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External Intervention or Internal Coordination? Incentives to Promote Sustainable Development through Green Supply Chains

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Abstract: To encourage firms to engage in green production, two different types of investment funding, namely external funds from agencies outside the supply chain (e.g., government subsidy), and internal funds from supply chain partners (e.g., greening cost-sharing with the retailer), are investigated in this paper. Based on game theory, the decision-making behavior and profits of a competitive supply chain consisting of a green manufacturer, a regular manufacturer, and a retailer are analyzed under both funding schemes. The results show that while both government subsidy and greening cost-sharing contract can achieve the goals of increasing a product's degree of greenness and increasing the sales of green products, there are differences between these two methods in reaching these goals. Further, both via theoretical and numerical analysis, we find that although both the green manufacturer and the retailer can greatly benefit from government subsidy and greening cost-sharing contract, they may have different preferences regarding these two methods, which are mainly related to the size of the government subsidy, the fraction of greening cost-sharing with the retailer, the Research and Development (R&D) cost coefficient, the greenness sensitivity coefficient, and price sensitivity coefficient. Finally, the supply chain members' behaviors (including the production and pricing decisions and, the choice of funds investment) are largely affected by the government subsidy mechanism.

Keywords: green supply chain; R&D cost; government subsidy; greening cost-sharing contract

1. Introduction

More and more people have recognized the significance of sustainable development because of the frequent occurrence of extreme weather events, the shortage of resources, as well as consumers' increasing awareness of environmental protection, which impels the rapid development of green production and a low-carbon economy [1,2]. It is reported that a growing number of consumers favor green and environment-friendly products as a result of their increasing environmental awareness. According to an investigation conducted by European Commission in 2008, the proportion of Europeans who are willing to purchase green products had increased by 31% (from 44% to 75%) in three years [3]. As a result, more and more enterprises now seek to promote sustainable development through both their products and their production techniques. However, the associated additional costs, e.g., R&D cost, and huge risks, e.g., demand uncertainty, diminish most firms' enthusiasm for green technology and green products. Furthermore, because firms generally seek to maximize profit, they will want to charge a higher price for a green product and to minimize the product's degree of 'greenness' in order to reduce costs (as greener products are generally more expensive to make), whereas consumers prefer a product that is as green as possible but at a lower price. This contradiction restrains the development of green products and processes, not to mention sustainable development more generally. Nonetheless, firms need to find adequate funds for their investment in sustainable development.

The issue of how to encourage firms to implement green technological innovation and offer green products has received much attention. Two methods have been widely employed and well-studied. First, external funds (i.e., from agencies outside the supply chain), such as a government subsidy, can be regarded as an effective method to support firms [4–6]. For example, the US government had subsidized the production of electric vehicles (EVs) and offered a $7500 tax credit to consumers who purchase them [7]. Similarly, the Chinese government has provided financial support to encourage consumers to buy new low-energy vehicles since 2015, and has also encouraged firms to offer green products [8]. Second, internal funds (e.g., greening cost-sharing between the members of a supply chain) is another method that can help firms to switch to the manufacture of green products [9–11].

In this paper, we consider these two methods used to induce firms to employ green technology and offer green products. The overwhelming majority of literature papers have focused on only one source of funds to promote green and sustainable development, while neglecting the differences between external funds and internal funds regarding the degree of greenness of the products and the sales volume, as well as the supply chain members' preferences for these two different methods. Thus, our study tries to answer three questions. Firstly, can these two methods drive firms to make greener products and increase their sales of these products? Secondly, are there differences between these two methods when considering these same goals? Lastly, of the two methods, which do different members of the supply chain prefer? In relation to the last point, we go on to examine whether the size of the government subsidy, the greening cost-sharing fraction, and the R&D cost coefficient affect the supply chain members' preferences for either of these two methods.

To address these questions, we consider a supply chain comprising a single green manufacturer and a single regular manufacturer that sell their products through a common retailer to end consumers. Consumers are thus offered two substitutable products, one made using green technology and environment-friendly, the other a 'regular' product. Then, we introduce external funds in the form of government subsidy, and internal funds via greening cost-sharing contract, to analyze the effect of these two methods on the goals of increasing the product's degree of greenness and increasing the sales of the green product. Finally, we determine which of the two methods will be better for the green manufacturer and for the retailer, under what circumstances. To better describe the decision behaviors and their influences among two manufacturers and the retailer, game theory is employed in this paper. Game theory, which can describe the influence of interactive decisions among several decision makers, has been widely used in green supply chain management literature to model the decision-making behavior among supply chain partners and is also used in this paper [3–6,9–11]. By analyzing the interactive relationship among the green manufacturer, the regular manufacturer and the retailer via game theory, and through both theoretical and numerical analysis, two key green supply chain management issues are the level of funding required to invest in green manufacturing and products, and which type of funding (external or internal) is better for the green manufacturer, the retailer, as well as the whole supply chain. Thus, we can provide theoretical support and decision-making reference information for the government and the retailer when deciding how many funds should be invested to support the green manufacturer, in production and pricing decisions based on the behaviors of the government (the retailer), its competitor.

The remainder of this paper is structured as follows. We provide a concise literature review in Section 2. The basic model is specified in Section 3. Our analysis and main findings are presented in Section 4. A numerical analysis is provided in Section 5 and finally Section 6 concludes the paper.

2. Literature Reviews

This study is closely related to the literature on government subsidy and the coordination of green supply chains.

2.1. Government Subsidy

Bansal and Gangopadhyay [12] showed that environmental performance, e.g., total population, average environmental quality, and social welfare may differ where a tax mechanism is used to that end and where a subsidy mechanism is used. Yalabik and Fairchild [13] analyzed the effect of consumer preference, and government regulatory and competitive pressure on a firm's environmental innovation. They concluded that it is better to offer firms subsidies rather than regulatory pressures, or to rely on competitive pressures, regarding environmental innovation. Sheu [14] developed a model with a producer and reverse-logistics suppliers to study how government intervention affects their negotiations when making cooperative agreements. He pointed out that supply chain members' profits and social welfare will deteriorate when there is excessive government financial intervention. Sheu and Chen [5] showed that government financial intervention has a positive impact on social welfare and supply chain profits in a competitive green supply chain, with social welfare and profits increasing by 27.8% and 306.6%, respectively. Zhao et al. [15] analyzed how government-imposed penalties and incentives influence manufacturers' strategic choices. Zhang and Liu [16] studied how government behavior affects supply chain members' bargaining power regarding the coordination of a three-level green supply chain. Cohen et al. [4] studied how government subsidy offered directly to consumers affects suppliers' decisions under demand uncertainty. They pointed out that government subsidy can achieve the predetermined target of increasing the sales of green products, as well as coordinate the actions of government and the supplier. Hafezalkotob [17] demonstrated that, in a setting where a green supply chain and an ordinary one compete for consumers, the stronger the government's sense of social responsibility is, the larger government revenue and supply chains' profits will be. Yang and Xiao [6] demonstrated that the retailer becomes the main promoter of green products where government interventions are made. They concluded that, due to fuzzy uncertainty (e.g., manufacturers' costs and consumer demand), the green supply chain and the manufacturer will be in a worse position economically where a subsidy offered to the manufacturer shifted to the retailer. Yu and Solvang [18] analyzed the effect of government subsidy on economic benefits and environmental impacts in a setting of a reverse-logistics network. They found that government subsidy can compensate for economic loss consequent to restrictions on carbon emissions.

2.2. Green Supply Chain Coordination

Our study is also related to green supply chain coordination. Subramanian et al. [19] analyzed the impact of different coordination contracts on manufacturers' design choices. Swami and Shah [20] found that a two-part tariff contract can be utilized to coordinate a two-stage green supply chain. Ghosh and Shah [9] proposed a cost-sharing contract to prompt manufacturers to increase a product's degree of greenness, but the proposed mechanism was not capable of achieving perfect coordination. Li et al. [21] considered a manufacturer selling the same green product through either the traditional retail channel or its own direct channel, and found that a dual-channel green supply chain could be coordinated through a two-part tariff contract. Xu et al. [22] analyzed a sustainable supply chain in which carbon emission is under a cap-and-trade regulation. They compared a revenue-sharing contract and a two-part contract to coordinate the supply chain and found that the latter can lead to perfect coordination. Xiao et al. [23] considered the use of a tax-sharing contract to coordinate the green supply chain when firms need to pay a carbon tax charged by a government. Basiri and Heydari [24] considered a two-level supply chain in which a new substitutable green product was introduced alongside a regular product. They showed that not all supply chain members can benefit from a centralized system and that it is necessary to propose a collaboration model. Yu and Han [11] designed a modified wholesale price contract and a modified cost-sharing contract to coordinate the supply chain. They showed that both contracts can achieve coordination but hurt the manufacturer's profit. Zhu and He [25] analyzed the effects of supply chain structures, green product types, and competition types on the products' degree of greenness. They showed that neither a wholesale contract nor a cost-sharing contract can fully coordinate the supply chain profit. Yi and Li [10] demonstrated that cost-sharing contracts to support investment in energy-saving technology and carbon emissions reduction can coordinate the supply chain, and, further, government subsidy can reduce the coordination efficiency of the supply chain.

