg game problem and this method will also be used in the subsequent scenario.

Theorem 2. *The optimal wholesale price, product green degree, retail price are as follows (see Appendix A for the specific solution process):*

$$w_2 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - 2\eta(\alpha + \beta c)}{(\gamma + \beta\theta)^2 - 4\beta\eta}, \quad (17)$$

$$g_2 = \frac{(\gamma + \beta\theta)(\beta c - \alpha)}{(\gamma + \beta\theta)^2 - 4\beta\eta}, \quad (18)$$

$$p_2 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(3\alpha + \beta c)}{(\gamma + \beta\theta)^2 - 4\beta\eta}. \quad (19)$$

The manufacturer's optimal profit, the retailer's optimal profit and the optimal total profit of green supply chain are as follows:

$$\pi_{M2} = \frac{\eta(\beta c - \alpha)^2}{2\left[4\beta\eta - (\gamma + \beta\theta)^2\right]}, \quad (20)$$

$$\pi_{R2} = \frac{\beta\eta^2(\beta c - \alpha)^2}{\left[4\beta\eta - (\gamma + \beta\theta)^2\right]^2}, \quad (21)$$

$$\pi_{SC2} = \frac{\eta(\beta c - \alpha)^2\left[6\beta\eta - (\gamma + \beta\theta)^2\right]}{2\left[4\beta\eta - (\gamma + \beta\theta)^2\right]^2}. \quad (22)$$

4.3. Decentralized Decision-Making Scenario Only Considering the Manufacturer's Fairness Preference Behavior. In this scenario, only the manufacturer has fairness preference behavior, the retailer is still fairness neutral, in other words, the decision objective of the manufacturer is to maximize its fairness preference utility, but the retailer will still make its own optimal decision to maximize its own profit.

Theorem 3. *The optimal wholesale price, product green degree and retail price are as follows (see Appendix A for the specific solution process):*

$$w_3 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - 2\eta(\alpha + \beta c) - \eta\lambda_M\alpha}{(\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta}, \quad (23)$$

$$g_3 = \frac{(\gamma + \beta\theta)(\beta c - \alpha)}{(\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta}, \quad (24)$$

$$p_3 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(3\alpha + \lambda_M\alpha + \beta c)}{(\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta}. \quad (25)$$

The manufacturer's optimal profit, the retailer's optimal profit and the optimal total profit of green supply chain are as follows:

$$\pi_{M3} = \frac{\eta(\beta c - \alpha)^2\left[(4 + 2\lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]}{2\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2}, \quad (26)$$

$$\pi_{R3} = \frac{\beta\eta^2(\beta c - \alpha)^2}{\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2}, \quad (27)$$

$$\pi_{SC3} = \frac{\eta(\beta c - \alpha)^2\left[(6 + 2\lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]}{2\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2}. \quad (28)$$

4.4. Decentralized Decision-Making Scenario Only Considering the Retailer's Fairness Preference Behavior. In this scenario, only the retailer has fairness preference behavior, the manufacturer is still fairness neutral, therefore, the retailer's decision objective is to maximize its fairness preference utility, but the manufacturer will still make its own optimal decisions to maximize its own profit.

Theorem 4. *The optimal wholesale price, product green degree and retail price are as follows (see Appendix A for the specific solution process):*

$$w_4 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - 2\eta(\alpha + \beta c + \lambda_R\beta c)}{(\gamma + \beta\theta)^2 - (4 + 2\lambda_R)\beta\eta}, \quad (29)$$

$$g_4 = \frac{(\gamma + \beta\theta)(\beta c - \alpha)}{(\gamma + \beta\theta)^2 - (4 + 2\lambda_R)\beta\eta}, \quad (30)$$

$$p_4 = \frac{(\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(1 + 0.5\lambda_R)(3\alpha + \beta c)}{(\gamma + \beta\theta)^2 - (4 + 2\lambda_R)\beta\eta}. \quad (31)$$

The manufacturer's optimal profit, the retailer's optimal profit and the optimal total profit of green supply chain are as follows:

$$\pi_{M4} = \frac{\eta(\beta c - \alpha)^2}{2\left[(4 + 2\lambda_R)\beta\eta - (\gamma + \beta\theta)^2\right]}, \quad (32)$$

$$\pi_{R4} = \frac{\beta\eta^2(\beta c - \alpha)^2(1 + 0.5\lambda_R)(1 + 1.5\lambda_R)}{\left[(4 + 2\lambda_R)\beta\eta - (\gamma + \beta\theta)^2\right]^2}, \quad (33)$$

$$\pi_{SC4} = \frac{\eta(\beta c - \alpha)^2\left[1.5\beta\eta(\lambda_R + 2)^2 - (\gamma + \beta\theta)^2\right]}{2\left[(4 + 2\lambda_R)\beta\eta - (\gamma + \beta\theta)^2\right]^2}. \quad (34)$$

5. Analysis and Discussion

Special Explanation. The precondition for the analysis and discussion below is $0 < (\gamma + \beta\theta)^2 < 2\beta\eta$, in other words, $0 < \theta < \left(\sqrt{2\beta\eta} - \gamma\right)/\beta$.

We give the precondition with the comprehensive consideration of four preconditions obtained from four scenarios. The precondition above suggests that in the emerging environmental protection industry, government will only provide limited subsidy for the manufacturer. Besides, government subsidy is relevant to R&D cost coefficient, the demand sensitivity coefficient to price, the consumers' green preference coefficient it will decrease as the R&D cost coefficient decreases and the consumers' green preference coefficient rises.

Next, we will first compare the relationship of equilibrium solutions in first two scenarios, then we will compare the relationship of equilibrium solutions among decentralized decision-making scenario not considering both parties' fairness preference behaviors, decentralized decision-making scenario only considering the manufacturer's fairness preference behavior and decentralized decision-making scenario only considering the retailer's fairness preference behavior. The four propositions we obtain are as follows (Proof. See Appendix B):

Proposition 1. *(1)* $g_1 > g_2$, $(\partial g_1/\partial\theta) > 0$, $(\partial g_2/\partial\theta) > 0$; *(2)* $\pi_{SC1} > \pi_{SC2}$, $(\partial\pi_{SC1}/\partial\theta) > 0$, $(\partial\pi_{SC2}/\partial\theta) > 0$; *(3) when* $0 < \left(\gamma^2/\beta\eta\right) < (1/2)$ *or when* $(1/2) < \left(\gamma^2/\beta\eta\right) < 1$ *and* $0 < \theta < \left(\beta\eta - \gamma^2\right)/\gamma\beta$, *then* $p_1 < p_2$; *when* $1 < \left(\gamma^2/\beta\eta\right) < 2$ *or when* $(1/2) < \left(\gamma^2/\beta\eta\right) < 1$ *and* $\left(\beta\eta - \gamma^2\right)/\gamma\beta < \theta < \left(\sqrt{2\beta\eta} - \gamma\right)/\beta$, *then* $p_1 > p_2$.

Proposition 1 shows that product green degree and green supply chain total profit in these two scenarios will increase as government subsidy increases. Product green degree and green supply chain total profit under centralized decision-making scenario are much higher than those under decentralized decision-making not considering both parties' fairness preference behavior. Besides, the relationship of retail price under these two decision scenarios is influenced by $\left(\gamma^2/\beta\eta\right)$ and θ at the same time. Based on previous researches, we define $\left(\gamma^2/\beta\eta\right)$ as the green product market expansion efficiency, and the larger the value of $\left(\gamma^2/\beta\eta\right)$, the more obvious the green product market expansion effect. When the green product market expansion efficiency is low $\left(0 < \left(\gamma^2/\beta\eta\right) < (1/2)\right)$ which means that consumers' response to green products is not obvious at this time, the retailer will try to expand the marginal profit to make up the loss of profit due to insufficient demand by increasing the retail price. When the green product market expansion efficiency is high $\left(1 < \left(\gamma^2/\beta\eta\right) < 2\right)$, the consumers' response to green products is so strong that the expansion effect of green products offsets the negative impact of a slight increase in retail price on the demand. However, when the green product market expansion efficiency is at a medium level $\left((1/2) < \left(\gamma^2/\beta\eta\right) < 1\right)$, the role of government subsidy can be highlighted at this time, the increase in government subsidy will effectively promote the retailer to lower retail price, and the effect of the increase in government subsidy at this time is equivalent to improving the green product market expansion efficiency indirectly.

Proposition 2. *(1)* $g_2 > g_3 > g_4$, $(\partial g_3/\partial\lambda_M) < 0$, $(\partial g_4/\partial\lambda_R) < 0$, $(\partial g_3/\partial\theta) > 0$, $(\partial g_4/\partial\theta) > 0$; *(2)* $w_3 > w_2 > w_4$, $(\partial w_3/\partial\lambda_M) > 0$, $(\partial w_4/\partial\lambda_R) > 0$.

Proposition 2 shows that product green degree will increase as government subsidy increases. To maintain its own profit, the manufacturer with fairness preference may increase the wholesale price to obtain higher marginal profit of products and meanwhile lower product green degree to reduce R&D cost. As the manufacturer's fairness-preference degree increases, the manufacturer's willingness to take this approach will be stronger and stronger.

