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Research Article

Coordination of a Green Supply Chain with One Manufacturer and Two Competing Retailers under Different Power Structures

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The main objective of this research is to examine the role of power relationship in a two-level green supply chain which is made up of one shared manufacturer and two competitive retailers. We develop six game theory-based models to explore the members' operational decisions in a supply chain taking into account three vertical power structures (*Manufacturer Stackelberg, Retailer Stackelberg, and Vertical Nash*) as well as two retailers' horizontal power structure (Bertrand or Stackelberg competition). Then, we design a two-part tariff contract which can encourage the supply chain members to promote cooperation and eventually coordinate the decentralized green supply chain under each power structure. Lastly, to further discuss the impact of the green awareness of consumers and the greening cost on supply chain players' operational decisions and profits, we employ some numerical examples to conduct sensitivity analysis. The main conclusions are as follows. Firstly, the impact of power structure on the supply chain players' operational decisions and profits mainly depends on the substitutability of the green products, the green awareness of consumers, and the greening cost for the manufacturer. Secondly, the more power the manufacturer has, the lower product greenness will be set. Thirdly, the consumer's environmental awareness (the greening cost) positively (negatively) influences the manufacturer's product greenness and wholesale price, the retailers' sales prices, and the player's profits under each power structure. Finally, the developed two-part tariff contract is practicable and beneficial for both the manufacturer and the two retailers.

1. Introduction

In recent years, the green supply chain (SC) concept is attracting more and more attention from the public, which is not only a hot topic in business circles but also captures the interest of academic researchers (see [1–4]). Scholars have proposed game theoretical models to quantitatively analyze optimal decisions of green SC members and examine the coordination contract in the green SC.

Ghosh and Shah [5] analyze the effect of various power structures on pricing and greening strategies of a SC which is made up of one manufacturer and one retailer. Swami and Shah [6] study the effort in greening of operations by the manufacturer or retailer and address the problem of coordination of a green SC including one manufacturer and one retailer. Zhang et al. [7] focus on the impact of consumer environmental consciousness on channel coordination in a SC with two kinds of products. Ghosh and Shah [8] investigate the effect of cost-sharing contract on the optimal decisions of SC participants including one manufacturer and one retailer. Zhang et al. [9] explore the performance of a green SC consisting of a single manufacturer and a single retailer, in which the former decides on the energy utilization efficiency and the wholesale price while the latter sets the sales price. Taking a dual-channel SC into account, Li et al. [10] examine the pricing and greening decisions in both centralized and decentralized models and further make a comparison of the SC players' profits between a single channel and a dual channel. Zhu and He [11] investigate the effect of SC structures and competition types on the optimal decisions of SC participants including one manufacturer and one retailer or two competing retailers. Song and Gao [12] analyze the impact of the two kinds of revenue-sharing contracts on the overall performance of a green SC consisting of a manufacturer and a retailer. Heydari [13] addresses the coordinated decision problem in a green three-level SC with two selling channels. Ma et al. [14] examine the pricing strategies in a two-stage SC with two competitive manufacturers and one retailer under *manufacturer Stackelberg, retailer Stackelberg, and cost-sharing contract games*. Taking into account a SC comprising one common manufacturer and two competing retailers, Hosseini-Motlagh et al. [15] investigate the optimal green degree of products and the optimal green guarantee periods in a SC with both non-green and green products. Nielsen et al. [16] study a two-period green SC, including a single manufacturer and a single retailer under both *manufacturer Stackelberg and retailer Stackelberg games*.

By summing up the previous literature on green SC, it can be easily found that green SC management requires a coordinated effort among all SC members to achieve the objective of improving the green degree of products. Nevertheless, there is no doubt that such an effort could be hampered by the power relationship among SC partners. That is, the power structure of SC members makes the coordination of a green SC even more complicated.

However, in accordance with the reviewed research above, there is no previous paper to explore the effects of power relationship when investigating the operational decisions and the coordination contract in green SC with one manufacturer and two competitive retailers. This study is going to fill the above gaps in the literature on green SC by addressing the following questions:

(i) How do the power structures, including vertical power structure among the one upstream manufacturer, the two downstream retailers and horizontal power structure between the two retailers, influence the optimal decisions and economic performance of SC players and the performance of the entire SC?

(ii) What are the influences of consumer's environmental consciousness and greening cost coefficient on key decision variables such as the green degree of products and wholesale and retail prices under different power structures?

(iii) What is the best mechanism for making the coordination of a decentralized green SC in each power structure?

With the aim of answering the above questions, a two-echelon green SC is explored in this paper. It consists of an upstream manufacturer and two competing downstream retailers who purchase green products from the common manufacturer and find a market for them. Consumers' demand is not only affected by the green degree of products, but also is dependent on the two retailers' retail prices. First, by using the game-theoretic approach, our study begins with a simple SC consisting of one shared manufacturer and two competing retailers in the centralized model. Then, six decentralized models are formulated by taking into account the firms' different market powers, which not only investigate the impact of different vertical power structures (including *Manufacturer Stackelberg*, *Retailer Stackelberg*, *and Vertical Nash*), but also explore the influences of the retailers' horizontal power structures (Bertrand or Stackelberg competition). Further, we definitely design a new two-part tariff contract in order to help the SC members obtain win-win results. Finally, we explicitly derive the effects of the consumer's environmental consciousness and greening cost coefficient on the optimal decisions and profits of SC members and the economic performance of the whole SC. Most related studies are presented in Table 1.

The main contributions of our work are as follows:

First, we take into account all possible power structures for the green SC with one manufacturer and two retailers, which capture all possible market competition situations that could be found in reality. There exists a unique equilibrium solution about SC members' operation decisions under each power structure. We show that the effect of power relationship on the SC members' operational decisions and profits mainly depends on the substitutability of the two green products, the green awareness of consumers, and greening cost coefficient.

Second, we propose that the power structure of SC participants has a significant impact on the product greenness. The more SC power the manufacturer has, the lower product greenness will be set.

Third, it is interesting to find that no matter which market position the SC members are in, the consumer's environmental awareness (the greening cost coefficient) positively (negatively) influences the optimal manufacturer's product greenness and wholesale price, the retailers' sales prices, the player's profits, and the SC profit.

Lastly, we precisely identify the conditions under which the manufacturer and the two retailers should accept a two-part tariff contract for each power structure that result in a win-win situation.

The remainder of the paper is organized as follows. Section 2 proposes the formulation of the basic model. Section 3 presents the optimal strategies in the centralized SC case. Section 4 identifies equilibrium solutions for the manufacturer and two retailers, such as the manufacturer's greenness of products and wholesale price and the retailers' prices in the decentralized case under different power structures. In Section 5, we study the green SC coordination under a two-part tariff contract. In Section 6, we illustrate some managerial insights through numerical examples. Section 7 summarizes this work and puts forward research directions in the future.

Table 1: Comparison of previous models with the current study.

Authors	SC structure	Power structure	Contract
Ghosh and Shah [5]	A single manufacturer-retailer	Manufacturer Stackelberg Retailer Stackelberg Vertical Nash	Two-part tariff
Swami and Shah [6]	A single manufacturer-retailer	Manufacturer Stackelberg	Two-part tariff
Zhang et al. [7]	A single manufacturer-retailer	Manufacturer Stackelberg	—
Ghosh and Shah [8]	A single manufacturer-retailer	Manufacturer Stackelberg	Cost sharing
Zhang et al. [9]	A single manufacturer-retailer	Manufacturer Stackelberg	—
Li et al. [10]	A single manufacturer-retailer	Manufacturer Stackelberg	Two-part tariff
Zhu and He [11]	A single manufacturer-retailer A single manufacturer and two competing retailers	Manufacturer Stackelberg	—
Song and Gao [12]	A single manufacturer-retailer	Manufacturer Stackelberg	Revenue-sharing contract
Heydari [13]	Two competing manufacturers and a single retailer	Manufacturer Stackelberg Retailer Stackelberg	Cost-sharing contract
Ma et al. [14]	A single manufacturer with a retailer and an e-channel	Manufacturer Stackelberg	—
Hosseini-Motlagh et al. [15]	A single manufacturer and two competing retailers	Manufacturer Stackelberg	Profit sharing
Nielsen et al. [16]	A single manufacturer-retailer	Manufacturer Stackelberg Retailer Stackelberg	—
This paper	*A single manufacturer and two competing retailers*	*Manufacturer Stackelberg* *Retailer Stackelberg* *Vertical Nash*	*Two-part tariff*

2. The Basic Model

We consider a two-level green SC including one upstream manufacturer and two competing downstream retailers, denoted by the subscript 0, 1, and 2, respectively. The two retailers purchase green products from the common manufacturer and find a market for them. The decision variables faced by the manufacturer are the products' greenness and wholesale prices to both retailers, while the decision variables of two retailers are retail prices.

It is assumed that the demand in the face of the retailer is related to its retail price p_i, competitor's retail price p_j, and the green degree of products θ. Then, the linear demand function of each retailer is expressed as follows [5, 17]:

$$q_i = \alpha - p_i + \beta p_j + k\theta, \quad i, j = 1, 2, i \neq j. \tag{1}$$

In this equation, $\alpha(>0)$ = the total market potential, $\beta \in (0, 1)$ = the substitutability of the green products, and $k(>0)$ = the consumer sensitivity to the green degree of products.

Also, ω = the manufacturer's wholesale price and c = the variable production cost of the manufacturer.

For simplicity, we assume that there are no constant marginal costs for retailers and no fixed costs for each SC member. We also suppose that the greening improvement in products has no impact on the manufacturer's marginal cost of production. The greening cost function is denoted by $\delta\theta^2$ in which δ is the greening investment cost coefficient [8]. Moreover, in our basic model, only the manufacturer bears the cost of greening investment.

According to the above assumptions, the retailer's, the manufacturer's, and the SC's profit functions thus are

$$\prod_i = (p_i - \omega)q_i, \quad i = 1, 2, \tag{2}$$

$$\prod_0 = \sum_{i=1}^{2} (\omega - c)q_i - \delta\theta^2, \quad i = 1, 2, \tag{3}$$

$$\prod_{SC} = \sum_{i=1}^{2} (p_i - c)q_i - \delta\theta^2, \quad i = 1, 2. \tag{4}$$

In the following, we propose a centralized model and six decentralized models with different SC power structures. The steps to obtain the equilibrium results and all proofs of propositions in this paper are provided in the Appendix. To improve the performance of decentralized models, we definitely design multiple two-part tariff contracts to make the coordination of the decentralized green SC under different power structures. Finally, we make sensitivity analyses of the consumer's environmental consciousness and the greening cost coefficient on SC members' operation decisions and economic performances under different power structures.

3. The Centralized Supply Chain Case

As a reference, we first examine the centralized SC case. The total profit of the centralized SC ($\prod_{SC}^{C}$) is as (4). By optimizing the profit function with respect to θ and p_i, we obtain the following proposition.

Proposition 1. *In the centralized setting, we have the optimal product greenness, the optimal retail prices, denoted by θ^C and p_i^C, $i = 1, 2$, and the SC profit are as follows:*

$$\theta^{C} = -\frac{[(\beta-1)c-\alpha]k}{k^2+2\delta(\beta-1)},$$

$$p_i^{C} = \frac{ck^2+[(\beta-1)c-\alpha]\delta}{k^2+2(\beta-1)\delta}, \quad (5)$$

$$\prod_{\mathrm{SC}}^{C} = -\frac{[(\beta-1)c-\alpha]^2\delta}{k^2+2(\beta-1)\delta}.$$

4. The Decentralized Supply Chain Case

In the decentralized SC models, the SC members make decisions independently with the aim of maximizing their own profits. The manufacturer determines the green degree of products and the wholesale price while the two retailers determine the retail prices. As discussed earlier, we investigate the models with three different vertical SC power structures including *the manufacturer Stackelberg*, *the retailer Stackelberg*, *and the vertical Nash*, respectively [14, 16]. In addition, Bertrand or Stackelberg competition is applied between the two retailers under different horizontal power structures.