In addition, many studies have taken consumer attitudes toward green products and environmental awareness into consideration in examining coordination of the green supply chain. Ghosh and Shah [26] developed a manufacturer-retailer supply chain to study how the degree of greenness, pricing strategies, and profits are affected by channel structure, as well as the impact of consumer sensitivity to green apparel on the supply chain members' strategies. They pointed out that a green supply chain can be coordinated via a two-part tariff contract. Zhang et al. [27] focused on the effect of consumer environmental awareness on order quantity and channel coordination in a two-stage supply chain, with a single manufacturer and a single retailer. They found that a return contract can help supply chain members to achieve their desired profit in a centralized system. Kim and Sim [28] analyzed how consumer attitudes toward pollution affect supply chain coordination between a manufacturer and a retailer. They demonstrated that consumer awareness plays a critical role in curbing pollution in the supply chain, and, interestingly, that supply chain coordination cannot reduce pollution when consumers are completely ignorant or sensitive enough to environmental protection. Yang et al. [29] considered the use of wholesale price contracts and revenue sharing contracts to coordinate a supply chain comprising a manufacturer and a retailer, where consumers are environment-friendly and the government can charge a carbon emission tax. They found that revenue sharing fails to coordinate the supply chain neither under an abatement level promise strategy nor an abatement level requirement strategy.

The present paper differs from the aforementioned papers in two important respects. First, the structure of the supply chain is different, in that we consider a supply chain consisting of a green manufacturer and a regular manufacturer, both of which sell products through a common retailer, and so directly compete for consumers, while other researchers have mainly considered only a single green supply chain or two separate (green and regular) supply chains. The retailer's profit is composed of two parts, namely the sale of the green product and the sale of the regular product; therefore, even though government subsidy or its own investment in green products may increase the sales of the green product, this may hurt the sales of the regular product. Thus, the green manufacturer and the retailer may have different preferences with regard to external funding and internal funding of investment in green technologies. For example, compared with the green manufacturer, the retailer may have a motive to resist external funding (e.g., government subsidy) whereas the green manufacturer can only gain from government subsidy. Second, we consider two different methods—external funds (i.e., government subsidy) and internal coordination (i.e., a greening cost-sharing contract)—to encourage the green manufacturer to develop a product with a higher degree of greenness and increase the sales of that product, while previous studies have focused on only one method and so neglected the differences between them. In this paper, we examine which is the better method (government subsidy or a greening cost-sharing contract) for the green manufacturer and the retailer.

3. The Model

Consider a two-level supply chain comprising of a manufacturer that produces green products, another manufacturer that produces regular products, and a common retailer, which sells both manufacturers' products to the end consumers. The government can offer a subsidy to the green manufacturer, or the retailer can share R&D costs with the green manufacturer to encourage it to produce green products. The supply chain structure is depicted in Figure 1.

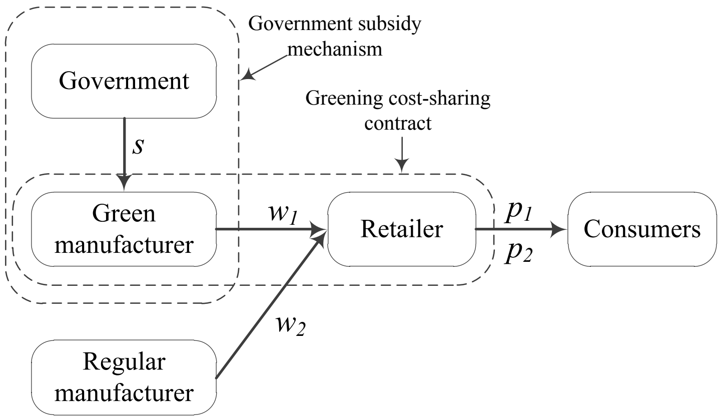

Figure 1. The supply chain structure.

The principal hypotheses are as follows:

(1) We denote the degree of 'greenness' of the product e ($e > 0$), and the higher the degree of greenness, the larger the cost of the green technology (i.e., R&D cost) will be. The green manufacturer incurs a total investment cost of βe^2, where $\beta > 0$ is the R&D cost coefficient, which implies a convex increasing cost regarding the product's greenness. The quadratic function is widely employed to describe the R&D cost, as it becomes increasingly difficult to increase greenness ever further, and hence costlier to achieve [20,26,30,31]. For simplicity, neither manufacturer has any other costs.

(2) The green and the regular manufacturers (respectively denoted 1 and 2) sell their products through the retailer at wholesale prices w_1 and w_2. Then, the retailer sells the products to the end consumers at retail prices p_1 and p_2.

(3) Government can provide a subsidy ($s > 0$) to the green manufacturer to encourage it to make a greener product; it will therefore be able to stimulate demand because of a higher degree of greenness of the product even with a higher retail price.

(4) Alternatively, the retailer can share a part of the R&D cost with the green manufacturer via a greening cost-sharing contract, to encourage the green manufacturer to offer a greener product.

(5) Linear demand functions are employed to describe consumer demand because they are tractable and widely utilized in supply chain analysis. Therefore, it is assumed that the market demands are influenced by retail prices and the product's degree of greenness [26,29,32,33]. The demand functions for the green and the regular product are $q_1 = 1 - p_1 + \theta p_2 + \tau e$ and $q_2 = 1 - p_2 + \theta p_1$, respectively, where $\theta \in (0, 1)$ is a price sensitivity coefficient and $\tau > 0$ is a greenness sensitivity coefficient.

(6) According to the aforementioned descriptions, the retailer's profit is $\pi_r = (p_1 - w_1)q_1 + (p_2 - w_2)q_2 - \varphi\beta e^2$ if the retailer shares the investment cost with the green manufacturer, where $\varphi \in [0, 1]$ denotes the cost-sharing fraction (i.e., $\varphi = 0$ means the retailer shares none of the investment cost with the green manufacturer). The green manufacturer's profit is $\pi_{m1} = (w_1 + s)q_1 - (1 - \varphi)\beta e^2$, where $s = 0$ indicates that the government does not offer a subsidy to the green manufacturer, and the regular manufacturer's profit is $\pi_{m2} = w_2 q_2$.

4. Sustainability Analysis

In this section, we analyze the sustainability of the green supply chain. We first consider, as a benchmark, a partially centralized system, in which the green manufacturer and the retailer make decisions together. We then consider external funding of green investment via government subsidy and internal funding via a greening cost-sharing contract, to analyze whether or not these two methods can encourage the green manufacturer to develop a greener product and increase the sales of that product. We look at the effect of the size of the government subsidy and the greening cost-sharing fraction on equilibrium decisions and expected profits.

4.1. The Benchmark: The Partially Centralized System

As a benchmark, we consider the situation in which the green manufacturer and the retailer act as a single enterprise. We consider this partially centralized system rather than the whole centralized system to highlight the importance of the characteristics of the green product, principally its degree of greenness and its sales volume. The decision sequence is as follows. In the first stage, the partially centralized system decides exactly how green the product will be. Secondly, the regular manufacturer decides the wholesale price of the regular product. Finally, the partially centralized system decides the retail prices of both the green product and the regular product. The combined profit of the green manufacturer and the retailer is $\pi_C = p_1 q_1 + (p_2 - w_2) q_2 - \beta e^2$. Then, Theorem 1 is obtained.

Theorem 1. *Under centralized decision-making, in which the green manufacturer and the retailer act as a single enterprise, when* $4\beta(1-\theta^2) - \tau^2 > 0$*, we have*

$$e^{C*} = \frac{\tau(1+\theta)}{4\beta(1-\theta^2)-\tau^2},\ w_2^{C*} = \frac{1}{2},\ p_1^{C*} = \frac{2\beta(1+\theta)}{4\beta(1-\theta^2)-\tau^2},$$

$$p_2^{C*} = \frac{4\beta(1+\theta)(3-\theta)-3\tau^2}{4[4\beta(1-\theta^2)-\tau^2]},\ q_1^{C*} = \frac{4\beta(1-\theta^2)(2+\theta)+\theta\tau^2}{4[4\beta(1-\theta^2)-\tau^2]},\ q_2^{C*} = \frac{1}{4},$$

$$\pi_C^{C*} = \frac{4\beta(1+\theta)(5+3\theta)-\tau^2}{16[4\beta(1-\theta^2)-\tau^2]},\ \pi_{m2}^{C*} = \frac{1}{8}.$$

Proof of Theorem 1. Under this partially centralized decision-making, the green manufacturer and the retailer act as a single enterprise, while the regular manufacturer makes decisions based on its own profit-maximization. Going backwards, the partially centralized system first decides retail prices p_1 and p_2. The combined profit of the green manufacturer and the retailer is $\pi_C = p_1 q_1 + (p_2 - w_2) q_2 - \beta e^2$. The corresponding Hessian matrix is $H(p_1, p_2) = \begin{bmatrix} -2 & 2\theta \\ 2\theta & -2 \end{bmatrix}$. As $\theta \in (0,1)$, the Hessian matrix is negative and π_C is concave in p_1 and p_2. Therefore, p_1^{C*} and p_2^{C*} can be determined as the unique solution to the implicit function $\frac{d\pi_C}{dp_1} = 1 - 2p_1 + 2\theta p_2 - \theta w_2 + \tau e = 0$ and $\frac{d\pi_C}{dp_2} = 1 - 2p_2 + 2\theta p_1 + w_2 = 0$, and $p_1^{C*} = \frac{1+\theta+\tau e}{2(1-\theta^2)}$, $p_2^{C*} = \frac{1+\theta+w_2(1-\theta^2)+\theta\tau e}{2(1-\theta^2)}$.

Then, the regular manufacturer decides the wholesale price, w_2. The regular manufacturer's profit is $\pi_{m2} = \frac{w_2(1-w_2)}{2}$. As $\frac{d^2\pi_{m2}}{dw_2^2} = -1$, π_{m2} is concave in w_2. Therefore, w_2^{C*} can be determined as the unique solution to the implicit function $\frac{d\pi_{m2}}{dw_2} = \frac{1-2w_2}{2} = 0$, and $w_2^{C*} = \frac{1}{2}$.