Besides, it can effectively enhance the retailer's bargaining power if the retailer is fairness preference, and the higher the retailer's fairness-preference degree, the stronger its negotiation bargaining power will be, which will force the manufacturer to lower the wholesale price significantly and increase its marginal profit of products. At the same time, the manufacturer will reduce R&D cost due to the reduction in its marginal profit of products, which results in a significant reduction in product green degree.

It should be noted that the situation mentioned above will happen as long as the manufacturer or the retailer is fairness preference whatever the level of government subsidy. In other words, the emergence of the above situation will not be affected by government subsidy.

Proposition 3. *(1) when* $0 < \left(\gamma^2/\beta\eta\right) < (1/8)$, *if* $0 < \theta < (3\gamma/\beta)$,, *then* $p_4 < p_2 < p_3$, *if* $(3\gamma/\beta) < \theta < \left(\sqrt{2\beta\eta} - \gamma\right)/\beta$, *then* $p_2 < p_4 < p_3$ *when* $(1/8) < \left(\gamma^2/\beta\eta\right) < (1/2)$, *then* $p_4 < p_2 < p_3$; *when* $(1/2) < \left(\gamma^2/\beta\eta\right) < 1$, *if* $0 < \theta < \left(\beta\eta - \gamma^2\right)/\gamma\beta$, *then* $p_4 < p_2 < p_3$,, *if* $\left(\beta\eta - \gamma^2\right)/\gamma\beta < \theta < \left(\sqrt{2\beta\eta} - \gamma\right)/\beta$, *then* $p_4 < p_3 < p_2$; *when* $1 < \left(\gamma^2/\beta\eta\right) < 2$, *then* $p_4 < p_3 < p_2$; *(2) when* $1 < \left(\gamma^2/\beta\eta\right) < 2$, *then* $(\partial p_3/\partial\lambda_M) < 0$; *when* $0 < \left(\gamma^2/\beta\eta\right) < (1/2)$, *then* $(\partial p_3/\partial\lambda_M) > 0$; *when* $(1/2) < \left(\gamma^2/\beta\eta\right) < 1$, *if* $\left(\beta\eta - \gamma^2/\gamma\beta\right) < \theta < \left(\sqrt{2\beta\eta} - \gamma/\beta\right)$, *then* $(\partial p_3/\partial\lambda_M) < 0$, *if* $0 < \theta < \left(\beta\eta - \gamma^2\right)/\gamma\beta$, *then* $(\partial p_3/\partial\lambda_M) > 0$; *(3) when* $(1/8) < \left(\gamma^2/\beta\eta\right) < 2$, *then* $(\partial p_4/\partial\lambda_R) < 0$; *when* $0 < \left(\gamma^2/\beta\eta\right) < (1/8)$, *if* $(3\gamma/\beta) < \theta < \left(\sqrt{2\beta\eta} - \gamma\right)/\beta$, *then* $(\partial p_4/\partial\lambda_R) > 0$, *if* $0 < \theta < (3\gamma/\beta)$, *then* $(\partial p_4/\partial\lambda_R) < 0$.

Proposition 3 shows that the relationship of retail price under these three decision scenarios is influenced by $\left(\gamma^2/\beta\eta\right)$ and θ at the same time. When the green product market expansion efficiency is low $\left(0 < \left(\gamma^2/\beta\eta\right) < (1/2)\right)$, the manufacturer with fairness preference will significantly increase the wholesale price in order to maintain its own profit, which forces the retailer to significantly increase the retail price in order to maintain its marginal profit of products. It will be difficult to promote the retailer to lower the retail price effectively even if the government increases subsidy at this time. When the green product market expansion efficiency rises to a certain level $\left((1/2) < \left(\gamma^2/\beta\eta\right) < 1\right)$, the increase in government subsidy will effectively promote the retailer to lower the retail price. When the green product market expansion efficiency rises to a higher level $\left(1 < \left(\gamma^2/\beta\eta\right) < 2\right)$, the retail price will decline even if the government does not provide subsidy.

Besides, when the green product market expansion efficiency is very low $\left(0 < \left(\gamma^2/\beta\eta\right) < (1/8)\right)$ and the retailer is fairness preference, the increase in government subsidy will lead to a further increase in retail price at this time. This is because when the green product market expansion efficiency is low, the retailer is already raising retail price to get enough marginal profit, if the government subsidy to the manufacturer increases at this time, the retailer will transfer partial government subsidy by further increasing the retail price. However, when the green product market expansion efficiency rises to a certain level $\left((1/8) < \left(\gamma^2/\beta\eta\right) < 2\right)$, the retail price will decline even if the government does not provide subsidy.

In addition, because the manufacturer's fairness preference behavior greatly damages the retailer's profit, and with the increase in fairness-preference degree of the manufacturer, such damage will be more and more serious, the retailer will take different countermeasures to minimize the loss of its profit. When the green product market expansion efficiency is low $\left(0 < \left(\gamma^2/\beta\eta\right) < (1/2)\right)$, the retailer will try to expand marginal profit of products by increasing retail price. When the green product market expansion efficiency rises to a higher level $\left(1 < \left(\gamma^2/\beta\eta\right) < 2\right)$, the retailer will try to lower retail price in exchange for product sales. When the green product market expansion efficiency is at a medium level $\left((1/2) < \left(\gamma^2/\beta\eta\right) < 1\right)$, the role of government subsidy can be highlighted at this time, the retailer will also try to lower retail price in exchange for product sales, because the role of the increase in government subsidy at this time is equivalent to improving the green product market expansion efficiency indirectly.

Furthermore, the retailer's fairness preference behavior makes itself very sensitive to the fairness of profit distribution. when the green product market expansion efficiency is very low $\left(0 < \left(\gamma^2/\beta\eta\right) < (1/8)\right)$, if the government increases the subsidy to the manufacturer, as mentioned earlier, the retailer will transfer partial government subsidy by raising retail price, and as the fairness-preference degree of the retailer increases, this behavior will intensify, if the amount of government subsidy to the manufacturer is so small that the retailer' s income gained by increasing retail price is much lower than the income of lowering price to exchange product sales, the retailer will decisively choose the way of lowering retail price to maintain product sales. When the green product market expansion efficiency rises to a certain level $\left((1/8) < \left(\gamma^2/\beta\eta\right) < 2\right)$, at this time, the income gained by maintaining product sales is far greater than the income gained by increasing retail price to expand marginal profit of products, obviously, the retailer will try to maintain product sales by lowering retail price.

Proposition 4. *(1)* $\pi_{M2} > \pi_{M3} > \pi_{M4}$, $\left(\partial\pi_{M3}/\partial\lambda_M\right) < 0$, $\left(\partial\pi_{M4}/\partial\lambda_R\right) < 0$, $\left(\partial\pi_{M2}/\partial\theta\right) > 0$, $\left(\partial\pi_{M3}/\partial\theta\right) > 0$, $\left(\partial\pi_{M4}/\partial\theta\right) > 0$, $\left(\partial\pi_{R2}/\partial\theta\right) > 0$, $\left(\partial\pi_{R3}/\partial\theta\right) > 0$, $\left(\partial\pi_{R4}/\partial\theta\right) > 0$; *(2) when* $0 < \left((\gamma + \beta\theta)^2/\beta\eta\right) < \left(12 + 6\lambda_R - 2\sqrt{4 + 8\lambda_R + 3\lambda_R^2}\right)/(4 + 1.5\lambda_R)$, *then* $\pi_{R4} > \pi_{R2} > \pi_{R3}$, *when* $\left(12 + 6\lambda_R - 2\sqrt{4 + 8\lambda_R + 3\lambda_R^2}\right)/(4 + 1.5\lambda_R) < \left((\gamma + \beta\theta)^2/\beta\eta\right) < 2$, *then* $\pi_{R2} > \pi_{R4} > \pi_{R3}$; $\left(\partial\pi_{R3}/\partial\lambda_M\right) < 0$, *when* $(4 + 2\lambda_R)/(2 + 1.5\lambda_R) < \left((\gamma + \beta\theta)^2/\beta\eta\right) < 2$, *then* $\left(\partial\pi_{R4}/\partial\lambda_R\right) < 0$; *when* $0 < \left((\gamma + \beta\theta)^2/\beta\eta\right) < (4 + 2\lambda_R)/(2 + 1.5\lambda_R)$, *then* $\left(\partial\pi_{R4}/\partial\lambda_R\right) > 0$; *(3)* $\pi_{SC2} > \pi_{SC4} > \pi_{SC3}$, $\left(\partial\pi_{SC3}/\partial\lambda_M\right) < 0$, $\left(\partial\pi_{SC4}/\partial\lambda_R\right) < 0$, $\left(\partial\pi_{SC3}/\partial\theta\right) > 0$, $\left(\partial\pi_{SC4}/\partial\theta\right) > 0$.

Proposition 4 indicates the manufacturer's profit, the retailer's profit and green supply chain total profit can rise with government subsidy. The manufacturer's fairness preference behavior will damage the retailer's profit, it can also damage its own interests at the same time, and as the manufacturer's fairness-preference degree increases, the damage degree will intensify.