Table 2 shows that there exist six game theory-based models *with different vertical and horizontal power structures* [14, 16]. Both models in the first row of Table 2 refer to the authority relationships under which the vertical competition is the manufacturer Stackelberg. To be more specific, in the $M_0(R_1R_2)$ or $M_0R_1R_2$ model, *the retailers are engaged in Bertrand or Stackelberg competition*. The two models in the second row of Table 2 concern the authority relationships under which the vertical competition is the retailer Stackelberg. In particular, in the $(R_1R_2)M_0$ or $R_1R_2M_0$ model, *the retailers are engaged in Bertrand or Stackelberg competition*. Additionally, the VB model refers to the authority relationship under which all members do not dominate the SC and each member makes their decisions simultaneously, while the VS model focuses on the authority relationship under which the vertical interaction is Bertrand competition and retailer 1 behaves as the first actor when competing with retailer 2.

4.1. Manufacturer Stackelberg. In this section, it is supposed that the upstream manufacturer behaves as the Stackelberg leader and the two downstream competing *retailers are engaged in Bertrand or Stackelberg competition*. The scenario arises in the market, where the two competing retailers' sizes are both smaller compared to the manufacturer's size.

Table 2: Six game models with different power structures.

Vertical competition	Horizontal completion	
	Bertrand	Stackelberg
Manufacturer Stackelberg	$M_0(R_1R_2)$	$M_0R_1R_2$
Retailer Stackelberg	$(R_1R_2)M_0$	$R_1R_2M_0$
Vertical Nash	VB	VS

4.1.1. The M_0 (R_1R_2) Model. In this model, the common manufacturer first chooses the wholesale price and the green degree of products and then the retailers decide their retail prices simultaneously.

Proposition 2. *In the $M_0(R_1R_2)$ model, there exists a unique optimal solution to the manufacturer's wholesale price ($\omega^{M_0(R_1R_2)}$) and product greenness ($\theta^{M_0(R_1R_2)}$) and the two retailers' retail prices ($p_1^{M_0(R_1R_2)}$ and $p_2^{M_0(R_1R_2)}$):*

$$\omega^{M_0(R_1R_2)} = \frac{k^2c+(\beta-2)[\alpha+(\beta-1)c]\delta}{k^2-2(\beta-1)(\beta-2)\delta},$$

$$\theta^{M_0(R_1R_2)} = -\frac{[\alpha+(\beta-1)c]k}{k^2-2(\beta-1)(\beta-2)\delta},$$

$$p_1^{M_0(R_1R_2)} = p_2^{M_0(R_1R_2)} = \frac{k^2c+[(2\beta-3)\alpha+(\beta-1)c]\delta}{k^2-2(\beta-1)(\beta-2)\delta}. \quad (6)$$

Based on these, we can further obtain the players' profits ($\prod_0^{M_0(R_1R_2)}$, $\prod_1^{M_0(R_1R_2)}$, and $\prod_2^{M_0(R_1R_2)}$) and the SC profit ($\prod_{\mathrm{SC}}^{(M_0R_1R_2)}$).

4.1.2. The $M_0R_1R_2$ Model. In this model, the two retailers play Stackelberg game and move sequentially. Without loss of generality, it is supposed that one of the retailers (e.g., retailer 1) behaves as the first mover and the other (i.e., retailer 2) as the second mover.

Proposition 3. *In the $M_0R_1R_2$ model, there exists a unique optimal solution to the manufacturer's wholesale price ($\omega^{M_0R_1R_2}$) and product greenness ($\theta^{M_0R_1R_2}$) and the two retailers'retail prices ($p_1^{M_0R_1R_2}$ and $p_2^{M_0R_1R_2}$):*

$$\omega^{M_0R_1R_2} = \frac{\left(\beta^3+3\beta^2-4\beta-8\right)ck^2+8\left(\beta^2-2\right)[\alpha+(\beta-1)c]\delta}{\left(\beta^3+3\beta^2-4\beta-8\right)k^2+16(\beta-1)\left(\beta^2-2\right)\delta},$$

$$\theta^{M_0R_1R_2} = -\frac{\left(\beta^3+3\beta^2-4\beta-8\right)[(\beta-1)c-\alpha]k}{\left(\beta^3+3\beta^2-4\beta-8\right)k^2+16(\beta-1)\left(\beta^2-2\right)\delta},$$

$$
\begin{aligned}
p_1^{M_0R_1R_2} &= -\frac{\left(\beta^3+3\beta^2-4\beta-8\right)ck^2-4\left[\left(3\beta^2+\beta-12\right)\alpha-\left(\beta^2-1\right)(\beta-2)c\right]\delta}{\left(\beta^3+3\beta^2-4\beta-8\right)k^2+16(\beta-1)\left(\beta^2-2\right)\delta},\\
p_2^{M_0R_1R_2} &= -\frac{\left(\beta^3+3\beta^2-4\beta-8\right)ck^2+2\left[\left(\beta^3-7\beta^2-2\beta+12\right)\alpha+(\beta+1)^2(\beta-2)\beta c+4\right]\delta}{\left(\beta^3+3\beta^2-4\beta-8\right)k^2+16(\beta-1)\left(\beta^2-2\right)\delta}.
\end{aligned} \tag{7}
$$

Based on these, we can further obtain the players' profits ($\prod_0^{M_0R_1R_2}$, $\prod_1^{M_0R_1R_2}$, and $\prod_2^{M_0R_1R_2}$) and the SC profit ($\prod_{SC}^{M_0R_1R_2}$).

4.2. Retailer Stackelberg. In certain industries, the manufacturer usually confronts some supper retailers which are of great power and dominate the SC. It is assumed that the two downstream retailers behave as Stackelberg leaders and the upstream manufacturer as a follower in this scenario.

4.2.1. The $(R_1R_2)M_0$ Model. In this model, the two retailers first decide on their retail prices simultaneously, and then the manufacturer determines the wholesale price and the green level of products to maximize its own profit.

Proposition 4. *In the $M_0R_1R_2$ model, there exists a unique optimal solution to the manufacturer's wholesale price ($\omega^{(R_1R_2)M_0}$) and product greenness ($\theta^{(R_1R_2)M_0}$) and the two retailers' retail prices ($p_1^{(R_1R_2)M_0}$ and $p_2^{(R_1R_2)M_0}$):*

$$
\begin{aligned}
\omega^{(R_1R_2)M_0} &= \frac{(\beta+1)ck^4+[6(\beta-1)c-(\beta+1)\alpha]\delta k^2+(1-\beta)[(3\beta-7)(\beta-1)c+(\beta+3)\alpha]\delta^2}{[k^2+2(\beta-1)\delta]\left[(\beta+1)k^2+\beta^2+6\beta-5\right]},\\
\theta^{(R_1R_2)M_0} &= -\frac{k[\alpha+(\beta-1)c][(\beta+1)k^2+(\beta+3)(\beta-1)\delta]}{[k^2+2(\beta-1)\delta]\left[(\beta+1)k^2+\beta^2+6\beta-5\right]},\\
p_1^{(R_1R_2)M_0} = p_2^{(R_1R_2)M_0} &= \frac{(\beta+1)ck^4+[2(\beta-1)(\beta+2)c+(\beta-3)\alpha]\delta k^2+(\beta-1)[(\beta-1)(\beta+3)c+(3\beta-7)\alpha]\delta^2}{[k^2+2(\beta-1)\delta]\left[(\beta+1)k^2+\beta^2+6\beta-5\right]}.
\end{aligned} \tag{8}
$$

Based on these, we can further calculate the players' profits ($\prod_0^{(R_1R_2)M_0}$, $\prod_1^{(R_1R_2)M_0}$, and $\prod_2^{(R_1R_2)M_0}$) and the SC profit ($\prod_{SC}^{(R_1R_2)M_0}$).

4.2.2. The $R_1R_2M_0$ Model. When the competing *retailers are engaged in Stackelberg game*, similarly, it is supposed that one of the retailers (e.g., retailer 1) behaves as the first mover and the other (i.e., retailer 2) as the second mover.

Proposition 5. *In the $R_1R_2M_0$ model, there exists a unique optimal solution to the manufacturer's wholesale price ($\omega^{R_1R_2M_0}$) and product greenness ($\theta^{R_1R_2M_0}$) and the two retailers' retail prices ($p_1^{R_1R_2M_0}$ and $p_2^{R_1R_2M_0}$):*

$$
\begin{aligned}
\omega^{R_1R_2M_0} &= \frac{2(\alpha\delta-k^2c)(2A_1+B_1)-(\beta-1)[(C_1+1)+2(2A_1+B_1)c]\delta}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},\\
\theta^{R_1R_2M_0} &= \frac{[2(2A_1+B_1)c-(\beta-1)(C_1+1)]k}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},\\
p_1^{R_1R_2M_0} &= \frac{2(2A_1+B_1)[(\alpha\delta-k^2c)-c(\beta-1)\delta]+2k^2C_1+(\beta-1)(3C_1-1)\delta}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},\\
p_2^{R_1R_2M_0} &= \frac{2(2A_1+B_1)(\alpha\delta-k^2c)-(\beta-1)[(C_1+1)+2(2A_1+B_1)c-4]\delta+2k^2}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},
\end{aligned} \tag{9}
$$

where

$$A_1 = -\frac{(\beta-1)[(\beta-1)\delta+k]}{2[k^2+2(\beta-1)\delta]} - 1,$$

$$B_1 = \beta - \frac{(\beta-1)[(\beta-1)\delta+k]}{2[k^2+2(\beta-1)\delta]}, \tag{10}$$

$$C_1 = \alpha - \frac{kc}{\delta} - \left[(\beta-1)+\frac{k}{\delta}\right]\left[\frac{\alpha\delta - c(\beta-1)\delta - k^2c}{k^2+2(\beta-1)\delta}\right].$$

Based on these, we can further calculate the players' profits ($\prod_0^{R_1R_2M_0}$, $\prod_1^{R_1R_2M_0}$, and $\prod_2^{R_1R_2M_0}$) and the SC profit ($\prod_{SC}^{R_1R_2M_0}$).

4.3. Vertical Nash. In certain industries, there exists no obvious dominant power in the SC. Hence, the SC members play a Nash game to make optimal decisions.

4.3.1. The VB Model. Here the manufacturer and two retailers do not dominate the SC and they simultaneously maximize their own profits and independently make optimal decisions.

Proposition 6. *In the VB model, there exists a unique optimal solution to the manufacturer's wholesale price (ω^{VB}) and product greenness (θ^{VB}) and the two retailers' retail prices (p_1^{VB} and p_2^{VB}):*

$$\omega^{VB} = \frac{k^2c - [(\beta-2)(\beta-1)c+\alpha]\delta}{k^2-(\beta-3)(\beta-1)\delta},$$

$$\theta^{VB} = -\frac{[\alpha+(\beta-1)c]k}{k^2-(\beta-3)(\beta-1)\delta}, \tag{11}$$

$$p_1^{VB} = p_2^{VB} = \frac{ck^2+[(\beta-1)c+(\beta-2)\alpha]\delta}{k^2-(\beta-3)(\beta-1)\delta}.$$

Based on these, we can further calculate the players' profits ($\prod_0^{VB}$, $\prod_1^{VB}$, and $\prod_2^{VB}$) and the SC profit ($\prod_{SC}^{VB}$).