Returning to the first stage, it is also necessary to decide the optimal degree of product greenness. The total profit can be rewritten as $\pi_C = \frac{(1+\theta)(5+3\theta)-4e^2[4\beta(1-\theta^2)-\tau^2]}{16(1-\theta^2)}$. As $\frac{d^2\pi_C}{de^2} = -\frac{4\beta(1-\theta^2)-\tau^2}{2(1-\theta^2)} < 0$ if $4\beta(1-\theta^2) - \tau^2 > 0$, then π_C is concave in e. Therefore, e^{C*}. can be determined as the unique solution to the implicit function $\frac{d\pi_C}{de} = \frac{\tau(1+\theta)-e[4\beta(1-\theta^2)-\tau^2]}{2(1-\theta^2)} = 0$, and $e^{C*} = \frac{\tau(1+\theta)}{4\beta(1-\theta^2)-\tau^2}$. Finally, inserting e^{C*} into the equilibrium retail prices, demand functions, and profits, Theorem 1 holds. □

Theorem 1 shows that the equilibrium decisions, sales of the green product, and the profit of the partially centralized system are related to the R&D cost coefficient (β), the price sensitivity coefficient (θ), and the greenness sensitivity coefficient (τ), while the wholesale price, sales, and profit of the regular manufacturer are unrelated to these parameters. Specifically, the profit of the partially centralized system increases as the R&D cost coefficient becomes smaller, the price sensitivity coefficient is higher, the greenness sensitivity coefficient is higher, the degree of greenness is greater, and the retail price and sales volume of the green product increase.

Intuitively, the green manufacturer produces the product with a lower degree of greenness because of higher total R&D cost with the increasing of β; this however, reduces product differentiation and intensifies competition between the green product and regular product. As a result, the product's degree of greenness, retail price, and sales volume and the profit of the partially centralized system all decrease in β. A higher price sensitivity coefficient denotes that consumers are willing to pay more to purchase a green product. Similarly, a higher greenness sensitivity coefficient means that consumers have a greater preference for the green product over the regular product (the greater the product's greenness, the more they will be willing to purchase it). Thus, the partially centralized system will favor a product with a higher degree of greenness, as it will increase the price sensitivity coefficient and the green sensitivity coefficient.

4.2. External Funds (Government Subsidy)

To promote sustainable development through greener supply chains, the government may intervene to encourage manufacturers to produce and increase the sales of greener products. We analyze how such external intervention, in the form of government subsidy, affects the equilibrium decisions of members of the green supply chain, as well as the sales of the green product and the regular product. We compare the results with those of the partially centralized system (above) to see whether or not government subsidy can increase product greenness and increase sales.

Theorem 2. *With government subsidy, when* $\beta\left(4-\theta^2\right)^2-2\tau^2>0$*, we have*

$$e^{GS*}=\frac{\tau\left[2+\theta+s\left(2-\theta^2\right)\right]}{\beta\left(4-\theta^2\right)^2-2\tau^2},\ w_1^{GS*}=\frac{\beta\left(4-\theta^2\right)\left[\theta+2(1-s)\right]+2s\tau^2}{\beta\left(4-\theta^2\right)^2-2\tau^2},$$

$$w_2^{GS*}=\frac{\beta\left(4-\theta^2\right)\left[2+\theta(1-s)\right]-\tau^2(1-\theta s)}{\beta\left(4-\theta^2\right)^2-2\tau^2},$$

$$p_1^{GS*}=\frac{\beta(1+\theta)\left(4-\theta^2\right)\left[6-\theta+2\theta^2+2s(1-\theta)\right]-\tau^2\left[\theta-s\left(4-3\theta^2\right)\right]}{2\left(1-\theta^2\right)\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]},$$

$$p_2^{GS*}=\frac{\beta(1+\theta)\left(4-\theta^2\right)\left[6-\theta(1+s)-\theta^2(2-s)\right]-\tau^2(1-\theta s)\left(3-2\theta^2\right)}{2\left(1-\theta^2\right)\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]},$$

$$q_1^{GS*}=\frac{\beta\left(4-\theta^2\right)\left[2+\theta+s\left(2-\theta^2\right)\right]}{2\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]},\ q_2^{GS*}=\frac{\beta\left(4-\theta^2\right)\left[2+\theta(1-s)\right]-\tau^2(1-\theta s)}{2\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]},$$

$$\pi_{m1}^{GS*}=\frac{\beta\left[2+\theta+s\left(2-\theta^2\right)\right]^2}{2\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]},\ \pi_{m2}^{GS*}=\frac{\left[\beta\left(4-\theta^2\right)\left[2+\theta(1-s)\right]-\tau^2(1-\theta s)\right]^2}{2\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]^2},$$

$$\pi_r^{GS*}=\frac{\beta(1+\theta)\left(4-\theta^2\right)\left[\left(4-\theta^2\right)\left[2(2+\theta)^2+s(1-\theta)\left[2(2+\theta)^2+s\left(4-3\theta^2\right)\right]\right]-2\tau^2(1-\theta s)\left[2+\theta+\theta s(1-\theta)\right]\right]+\tau^4(1-\theta s)^2}{4\left(1-\theta^2\right)\left[\beta\left(4-\theta^2\right)^2-2\tau^2\right]^2}.$$

Proof of Theorem 2. When government offers a subsidy to the green manufacturer, the green manufacturer, the regular manufacturer, and the retailer make decisions based on their own profit-maximization. Going backwards, the retailer decides retail prices p_1 and p_2. The retailer's profit is $\pi_r=(p_1-w_1)q_1+(p_2-w_2)q_2$. The corresponding Hessian matrix is $H(p_1,p_2)=\begin{bmatrix}-2 & 2\theta\\ 2\theta & -2\end{bmatrix}$. As $\theta\in(0,1)$, the Hessian matrix is negative and π_r is concave in p_1 and p_2. Therefore, p_1^{GS*} and p_2^{GS*} can be determined as the unique solution to the implicit function $\frac{d\pi_r}{dp_1}=1-2p_1+2\theta p_2+$

$w_1 - \theta w_2 + \tau e = 0$ and $\frac{d\pi_r}{dp_2} = 1 - 2p_2 + 2\theta p_1 + w_2 - \theta w_1 = 0$, and $p_1^{GS*} = \frac{1+\theta+w_1(1-\theta^2)+\tau e}{2(1-\theta^2)}$, $p_2^{GS*} = \frac{1+\theta+w_2(1-\theta^2)+\theta\tau e}{2(1-\theta^2)}$.

Next, both manufacturers simultaneously decide their wholesale prices, w_1 and w_2. As $\frac{d^2\pi_{m1}}{dw_1^2} = \frac{d^2\pi_{m2}}{dw_2^2} = -1$, π_{m1} (π_{m2}) is concave in w_1 (w_2). Therefore, w_1^{GS*} and w_2^{GS*} can be determined as the unique solution to the implicit function $\frac{d\pi_{m1}}{dw_1} = \frac{1-2w_1+\theta w_2-s+\tau e}{2} = 0$ and $\frac{d\pi_{m2}}{dw_2} = \frac{1-2w_2+\theta w_1}{2} = 0$, and $w_1^{GS*} = \frac{\theta+2(1-s+\tau e)}{4-\theta^2}$ and $w_2^{GS*} = \frac{2+\theta(1-s+\tau e)}{4-\theta^2}$.

Finally, the green manufacturer decides the optimal degree of greenness. The green manufacturer's profit is $\pi_{m1} = \frac{\left[2+\theta+s(2-\theta^2)+2\tau e\right]^2}{2(4-\theta^2)^2} - \beta e^2$. As $\frac{d^2\pi_{m1}}{de^2} = -\frac{2\beta(4-\theta^2)^2-4\tau^2}{(4-\theta^2)^2} < 0$ if $\beta(4-\theta^2)^2 - 2\tau^2 > 0$, then π_{m1} is concave in e. Therefore, e^{GS*} can be determined as the unique solution to the implicit function $\frac{d\pi_{m1}}{de} = -2\beta e + \frac{2\tau\left[2+\theta+s(2-\theta^2)+2\tau e\right]}{(4-\theta^2)^2} = 0$, and $e^{GS*} = \frac{\tau\left[2+\theta+s(2-\theta^2)\right]}{\beta(4-\theta^2)^2-2\tau^2}$. Inserting e^{GS*} into the equilibrium retail prices, wholesale prices, demand functions, and profits, Theorem 2 holds. □

It can be seen from Theorem 2 that government subsidy has an effect on the equilibrium decisions, sales, and the expected profits of the green manufacturer and regular manufacturer, as well as the retailer. According to Theorem 2, we obtain Corollary 1.

Corollary 1.

(i) e^{GS*}, q_1^{GS*}, π_{m1}^{GS*} *and* π_r^{GS*} *are always increasing in s, while always decreasing in* β*;*

(ii) w_1^{GS*}, w_2^{GS*}, q_2^{GS*} *and* π_{m2}^{GS*} *are increasing in s when* $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2}{4-\theta^2}\right)$ *and decreasing when* $\beta > \frac{\tau^2}{4-\theta^2}$*, while always decreasing in* β*;*

(iii) p_1^{GS*} *is increasing in s when* $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2(4-3\theta^2)}{2(4-5\theta^2+\theta^4)}\right)$ *and decreasing when* $\beta > \frac{\tau^2(4-3\theta^2)}{2(4-5\theta^2+\theta^4)}$*, while always decreasing in* β*;*

(iv) p_2^{GS*} *is increasing in s when* $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2(3-2\theta^2)}{4-5\theta^2+\theta^4}\right)$ *and decreasing when* $\beta > \frac{\tau^2(3-2\theta^2)}{4-5\theta^2+\theta^4}$*, while always decreasing in* β*.*

Proof of Corollary 1.