Besides, the retailer's fairness preference behavior will also seriously damage the manufacturer's profit, and as the fairness-preference degree of the retailer increases, the damage degree will also intensify. but the difference is that when the retailer is taking measures to punish the manufacturer and damage the manufacturer's profit, particularly, keeping other factors unchanged, if the fairness-preference degree of the retailer is lower and the amount of government subsidy is also smaller, then its profit may be higher than its fairness neutral, and if the fairness-preference degree of the retailer is higher and the amount of government subsidy is also bigger, then its profit may be lower than its fairness neutral. Similarly, keeping other factors unchanged, if the fairness-preference degree of the retailer is lower and the amount of government subsidy is also smaller, then its profit may increase as the fairness-preference degree of the retailer increases, if the fairness-preference degree of the retailer is higher and the amount of government subsidy is also bigger, then its profit may decline as the fairness-preference degree of the retailer increases.

Furthermore, both two parties' fairness preference behaviors can damage green supply chain total profit, when these two parties' fairness-preference degree is equal, the manufacturer's fairness preference behavior will cause more serious damage to green supply chain total profit than that caused by fairness preference behavior of the retailer.

6. Numerical Analysis

To verify the conclusions mentioned above and more intuitively reflect the joint impact of government subsidy coefficient, fairness preference coefficients of the manufacturer and the retailer on product green degree, product wholesale price and retail price, the profit of the manufacturer and the retailer, total profit of green supply chain, we give some numerical examples.

The parameters are specified as follows: $\alpha = 100$, $\beta = 1$, $c = 20$, $\eta = 10$, $\gamma = 3$, the parameters are in line with the research assumptions and realistic practice.

Special Explanation. To highlight the special target of this paper to reveal the impact difference between the fairness preference behaviors of the manufacturer and retailer on the equilibrium solutions, we will mainly concentrate on the latter two decision-making scenarios in this section. Besides, because here we fix the values of these parameters, we cannot fully present all cases gained in "Analysis and Discussion section", we will present the case according to the parameters' values.

(1) Sensitivity analysis of government subsidy coefficient, the fairness preference coefficients of the manufacturer and the retailer on product green degree.

Figure 1 shows that the product green degree increases with θ and decreases with λ_M and λ_R, and when $\lambda_M = \lambda_R$, there is always $g_1 > g_2 > g_3 > g_4$ whatever the level of government subsidy. But it is clear that as government subsidy gradually increases, the magnitude of decline in g_3 and g_4 gradually increases with λ_M and λ_R. This means that government increase in subsidy will aggravate the damage of both two parties' fairness preference behaviors to the product green degree to a certain extent.

(2) Sensitivity analysis of government subsidy coefficient, the fairness preference coefficients of the manufacturer and the retailer on the green products' wholesale price and retail price.

Figures 2 and 3 show that the wholesale price w_3 increases with λ_M and the wholesale price w_4 decreases with λ_R, and when $\lambda_M = \lambda_R$, there is always $w_3 > w_2 > w_4$ whatever the level of government subsidy. When the government subsidy coefficient is larger, the retail price p_3 decreases with λ_M and when the government subsidy coefficient is smaller, the retail price p_3 increases with λ_M. However, the retail price p_4 always decreases with λ_R whatever the level of government subsidy. Besides, as government subsidy gradually increases, the relationship gradually changes from $p_4 < p_1 < p_2 < p_3$ to $p_4 < p_3 < p_2 < p_1$ at this time, therefore, if the fairness preference degree of the manufacturer is higher, in order to ensure green products' retail price will not rise significantly, government should increase the subsidy to manufacturers at this time.

Figures 4 and 5 show that the difference between w_3 and p_3 decreases with λ_M, and the difference between w_4 and p_4 increases with λ_R whatever the level of government subsidy. It shows the decisions made by the manufacturer with fairness preference can reduce the marginal profit of the retailer, but the decisions made by the retailer with fairness preference will expand its own marginal profit.

(3) Sensitivity analysis of government subsidy coefficient, the fairness preference coefficients of the manufacturer and the retailer on the profit of the manufacturer and the retailer as well as green supply chain total profit.

Figures 6–8 show that the manufacturer's profit, retailer's profit and overall profit of green supply chain increase with θ, the manufacturer's profit and overall profit of green supply chain decrease with λ_M and λ_R whatever the level of government subsidy, the retailer's profit π_{R3} decreases with λ_M whatever the level of government subsidy, the retailer's profit π_{R4} increases with λ_R at this time, but the magnitude of increase in its profit is still not enough to offset the magnitude of decline in the manufacturer's profit. When $\lambda_M = \lambda_R$, there is always $\pi_{M2} > \pi_{M3} > \pi_{M4}$, $\pi_{SC1} > \pi_{SC2} > \pi_{SC4} > \pi_{SC3}$, $\pi_{R4} > \pi_{R3}$, $\pi_{R2} > \pi_{R3}$ whatever the level of government subsidy, and there is $\pi_{R4} > \pi_{R2}$ at this time. it shows that whether the manufacturer or the retailer is fairness preference, its decisions will damage the profit of the other party and the overall profit of green supply chain, and when their fairness-preference degrees are equal, the damage caused by the manufacturer's fairness preference behavior will be more serious compared with the retailer's fairness preference behavior. Besides, it is clear that as government subsidy gradually increases, the magnitude of decline in π_{M3}, π_{M4}, π_{R3}, π_{SC3}, and π_{SC4} gradually increases with λ_M and λ_R, and π_{R4} is gradually close to π_{R2} even if there is $\pi_{R4} > \pi_{R2}$ at this time. This means that government increases the level of subsidy to the manufacturer will aggravate the damage of both the manufacturer's and retailer's fairness preference behaviors to their own profit, the other party's profit and the overall profit of green supply chain indirectly to a certain extent.

Figures 9 and 10 show that π_{M3}, π_{R3}, and π_{SC3} decrease with λ_M whether the government subsidy is larger or smaller, and π_{M4} and π_{SC4} decrease with λ_R whether the government subsidy is larger or smaller. Besides, both two parties' decisions based on fairness preference behavior will increase the proportion of its own profit to the overall profit of green supply chain.

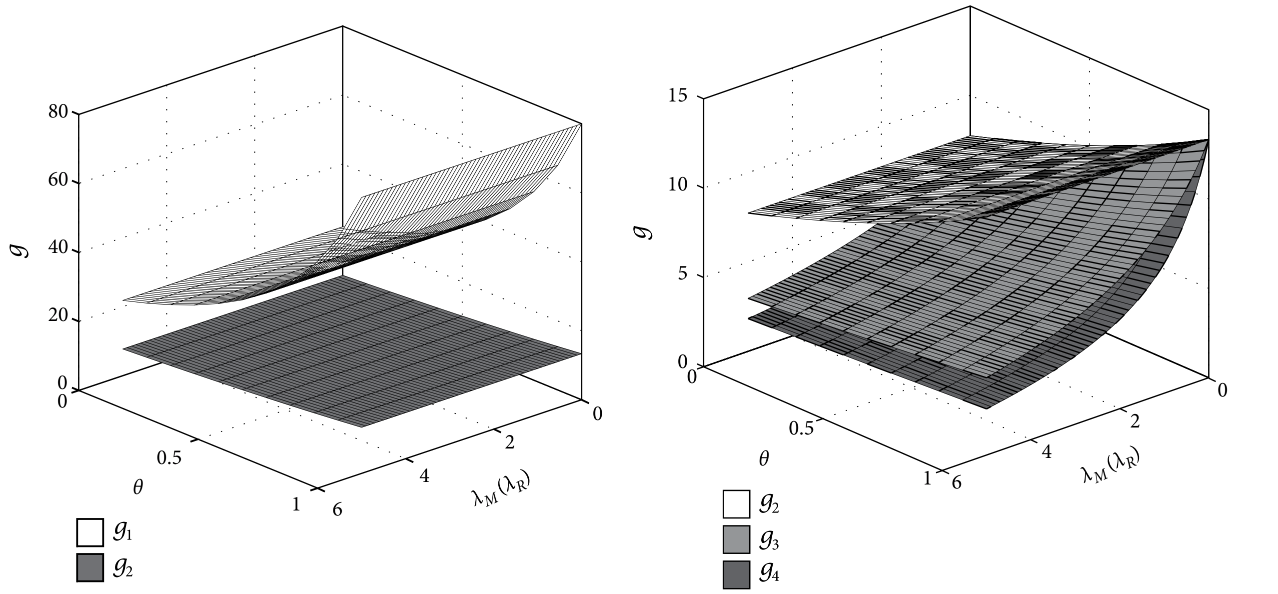
7. Conclusions and Limitations

Taking government subsidy, manufacturer's fairness preference behavior and retailer's fairness preference behavior into consideration, this paper obtains the equilibrium solutions under four decision-making scenarios and some valuable conclusions. In short, this paper mainly reveals how both two parties' fairness preference behaviors and the subsidy government provides for the manufacturer simultaneously affect the optimal product green degree, the wholesale price, the retail price, both two parties' profit, green supply chain total profit, and meanwhile this paper also reveals the impact difference between the manufacturer's fairness preference behavior and retailer's fairness preference behavior on the equilibrium solutions in the context of such subsidy.

To better demonstrate the research contribution of this article, here we will answer the questions raised above.

(1) How do the manufacturer's and retailer's fairness preference behaviors affect the two parties' optimal decisions when there is a government subsidy?

When only the manufacturer is fairness preference, product's green degree will decrease, while the wholesale price of green products will increase, the retail price has risen and fallen in these two cases depending on the government subsidy and the green product market expansion efficiency. Besides, when the manufacturer's fairness-preference degree increases, the product green degree will decrease,



(a)

(b)

Figure 1: The effect of θ, $\lambda_M(\lambda_R)$ on g.