4.3.2. The VS Model. In this model, after the wholesale price and product greenness and retailer 1's retail price have been determined, retailer 2 chooses its retail price.

Proposition 7. *In the VS model, there exists a unique optimal solution to the manufacturer's wholesale price (ω^{VS}) and product greenness (θ^{VS}) and the two retailers' retail prices (p_1^{VS} and p_2^{VS}):*

$$\begin{aligned}
\omega^{VS} &= -\frac{[\alpha+\beta C_4+(\beta-1)(B_2C_3+C_2)+kC_3](A_2+B_2A_3)}{2[(\beta-1)(A_2+B_2A_3)+kA_3+\beta A_4-1]} + B_2C_3+C_2,\\
\theta^{VS} &= -\frac{[\alpha+\beta C_4+(\beta-1)(B_2C_3+C_2)+kC_3]A_3}{2[(\beta-1)(A_2+B_2A_3)+kA_3+\beta A_4-1]} + C_3,\\
p_1^{VS} &= \frac{2(2A_1+B_1)[(\alpha\delta-k^2c)-c(\beta-1)\delta]+2k^2C_1+(\beta-1)(3C_1-1)\delta}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},\\
p_2^{VS} &= \frac{2(2A_1+B_1)(\alpha\delta-k^2c)-(\beta-1)[(C_1+1)+2(2A_1+B_1)c-4]\delta+2k^2}{-2(2A_1+B_1)[k^2+2(\beta-1)\delta]},
\end{aligned} \tag{12}$$

where

$$A_2 = -\frac{\beta+2}{1+\beta},$$

$$B_2 = \frac{(\beta+3)k}{1-\beta^2},$$

$$C_2 = \frac{(\beta+3)\alpha}{1-\beta^2},$$

$$A_3 = \frac{A_2k}{(\delta-B_2k)},$$

$$C_3 = \frac{(C_2-c)k}{\delta-B_2k},$$

$$A_4 = \frac{\beta+kA_3+(\beta-1)(A_2+B_2A_3)}{2},$$

$$C_4 = \frac{\alpha+(\beta-1)(B_2C_3+C_2)+kC_3}{2}. \tag{13}$$

Based on these, we can further calculate the players' profits ($\prod_0^{VS}$, $\prod_1^{VS}$, and $\prod_2^{VS}$) and the SC profit ($\prod_{SC}^{VS}$).

According to the above propositions, we can further compare the equilibrium values of the green degree of products and obtain the following proposition.

Proposition 8. *The green degree of products in the centralized model and in the decentralized models satisfy the following condition:*

$$\theta^{C} > \theta^{\mathrm{VB}} > \theta^{(R_1R_2)M_0} > \theta^{\mathrm{VS}} > \theta^{R_1R_2M_0} > \theta^{M_0(R_1R_2)} > \theta^{M_0R_1R_2}. \tag{14}$$

First, Proposition 8 implies that the green degree of products in the centralized model is larger than that in the decentralized models. As it is well known, the greenness of products denotes the degree of protection of greening production for the environment. When the upstream manufacturer and the downstream retailers are vertically integrated as an entire system, the manufacturer can set a higher green level indicating that the products are more environmental friendly.

Second, Proposition 8 shows that the optimal product greenness is the highest (lowest) in the VB ($M_0R_1R_2$) authority relationship among the six decentralized cases. In other words, the more SC power the manufacturer owns, the lower product greenness will be determined, which suggests that a dominant manufacturer is willing to exercise its SC power to create economic benefit rather than to invest on greening improvement. This result can be illustrated by the truth that a balanceable SC power structure stimulates a more competitive and equitable SC environment. Thus, an enhanced but more impartial competition in the green SC will drive the manufacturer to be more aggressive in producing greening products.

Finally, Proposition 8 allows us to see that, in the same SC power structure, compared to the case that the two retailers act as Stackelberg competition, the case that the two retailers are engaged in Bertrand competition leads to higher product greenness. The result shows that the horizontal power structure of the two retailers also have a significant influence on the manufacturer's decision on greening improvement.

Based on the equilibrium results, we observe that the SC members' decisions and profits are heavily dependent on the consumer's environmental consciousness (k) and the greening cost coefficient (δ). Hence, we now examine the impact of them on the SC members' optimal decisions and profits and obtain Proposition 9.

Proposition 9. *For any game model $l \in \{M_0(R_1R_2), M_0R_1R_2, (R_1R_2)M_0, R_1R_2M_0, VB, VS\}$, we have the following:*

(i) $(\partial\theta^l/\partial k) > 0$, $(\partial\omega^l/\partial k) > 0$, $(\partial p_i^l/\partial k) > 0$, $(\partial\prod_0^l/\partial k) > 0$, $(\partial\prod_i^l/\partial k) > 0$, *and* $(\partial\prod_{SC}^l/\partial k) > 0$

(ii) $(\partial\theta^l/\partial\delta) < 0$, $(\partial\omega^l/\partial\delta) < 0$, $(\partial p_i^l/\partial\delta) < 0$, $(\partial\prod_0^l/\partial\delta) < 0$, $(\partial\prod_i^l/\partial\delta) < 0$, *and* $(\partial\prod_{SC}^l/\partial\delta) < 0$

Proposition 9(i) indicates that the green degree of products, the manufacturer's wholesale price, the retailers' retail prices, and the players' profits increase with the consumer's environmental awareness. This phenomenon is straight forward because consumers with high green awareness have a strong preference for the environmental attribute of the product and will pay more for green products with pleasure. Then, the manufacturer is willing to make the investment in green product innovation to stimulate the demand and thus boost his profit. Thus, the manufacturer charges a larger wholesale price than before. It is also well known that an increment in the wholesale price will result in an increment in the retailers' retail prices. Therefore, the two retailers' profits and the SC profits increase with the green awareness of consumers.

Proposition 9(ii) shows that the green degree of products, the manufacturer's wholesale price, the retailers' retail prices, and the players' profits decrease with greening cost coefficient. The reason is that a large greening cost coefficient hampers the manufacturer from bending himself to green technology innovations as well as inhibits the consumers' willingness of buying green products. Thus, the manufacturer and the retailers will adopt a low-price strategy to attract more customers, which would impair the profits of SC members.

5. Supply Chain Coordination

This section designs multiple two-part tariff contracts as incentive schemes to promote SC members to make the globally optimal decisions. In each proposed two-part tariff contract, the upstream manufacturer first chooses the wholesale price for the green products and then charges a *franchise fee* f_i to downstream retailer i ($i = 1, 2$), respectively [18]. The SC members' decision variables and profit in the coordination scenario are denoted by superscript, co, with regard to different power relationships l, $l \in \{M_0(R_1R_2), M_0R_1R_2, (R_1R_2)M_0, R_1R_2M_0, \mathrm{VB}, \mathrm{VS}\}$.

Therefore, the profit functions for the manufacturer and the two retailers in the designed two-part tariff agreement are, respectively, as follows:

$$\prod_0^{\mathrm{co}/l} = \sum_{i=1}^{2}\left(\omega^{\mathrm{co}/l} - c\right)q_i - \delta\theta^2 + \sum_{i=1}^{2} f_i^l,$$

$$\prod_i^{\mathrm{co}/l} = \left(p_i - \omega^{\mathrm{co}/l}\right)q_i - f_i^l, \quad i = 1, 2. \tag{15}$$

To achieve the goal of SC coordination, we employ the values of θ^C and p_i^C in the centralized green SC (see equation (5)) to obtain the expression of the parameters $\omega^{\mathrm{co}/l}$. In the $M_0(R_1R_2)$, $(R_1R_2)M_0$, and VB models, $f_i^l \le \Pi_i^{\mathrm{co}/l} - \Pi_i^l$ and $f_i^l \ge (1/2)(\Pi_0^l - \Pi_0^{\mathrm{co}/l})$ are incentive constraints that ensure the two-part tariff contract can promote the coordination of the manufacturer and retailers and realize a win-win situation. In the $M_0R_1R_2$, $R_1R_2M_0$, and VS models, the incentive constraint $f_i^l \le \Pi_i^{\mathrm{co}/l} - \Pi_i^l$ still holds, but we cannot derive each retailer's *lower bound* of franchise fee ($\underline{f_i^l}$) from the equation $f_i^l \ge (1/2)(\Pi_0^l - \Pi_0^{\mathrm{co}/l})$. According to [18], the *lower bound* of franchise fee from the view point of the manufacturer can be determined based on the retailer i's *share of cost coefficient* of the manufacturer's greening improvement, which can be shown as follows:

$$\delta_i^l = \left[\frac{q_i^l(\theta, p_i, p_j)}{\sum_{i=1}^2 q_i^l(\theta, p_i, p_j)}\right]\delta,$$
$$\delta_i^{\mathrm{co}/l} = \left[\frac{q_i^{\mathrm{co}/l}(\theta^C, p_i^C, p_j^C)}{\sum_{i=1}^2 q_i^{\mathrm{co}/l}(\theta^C, p_i^C, p_j^C)}\right]\delta. \tag{16}$$

Term δ_i^l indicates a share of retailer i from the cost parameter of the manufacturer's greening improvement in decentralized SC models ($M_0R_1R_2$, $R_1R_2M_0$, and VS) and term $\delta_i^{\mathrm{co}/l}$ represents share of retailer i from the cost parameter of the manufacturer's greening improvement in the coordinated SC model. Then, the *lower bound* of franchise fee $\underline{f_i^l}$ for retailer i is determined as follows:

$$f_i^l \geq \prod_0^l -\left(\omega^{\mathrm{co}/l} - c\right)q_i^C + \delta_i^{\mathrm{co}/l}\left(\theta^C\right)^2. \tag{17}$$

Therefore, we can derive the *lower bound* of franchise fee $(\underline{f_i^l},\ i = 1, 2)$ for any game structures $\underline{l \in} \{M_0R_1R_2, R_1R_2M_0, \mathrm{VS}\}$. Thus, we can derive the following proposition.

Proposition 10.

(i) For any game structures $l \in \{M_0(R_1R_2), (R_1R_2)M_0, VB\}$, $\omega^{\mathrm{co}/l} = (k^2c + [(\beta - 2)(1 - \beta)c - \alpha\beta]\delta)/(\underline{k}^2 + 2(\beta - 1)\delta)$, *and* f_i^l $(i = 1, 2)$ *in an interval* $(\underline{f_i^l}, \underline{f_i^l})$, *where* $\underline{f_i^l}$ *is the lower bound of franchise fee and* f_i^l *is the higher bound of franchise fee*

(ii) For any game structures $l \in \{M_0R_1R_2, R_1R_2M_0, VS\}$, *we can decide* $\omega^{co/l} = ((\beta + 1)(\beta - 2)ck^2 + 2\delta[(\beta - 1)(\beta^2 - 2)c + \beta\alpha])/((\beta + 1)(\beta - 2)[\overline{k}^2 + 2(\beta - 1)\delta]^{\overline{2}})$ *and* f_i^l $(i = 1, 2)$ *in an interval* $(\underline{f_i^l}, \overline{f_i^l})$, *where* $\underline{f_i^l}$ $(\overline{f_i^l})$ *is the lower (higher) bound of franchise fee*

Proposition 10 implies the conditions under which the manufacturer and the two retailers would accept a two-part tariff contract under different power relationships. Under such conditions, the two-part tariff agreement can effectively make the coordination of the SC and realize the Pareto improvement, that is, all SC members can make more profits than those in the decentralized decision-making settings. Here, the important implication is that chain players' collaboration can facilitate sustainable operation of the green SC over the long haul.