(i) $\frac{\partial e^{GS*}}{\partial s} = \frac{\tau(2-\theta^2)}{\beta(4-\theta^2)^2-2\tau^2} > 0$, $\frac{\partial q_1^{GS*}}{\partial s} = \frac{\beta(2-\theta^2)(4-\theta^2)}{2\beta(4-\theta^2)^2-4\tau^2} > 0$, $\frac{\partial \pi_{m1}^{GS*}}{\partial s} = \frac{\beta(2-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\beta(4-\theta^2)^2-2\tau^2} > 0$, $\frac{\partial \pi_r^{GS*}}{\partial s} = \frac{\beta^2(1-\theta^2)(4-\theta^2)^2\left[(2+\theta)^2+s(4-3\theta^2)\right]+\theta\beta\tau^2(1+\theta)(4-\theta^2)[1+2\theta+2\theta s(1-\theta)]-\theta\tau^4(1-\theta s)}{2(1-\theta^2)\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial e^{GS*}}{\partial \beta} = -\frac{\tau(4-\theta^2)^2\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial q_1^{GS*}}{\partial \beta} = -\frac{\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial \pi_{m1}^{GS*}}{\partial \beta} = -\frac{\tau^2\left[2+\theta+s(2-\theta^2)\right]^2}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial \pi_r^{GS*}}{\partial \beta} = -\frac{\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]\left[\beta(1+\theta)(4-\theta^2)\left[(2+\theta)^2+s(1-\theta)(4+\theta^2)\right]-3\theta\tau^2(1-\theta s)\right]}{2(1-\theta^2)\left[\beta(4-\theta^2)^2-2\tau^2\right]^3} < 0$;

(ii) $\frac{\partial w_1^{GS*}}{\partial s} = \frac{2\left[\tau^2-\beta(4-\theta^2)\right]}{\beta(4-\theta^2)^2-2\tau^2}$, $\frac{\partial w_2^{GS*}}{\partial s} = \frac{\theta\left[\tau^2-\beta(4-\theta^2)\right]}{\beta(4-\theta^2)^2-2\tau^2}$, $\frac{\partial q_2^{GS*}}{\partial s} = \frac{\theta\left[\tau^2-\beta(4-\theta^2)\right]}{2\beta(4-\theta^2)^2-4\tau^2}$, $\frac{\partial \pi_{m2}^{GS*}}{\partial s} = \frac{\theta\left[\tau^2-\beta(4-\theta^2)\right]\left[\beta(4-\theta^2)(2+\theta-\theta s)-\tau^2(1-\theta s)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2}$, $\frac{\partial w_1^{GS*}}{\partial \beta} = -\frac{2\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial w_2^{GS*}}{\partial \beta} = -\frac{\theta\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial q_2^{GS*}}{\partial \beta} = -\frac{\theta\tau^2\left[2+\theta+s(2-\theta^2)\right]^2}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$, $\frac{\partial \pi_{m2}^{GS*}}{\partial \beta} = -\frac{\theta\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]\left[\beta(4-\theta^2)(2+\theta-\theta s)-\tau^2(1-\theta s)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^3} < 0$; thus, when $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2}{4-\theta^2}\right)$, we have $\frac{\partial w_1^{GS*}}{\partial s} > 0$, $\frac{\partial w_2^{GS*}}{\partial s} > 0$, $\frac{\partial q_2^{GS*}}{\partial s} > 0$ and $\frac{\partial \pi_{m2}^{GS*}}{\partial s} > 0$, and when $\beta > \frac{\tau^2}{4-\theta^2}$, we have $\frac{\partial w_1^{GS*}}{\partial s} < 0$, $\frac{\partial w_2^{GS*}}{\partial s} < 0$, $\frac{\partial q_2^{GS*}}{\partial s} < 0$ and $\frac{\partial \pi_{m2}^{GS*}}{\partial s} < 0$;

(iii) $\frac{\partial p_1^{GS*}}{\partial s} = \frac{\tau^2(4-3\theta^2)-2\beta(4-5\theta^2+\theta^4)}{2(1-\theta^2)\left[\beta(4-\theta^2)^2-2\tau^2\right]}$, $\frac{\partial p_1^{GS*}}{\partial \beta} = -\frac{2\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$; thus, when $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2(4-3\theta^2)}{2(4-5\theta^2+\theta^4)}\right)$, we have $\frac{\partial p_1^{W*}}{\partial s} > 0$, and when $\beta > \frac{\tau^2(4-3\theta^2)}{2(4-5\theta^2+\theta^4)}$, $\frac{\partial p_1^{W*}}{\partial s} < 0$;

(iv) $\frac{\partial p_2^{GS*}}{\partial s} = \frac{\theta\left[\tau^2(3-2\theta^2)-\beta(4-5\theta^2+\theta^4)\right]}{2(1-\theta^2)\left[\beta(4-\theta^2)^2-2\tau^2\right]}$, $\frac{\partial p_2^{GS*}}{\partial \beta} = -\frac{\theta\tau^2(4-\theta^2)\left[2+\theta+s(2-\theta^2)\right]}{\left[\beta(4-\theta^2)^2-2\tau^2\right]^2} < 0$; thus, when $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2(3-2\theta^2)}{4-5\theta^2+\theta^4}\right)$, we have $\frac{\partial p_2^{GS*}}{\partial s} > 0$, and when $\beta > \frac{\tau^2(3-2\theta^2)}{4-5\theta^2+\theta^4}$, $\frac{\partial p_2^{GS*}}{\partial s} < 0$. □

Intuitively, the green manufacturer is expected to develop a product with a lower degree of greenness to reduce costs (total R&D costs increase with increases in β), but this reduces product differentiation and intensifies competition between the green product and the regular product. Therefore, both the green manufacturer and the regular manufacturer set a lower wholesale price, to induce the retailer to charge a lower retail price. In addition, the lower degree of greenness decreases the sales of the green product. Therefore, the sales of both products decrease in β even when the retailer charges a lower retail price, and thus the profits of all members of the supply chain decrease.

Interestingly, both the green manufacturer and the retailer can be always better off from government subsidy, while the effect of government subsidy on the regular manufacturer's profit is related to the R&D cost coefficient (β). When β is sufficiently small, i.e., $\beta \in \left(\frac{2\tau^2}{(4-\theta^2)^2}, \frac{\tau^2}{4-\theta^2}\right)$, government subsidy has a positive effect on the regular manufacturer's profit; that is, all supply chain members—the green manufacturer, the regular manufacturer, and the retailer—can in effect share the subsidy, even though the government provides a subsidy only to the green manufacturer. However, when β is sufficiently large, i.e., $\beta > \frac{\tau^2}{4-\theta^2}$, the regular manufacturer's profit decreases with the size of the subsidy, and so the government subsidy can promote the development of green technology while restraining the regular technology, and thereby encourage the manufacturers to invest in green technology, and thus promote sustainable development. The reason is that the smaller R&D cost increases the product's degree of greenness, thereby making the product differentiation larger and weakening the competition. Thus, the regular manufacturer can also be better off from government subsidy. However, when the R&D cost is large, the consequence is completely opposite and then the regular manufacturer is worse off from government subsidy.

Proposition 1. *There exists* $s_1 = \frac{4\beta^2(1-\theta^2)(2-\theta)(2-\theta^2)(2+\theta)^2+\theta\beta\tau^2\left[16+\theta(12-2\theta+\theta^3)\right]-2\theta\tau^4}{2\beta(8-\theta^2+\theta^4)\left[4\beta(1-\theta^2)^2-\tau^2\right]}$, $s_2 = \frac{\beta(1+\theta)(2+\theta)\left[4-\theta^2(2-\theta)\right]-\theta\tau^2}{(2-\theta^2)\left[4\beta(1-\theta^2)^2-\tau^2\right]}$, *where* $s_1 < s_2$, *that:*

(i) *when* $s \in [0, s_1)$, *then* $q_1^{GS*} < q_1^{C*}$ *and* $e^{GS*} < e^{C*}$;

(i) *when* $s \in [s_1, s_2)$, *then* $q_1^{GS*} \geq q_1^{C*}$ *and* $e^{GS*} < e^{C*}$;

(iii) *when* $s \geq s_2$, *then* $q_1^{GS*} > q_1^{C*}$ *and* $e^{GS*} \geq e^{C*}$.

Proof of Proposition 1. Let $q_1^{GS*} = q_1^{C*}$ and $e^{GS*} = e^{C*}$, we have $s_1 = \frac{4\beta^2(1-\theta^2)(2-\theta)(2-\theta^2)(2+\theta)^2+\theta\beta\tau^2\left[16+\theta(12-2\theta+\theta^3)\right]-2\theta\tau^4}{2\beta(8-\theta^2+\theta^4)\left[4\beta(1-\theta^2)^2-\tau^2\right]}$ and $s_2 = \frac{\beta(1+\theta)(2+\theta)\left[4-\theta^2(2-\theta)\right]-\theta\tau^2}{(2-\theta^2)\left[4\beta(1-\theta^2)^2-\tau^2\right]}$. Further, $s_1 - s_2 = -\frac{\theta\left[\beta(4-\theta^2)^2-2\tau^2\right]\left[2\beta(1+\theta)(2+\theta)-\tau^2\right]}{2\beta(8-\theta^2+\theta^4)\left[4\beta(1-\theta^2)-\tau^2\right]} < 0$. Thus, Proposition 1 holds. □

Proposition 1 reveals that government can employ financial intervention, such as subsidy, to encourage manufacturers to offer greener products and increase the sales of those green products, to reach the levels under the partially centralized system; indeed, the more the subsidy, the higher the degree of greenness and the sales of the green product will be. However, there is an interval ($s \in [0, s_1)$) where government subsidy cannot achieve the desired goals, i.e., $q_1^{GS*} < q_1^{C*}$ and $e^{GS*} < e^{C*}$. When $s \in [s_1, s_2)$, the sales of the green product firstly exceed the level under the partially centralized system, while the degree of greenness is lower than that under the partially centralized system. When government subsidy exceeds a certain value, e.g., $s \geq s_2$, both the degree of greenness and sales can be larger than under the partially centralized system. However, government may naturally be reluctant to offer large subsidies because of the increased expenditure.