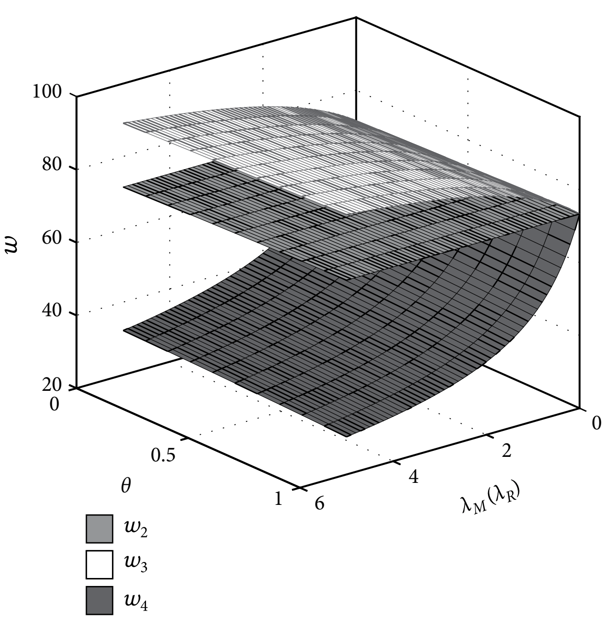


Figure 2: The effect of θ, $\lambda_M(\lambda_R)$ on w.

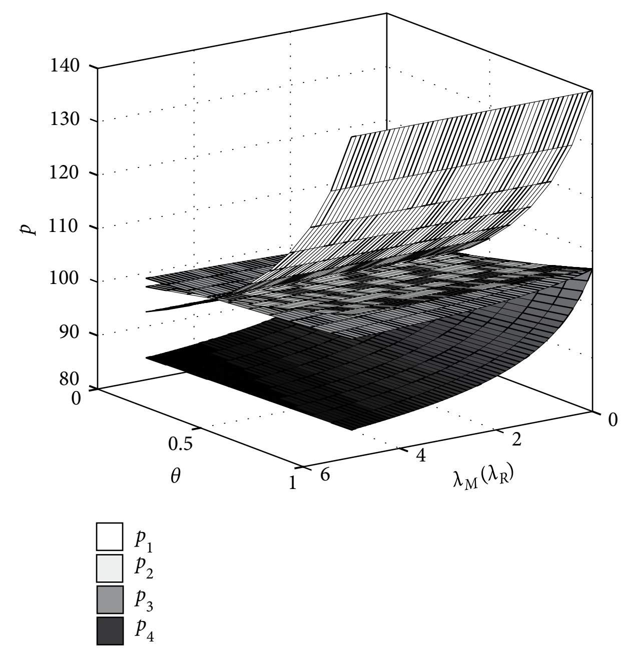


Figure 3: The effect of θ, $\lambda_M(\lambda_R)$ on p.

while the wholesale price will increase whatever the level of government subsidy, the retail price will have risen and fallen these two cases depending on the government subsidy and the green product market expansion efficiency.

When only the retailer has fairness preference behavior, the product's green degree and wholesale price will decrease, while the retail price will have both rising and falling cases depending on the government subsidy and the green product market expansion efficiency. Besides, when the retailer's fairness-preference degree increases, the product green degree and wholesale price will decrease whatever the level of government subsidy, while the retail price may increase or decrease depending on the government subsidy and the green product market expansion efficiency.

(2) How do the manufacturer's and retailer's fairness preference behaviors affect the two parties' optimal profit and green supply chain total profit when there is a government subsidy?

When only the manufacturer is fairness preference, its own profit, the profit of the retailer and green supply chain will decrease. Besides, when the manufacturer's

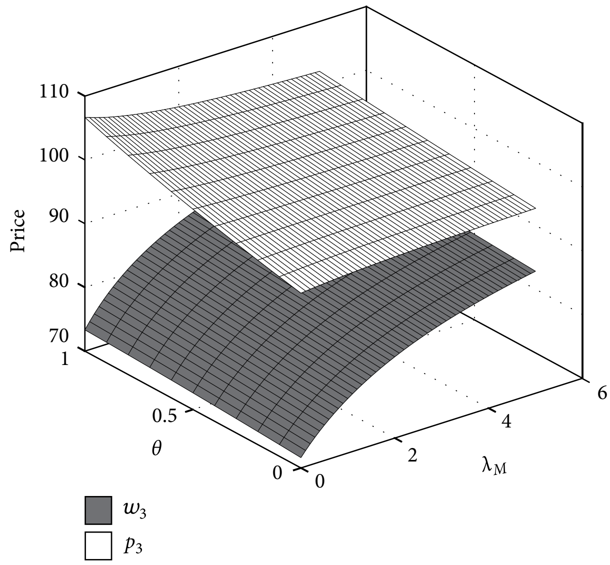


FIGURE 4: The effects of θ, λ_M on p_3 and w_3.

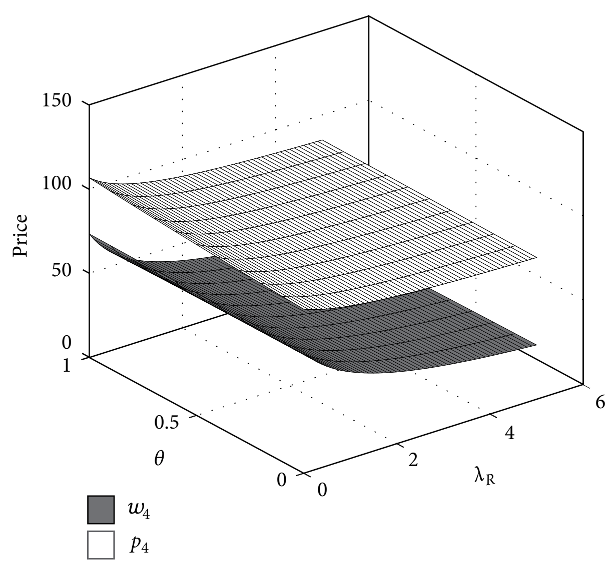


FIGURE 5: The effects of θ, λ_R on p_4 and w_4.

fairness-preference degree increases, its own profit, the profit of the retailer, and green supply chain will decrease.

When only the retailer has fairness preference behavior, the profit of the manufacturer and green supply chain will decrease, while its own profit will have both rising and falling cases depending on the government subsidy and the green product market expansion efficiency. Besides, when the retailer's fairness-preference degree increases, the profit of the manufacturer and green supply chain will decrease whatever the level of government subsidy, while its own profit may increase or decrease depending on the government subsidy and the green product market expansion efficiency.

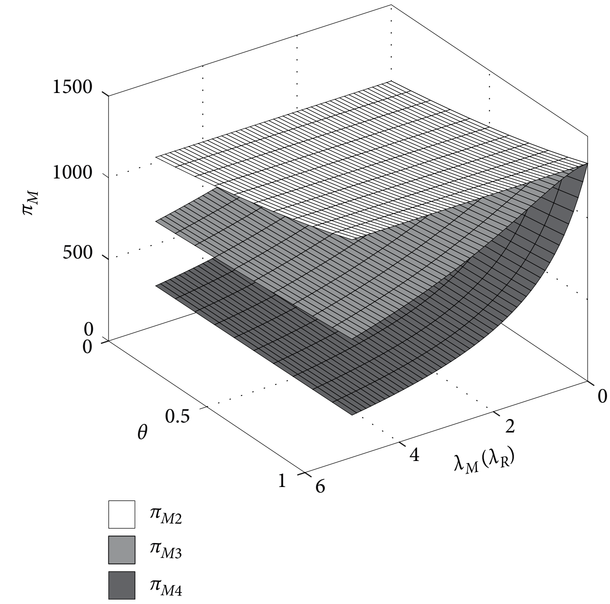


FIGURE 6: The effect of θ, $\lambda_M(\lambda_R)$ on π_M.