Owing to the sophisticated form of the equilibrium results above, in the next section, numerical examples are illustrated to the bound interval of franchise fee in different game structures.

6. Numerical Analysis

In this section, numerical examples are illustrated to compare the SC members' optimal decisions and profits in different game structures to obtain more managerial insights. Firstly, we discuss the effect of consumers' environmental awareness (k) and greening cost coefficient (δ) on SC members' operational decisions and economic performances under different decision scenarios. Secondly, we investigate the variability in lower and upper bounds of franchise fees with both the consumers' environmental consciousness (k) and greening cost coefficient (δ) in the decentralized structures.

6.1. Sensitivity Analysis of Consumer's Environmental Awareness. First, we explore how the manufacturer's product greenness and wholesale price, the retailers' sales prices, the player's profits, and the SC profit are affected by changes in the value of consumer's environmental consciousness. We set $\alpha = 1$, $\beta = 0.5$, $c = 0.5$, and $\delta = 10$, and the value of k varies from 0.4 to 1. The results of our numerical analyses are given in Figures 1–4.

Figure 1 depicts the changes in product greenness with the green awareness of consumers (k) in all centralized and decentralized game structures. It can be seen from Figure 1 that the product greenness increases in all decision-making structures. Moreover, the coordination model results in the highest product greenness provided by the manufacturer in comparison with the decentralized models. Comparing all decentralized SC structures implies that, in the vertical authority relationship, the manufacturer's Stackelberg behavior decreases the product greenness compared to the retailer's Stackelberg behavior and the vertical Nash. Further, in the field of the horizontal power structure of the two retailers, the case that the two retailers are engaged in Bertrand competition leads to higher product greenness than the case that the two retailers act as Stackelberg competition.

It can be seen from Figure 2 that the manufacturer's wholesale price increases with the green awareness of consumers (k) in all decentralized game structures. Comparing all decentralized SC structures reveals that the different vertical power structures result in different optimal wholesale prices. We can also find that the manufacturer will charge the highest wholesale price if it behaves as the leader of the SC. Moreover, in the field of the horizontal power structure of the two retailers, the case that the two retailers are engaged in Bertrand competition leads to higher wholesale price than the case that the two retailers act as Stackelberg competition.

Figure 3 depicts the effects of the green awareness of consumers (k) on the retailers' sales prices. It means that the retailers should rise their retail prices when the value of k increases. Figure 3 also indicates that both the retailers charge the highest sales prices in the manufacturer Stackelberg game structure. This is because under the decentralized game structures, when the manufacturers are pricing protagonists, they will charge high wholesale prices and then push up the retail price of the green products, which is larger than the retail price charged in both the retailers Stackelberg and the vertical Nash game structures.

Figure 4 depicts the changes in SC members' profits and the entire SC profit with the green awareness of consumers in all game structures. According to Figure 4, both the manufacturer and the two retailers benefit from the

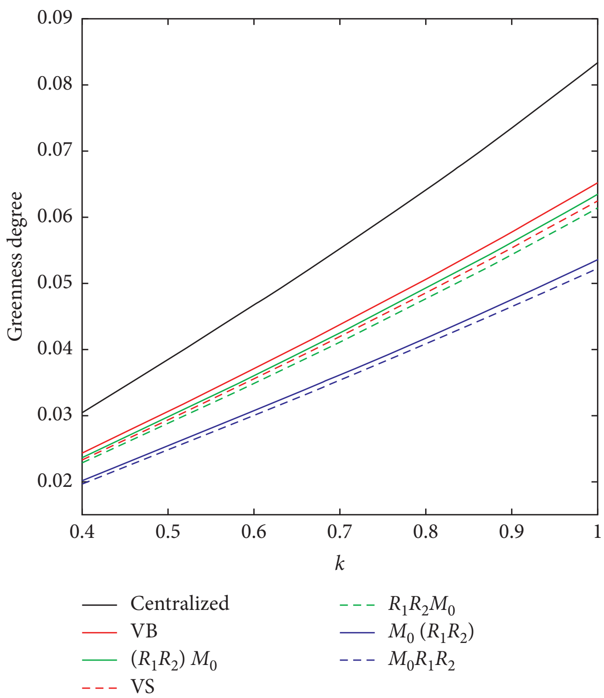


Figure 1: Effect of k on the product greenness in centralized and decentralized models.

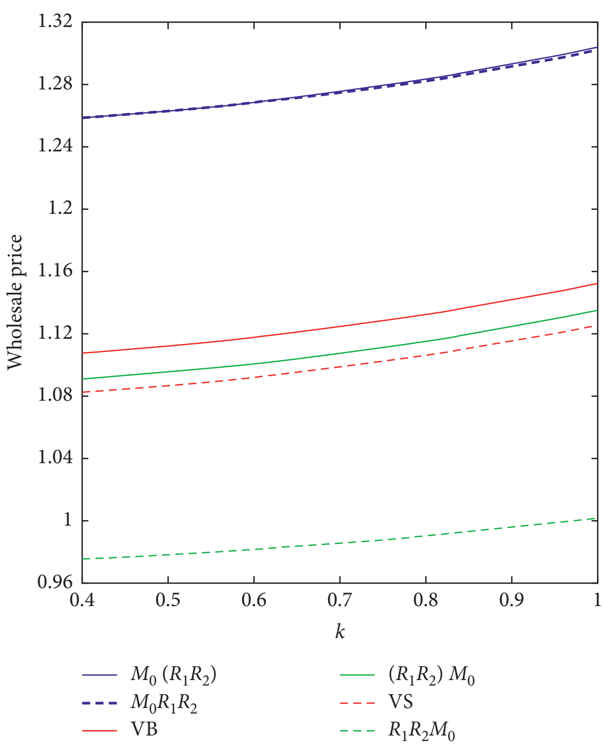


Figure 2: Effect of k on the wholesale price in decentralized models.

increasing consumer sensitivity towards greening innovation. Therefore, the SC profits increase with the green awareness of consumers (refer Figure 4(d)). Figure 4(a) shows that in the vertical power structure, the manufacturer with more power creates more profit. In the field of the horizontal power structure of the two retailers, the manufacturer will always make the most profit if the two retailers have equal right in the game structures. Figures 4(b)and 4(c) propose that in the vertical power structure, the retailers with more power have more profit. In the field of the horizontal power structure of the two retailers, the manufacturer will always gain the most profit if the two retailers act as Stackelberg competition. Figure 4(d) displays that the centralized SC earns more profit in comparison with the decentralized ones. Furthermore, comparing all decentralized SC structures suggests that in the vertical power structure, the SC under Nash game structures will gain the most profit. In the field of the horizontal power structure of the two retailers, the SC will always creates the most profit if the two retailers have equal right in the game structures. This result reveals that the whole SC system would like to be in a balanceable power structure to optimize the chain-wide economic performance.

6.2. Sensitivity Analysis of Greening Cost Coefficient. Next, the mechanism by which the manufacturer's product greenness and wholesale price, the retailers' sales prices, the player's profits, and the SC profit are influenced by the variability in the greening cost is investigated. The results of our numerical analyses are presented in Figures 5–8, where the values of the parameters are $\alpha = 1$, $\beta = 0.5$, $c = 0.5$, and $k = 0.5$ and the value of δ varies from 4 to 10.

Figure 5 depicts that the changes in product greenness with greening cost coefficient (δ) in all centralized and decentralized game models. It can be found that the product greenness decreases in all decision-making structures. Furthermore, the centralized SC model results in higher product greenness provided by the manufacturer in comparison with the decentralized models. Comparing all decentralized game structures indicates that, in the vertical power structure, the manufacturer's Stackelberg behavior decreases the product greenness compared to the retailer's Stackelberg behavior and the vertical Nash. Moreover, in the field of the horizontal power structure of the two retailers, the case that the two retailers are engaged in Bertrand competition leads to higher product greenness than the case that the two retailers act as Stackelberg competition.

Figure 6 shows that the manufacturer's wholesale price decreases with greening cost parameter (δ) in all decentralized SC models. Comparing all decentralized SC structures reveals that the different vertical power structures result in different optimal wholesale prices. We can also find that the manufacturer will charge the highest wholesale price if he behaves as the leader of the SC. Moreover, in the field of the horizontal power structure of the two retailers, the case that the two retailers are engaged in Bertrand competition leads to higher wholesale price than the case that the two retailers act as Stackelberg competition.

Figure 7 depicts the effects of the greening cost coefficient (δ) on the retailers' sales prices. It means that the

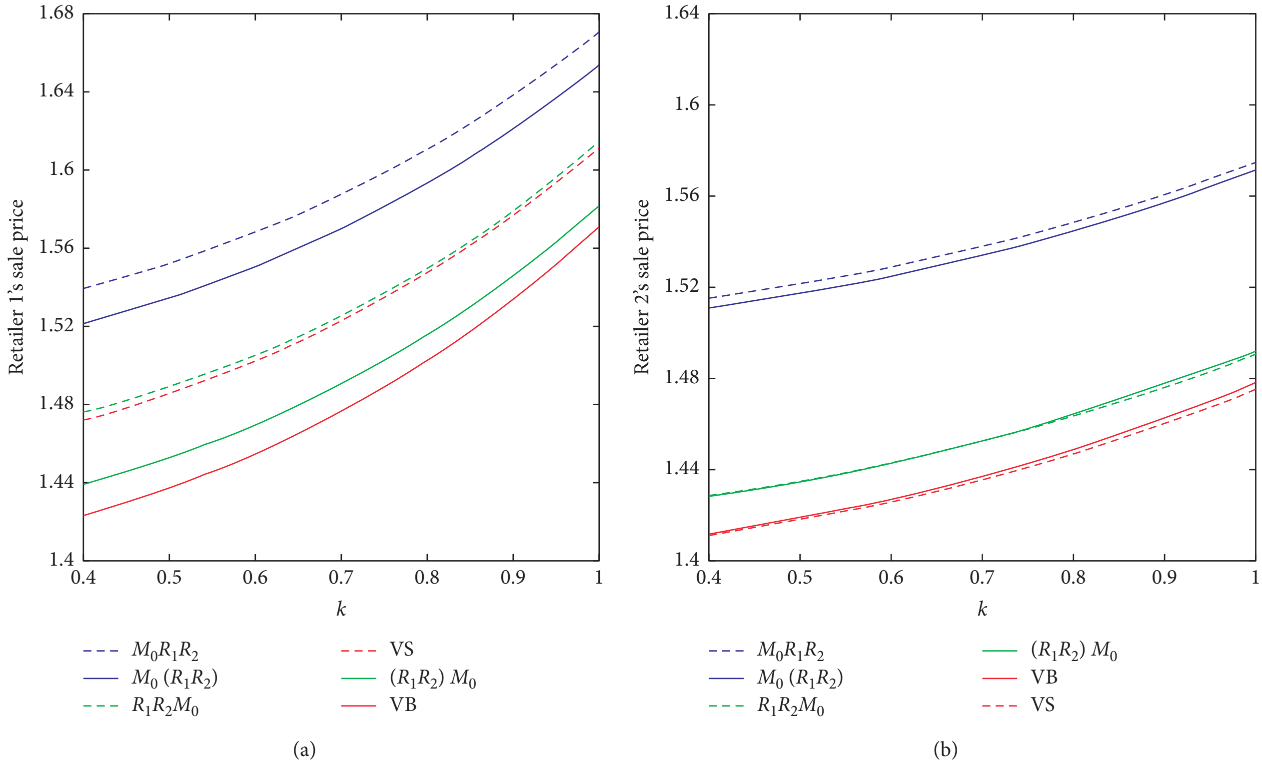


Figure 3: Effect of k on the retail price in decentralized models.