As mentioned above, on the one hand, if the government subsidy is too small, it cannot increase the product's degree of greenness and sales above the levels achieved under the partially centralized system. On the other hand, government may be reluctant to offer too much subsidy, as it is always necessary for government to trade off financial expenditure against its environmental and social goals [4].

4.3. Internal Funds (Greening Cost-Sharing Contract)

In this section, we consider the internal funding of a green investment from supply chain partners, in the form of a greening cost-sharing contract between the green manufacturer and the retailer. The total cost of producing the product with degree of greenness e is βe^2. In the contract, the retailer first sets the cost-sharing fraction, φ. The green manufacturer then decides the degree of greenness, e, and then the green manufacturer and the regular manufacturer decide their wholesale prices, w_1 and w_2, respectively. Finally, the retailer decides the retail prices, p_1 and p_2, for the green product and the regular product. The results are presented through Theorem 3.

Theorem 3. *With the cost-sharing contract, when* $\beta(1-\varphi)\left(4-\theta^2\right)^2 - 2\tau^2 > 0$, *we have*

$$e^{CS*} = \frac{\tau(2+\theta)}{\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2},\ w_1^{CS*} = \frac{\beta(1-\varphi)(2-\theta)(2+\theta)^2}{\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2},$$

$$w_2^{CS*} = \frac{\beta(1-\varphi)(2-\theta)(2+\theta)^2 - \tau^2}{\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2}, p_1^{CS*} = \frac{\beta(1-\varphi)(1+\theta)\left(4-\theta^2\right)(2+\theta)(3-2\theta) - \theta\tau^2}{2(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]},$$

$$p_2^{CS*} = \frac{\beta(1-\varphi)(1+\theta)\left(4-\theta^2\right)(2+\theta)(3-2\theta) - \tau^2\left(3-2\theta^2\right)}{2(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]},$$

$$q_1^{CS*} = \frac{\beta(1-\varphi)\left(4-\theta^2\right)(2+\theta)}{2\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]},\ q_2^{CS*} = \frac{\beta(1-\varphi)\left(4-\theta^2\right)(2+\theta) - \tau^2}{2\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]},$$

$$\pi_{m1}^{CS*} = \frac{\beta(1-\varphi)(2+\theta)^2}{2\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]},\ \pi_{m2}^{CS*} = \frac{\left[\beta(1-\varphi)\left(4-\theta^2\right)(2+\theta) - \tau^2\right]^2}{2\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]^2},$$

$$\pi_r^{CS*} = \frac{\tau^4 - 2\beta\tau^2(1+\theta)(2+\theta)^2[2-\theta-\theta\varphi(1+\theta)] + 2\beta^2(1-\varphi)^2(1+\theta)(2+\theta)^2\left(4-\theta^2\right)^2}{4(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2\right]^2}.$$

Proof of Theorem 3. With the cost-sharing contract, the green manufacturer, the regular manufacturer, and the retailer still make decisions based on their own profit-maximization. Going backwards, the retailer decides retail prices p_1 and p_2. The retailer's profit is $\pi_r = (p_1 - w_1)q_1 + (p_2 - w_2)q_2 - \varphi\beta e^2$. The corresponding Hessian matrix is $H(p_1, p_2) = \begin{bmatrix} -2 & 2\theta \\ 2\theta & -2 \end{bmatrix}$. As $\theta \in (0,1)$, the Hessian matrix is negative and π_r is concave in p_1 and p_2. Therefore, p_1^{CS*} and p_2^{CS*} can be determined as the unique solution to the implicit function $\frac{d\pi_r}{dp_1} = 1 - 2p_1 + 2\theta p_2 + w_1 - \theta w_2 + \tau e = 0$ and $\frac{d\pi_r}{dp_2} = 1 - 2p_2 + 2\theta p_1 + w_2 - \theta w_1 = 0$, and $p_1^{CS*} = \frac{1+\theta+w_1(1-\theta^2)+\tau e}{2(1-\theta^2)}$, $p_2^{CS*} = \frac{1+\theta+w_2(1-\theta^2)+\theta\tau e}{2(1-\theta^2)}$.

Next, the two manufacturers simultaneously decide their wholesale prices, w_1 and w_2. As $\frac{d^2\pi_{m1}}{dw_1^2} = \frac{d^2\pi_{m2}}{dw_2^2} = -1$, π_{m1} (π_{m2}) is concave in w_1 (w_2). Therefore, w_1^{CS*} and w_2^{CS*} can be determined as the unique solution to the implicit function $\frac{d\pi_{m1}}{dw_1} = \frac{1-2w_1+\theta w_2+\tau e}{2} = 0$ and $\frac{d\pi_{m2}}{dw_2} = \frac{1-2w_2+\theta w_1}{2} = 0$, and $w_1^{CS*} = \frac{2+\theta(1+\tau e)}{4-\theta^2}$ and $w_2^{CS*} = \frac{2+\theta(1+\tau e)}{4-\theta^2}$.

Finally, the green manufacturer decides the optimal degree of greenness. The green manufacturer's profit is $\pi_{m1} = \frac{[2+\theta+s(2-\theta^2)+2\tau e]^2}{2(4-\theta^2)^2} - \beta e^2$. As $\frac{d^2\pi_{m1}}{de^2} = -\frac{2\beta(4-\theta^2)^2-4\tau^2}{(4-\theta^2)^2} < 0$ if $\beta(1-\varphi)(4-\theta^2)^2 - 2\tau^2 > 0$, then π_{m1}. is concave in e. Therefore, e^{CS*} can be determined as the unique solution to the implicit function $\frac{d\pi_{m1}}{de} = \frac{2\tau\left[2+\theta+s(2-\theta^2)\right]-e[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2]}{(4-\theta^2)^2} = 0$, and $e^{CS*} = \frac{2\tau(2+\theta)}{\beta(1-\varphi)(4-\theta^2)^2-2\tau^2}$. Inserting e^{CS*} into the equilibrium retail prices, wholesale prices, demand functions, and profits, Theorem 3 holds. □

Corollary 2.

(i) e^{CS*} w_1^{CS*}, w_2^{CS*}, p_1^{CS*}, p_2^{CS*}, p_2^{CS*}, q_1^{CS*}, q_2^{CS*}, π_{m1}^{CS*}, *and* π_{m2}^{CS*} *are all increasing in* φ;

(ii) π_r^{CS*} *is increasing in* φ *if* $\varphi \in [0, \varphi^*]$, *and decreasing in* φ *if* $\varphi \in [\varphi^*, 1]$, *namely, the optimal greening cost-sharing fraction is* φ^*, *where* $\varphi^* = \frac{3\theta}{4-\theta} - \frac{\tau^2[4-\theta(6+\theta)]}{\beta(1+\theta)(4-\theta)(4-\theta^2)^2}$.

Proof of Corollary 2.

(i) $\frac{\partial e^{CS*}}{\partial\varphi} = \frac{\beta\tau(2+\theta)(4-\theta^2)^2}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial w_1^{CS*}}{\partial\varphi} = \frac{2\beta\tau^2(2-\theta)(2+\theta)^2}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial w_2^{CS*}}{\partial\varphi} = \frac{\theta\beta\tau^2(2-\theta)(2+\theta)^2}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial p_1^{CS*}}{\partial\varphi} = \frac{3\beta\tau^2(2-\theta)(2-\theta^2)(2+\theta)^2}{2(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial p_2^{CS*}}{\partial\varphi} = \frac{\theta\beta\tau^2(2-\theta)(5-2\theta^2)(2+\theta)^2}{2(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial q_1^{CS*}}{\partial\varphi} = \frac{\beta\tau^2(2-\theta)(2+\theta)^2}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial q_1^{CS*}}{\partial\varphi} = \frac{\theta\beta\tau^2(2-\theta)(2+\theta)^2}{2\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial\pi_{m1}^{CS*}}{\partial\varphi} = \frac{\beta\tau^2(2+\theta)^2}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^2} > 0$, $\frac{\partial\pi_{m2}^{CS*}}{\partial\varphi} = \frac{\theta\beta\tau^2(2-\theta)(2+\theta)^2\left[\beta(1-\varphi)(2-\theta)(2+\theta)^2-\tau^2\right]}{\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^3} > 0$;

(ii) $\frac{\partial\pi_r^{CS*}}{\partial\varphi} = \frac{\beta\tau^2(2+\theta)^2\left[\beta(1+\theta)(4-\theta^2)^2[3\theta-\varphi(4-\theta)]+\tau^2[4-\theta(6+\theta)]\right]}{2(1-\theta^2)\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]^3}$; thus, when $\varphi \in [0, \varphi^*]$, we have $\frac{\partial\pi_r^{CS*}}{\partial\varphi} > 0$, and when $\varphi \in [\varphi^*, 1]$, we have $\frac{\partial\pi_r^{CS*}}{\partial\varphi} < 0$, namely the optimal greening cost-sharing fraction is φ^*, where $\varphi^* = \frac{3\theta}{4-\theta} - \frac{\tau^2[4-\theta(6+\theta)]}{\beta(1+\theta)(4-\theta)(4-\theta^2)^2}$. □

The reasoning in (i) can be explained intuitively: increases in φ mean that the total R&D cost decreases and the green manufacturer has an incentive to offer a product with a higher degree of greenness, which leads to an increase in the wholesale price, retail price, sales, as well as the profit of the green manufacturer. The increase in the degree of greenness will increase product differentiation, which reduces the competition between the green product and the regular product. Thus, the regular manufacturer can also benefit from an increase in φ. The retailer's profit is also influenced by φ. When φ is sufficiently small, the reason why the retailer's profit increases is obvious (the retailer is investing less). When φ increases beyond a certain point, the retailer's profit begins to decrease in φ because the sum paid to support the R&D cost outweighs the increasing sales revenue, and this decreases the retailer's total profit. As a result, there exists an optimal fraction of cost-sharing, φ^*, where the retailer's profit is maximized.