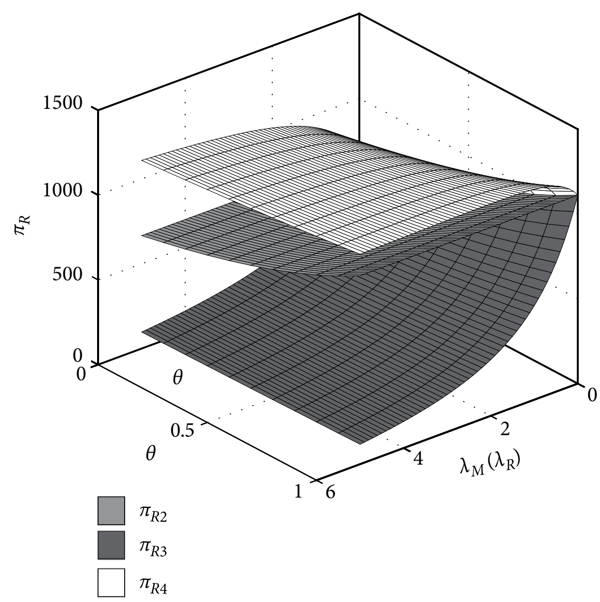
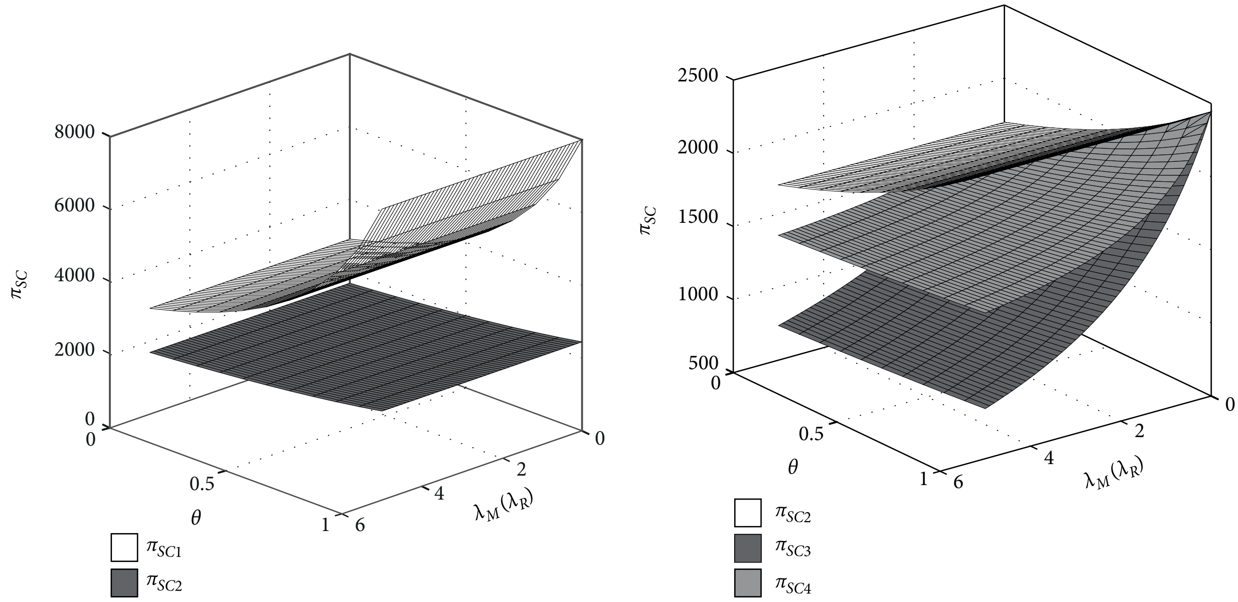


FIGURE 7: The effect of θ, $\lambda_M(\lambda_R)$ on π_R.

(3) What is the difference between the impacts of the two parties' fairness preference behaviors on equilibrium solutions when there is a government subsidy?

The fairness preference behaviors of the manufacturer and retailer are harmful to each other and the interests of green supply chain. The subsidy for the manufacturer and both two parties' fairness preference behaviors will cause a stack effect on the equilibrium results (such as product green degree, retailer's profit, manufacturer's profit and the total profit of green supply chain) which means that government subsidy to manufacturer can aggravate the negative influence caused by both



(a) (b)

Figure 8: The effect of θ, $\lambda_M(\lambda_R)$ on π_{SC}.

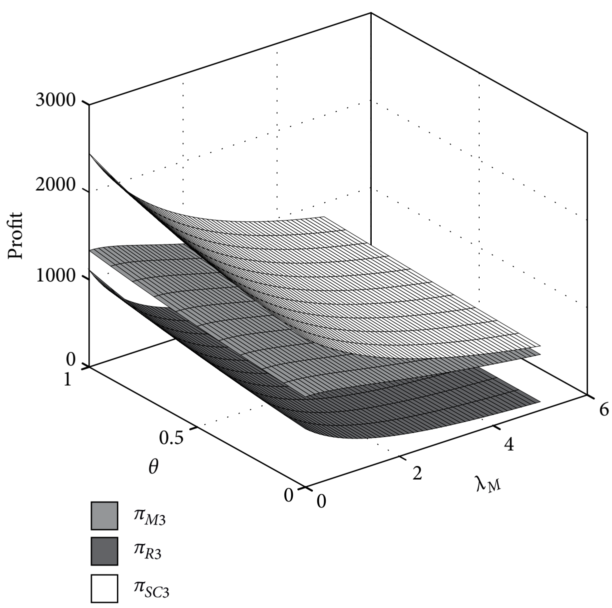


Figure 9: The effects of θ, λ_M on π_{M3}, π_{R3}, and π_{SC3}.

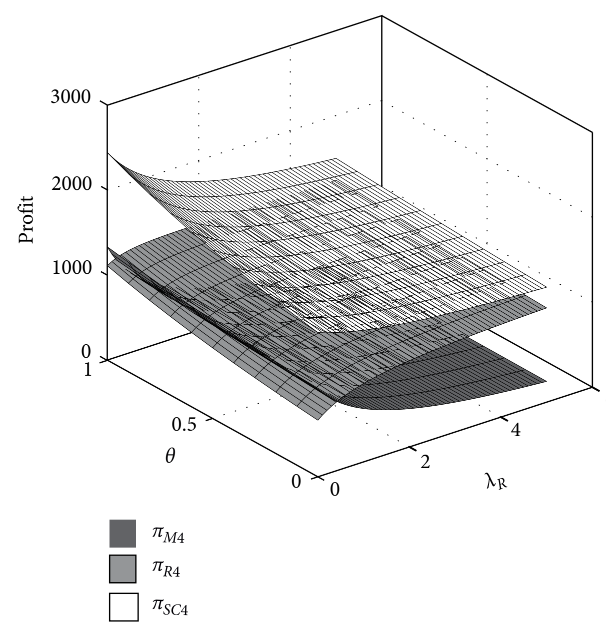


Figure 10: The effect of θ, λ_R on π_{M4}, π_{R4}, and π_{SC4}.

two parties' fairness preference behaviors. However, what the difference is that if manufacturer has fairness preference behavior, its profit is always lower compared with its fairness neutrality, but if the retailer has fairness preference behavior, there exists such a case where its profit with fairness-preference retailer is higher than that with fairness-neutral retailer under government subsidy. Besides, when the level of fairness preference between the two parties is equal, the retailer's fairness preference behavior will cause greater damage to the product green degree, but the fairness preference behavior of the manufacturer can lead to greater damage to green supply chain total profit.

Based on the above research conclusions, we can obtain some managerial insights:

Firstly, when the manufacturer or the retailer is fairness preference, government should not offer the manufacturer too much subsidy to avoid aggravating the negative impact of both parties' fairness preference behaviors on the product green degree, profit of both parties, and overall profit of green supply chain. Secondly, when the manufacturer is highly concerned about fairness, the government should increase subsidies to the manufacturer at this time to ensure that the retail price of green products in the market will not increase significantly. Finally, whether the manufacturer or the retailer has fairness preference behavior, the other party should be vigilant, and the government should also pay attention to the fairness preference behaviors of members of the green supply chain and provide appropriate subsidies at the appropriate time.

Our research has some limitations which needs future research for further discussion. Firstly, we only study a simple green supply chain composed of a manufacturer and a retailer. Future research can expand this single green supply chain to a green supply chain network including multiple manufacturers and retailers. Secondly, we only study the manufacturer-led green supply chain. Further research can study the green supply chain dominated by retailers. Third, we only consider decision makers' fairness preference. Further research can explore the impact of various preference behaviors on the green supply chain members' optimal decisions.

Data Availability

The data used to support the findings of this study titled "Optimal Decisions of a Green Supply Chain under the Joint Action of Fairness Preference and Subsidy to the Manufacturer" are included within the article. In addition, this article does not use any other data.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Appendix

A. Proof of Theorems 1–4

A.1. Proof of Theorem 1. Centralized Decision-Making Scenario. Taking the second derivatives of π_{SC} in formula (4) about p and g, we can get the Hessian matrix: $H = \begin{pmatrix} -2\beta & \gamma - \beta\theta \\ \gamma - \beta\theta & 2\theta\gamma - \eta \end{pmatrix}$. Observing the Hessian matrix, we can obtain the precondition for the existence of the optimal solutions is $(\gamma + \beta\theta)^2 - 2\beta\eta < 0$, which means that the Hessian matrix is negative definite, and meanwhile this verifies the objective function of π_{SC} is a joint concave function of p and g. Continue the solution process, we can get the optimal retail price $p_1 = ((\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(\alpha + \beta c))/\left((\gamma + \beta\theta)^2 - 2\beta\eta\right)$, the optimal product green degree $g_1 = ((\gamma + \beta\theta)(\beta c - \alpha))/\left((\gamma + \beta\theta)^2 - 2\beta\eta\right)$ and the optimal total profit of green supply chain $\left(\pi_{SC1} = \eta(\beta c - \alpha)^2\right)/\left(2\left[2\beta\eta - (\gamma + \beta\theta)^2\right]\right)$.