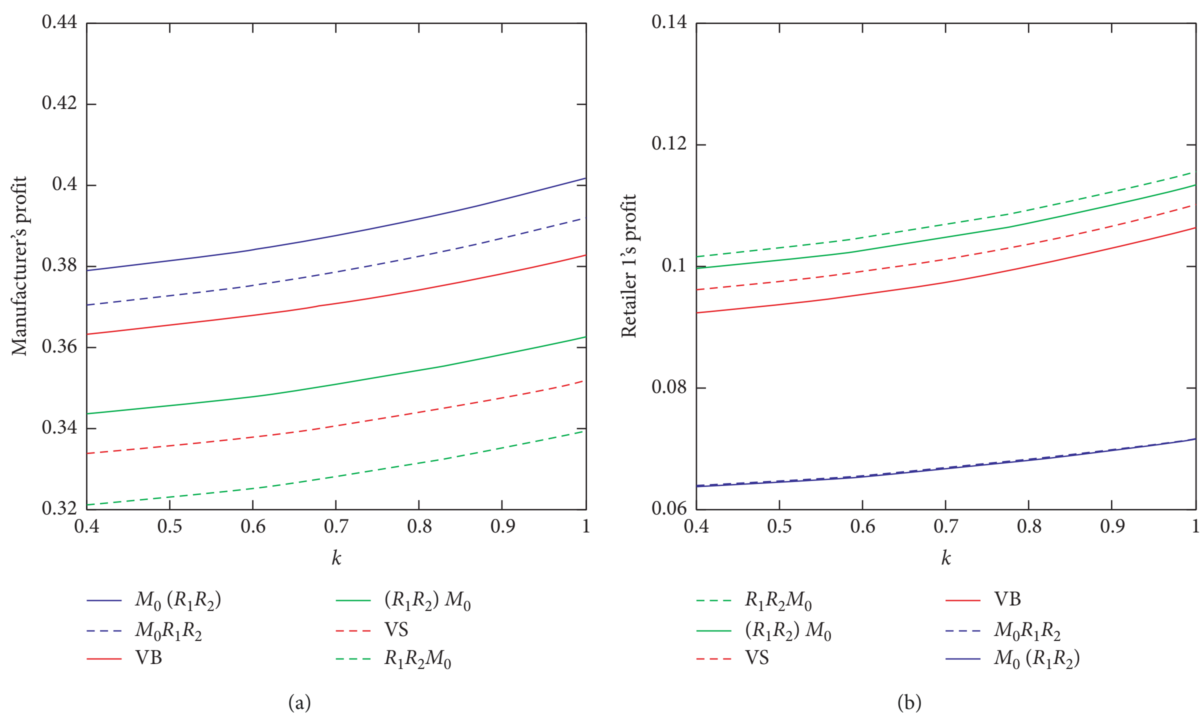


Figure 4: Continued.

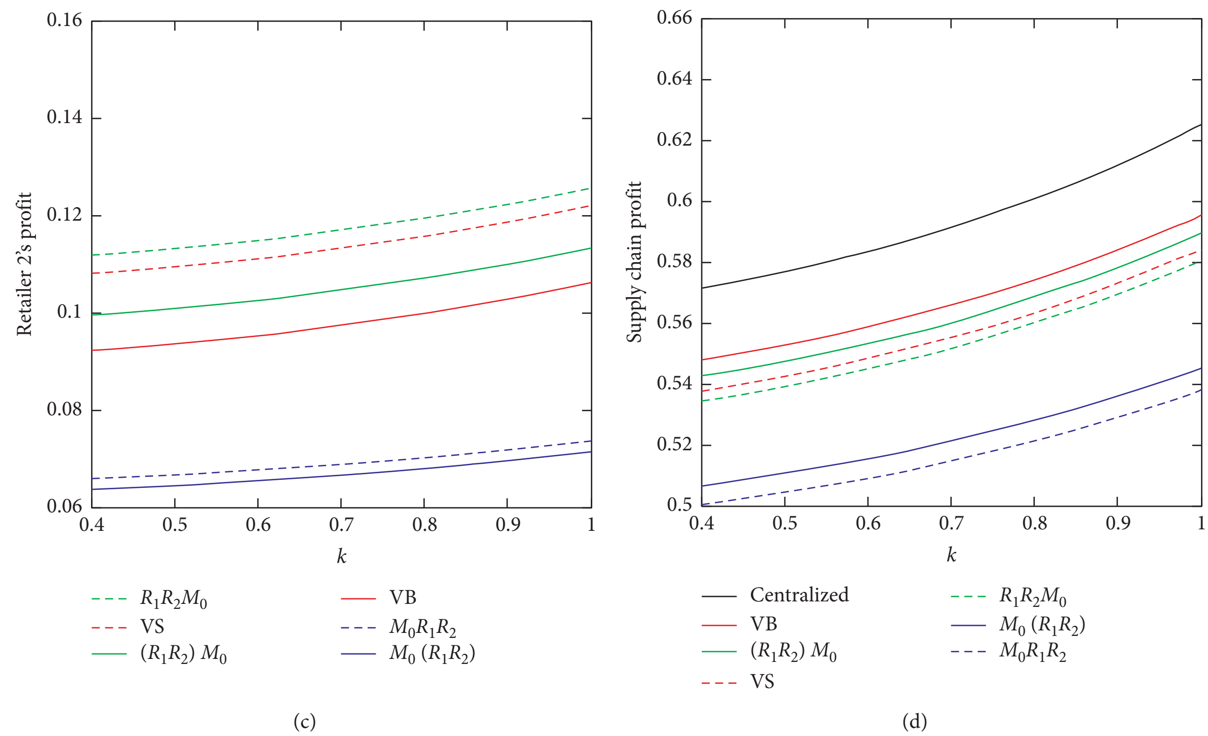


Figure 4: Effect of k on the profits in centralized and decentralized models.

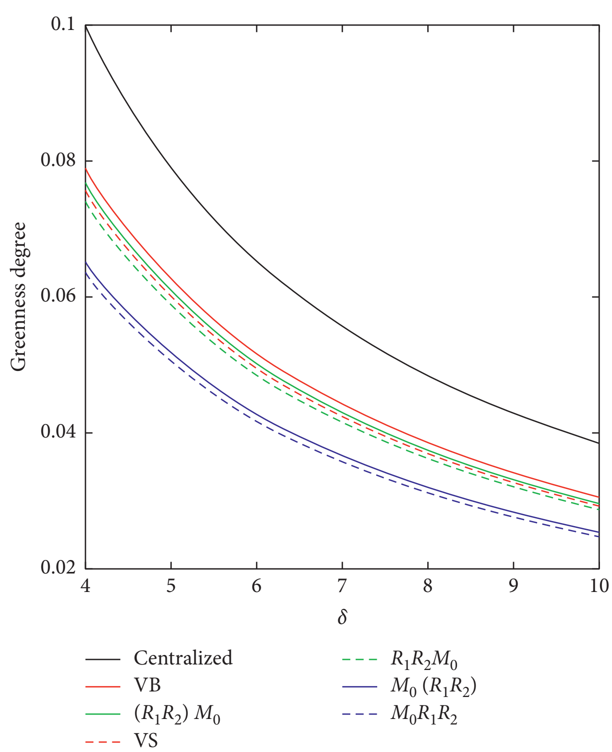


Figure 5: Effect of δ on the product greenness in centralized and decentralized models.

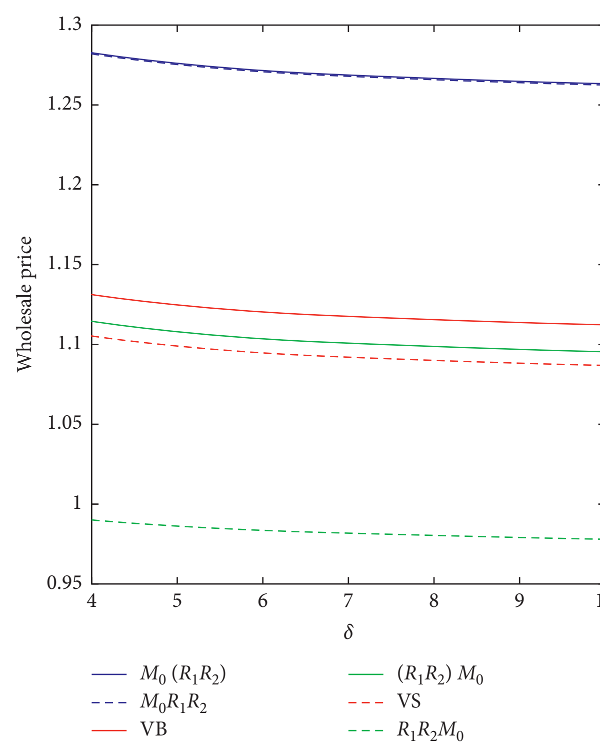
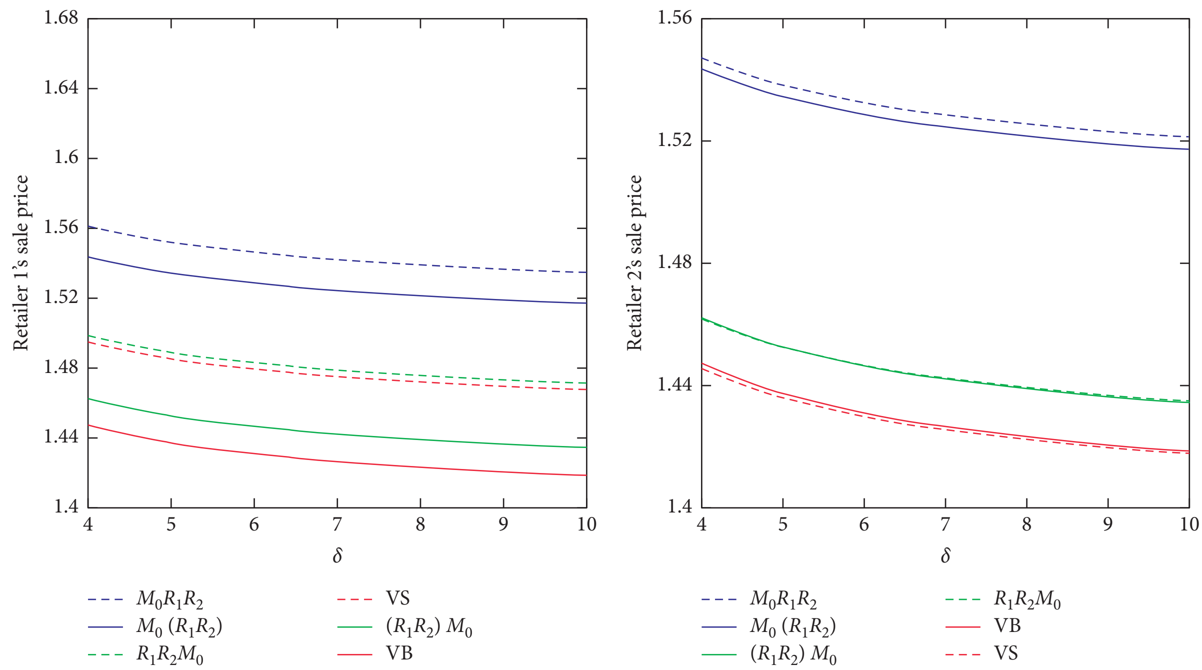