Proposition 2. *Given* $\varphi_1 = \frac{2\left[3\theta\beta(1+\theta)\left(4-\theta^2\right)^4-\beta\tau^2(7\theta-2)(2-\theta)^2(2+\theta)^3-2\tau^4[4-\theta(6-\theta)]\right]}{\beta(4-\theta^2)^2\left[2\beta(1+\theta)(2-\theta)^2(2+\theta)^3-\tau^2[4+\theta(12-\theta)]\right]}$, *when* $\varphi \in [0, \varphi_1]$, *the green supply chain consists of the green manufacturer and the retailer, and can be coordinated through greening cost-sharing contract.*

Proof of Proposition 2. $\pi_{m1}^{CS*} - \pi_{m1}^{W*}\big|_{s=0} = \frac{\beta\varphi\tau^2(2+\theta)^2}{\left[\beta(4-\theta^2)^2-2\tau^2\right]\left[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2\right]} > 0$, $\pi_r^{CS*} - \pi_r^{W*}\big|_{s=0} = \frac{\beta\varphi\tau^2(2+\theta)^2\left[4\tau^4[4-\theta(6+\theta)]+2\beta^2(1+\theta)(4-\theta^2)^4[\varphi(2+\theta)-3\theta]+\beta\tau^2(4-\theta^2)^2[12\theta(2-\varphi)-4(2+\varphi)+\theta^2(14+\varphi)]\right]}{4(1-\theta^2)[\beta(4-\theta^2)^2-2\tau^2]^2[\beta(1-\varphi)(4-\theta^2)^2-2\tau^2]^2}$. Let $\pi_r^{CS*} = \pi_r^{W*}\big|_{s=0}$, we have $\varphi = 0$ and $\varphi_1 = \frac{2\left[3\theta\beta(1+\theta)\left(4-\theta^2\right)^4-\beta\tau^2(7\theta-2)(2-\theta)^2(2+\theta)^3-2\tau^4[4-\theta(6-\theta)]\right]}{\beta(4-\theta^2)^2\left[2\beta(1+\theta)(2-\theta)^2(2+\theta)^3-\tau^2[4+\theta(12-\theta)]\right]}$, and when $\varphi \in [0, \varphi_1]$, $\pi_r^{CS*} \geq \pi_r^{W*}\big|_{s=0}$, namely the retailer can be much better off from greening cost-sharing contract. Thus, Proposition 2 holds. □

Consistent with the literature about greening cost-sharing contracts on supply chain coordination, Proposition 2 also shows that a greening cost-sharing contract can coordinate the green supply chain. The green manufacturer has a motivation to offer greener products as it can charge a higher price if the retailer shares a part of the R&D cost. In addition, the product differentiation will be larger. Then, consumers who are more conscious of the environment will purchase the green product even though the retail price is high, although consumers who are sensitive to price will buy the regular product. Thus, both the green manufacturer and the retailer can be better off with a greening cost-sharing contract compared with a single wholesale contract without government subsidy. When the greening cost-sharing fraction is sufficiently large, the green manufacturer is still likely to be better off from the greening cost-sharing contract, but the retailer will be worse off. As a result, both the green manufacturer and the retailer have an incentive to accept a cost-sharing contract when φ is within some range, i.e., $\varphi \in [0, \varphi_1]$.

Proposition 3. *There exists* $\varphi_2 = \frac{\beta(1+\theta)(2+\theta)\left[4-\theta^2(2-\theta)\right]-2\theta\tau^4}{\beta(1+\theta)(4-\theta^2)^2}$, $\varphi_3 = \frac{\beta(1+\theta)(2+\theta)\left[4-\theta^2(2-\theta)\right]-2\theta\tau^4}{\beta(2-\theta)(2+\theta)^2\left[4\beta\left(2-3\theta^2+\theta^4\right)+\tau^2[2+\theta(2-\theta)]\right]}$, *where* $\varphi_2 < \varphi_3$, *that:*

(i) *when* $\varphi \in [0, \varphi_2)$, *then* $e^{CS*} < e^{C*}$ *and* $q_1^{CS*} < q_1^{C*}$;
(ii) *when* $\varphi \in [\varphi_2,\ \varphi_3)$, *then* $e^{CS*} \geq e^{C*}$ *and* $q_1^{CS*} < q_1^{C*}$;
(iii) *when* $\varphi \in [\varphi_3,\ 1]$, *then* $e^{CS*} > e^{C*}$ *and* $q_1^{CS*} \geq q_1^{C*}$;

Proof of Proposition 3. Let $q_1^{CS*} = q_1^{C*}$ and $e^{CS*} = e^{C*}$, we have $\varphi_2 = \frac{\beta(1+\theta)(2+\theta)\left[4-\theta^2(2-\theta)\right]-\theta\tau^2}{\beta(1+\theta)(4-\theta^2)^2}$ and $\varphi_3 = \frac{4\beta^2\left(1-\theta^2\right)(2-\theta)(2+\theta)^2\left(2-\theta^2\right)+\theta\beta\tau^2\left[16+\theta\left(12-2\theta+\theta^3\right)\right]-2\theta\tau^4}{\beta(2-\theta)(2+\theta)^2\left[4\beta\left(2-3\theta^2+\theta^4\right)+\tau^2[2+\theta(2-\theta)]\right]}$. Further, $\varphi_2 - \varphi_3 = -\frac{\left(2-\theta^2\right)\left[4\beta\left(1-\theta^2\right)-\tau^2\right]\left[4\beta(2+\theta)\left(1-\theta^2\right)+\theta\tau^2\right]}{\beta(1+\theta)(4-\theta^2)^2\left[4\beta\left(2-3\theta^2+\theta^4\right)+\tau^2(2+2\theta-\theta^2)\right]} < 0$. Thus, Proposition 3 holds. □

We find the government subsidy (Proposition 1) and greening cost-sharing contract have some similar consequences, which might be expected given that the retailer effectively offers a subsidy to the green manufacturer to encourage it to make a greener product. However, when the fraction of the cost-sharing is at a medium level, e.g., $\varphi \in [\varphi_2,\ \varphi_3)$, there are some differences compared with the government subsidy mechanism. With an increase in the fraction of the cost-sharing, the equilibrium degree of greenness reaches the level achieved under the partially centralized system, and then the sales of the green product reach the level achieved under the partially centralized system, which is completely opposite to the consequence under the government subsidy mechanism. The reason for this relates to the difference between the government subsidy and greening cost-sharing contract on the increase of sales and reduction of R&D cost. Under a greening cost-sharing contract, the effect of φ is directly reflected in the R&D cost, and an increase in φ reduces the R&D cost. As a result, the green manufacturer will increase the product's degree of greenness, first to achieve the level achieved under the partially centralized system. Under the government subsidy method, the subsidy is provided to encourage the consumers to purchase green product. Therefore, the sales of the green product are more sensitive to subsidy than to the degree of greenness.

Corollary 3. $\varphi^* < \varphi_1$ *and* $\varphi^* < \varphi_2$.

Proof of Corollary 3. $\varphi^* - \varphi_1 = -\frac{\left[4\beta\left(4-5\theta^2+\theta^4\right)-3\tau^2\right]\left[3\theta\beta(1+\theta)\left(4-\theta^2\right)^2+\tau^2[4-\theta(6+\theta)]\right]}{\beta(1+\theta)(4-\theta)(4-\theta^2)\left[2\beta(1+\theta)(2-\theta)^2(2+\theta)^3-\tau^2[4+\theta(12-\theta)]\right]} < 0$, $\varphi^* - \varphi_2 = -\frac{2(1-\theta)\left[2\beta(1-\theta)\left(4+5\theta-\theta^3\right)-\tau^2\right]}{\beta(1+\theta)(2+\theta)(4-\theta)(2-\theta)^2} < 0$. □

Corollary 3 reveals that the equilibrium value of the greening cost-sharing fraction can be used to coordinate the green supply chain, but it cannot achieve the goals of increasing the product's degree of greenness and increasing sales of the green product to the levels achieved under the partially centralized system. Therefore, a greening cost-sharing contract can improve the efficiency of the green supply chain, but the retailer cannot encourage the green manufacturer to develop a product of the degree of greenness and stimulate sales to the levels achieved under the partially centralized system for the purpose of maximizing its own profit. Therefore, other contracts can be employed to coordinate the green supply chain, increase the degree of greenness and increase the sales of green products.

5. Numerical Analysis

To further explore the effect of government subsidy and cost-sharing contracts on the product's degree of greenness, sales, as well as the profits of supply chain members, we employ numerical analysis to elaborate on the findings presented above. In addition, the differences between these two mechanisms are also examined via numerical analysis.