A.2. Proof of Theorem 2. Decentralized Decision-Making Scenario Not Considering Both Parties' Fairness Preference Behaviours. Firstly, we derive the first partial derivative of π_R in formula (3) on p and make it equal to 0, then we can get the reflection function of retailer's optimal retail price: $p = (\alpha + \gamma g + \beta w)/2\beta$. By substituting $p = (\alpha + \gamma g + \beta w)/2\beta$ into the formula (2) and taking the second derivatives of π_M in formula (2) about w and g, we can get the Hessian matrix: $H = \begin{pmatrix} -\beta & (\gamma - \beta\theta)/2 \\ (\gamma - \beta\theta)/2 & \gamma\theta - \eta \end{pmatrix}$. Observing the Hessian matrix, we can obtain the precondition for the existence of the optimal solutions is $(\gamma + \beta\theta)^2 - 4\beta\eta < 0$, which means that the Hessian matrix is negative definite, and meanwhile this verifies the objective function of π_M is a joint concave function of w and g. Continue the solution process, we can get the optimal wholesale price $w_2 = ((\gamma + \beta\theta)(\alpha\theta + \gamma c) - 2\eta(\alpha + \beta c))/\left((\gamma + \beta\theta)^2 - 4\beta\eta\right)$, the optimal product green degree $g_2 = ((\gamma + \beta\theta)(\beta c - \alpha))/\left((\gamma + \beta\theta)^2 - 4\beta\eta\right)$, the optimal retail price $p_2 = ((\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(3\alpha + \beta c))/(\gamma + \beta\theta)^2 - 4\beta\eta$, the manufacturer's optimal profit $\left(\pi_{M2} = \eta(\beta c - \alpha)^2\right)/(2[4\beta\eta - (\gamma + \beta\theta)^2])$, the retailer's optimal profit $\pi_{R2} = \beta\eta^2(\beta c - \alpha)^2/\left(\left[4\beta\eta - (\gamma + \beta\theta)^2\right]^2\right)$ and the optimal total profit of green supply chain $\pi_{SC2} = \left(\eta(\beta c - \alpha)^2\left[6\beta\eta - (\gamma + \beta\theta)^2\right]\right)/\left(2\left[4\beta\eta - (\gamma + \beta\theta)^2\right]^2\right)$.

A.3. Proof of Theorem 3. Decentralized Decision-Making Scenario Only Considering the Manufacturer's Fairness Preference Behaviour. Firstly, we derive the first partial derivative of π_R in formula (3) on p and make it equal to 0,then we can get the reflection function of retailer's optimal retail price $p = (\alpha + \gamma g + \beta w)/2\beta$. By substituting $p = (\alpha + \gamma g + \beta w)/2\beta$ into the formula (12) and taking the second derivatives of U_M in formula (12) about w and g, we can get the Hessian matrix:

$$H = \begin{pmatrix} -((4 + \lambda_M)(1 + \lambda_M)\beta)/(2(2 + \lambda_M)) & ((1 + \lambda_M)[(2 + \lambda_M)\gamma - 2\beta\theta])/(2(2 + \lambda_M)) \\ ((1 + \lambda_M)[(2 + \lambda_M)\gamma - 2\beta\theta])/(2(2 + \lambda_M)) & ((1 + \lambda_M)\left[4\gamma\beta\theta - 4\beta\eta - \lambda_M\gamma^2\right])/(2\beta(2 + \lambda_M)) \end{pmatrix}.$$

Observing the Hessian matrix above, we can obtain the precondition for the existence of the optimal solutions is $(\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta < 0$, *which means that the Hessian matrix is negative definite, and meanwhile this verifies the objective function of* U_M *is a joint concave function of* w and g. Continue the solution process, we can obtain the optimal wholesale price $w_3 = ((\gamma + \beta\theta)(\alpha\theta + \gamma c) - 2\eta(\alpha + \beta c) - \eta\lambda_M\alpha)/\left((\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta\right)$, the optimal product green degree $g_3 = ((\gamma + \beta\theta)(\beta c - \alpha))/(\gamma + \beta\theta)^2 - (4 + \lambda_M)\beta\eta$, the optimal retail price $p_3 = ((\gamma + \beta\theta)(\alpha\theta + \gamma c) - \eta(3\alpha + \lambda_M\alpha + \beta c))/\left((\gamma + \beta\theta)^2\left(- (4 + \lambda_M)\beta\eta\right)\right.$, the manufacturer's optimal profit $\pi_{M3} = \left(\eta(\beta c - \alpha)^2\left[(4 + 2\lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]\right)/\left(2\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2\right)$, the retailer's optimal profit $\pi_{R3} = \left(\beta\eta^2(\beta c - \alpha)^2\right)/\left(\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2\right)$ and the optimal total profit of the green supply chain $\pi_{SC3} = \left(\eta(\beta c - \alpha)^2\left[(6 + 2\lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]\right)/\left(2\left[(4 + \lambda_M)\beta\eta - (\gamma + \beta\theta)^2\right]^2\right)$.

A.4. Proof of Theorem 4 Decentralized Decision-Making Scenario Only Considering the Retailer's Fairness Preference Behaviour. Firstly, by solving the first order partial derivative of U_R in formula (13) about p, we can get the reflection function of the retailer's optimal retail price $p = (2\alpha + (2\gamma + \lambda_R\beta\theta)g + (2\beta + \lambda_R\beta)w - \lambda_R\beta c)/4\beta$.
By substituting the reflection function of the retailer's optimal retail price into the formula (2) and taking the second derivatives of π_M in formula (2) about w and g, we can get the Hessian matrix

$H = \begin{pmatrix} -((2+\lambda_R)\beta)/2 & (\gamma-(1+\lambda_R)\beta\theta)/2 \\ (\gamma-(1+\lambda_R)\beta\theta)/2 & ((2\gamma-\lambda_R\beta\theta)\theta-2\eta)/2 \end{pmatrix}$. Observing the Hessian matrix, we can obtain the precondition for the existence of the optimal solutions is $(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta<0$, which means that the Hessian matrix is negative definite, and meanwhile this verifies the objective function of π_M is a joint concave function of w and g. Continue the solution process, we can obtain the optimal wholesale price $w_4=((\gamma+\beta\theta)(\alpha\theta+\gamma c)-2\eta(\alpha+\beta c+\lambda_R\beta c))/(\gamma+\beta\theta)^2$ $(-(4+2\lambda_R)\beta\eta)$ the optimal product green degree $g_4=((\gamma+\beta\theta)(\beta c-\alpha))/\left((\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right)$ the optimal retail price $(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta$ the manufacturer's optimal profit $\pi_{M4}=\left(\eta(\beta c-\alpha)^2\right)/\left(2\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]\right)$, the retailer's optimal profit $\pi_{R4}=\left(\beta\eta^2(\beta c-\alpha)^2(1+0.5\lambda_R)\right.$ $\left.(1+1.5\lambda_R)\right)/\left(\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2\right)$ and the optimal total profit of the green supply chain $\pi_{SC4}=\left(\eta(\beta c-\alpha)^2\left[1.5\beta\eta(\lambda_R+2)^2\right.\right.$ $\left.\left.-(\gamma+\beta\theta)^2\right]\right)/\left(2\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2\right)$.

B. Proof of Propositions 1–4

B.1. Proof of Proposition 1. According to formula (15) and (18), we can obtain:

$$\frac{g_1}{g_2}=\frac{4\beta\eta-(\gamma+\beta\theta)^2}{2\beta\eta-(\gamma+\beta\theta)^2}>1. \tag{B.1.1}$$

The first derivatives of g_1 and g_2 on θ are as follows:

$$\frac{\partial g_1}{\partial\theta}=\frac{\beta(\alpha-\beta c)\left[(\gamma+\beta\theta)^2+2\beta\eta\right]}{\left[(\gamma+\beta\theta)^2-2\beta\eta\right]^2}>0, \tag{B.1.2}$$

$$\frac{\partial g_2}{\partial\theta}=\frac{\beta(\alpha-\beta c)\left[(\gamma+\beta\theta)^2+4\beta\eta\right]}{\left[(\gamma+\beta\theta)^2-4\beta\eta\right]^2}>0. \tag{B.1.3}$$

According to formula (16) and (22), we can obtain:

$$\frac{\pi_{SC1}}{\pi_{SC2}}=\frac{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2-4\beta^2\eta^2}>1. \tag{B.1.4}$$

The first derivative of π_{SC1} and π_{SC2} on θ is as follows:

$$\frac{\partial\pi_{SC1}}{\partial\theta}=\frac{\beta\eta(\alpha-\beta c)^2(\gamma+\beta\theta)}{\left[2\beta\eta-(\gamma+\beta\theta)^2\right]^2}>0, \tag{B.1.5}$$

$$\frac{\partial\pi_{SC2}}{\partial\theta}=\frac{\beta\eta(\alpha-\beta c)^2\left[8\beta\eta-(\gamma+\beta\theta)^2\right]}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^3}>0. \tag{B.1.6}$$

According to formula (14) and (19), we can obtain:

$$p_1-p_2=\frac{2\eta(\alpha-\beta c)\left(\gamma^2+\gamma\beta\theta-\beta\eta\right)}{\left[2\beta\eta-(\gamma+\beta\theta)^2\right]\left[4\beta\eta-(\gamma+\beta\theta)^2\right]}. \tag{B.1.7}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$ when $0<\left(\gamma^2/\beta\eta\right)<(1/2)$, we can obtain $\gamma^2+\gamma\beta\theta-\beta\eta<0$, then $p_1<p_2$; when $1<\left(\gamma^2/\beta\eta\right)<2$, $\gamma^2+\gamma\beta\theta-\beta\eta>0$, then $p_1>p_2$; when $(1/2)<\left(\gamma^2/\beta\eta\right)<1$, let $\gamma^2+\gamma\beta\theta-\beta\eta>0$, we can obtain $\left(\beta\eta-\gamma^2\right)/\gamma\beta<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $p_1>p_2$, let $\gamma^2+\gamma\beta\theta-\beta\eta<0$, we can obtain $0<\theta<\left(\beta\eta-\gamma^2\right)/\gamma\beta$, then $p_1<p_2$.