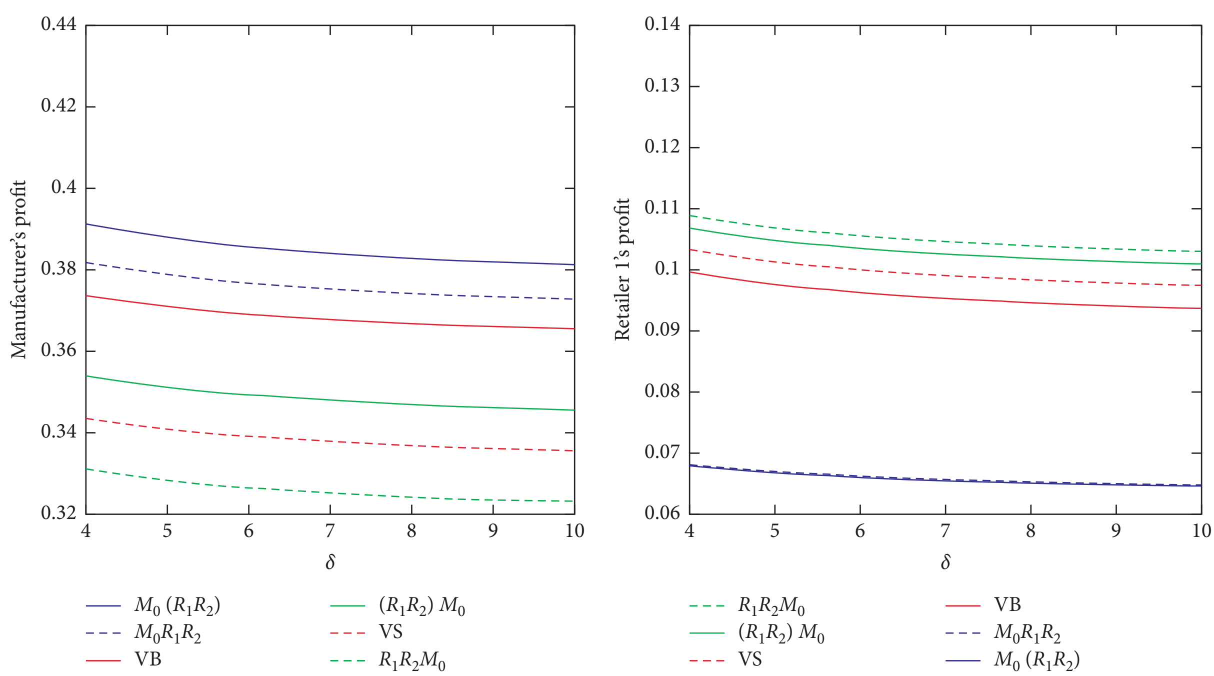
Figure 6: Effect of δ on the wholesale price in decentralized models.

retailers should reduce their retail prices when the value of δ increases. Figure 7 also illustrates that both the retailers charge the highest sales prices in the manufacturer Stackelberg game model, which is consistent to the fact that the manufacturer charges greater wholesale prices than the ones charged in both the retailers Stackelberg and the vertical Nash game structures.



(a) (b)

Figure 7: Effect of δ on the retail price in decentralized models.



(a) (b)

Figure 8: Continued.

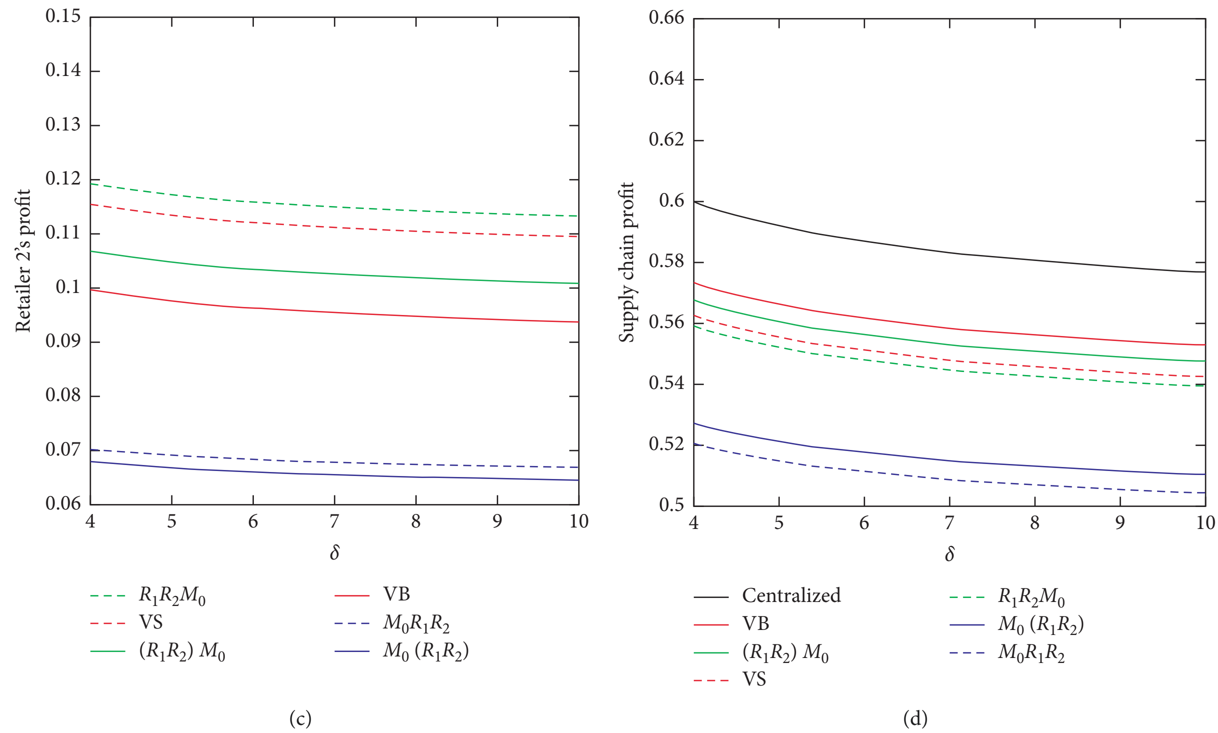


FIGURE 8: Effect of δ on the SC profit in centralized and decentralized models.

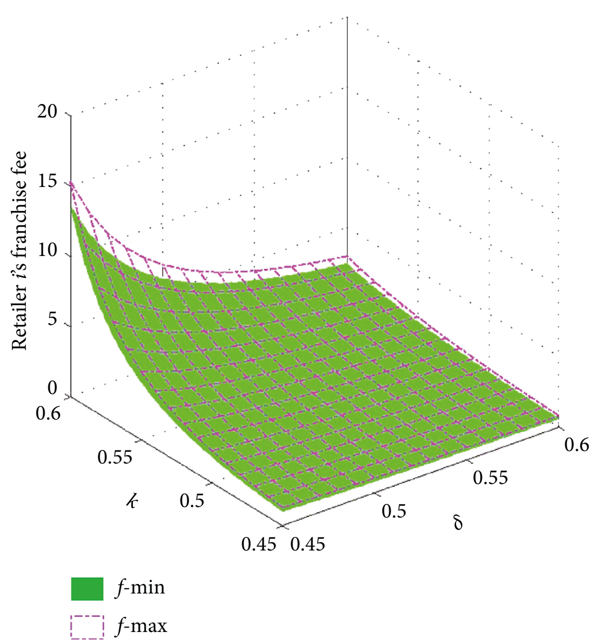


FIGURE 9: Feasible lower and upper bounds of franchise fees vs. k and δ in the $M_0\,(R_1R_2)$ model.

Figure 8 depicts that the changes in SC members' profits and the entire SC profit with the greening cost parameter in all decentralized game models. According to Figure 8, both the manufacturer's and the two retailers' profit decreases with the greening cost coefficient. Therefore, the SC profits decrease with the greening cost coefficient (refer Figure 8(d)). Figure 8(a) shows that in the vertical power structure, the manufacturer with more power obtains more profit. In the field of the horizontal power structure of the two retailers, the manufacturer will always make the most profit if the two retailers have equal right in the game structures. Figures 8(b) and 8(c) propose that, in the vertical power structure, the retailers with more power create more profit. In the field of the horizontal power structure of the two retailers, the manufacturer will always make the most profit if the two retailers have unequal right in the game structures. Figure 8(d) illustrates that the centralized SC earns more profit in comparison with the decentralized ones. Furthermore, comparing all decentralized SC structures implies that in the vertical power structure, the SC under Nash game structures will create the most profit. In the field of the horizontal power structure, the SC will always make the most profit if the two retailers have equal right in the game structures. This result reveals that it is very important for SC members to balance power structure in the SC, which can improve the SC performance.

When comparing the results of the different models, we find that the manufacturer and the two retailers participate in the vertical competition with more power creating more profit, as shown in Figures 4(a)–4(c) and 8(a)–8(c). Besides, we also can find that the two retailers engaging in the horizontal competition have more profits. Therefore, they will strive to create a fierce competitive market environment to improve their own profit. However, from the overall SC point of view, both the vertical and horizontal competition will decrease the green degree of products and the profits of

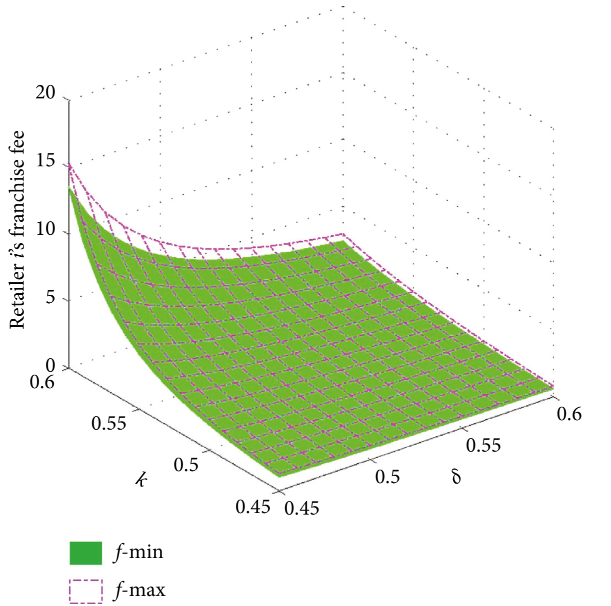
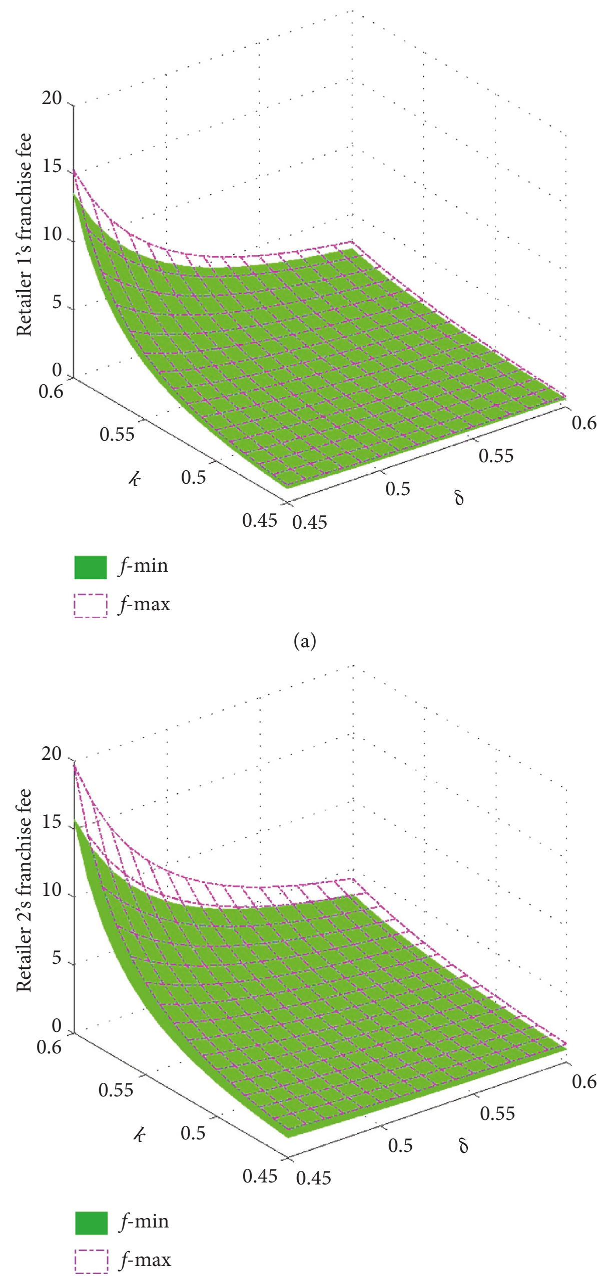