We assume that a green supply chain has the following characteristics: the R&D cost coefficient $\beta \in [1, 6]$, the price sensitivity coefficient $\theta \in (0, 1)$, the greenness sensitivity coefficient $\tau \in (0, 1.5)$, the government subsidy $s \in [0, 1]$, and the greening cost-sharing fraction $\varphi \in [0, 1]$. In addition, the larger the β is, the higher the R&D cost for unit greenness improvement will be; the larger the θ is, consumers are more likely to pay a higher price to buy green products; the larger the τ is, consumers are more likely to buy green products; the higher the s (φ) is, the more funds are provided by the government (the retailer) to the green manufacturer to engage in green product.

5.1. Effects on the Optimal Greenness, the Sales of Green Product and the Profits

As can be seen from Figures 2 and 3, the larger government subsidy and the cost-sharing fraction, the greater degree of greenness and sales there will be, in fact larger than that under the partially centralized system. In other words, both external funds from government subsidy and internal funds from the retailer via a greening cost-sharing contract can increase both the degree of greenness and the sales of the green product, which is consistent with Propositions 1 and 3. In addition, there exists a range of both government subsidy and cost-sharing fraction that cannot encourage the manufacturer to offer a product with the same degree of greenness and sales volume as under the partially centralized system. Therefore, when offering a subsidy or sharing the costs of R&D, it is necessary for government and the retailer to offer a certain amount of funds to support the green manufacturer. However, there are some differences between these two methods regarding improving the degree of greenness and increasing the sales of the green product. With an increase in the cost-sharing fraction, the degree of greenness first reaches the level achieved under the partially centralized system, and then the sales volume of the green product. However, under the government subsidy mechanism, the sequence of achieving the level under the partially centralized system is opposite. The reason for this relates to the difference between government subsidy and the greening cost-sharing contract on the increase of sales and the reduction of R&D cost. When the retailer shares the R&D cost with the green manufacturer, the green manufacturer has an incentive to develop a product with a higher degree of greenness than under the partially centralized system. But when government offers a subsidy to the green manufacturer for selling the green product, the consumers are willing to purchase green products to increase the sales of green product. Thus, there are differences between these two methods regarding improving greenness and increasing sales.

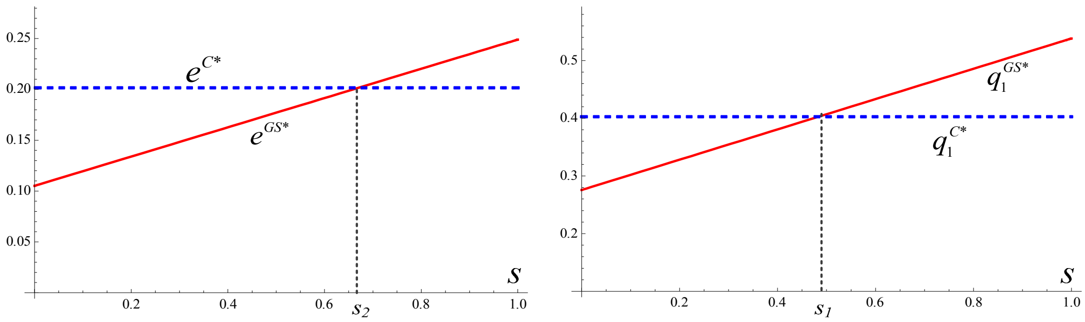

Figure 2. The effect of s on the equilibrium degree of greenness and sales of the green product.

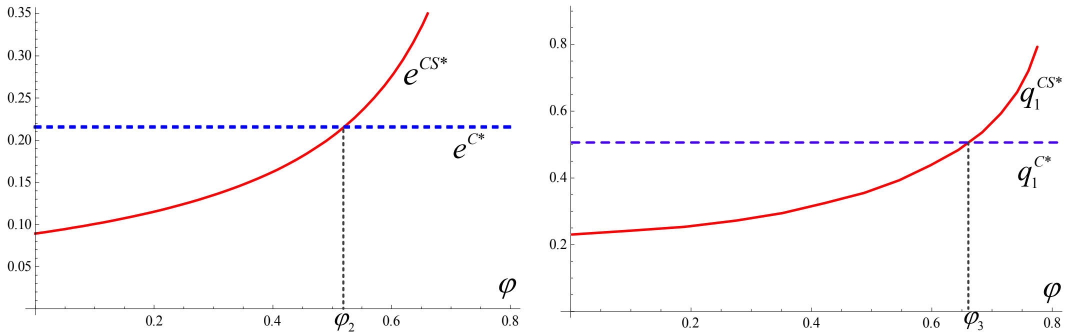

Figure 3. The effect of φ on the equilibrium degree of greenness and sales of the green product.

Figure 4 reveals that the green supply chain (i.e., the green manufacturer and the retailer) can be coordinated via a greening cost-sharing contract when the cost-sharing fraction is smaller than φ_1, which is consistent with Proposition 2. In addition, the green manufacturer's profit always increases in the cost-sharing fraction, while the retailer's profit initially increases in φ, but then decreases. It is obvious that the green manufacturer's profit is increasing with φ as the retailer is sharing more of the R&D cost, and, thus, the green manufacturer can be much better off by selling a greener product. The retailer can also be better off when the cost-sharing fraction is small because the increase in product differentiation leads to less competition. However, a larger φ means the retailer needs to pay more and the increase in these costs may outweigh the increase in profit because the higher degree of greenness leads to a decrease in total profit. Thus, the retailer's profit is maximized at φ^*.

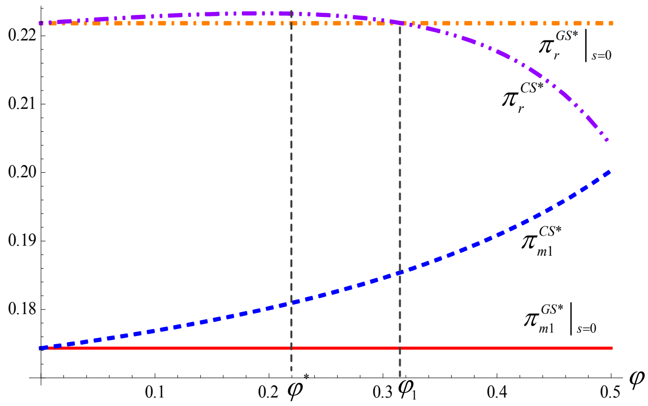

Figure 4. The effect of φ on the profits of the green manufacturer and the retailer.

In Figure 5, we compare the two mechanisms in terms of the profits of the supply chain members. When the retailer chooses the optimal cost-sharing fraction, φ^*, the green manufacturer and the retailer's profits under the government subsidy mechanism are smaller than under a greening cost-sharing contract if the subsidy is sufficiently small, and, thus, both the green manufacturer and the retailer can be much better off through internal coordination than through external funds. On the contrary, when the subsidy is sufficiently large, both the green manufacturer and the retailer can be much better off through external funds than through internal coordination. Further, with increasing government subsidy, the green manufacturer is more prone to choose external funds (i.e., government subsidy) than the retailer. The retailer chooses the optimal cost-sharing fraction to maximize its own profit, while neglecting the green manufacturer's profit. As a result, when government subsidy exceeds a particular level, the green manufacturer will switch to choose external funding.

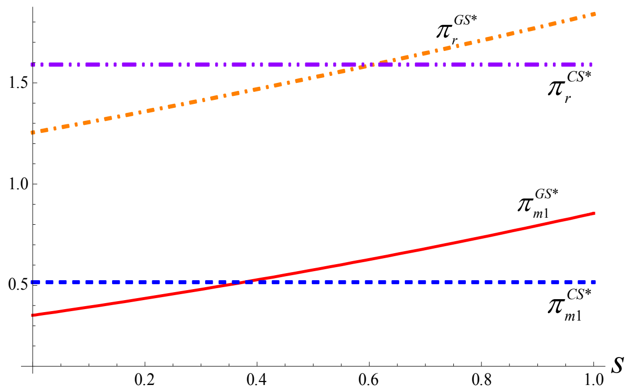

Figure 5. A comparison between the government subsidy mechanism and a greening cost-sharing contract on the profits of the green manufacturer and the retailer.

5.2. Effects on the Differences in the Profit between the Subsidy and Cost-Sharing Scenarios

To further analyze the effect of government subsidy and greening cost-sharing contracts and the supply chain members' preference for either of these two methods, we compare the profit difference from the perspective of the green manufacturer and the retailer. The consequences are shown in Figures 6 and 7.

We find that both the green manufacturer and the retailer prefer a greening cost-sharing contract to the government subsidy if and only if that subsidy is sufficiently small and the retailer shares a part of R&D cost with the green manufacturer; otherwise, both the green manufacturer and the retailer prefer government subsidy to a greening cost-sharing contract, no matter how large the cost-sharing fraction is. The green manufacturer and the retailer can be much better off through a greening cost-sharing contract if the government subsidy is sufficiently small. When the government subsidy is sufficiently large, the green manufacturer and the retailer always prefer subsidy to a greening cost-sharing contract. Recall that both government subsidy and a greening cost-sharing contract can increase the green manufacturer's profit, but the increase in profit via government subsidy is larger than that via a greening cost-sharing contract. As a result, the green manufacturer prefers government subsidy to a greening cost-sharing contract. The retailer has to share a part of R&D cost under the contract, and so also prefers the government subsidy method to the greening cost-sharing contract so long as the government subsidy exceeds a certain value.