B.2. Proof of Proposition 2. According to formula (18), (24), (30), we can obtain:

$$\frac{g_2}{g_3}=\frac{(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2}{4\beta\eta-(\gamma+\beta\theta)^2}>1, \tag{B.2.1}$$

$$\frac{g_2}{g_4}=\frac{(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2}{4\beta\eta-(\gamma+\beta\theta)^2}>1. \tag{B.2.2}$$

When $\lambda_M=\lambda_R$ there is $(g_3/g_4)=\left((4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right)$ $\left(/(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right)>1$.

The first derivatives of g_3 and g_4 on λ_M, λ_R respectively are as follows:

$$\frac{\partial g_3}{\partial\lambda_M}=\frac{-\beta\eta(\gamma+\beta\theta)(\alpha-\beta c)}{\left[(\gamma+\beta\theta)^2-(4+\lambda_M)\beta\eta\right]^2}<0, \tag{B.2.3}$$

$$\frac{\partial g_4}{\partial\lambda_R}=\frac{-2\beta\eta(\gamma+\beta\theta)(\alpha-\beta c)}{\left[(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right]^2}<0, \tag{B.2.4}$$

The first derivatives of g_3 and g_4 on θ are as follows:

$$\frac{\partial g_3}{\partial\theta}=\frac{\beta(\alpha-\beta c)\left[(\gamma+\beta\theta)^2+(4+\lambda_M)\beta\eta\right]}{\left[(\gamma+\beta\theta)^2-(4+\lambda_M)\beta\eta\right]^2}>0, \tag{B.2.5}$$

$$\frac{\partial g_4}{\partial\theta}=\frac{\beta(\alpha-\beta c)\left[(\gamma+\beta\theta)^2+(4+2\lambda_R)\beta\eta\right]}{\left[(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right]^2}>0. \tag{B.2.6}$$

According to formula (17), (23), (29), we can obtain:

$$w_2-w_3=\frac{\lambda_M\eta(\alpha-\beta c)\left(\gamma^2+\gamma\beta\theta-2\beta\eta\right)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]}. \tag{B.2.7}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we can obtain $\gamma^2+\gamma\beta\theta-2\beta\eta<0$, then $w_3>w_2$.

$$w_2-w_4=\frac{2\lambda_R\eta(\alpha-\beta c)\left(2\beta\eta-\beta^2\theta^2-\gamma\beta\theta\right)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]}. \tag{B.2.8}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we can obtain $2\beta\eta-\beta^2\theta^2-\gamma\beta\theta>0$, then $w_2>w_4$.

The first derivative of w_3 on λ_M is as follows:

$$\frac{\partial w_3}{\partial\lambda_M}=\frac{\eta(\alpha-\beta c)\left(2\beta\eta-\gamma\beta\theta-\gamma^2\right)}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2}. \tag{B.2.9}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we can obtain $2\beta\eta-\gamma\beta\theta-\gamma^2>0$, then $(\partial w_3/\partial\lambda_M)>0$.

The first derivative of w_4 on λ_R is as follows:

$$\frac{\partial w_4}{\partial \lambda_R} = \frac{2\beta\eta(\alpha-\beta c)\left(\beta\theta^2+\gamma\theta-2\eta\right)}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2}. \quad \text{(B.2.10)}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we can obtain $\beta\theta^2+\gamma\theta-2\eta<0$, then $\partial w_4/\partial\lambda_R<0$.

B.3. Proof of Proposition 3. According to formula (19), (25), (31), we can obtain:

$$p_2-p_3=\frac{\lambda_M\eta(\alpha-\beta c)\left(\gamma^2+\gamma\beta\theta-\beta\eta\right)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]}. \quad \text{(B.3.1)}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we have: when $0<\left(\gamma^2/\beta\eta\right)<(1/2)$, there is $\gamma^2+\gamma\beta\theta-\beta\eta<0$, then $p_2<p_3$; when $1<\left(\gamma^2/\beta\eta\right)<2$, there is $\gamma^2+\gamma\beta\theta-\beta\eta>0$, the $p_2>p_3$; when $(1/2)<\left(\gamma^2/\beta\eta\right)<1$, let $\gamma^2+\gamma\beta\theta-\beta\eta>0$, we can obtain $\left(\beta\eta-\gamma^2\right)/\gamma\beta<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $p_2>p_3$, let $\gamma^2+\gamma\beta\theta-\beta\eta<0$, we can obtain $0<\theta<\left(\beta\eta-\gamma^2\right)/\gamma\beta$, then $p_2<p_3$.

$$p_2-p_4=\frac{0.5\lambda_R\eta(\alpha-\beta c)(\gamma+\beta\theta)(3\gamma-\beta\theta)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]}. \quad \text{(B.3.2)}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we have: when $(1/8)<\left(\gamma^2/\beta\eta\right)<2$, there is $3\gamma-\beta\theta>0$, then $p_2>p_4$; when $0<\left(\gamma^2/\beta\eta\right)<(1/8)$, let $3\gamma-\beta\theta>0$, we can obtain $0<\theta<(3\gamma/\beta)$, then $p_2>p_4$, let $3\gamma-\beta\theta<0$, we can obtain $(3\gamma/\beta)<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $p_4>p_2$.

When $\lambda_M=\lambda_R=\lambda$, $p_3-p_4=\left(\lambda\eta\left[(1+0.5\lambda)\beta\eta+0.5(\gamma+\beta\theta)^2-\beta\theta(\gamma+\beta\theta)\right]\right)/\left[(4+\lambda)\beta\eta-(\gamma+\beta\theta)^2\right]\left[(4+2\lambda)\beta\eta-(\gamma+\beta\theta)^2\right]>0$.

Summarizing the above conclusions, we can obtain: when $0<\left(\gamma^2/\beta\eta\right)<(1/8)$, if $0<\theta<(3\gamma/\beta)$, then $p_4<p_2<p_3$, if $(3\gamma/\beta)<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $p_2<p_4<p_3$; when $(1/8)<\left(\gamma^2/\beta\eta\right)<(1/2)$, then $p_4<p_2<p_3$; when $(1/2)<\left(\gamma^2/\beta\eta\right)<1$, if $0<\theta<\left(\beta\eta-\gamma^2/\gamma\beta\right)$, then $p_4<p_2<p_3$, if $\left(\beta\eta-\gamma^2/\gamma\beta\right)<\theta<\left(\sqrt{2\beta\eta}-\gamma/\beta\right)$, then $p_4<p_3<p_2$; when $1<\left(\gamma^2/\beta\eta\right)<2$, then $p_4<p_3<p_2$.

The first derivative of p_3 on λ_M is as follows:

$$\frac{\partial p_3}{\partial\lambda_M}=\frac{\eta(\alpha-\beta c)\left(\beta\eta-\gamma\beta\theta-\gamma^2\right)}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2}. \quad \text{(B.3.3)}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we have: when $1<\left(\gamma^2/\beta\eta\right)<2$, we can obtain $\beta\eta-\gamma\beta\theta-\gamma^2<0$, then $\left(\partial p_3/\partial\lambda_M\right)<0$; when $0<\left(\gamma^2/\beta\eta\right)<(1/2)$, we can obtain $\beta\eta-\gamma\beta\theta-\gamma^2>0$, then $\left(\partial p_3/\partial\lambda_M\right)>0$; when $(1/2)<\left(\gamma^2/\beta\eta\right)<1$, let $\beta\eta-\gamma\beta\theta-\gamma^2<0$, we can obtain $\left(\beta\eta-\gamma^2\right)/\gamma\beta<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $\left(\partial p_3/\partial\lambda_M\right)<0$, let $\beta\eta-\gamma\beta\theta-\gamma^2>0$, we can obtain $0<\theta<\left(\beta\eta-\gamma^2\right)/\gamma\beta$, then $\left(\partial p_3/\partial\lambda_M\right)>0$.

The first derivative of p_4 on λ_R is as follows:

$$\frac{\partial p_4}{\partial\lambda_R}=\frac{0.5\eta(\alpha-\beta c)(\gamma+\beta\theta)(\beta\theta-3\gamma)}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2}. \quad \text{(B.3.4)}$$

According to the precondition $0<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, we have: when $(1/8)<\left(\gamma^2/\beta\eta\right)<2$, we can obtain $\beta\theta-3\gamma<0$, then $\left(\partial p_4/\partial\lambda_R\right)<0$; when $0<\left(\gamma^2/\beta\eta\right)<(1/8)$, let $\beta\theta-3\gamma>0$, we can obtain $(3\gamma/\beta)<\theta<\left(\sqrt{2\beta\eta}-\gamma\right)/\beta$, then $\left(\partial p_4/\partial\lambda_R\right)>0$; let $\beta\theta-3\gamma<0$, we can obtain $0<\theta<(3\gamma/\beta)$ then $\left(\partial p_4/\partial\lambda_R\right)<0$.