Figure 10: Feasible lower and upper bounds of franchise fees vs. k and δ in the $(R_1R_2)M_0$ model.



(a)

(b)

Figure 12: Feasible lower and upper bounds of franchise fees vs. k and δ in the $M_0R_1R_2$ model.

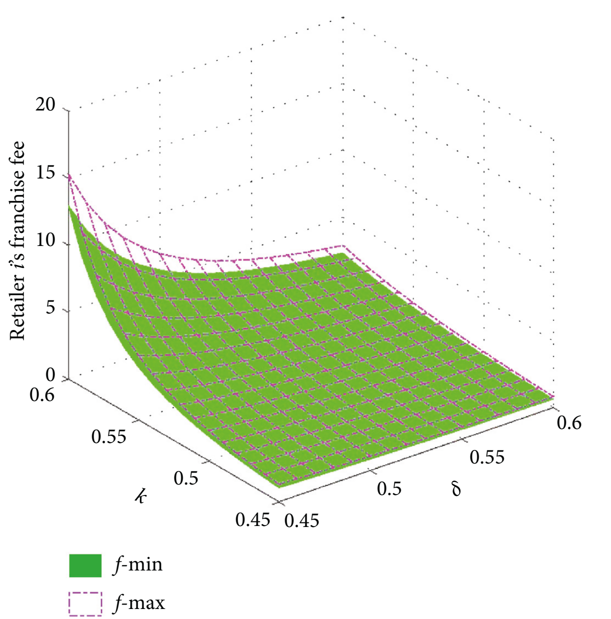
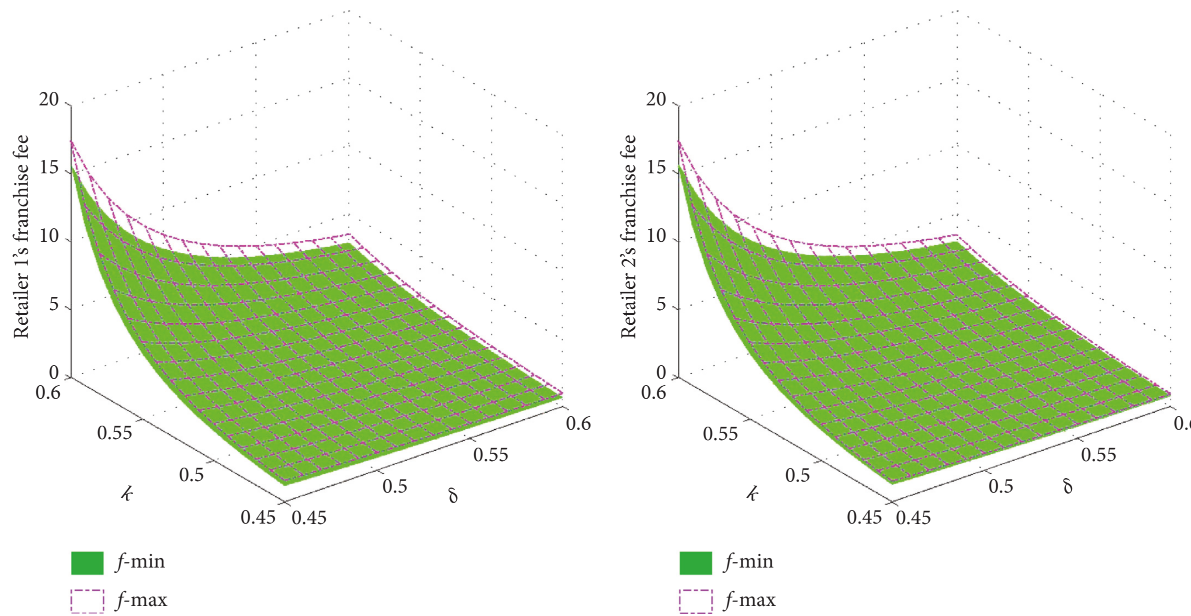


Figure 11: Feasible lower and upper bounds of franchise fees vs. k and δ in the VB model.

SC, as shown in Figures 1, 4(d), 5, and 8(d). We can draw the conclusion that a fierce competitive market environment will lead to the deterioration of product quality and waste of resources. To achieve sustainable development, we need to come up with a win-win contract for SC members.

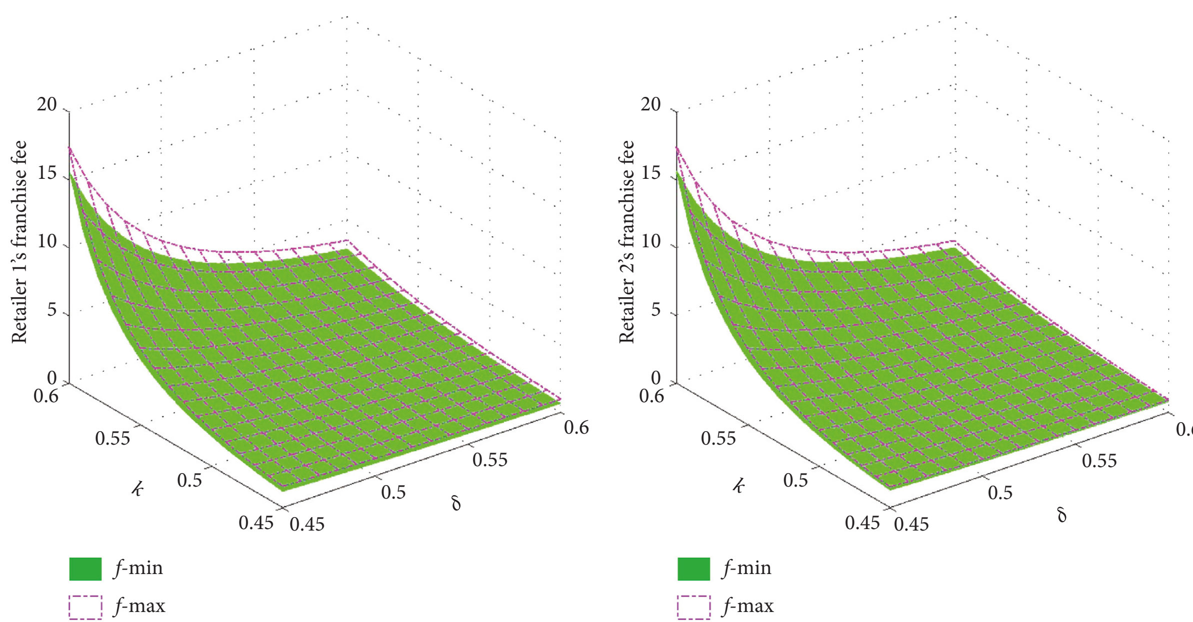
6.3. Sensitivity Analysis of Franchise Fees. Finally, we explore how the lower and upper bounds of franchise fees, indicated by f-min and f-max, are affected by changes in the value of consumer's environmental consciousness and greening cost coefficient in the decentralized SC models. The results of numerical analyses are proposed in Figures 9–14, where the values of relevant parameters are $\alpha = 1$, $\beta = 0.5$, and $c = 0.5$ and the value of δ and k varies from 0.45 to 0.6. These figures indicate that the designed two-part tariff contracts are flexible enough to promote cooperation among the SC members under different SC power structures.

The numerical results indicate the efficiency of the proposed model. From the results, we can see that the two-part tariff contract can improve the profits of the manufacturer, the two retailers, and the entire SC. When



(a) (b)

Figure 13: Feasible lower and upper bounds of franchise fees vs. k and δ in the $R_1R_2M_0$ model.



(a) (b)

Figure 14: Feasible lower and upper bounds of franchise fees vs. k and δ in the VS model.

the manufacturer charges a franchise fee f_i to downstream retailer i, the manufacturer will probably enhance the green degree of product, which benefits both the two retailers and the manufacturer. However, when the franchise fee f_i is relatively too large, the retailer obtains less profits under the coordination model than those under the decentralized models. In this case, the manufacturer should determine appropriate contract parameters to motivate the retailers.

7. Conclusions

In this work, a two-echelon green SC consisting of one upstream manufacturer and two downstream competing retailers whose customer demand is greenness sensitive is taken into account. First of all, the green SC is regarded as a whole (named the centralized model) to discuss the operational decisions. Afterwards, the SC players' operational decisions and the entire SC performance are explored under the decentralized setting. We examine the decentralized models under three different vertical power structures (i.e., *Manufacturer Stackelberg*, *Retail Stackelberg*, *and Vertical Nash*) and two different horizontal power structures (including Bertrand or Stackelberg competition between the two retailers). Thirdly, a two-part tariff agreement is designed to promote SC members to cooperate with each other. Finally, we explore how the manufacturer's wholesale price, the retailers' retail prices, and the players' profits are affected by the consumers' environmental awareness and greening cost coefficient.

Through the above analyses, there are four main findings. First, the influence of power relationship on the SC members' decisions and profits mainly depends on the substitutability of the green products, the green awareness of consumers, and greening cost coefficient. Second, the more SC power that the manufacturer possesses, the lower product greenness will be determined. In other words, a green SC in which all the players have balanced power will give rise to the greater product greenness. Third, in each model, the consumer's environmental awareness (the greening cost coefficient) positively (negatively) influences the manufacturer's product greenness and wholesale price, the retailers' sales prices, the players' profits, and the SC profit. Fourth, the manufacturer's and the two retailers' profits are higher under the two-part tariff contracts than under the decentralized models. Therefore, they will accept the two-part tariff contract designed for the SC.

Besides contributing to the green SC management theory, this study also generates some managerial insights which are summarized as follows. Firstly, SC members should change their mind to pay attention to the whole SC performance rather than focusing solely on improving their own profits. They should strengthen information sharing and share responsibility for promoting the sale of green products. Secondly, the manufacturer should take measures to improve the product green degree and reduce the production cost of green products, such as optimizing the production process, adopting the new technologies, and improving the comprehensive utilization rate of resources. Lastly, retailers should vigorously spread the concept of green product experience and guide consumers to adopt a green lifestyle. For example, they should publicize their green products to consumers through news media, Internet, and other channels.