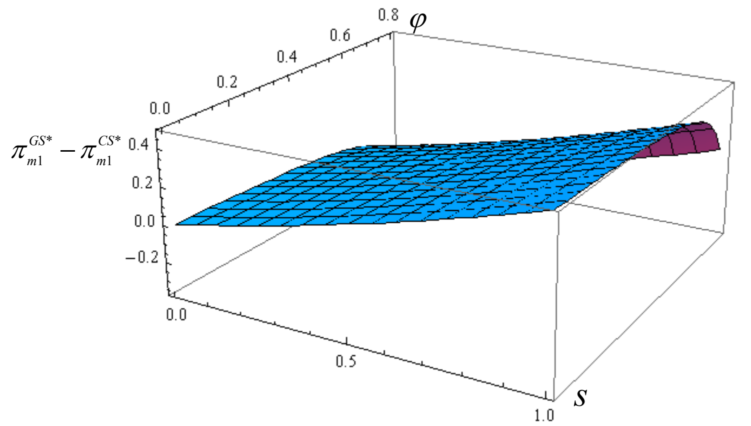

Figure 6. The effect of different levels of s and different values of φ in the green manufacturer's equilibrium profit between the subsidy and cost-sharing scenarios ($\pi_{m1}^{GS*} - \pi_{m1}^{CS*}$).

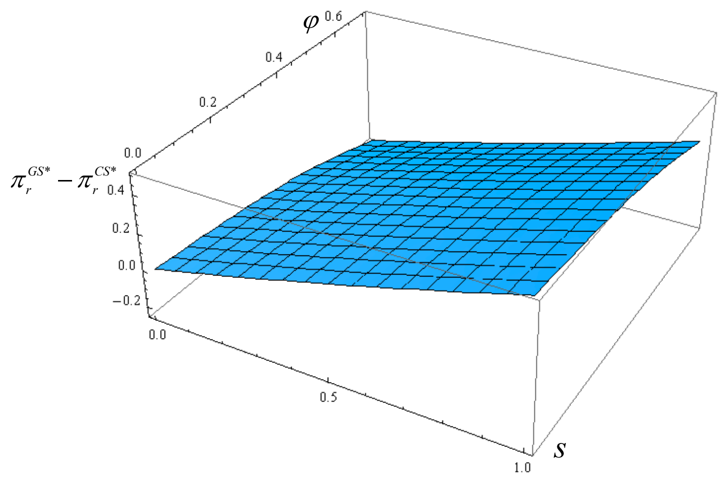

Figure 7. The effect of different levels of s and different values of φ on the difference in the retailer's equilibrium profit between the subsidy and cost-sharing scenarios ($\pi_r^{GS*} - \pi_r^{CS*}$).

What is more, we analyze the effect of the R&D cost coefficient, greenness sensitivity coefficient, and price sensitivity coefficient on the difference in the equilibrium profits of the green manufacturer and the retailer between the subsidy mechanism and greening cost-sharing contract. The conclusions can be shown in Figures 8–10.

According to Figures 8–10, we find that for a given level of government subsidy and greening cost-sharing fraction, the green manufacturer and the retailer are more in favor of the government subsidy mechanism than the greening cost-sharing contract when the R&D cost coefficient is sufficiently large, and the larger the R&D cost sharing coefficient, the larger the difference on the profit ($\pi^{GS*} - \pi^{CS*}$) will be. On the contrary, the green manufacturer and the retailer are more in favor of the greening cost-sharing contract than the government subsidy mechanism when the price (greenness) sensitivity coefficient is large, and the larger the price (greenness) sensitivity coefficient, the larger the difference on the profit ($\pi^{CS*} - \pi^{GS*}$). Therefore, the value of the R&D cost coefficient, greenness sensitivity coefficient, and price sensitivity coefficient will affect the green manufacturer and the retailer's preference of the government subsidy mechanism and greening cost-sharing contract. Thus, when making production and pricing decisions, the manufacturers and the retailer should take different factors into consideration.

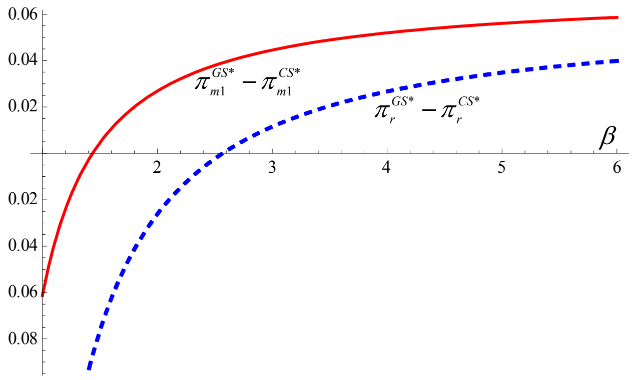

Figure 8. The effect of different levels of β on the difference in the equilibrium profit between the subsidy and cost-sharing scenarios.

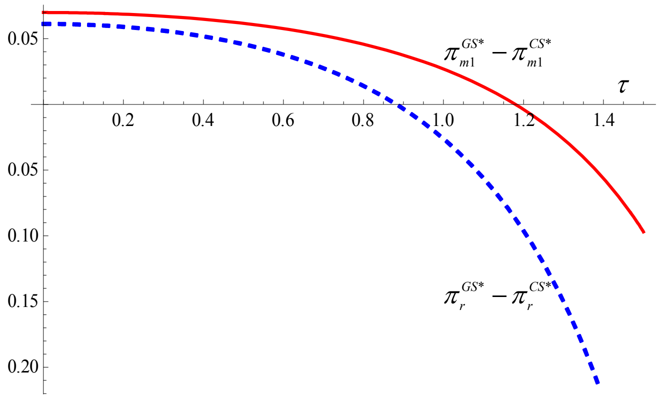

Figure 9. The effect of different levels of τ on the difference in the equilibrium profit between the subsidy and cost-sharing scenarios.

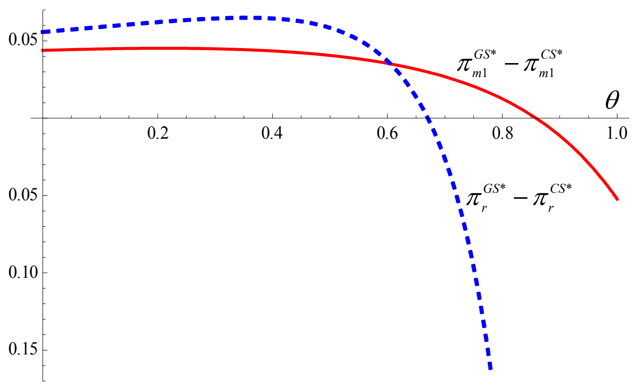

Figure 10. The effect of different levels of θ on the difference in the equilibrium profit between the subsidy and cost-sharing scenarios.

6. Conclusions

In this paper, we construct a supply chain with a green manufacturer that produces a green product and a regular manufacturer that produces a regular product, and sell their products through a common retailer to end consumers. The typically huge investment cost associated with green technology inhibits the manufacturer from offering green products and, as a result, investment funding plays an important role in the development of green supply chains. We consider two methods of investment funding, namely external funds from agencies outside the supply chain (e.g., government subsidy) and internal funds from supply chain partners (e.g., greening cost-sharing with the retailer), to analyze their effects on the supply chain members' production and operation strategy, such as the product's greenness and pricing decisions. We first consider a benchmark in the form of a partially centralized system consisting of the green manufacturer and the retailer, and then study the decentralized system with the government subsidy method and the greening cost-sharing contract to derive the optimal degree of product greenness, retail prices, sales, and expected profits of supply chain members.

By analyzing the impact of government subsidy and the greening cost-sharing fraction, we come to the following conclusions: (1) both government subsidy and a greening cost-sharing contract can increase the product's greenness and sales volume, even to levels above those achieved under the partially centralized system. However, (2) the two methods are different, in that a greening cost-sharing contract primarily operates to maximize the degree of greenness, while the government subsidy mechanism primarily operates to increase sales of the green product..

By analyzing the conditions necessary to coordinate the green supply chain, we find that: (1) both the green manufacturer's and the retailer's profits increase in the subsidy, and the green supply chain can be coordinated (however, increasing the subsidy increases government expenditure and government has to maximize social and environmental welfare more widely [4]); (2) a greening cost-sharing contract cannot coordinate the green supply chain perfectly, although it does increase the profits of the green manufacturer and the retailer. Therefore, other coordination mechanisms should be designed to coordinate the supply chain perfectly.

By comparing these two methods, we find that: (1) when government subsidy is sufficiently small, both the green manufacturer and the retailer prefer a greening cost-sharing contract to government subsidy if the cost-sharing fraction exceeds a certain value; (2) when government subsidy is sufficiently large, both the green manufacturer and the retailer always prefer government subsidy to a greening cost-sharing contract, no matter how large the cost-sharing fraction is.

Through the above analysis, some practical implications for the manufacturers, the retailer, as well as the government can be put forward to better promote green and sustainable development of green supply chain. First, to encourage the green manufacturer to engage in green products, the government should offer sufficient funds to avoid invalid investment, while at the same time, trade off the budget constraint against environmental impact. Second, it is critical for the green supply chain members (including the green manufacturer and the retailer) to decide whether or not to introduce external funds (e.g., government subsidy), as to some extent, the green supply chain can be much better off via internal coordination (e.g., greening cost-sharing contract) compared with external funds. Last but not least, the supply chain members' behaviors (including the production and pricing decisions and the choice of funds investment) are largely affected by the government subsidy mechanism.

There are some limitations to our study. First, it would be interesting to take demand uncertainty into consideration. Compared with regular products, green products may face greater uncertainty on first entering the market, which will thus affect supply chain members' production and operation. Second, from the perspective of government, it is more practical and interesting to incorporate government budget as a constraint in the model, or investigate the dynamic government subsidy mechanism in green supply chain management in the future. Last but not least, it would be interesting to use empirical data from enterprises to carry out a similar numerical analysis, as this would be of more practical value for government when providing subsidies and in examining the coordination between the manufacturer and the retailer.

Author Contributions: Y.T. designed the model, improved the model, and wrote the manuscript. Y.L. analyzed the model and revised the manuscript. Both authors contributed to discussion and revision of the manuscript.

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