B.4. Proof of Proposition 4. According to formula (20), (26), (32), we can obtain:

$$\frac{\pi_{M2}}{\pi_{M3}}=\frac{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2-\lambda_M^2\beta^2\eta^2}>1, \quad \text{(B.4.1)}$$

$$\frac{\pi_{M2}}{\pi_{M4}}=\frac{(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2}{4\beta\eta-(\gamma+\beta\theta)^2}>1. \quad \text{(B.4.2)}$$

When $\lambda_M=\lambda_R$, then $(\pi_{M3}/\pi_{M4})=\left(\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2\right)/\left(\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2\right)>1$;

The first derivatives of π_{M3}, π_{M4} on λ_M, λ_R respectively are as follows:

$$\frac{\partial\pi_{M3}}{\partial\lambda_M}=\frac{\lambda_M\beta^2\eta^3(\beta c-\alpha)^2}{\left[(\gamma+\beta\theta)^2-(4+\lambda_M)\beta\eta\right]^3}<0, \quad \text{(B.4.3)}$$

$$\frac{\partial\pi_{M4}}{\partial\lambda_R}=\frac{-\beta\eta^2(\beta c-\alpha)^2}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2}<0. \quad \text{(B.4.4)}$$

The first derivatives of π_{M2}, π_{M3}, π_{M4} on θ respectively are as follows:

$$\frac{\partial\pi_{M2}}{\partial\theta}=\frac{\beta\eta(\beta c-\alpha)^2(\gamma+\beta\theta)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2}>0, \quad \text{(B.4.5)}$$

$$\frac{\partial\pi_{M3}}{\partial\theta}=\frac{2\beta\eta(\gamma+\beta\theta)(\beta c-\alpha)^2\left[(4+3\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^3}>0, \quad \text{(B.4.6)}$$

$$\frac{\partial\pi_{M4}}{\partial\theta}=\frac{\beta\eta(\beta c-\alpha)^2(\gamma+\beta\theta)}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2}>0. \quad \text{(B.4.7)}$$

According to formula (21), (27), (33), we can obtain:

The first derivatives of π_{R2}, π_{R3}, π_{R4} on θ are as follows:

$$\frac{\partial\pi_{R2}}{\partial\theta}=\frac{4\beta^2\eta^2(\beta c-\alpha)^2(\gamma+\beta\theta)}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^3}>0, \quad \text{(B.4.8)}$$

$$\frac{\partial\pi_{R3}}{\partial\theta}=\frac{4\beta^2\eta^2(\beta c-\alpha)^2(\gamma+\beta\theta)}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^3}>0, \quad \text{(B.4.9)}$$

$$\frac{\partial\pi_{R4}}{\partial\theta} = \frac{4\beta^2\eta^2(\beta c-\alpha)^2(\gamma+\beta\theta)(1+0.5\lambda_R)(1+1.5\lambda_R)}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^3} > 0. \tag{B.4.10}$$

According to formula (21), (27), (33), we can obtain:

$$\frac{\pi_{R2}}{\pi_{R3}} = \frac{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^2}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2} > 1, \tag{B.4.11}$$

$$\frac{\pi_{R3}}{\pi_{R4}} = \frac{\left[(\gamma+\beta\theta)^2-(4+2\lambda)\beta\eta\right]^2}{(1+0.5\lambda)(1+1.5\lambda)\left[(\gamma+\beta\theta)^2-(4+\lambda)\beta\eta\right]^2}. \tag{B.4.12}$$

According to the precondition $(\gamma+\beta\theta)^2-2\beta\eta<0$, when $\lambda_M=\lambda_R$, we can obtain $\pi_{R3}/\pi_{R4}<1$.

$$\frac{\pi_{R2}}{\pi_{R4}} = \frac{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^2+\left(16\lambda_R+8\lambda_R^2\right)\beta^2\eta^2+\left(2\lambda_R+0.75\lambda_R^2\right)(\gamma+\beta\theta)^4-\left(12\lambda_R+6\lambda_R^2\right)(\gamma+\beta\theta)^2\beta\eta}. \tag{B.4.13}$$

According to the precondition $(\gamma+\beta\theta)^2-2\beta\eta<0$, we can obtain: when $0<\left((\gamma+\beta\theta)^2\right)/\beta\eta<\left(12+6\lambda_R-2\sqrt{4+8\lambda_R+3\lambda_R^2}\right)/(4+1.5\lambda_R)$, then $\pi_{R4}>\pi_{R2}$; when $\left(12+6\lambda_R-2\sqrt{4+8\lambda_R+3\lambda_R^2}\right)(4+1.5\lambda_R)<\left((\gamma+\beta\theta)^2\right)/\beta\eta<2$, then $\pi_{R2}>\pi_{R4}$.

The first derivatives of π_{R3}, π_{R4} on λ_M, λ_R respectively are as follows:

$$\frac{\partial\pi_{R3}}{\partial\lambda_M} = \frac{2\beta^2\eta^3(\beta c-\alpha)^2}{\left[(\gamma+\beta\theta)^2-(4+\lambda_M)\beta\eta\right]^3} < 0, \tag{B.4.14}$$

$$\frac{\partial\pi_{R4}}{\partial\lambda_R} = \frac{\beta\eta^2(\beta c-\alpha)^2\left[(2+1.5\lambda_R)(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right]}{\left[(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right]^3}. \tag{B.4.15}$$

According to the precondition $(\gamma+\beta\theta)^2-2\beta\eta<0$, we can obtain: when $(4+2\lambda_R)/(2+1.5\lambda_R)<\left((\gamma+\beta\theta)^2\right)/\beta\eta<2$, then $\partial\pi_{R4}/\partial\lambda_R<0$; when $0<\left((\gamma+\beta\theta)^2\right)/\beta\eta<(4+2\lambda_R)/(2+1.5\lambda_R)$, then $\partial\pi_{R4}/\partial\lambda_R>0$.

According to formula (22), (28), (34), we can obtain:

$$\frac{\pi_{SC2}}{\pi_{SC3}} = 1+\frac{\lambda_M\beta\eta\left[(16+6\lambda_M)\beta^2\eta^2-(4+\lambda_M)(\gamma+\beta\theta)^2\beta\eta\right]}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2\left[(6+2\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]}, \tag{B.4.16}$$

$$\frac{\pi_{SC2}}{\pi_{SC4}} = 1+\frac{\lambda_R\beta\eta(\gamma+\beta\theta)^2\left[(8+8\lambda_R)\beta\eta-(2+1.5\lambda_R)(\gamma+\beta\theta)^2\right]}{\left[4\beta\eta-(\gamma+\beta\theta)^2\right]^2\left[1.5(\lambda_R+2)^2\beta\eta-(\gamma+\beta\theta)^2\right]}. \tag{B.4.17}$$

According to the precondition $(\gamma+\beta\theta)^2-2\beta\eta<0$, we can obtain: $(\pi_{SC2}/\pi_{SC3})>1$, $(\pi_{SC2}/\pi_{SC4})>1$.

$$\frac{\pi_{SC3}}{\pi_{SC4}} = \frac{\left[(6+2\lambda)\beta\eta-(\gamma+\beta\theta)^2\right]\left[(\gamma+\beta\theta)^2-(4+2\lambda)\beta\eta\right]^2}{\left[(\gamma+\beta\theta)^2-(4+\lambda)\beta\eta\right]^2\left[1.5(\lambda+2)^2\beta\eta-(\gamma+\beta\theta)^2\right]}. \tag{B.4.18}$$

According to the precondition $(\gamma+\beta\theta)^2-2\beta\eta<0$, when $\lambda_M=\lambda_R$we can obtain: $(\pi_{SC3}/\pi_{SC4})<1$.

The first derivatives of π_{SC3}, π_{SC4} on λ_M, λ_R respectively are as follows:

$$\frac{\partial\pi_{SC3}}{\partial\lambda_M} = \frac{(2+\lambda_M)\beta^2\eta^3(\beta c-\alpha)^2}{\left[(\gamma+\beta\theta)^2-(4+\lambda_M)\beta\eta\right]^3} < 0, \tag{B.4.19}$$

$$\frac{\partial\pi_{SC4}}{\partial\lambda_R} = \frac{\beta\eta^2(\beta c-\alpha)^2(2+3\lambda_R)(\gamma+\beta\theta)^2}{2\left[(\gamma+\beta\theta)^2-(4+2\lambda_R)\beta\eta\right]^3} < 0. \tag{B.4.20}$$

The first derivatives of π_{SC3}, π_{SC4} on θ are as follows:

$$\frac{\partial\pi_{SC3}}{\partial\theta} = \frac{\beta\eta(\beta c-\alpha)^2(\gamma+\beta\theta)\left[8\beta\eta+3\lambda_M\beta\eta-(\gamma+\beta\theta)^2\right]}{\left[(4+\lambda_M)\beta\eta-(\gamma+\beta\theta)^2\right]^3} > 0, \tag{B.4.21}$$

$$\frac{\partial\pi_{SC4}}{\partial\theta} = \frac{\beta\eta(\beta c-\alpha)^2(\gamma+\beta\theta)\left[\beta\eta(\lambda_R+2)(3\lambda_R+4)-(\gamma+\beta\theta)^2\right]}{\left[(4+2\lambda_R)\beta\eta-(\gamma+\beta\theta)^2\right]^3} > 0. \tag{B.4.22}$$

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