Several extensions to this work are possible. To begin with, this research only focuses on a two-echelon green SC comprising one manufacturer and two retailers. In reality, there exist some other SC structures, e.g., dual-channel SC and three-echelon SC. Secondly, demand uncertainty and SC members' risk attitudes are not examined in this paper, which would have a significant effect on SC players' optimal decisions. Thirdly, the influences of advertise strategies and sale effort by retailers on SC members' optimal decisions should also be considered.

Appendix

Proof of Proposition 1. In the centralized model, by solving $(\partial\prod_{SC}/\partial\theta) = 0$ and $(\partial\prod_{SC}/\partial p_i) = 0$, $\theta^c = -((\alpha - c + \beta c)k)/(k^2 + 2\beta\delta - 2\delta)$, $p_i^c = (k^2 c + (\beta - 1)\delta c - \delta\alpha)/(k^2 + 2\beta\delta - 2\delta)$.

Then, substituting θ^c and p_i^c into $\prod_{SC}$ in (4) gives the maximal SC profit $\prod_{SC}^c$ for the integrated model: $\prod_{SC}^C = -((\alpha - c + \beta c)^2\delta)/(k^2 + 2\beta\delta - 2\delta)$. □

Proof of Proposition 2. In the decentralized model, it is assumed that the unit marginal profit of the retailer is m_i, then $p_i = m_i + \omega$, $(i = 1, 2)$. In the $M_0(R_1R_2)$ model, to derive the equilibrium decisions of the SC players, we obtain the retailers' best reaction functions for a fixed value ω and θ by setting $\partial\prod_i/\partial m_i$ equal to zero and solving for m_i: $m_i = -(\alpha + k\theta + \beta\omega - \omega)/(\beta - 2)$. Substituting m_i into the manufacturer's profit $\prod_0$ in equation (3) and employing the first-order derivative for the corresponding profit function with respect to the wholesale price ω and the greenness level of products θ provides the manufacturer's equilibrium wholesale price $\omega^{M_0(R_1R_2)}$, and the greening improvement level of products $\theta^{M_0(R_1R_2)}$ are as follows: $\omega^{M_0(R_1R_2)} = (k^2 c + (\beta - 2)[\alpha - (\beta - 1)]\delta c)/(k^2 - 2\delta\beta^2 + 6\delta\beta - 4\delta)$ and $\theta^{M_0(R_1R_2)} = -((\alpha - c + \beta c)k)/(k^2 - 2\delta\beta^2 + 6\delta\beta - 4\delta)$. With $\omega^{M_0(R_1R_2)}$ and $\theta^{M_0(R_1R_2)}$, we can obtain the equilibrium wholesale prices $(\omega^{(R_1R_2)M_0})$, product greening improvement level $(\theta^{(R_1R_2)M_0})$, pricing $(p_i^{(R_1R_2)M_0})$, demand $(q_i^{(R_1R_2)M_0})$, and profits $(\prod_0^{(R_1R_2)M_0}, \prod_i^{(R_1R_2)M_0}$, and $\prod_{SC}^{(R_1R_2)M_0})$ of this model. □

Proofs of Propositions 3–7. Proofs of Propositions 3–7 are similar to that of Proposition 2 and, hence, are omitted. □

Proof of Proposition 8. From Proposition 1–7, we can further compare the equilibrium values of the green degree of products:

$$
\begin{aligned}
\theta^{M_0(R_1R_2)} - \theta^{M_0R_1R_2} &= -\frac{2k\beta^2(2+\beta)(\beta-1)^2[\alpha+(\beta-1)c]\delta}{[k^2-2(\beta-1)(\beta-2)\delta]\left[((\beta-1)(\beta+4)\beta-8)k^2+16(\beta-1)\left(\beta^2-2\right)\delta\right]} > 0,\\
\theta^{R_1R_2M_0} - \theta^{M_0(R_1R_2)} &= \frac{(\beta-1)^2[\alpha+(\beta-1)c]\delta k\left[(\beta+1)^2(8\beta-3)k^6+2\left(\beta^2-1\right)((7\beta+24)\beta-1)\delta k^4-(\beta-1)^2(\beta-5)((20\beta+31)\beta+9)\delta^2k^2-2(\beta-1)^3\left((17\beta-59)\beta^2-38\right)\delta^3\right]}{4\left[k^2-2(\beta-1)(\beta-2)\delta\right][k^2+2(\beta-1)\delta][(\beta+1)k^2+(\beta+3)(\beta-1)\delta]\left[(\beta+1)((\beta+1)k^2-2(\beta-1)(\beta-5)\delta)k^2-(\beta-1)^2((7\beta-6)\beta-17)\delta^2\right]} > 0,\\
\theta^{VS} - \theta^{R_1R_2M_0} &= -\frac{-(\beta-1)^3[k^2+(\beta-1)\delta][\alpha+(\beta-1)c]\delta k\left[(\beta+1)^3(4\beta+13)k^6+(\beta-1)(\beta+1)^2((14\beta+87)\beta+103)\delta k^4+(\beta-1)^2(\beta+1)\left((24\beta+143)\beta^2+370\beta+279\right)\delta^2k^2+(\beta-1)^3\left(11(2\beta+7)\beta^3+(273\beta+463)\beta+253\right)\delta^3\right]}{4\left[k^2+2(\beta-1)\delta\right]\left[(\beta+1)k^2-(\beta-1)\left(2\beta^2-\beta-5\right)\delta\right][(\beta+3)k^2+(\beta-1)(\beta+7)\delta][(\beta+1)k^2+(\beta-1)(\beta+3)\delta]\left[(\beta+1)((\beta+1)k^2-2(\beta-1)(\beta-5)\delta)k^2-(\beta-1)^2((7\beta-6)\beta-17)\delta^2\right]} > 0,\\
\theta^{(R_1R_2)M_0} - \theta^{VS} &= \frac{(\beta-1)^2[\alpha+(\beta-1)c]\delta k[3(\beta+1)k^2+(\beta-1)(5\beta+7)\delta]^2[(\beta+1)k^2+(\beta-1)(3\beta+1)\delta]^2}{4\left[k^2+2(\beta-1)\delta\right][(\beta+1)k^2+(\beta-1)(\beta+3)\delta][(\beta+1)k^2-(\beta-1)(\beta-5)\delta]\left[(\beta+1)((\beta+1)k^2-2(\beta-1)(\beta-5)\delta)k^2-(\beta-1)^2((7\beta-6)\beta-17)\delta^2\right]} > 0,\\
\theta^{VN} - \theta^{(R_1R_2)M_0} &= -\frac{(\beta-1)^3[\alpha+(\beta-1)c][k^2+(\beta-1)\delta]\delta k}{[k^2+2(\beta-1)\delta][(\beta+1)k^2-(\beta-1)(\beta-5)\delta]\left[k^2+(\beta-1)((\beta+1)(3\beta-7)c-(\beta+3)\alpha)\delta^2\right]} > 0,\\
\theta^{C} - \theta^{VN} &= -\frac{2(\beta-1)^2[\alpha+(\beta-1)c]\left[\beta k^2+\left(\beta^2-1\right)\delta\right]\delta k}{[k^2-2(\beta-1)(\beta-2)\delta][k^2+2(\beta-1)\delta][(1+\beta)k^2-(\beta-1)(\beta-5)\delta]} > 0.
\end{aligned}
\tag{A.1}
$$

The other relationships are also using the same method and, hence, are omitted. □

Proof of Proposition 9. From Proposition 1–7, we can further obtain the following partial derivatives:

$$\frac{\partial\theta^{M_0(R_1R_2)}}{\partial k} = \frac{[\alpha+(\beta-1)c]\left[k^2+2(\beta-1)(\beta-2)\delta\right]}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} > 0,$$

$$\frac{\partial\omega^{M_0(R_1R_2)}}{\partial k} = -\frac{2(\beta-2)[\alpha+(\beta-1)c]\delta k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} > 0,$$

$$\frac{\partial p^{M_0(R_1R_2)}}{\partial k} = -\frac{2(2\beta-3)[\alpha+(\beta-1)c]\delta k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} > 0,$$

$$\frac{\partial\prod_i^{M_0(R_1R_2)}}{\partial k} = -\frac{4(\beta-1)^2[\alpha+(\beta-1)c]\delta^2 k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^3} > 0,$$

$$\frac{\partial\prod_0^{M_0(R_1R_2)}}{\partial k} = \frac{2[\alpha+(\beta-1)c]^2\delta k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} > 0,$$

$$\frac{\partial\prod^{M_0(R_1R_2)}}{\partial k} = \frac{2[\alpha+(\beta-1)c]^2\left[k^2-2(\beta-1)(3\beta-4)\delta\right]\delta k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^3} > 0,$$

$$\frac{\partial\theta^{M_0(R_1R_2)}}{\partial\delta} = -\frac{2(\beta-1)(\beta-2)[\alpha+(\beta-1)c]\delta k}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} < 0,$$

$$\frac{\partial\omega^{M_0(R_1R_2)}}{\partial\delta} = \frac{(\beta-2)[\alpha+(\beta-1)c]k^2}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} < 0,$$

$$\frac{\partial p^{M_0(R_1R_2)}}{\partial\delta} = \frac{(2\beta-3)[\alpha+(\beta-1)c]k^2}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} < 0,$$

$$\frac{\partial\prod_i^{M_0(R_1R_2)}}{\partial\delta} = \frac{2(\beta-1)^2[\alpha+(\beta-1)c]^2\delta k^2}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^3} < 0,$$

$$\frac{\partial\prod_0^{M_0(R_1R_2)}}{\partial\delta} = -\frac{[\alpha+(\beta-1)c]^2 k^2}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^2} < 0,$$

$$\frac{\partial\prod^{M_0(R_1R_2)}}{\partial\delta} = -\frac{[\alpha+(\beta-1)c]^2\left[k^2-2(\beta-1)(3\beta-4)\delta\right]k^2}{\left[k^2-2(\beta-1)(\beta-2)\delta\right]^3} < 0. \tag{A.2}$$

□

Proof of Proposition 10

(i) From $(\partial\prod_i/\partial p_i) = 0$, we get $p_i = -(\alpha+k\theta+\omega)/(\beta-2)$. In order to coordinate the SC, we define the optimal product greenness and the optimal retail prices as in equation (5). Thus, we can get $\omega^{co} = (k^2c + [(\beta-2)\ (1-\beta)c-\alpha\beta]\delta)/\ (k^2+2(\beta-1)\delta)$.

(ii) From $(\partial\prod_2/\partial p_2) = 0$, we get $p_2 = (\alpha+k\theta+\omega+\beta p_1)/2$. Then, substituting p_2 into retailer 1's profit $\prod_1$ in equation (4) and solving the first-order derivatives of this function for the equilibrium value of p_1: $p_1 = -((2+\beta)(\alpha+k\theta)-(1+\beta)(\beta-2)\omega)/(2(\beta^2-2))$. In order to coordinate the SC, we define the optimal product greenness and the optimal retail prices as in equation (5). Thus, we can get $\omega^{co} = ((\beta+1)(\beta-2)ck^2+2\delta[(\beta-1)(\beta^2-2)c+\beta\alpha])/((\beta+1)(\beta-2)[k^2+2(\beta-1)\delta]^2)$. □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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