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Pricing and Sales Effort Decisions in a Closed-Loop Supply Chain Considering the Network Externality of Remanufactured Product

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Abstract: Considering the network externality of remanufactured product, this paper develops the Stackelberg game models in a closed-loop supply chain (CLSC) consisting of an original equipment manufacturer (OEM) and a retailer with dual sales channel under three scenarios, i.e., no sales effort (Model N), the retailer exerting sales effort (Model R) and the OEM exerting sales effort (Model M). The study investigates the pricing and sales effort decisions for CLSC members. The results show that: (1) Compared with no sales effort, the sales effort behavior can always improve the profits of the OEM and entire CLSC. The retailer's profit can be improved in Model R, so OEM exerting sales effort could cause a loss for the retailer and the sales effort behavior can promote the sales of remanufactured products and further cannibalize the new product market. (2) Model M is more favorable to improve the profits of the OEM and entire CLSC, while the retailer prefers Model R. Model M is more beneficial for boosting the sales of remanufactured products. (3) As the network externality/consumer's sensitivity of sales effort becomes more obvious, CLSC members exert more sales effort, and the OEM exerts more sales effort compared to the retailer. (4) Only when the retailer's sales effort cost is much lower than the OEM sales effort cost is it that OEM could obtain more profit when the retailer exerts sales effort; then, the win-win situation between OEM and the retailer is achieved.

Keywords: closed-loop supply chain; remanufacturing; sales effort; network externality; dual sales channel

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1. Introduction

Recently, due to resource shortage and environmental degradation, both business and academia have been paying more and more attention to closed-loop supply chain (CLSC) management to attain sustainable development. It has been a global trend to recycle end-of-use products and produce remanufactured products. Remanufacturing could extract residual values in used products and then decrease the usage of raw materials and energy, so it can be more profitable and fast-growing than manufacturing in some cases [1]. For example, Caterpillar established a remanufacturing division which generated over $2 billion in 2007, and Xerox saved 40–65% of manufacturing costs through its green remanufacturing program [2].

However, overall, the Chinese remanufacturing industry is in the primary stage of development [3]. The development of the remanufacturing industry is faced with many challenges and opportunities. Consumers' concerns about the quality of remanufactured products are hindering the progression of CLSC. In fact, consumers' acceptance and willingness to pay for remanufactured products is lower than for new products [4,5]. To reduce consumers' concerns, government subsidy programs have been implemented to stimulate consumption. For example, the Chinese government issued a program named Trade the Old for Remanufacturing in 2013. In addition to the government intervention, enterprises usually exert efforts to promote the sales of remanufactured products such as media advertising, increasing brand reputation, providing attractive shelf space, etc. Sales effort can effectively increase the product market share and profitability [6]. In reality, many manufacturers and retailers are willing to exert sales effort to improve possible market demand. For instance, Tesco, Casino, etc., attach the carbon footprint label to the products to attract the customers [7].

In addition to the enterprises' behavior, consumers are also influenced by the purchasing behavior of others. Due to consumers' concerns about the quality of remanufactured products, when more consumers purchase remanufactured products, their concerns can be eased [8]. This behavior can be explained by network externality theory. Network externality states that consumer's anxiety subsides when many others adopt the product, and consumers' utility increases with the number of other consumers consuming the product [9]. Therefore, sales effort stimulates consumers' desire to buy remanufactured products, simultaneously in the presence of network externality, consumers' willingness to pay for remanufactured products will be further improved, thus inducing more potential consumers to make a purchase.

In addition, with the advances of technology and e-commerce, traditional retail channel and online direct channel have become the main operating modes for CLSC. For example, Apple and Philips sell new products through retail channels and both remanufactured and new products through their websites simultaneously. In addition to selling its products through the retail channel, Dell also sells both its new and authorized remanufactured products through its online channel [10]. Thus, the competition between the retail channel and direct channel could not be ignored.

1.1. Research Questions

Considering the network externality of remanufactured product and dual sales channels, the main purpose of this study is to answer the following questions:

(1) What are the optimal pricing decisions and sales effort level under different models, i.e., no sales effort (Model N), the retailer exerting sales effort (Model R) and the OEM exerting sales effort (Model M)?
(2) Comparing the three models, which is optimal for the OEM/retailer/entire CLSC?
(3) How do the network externality, the consumers' sensitivity of sales effort and the sales effort cost affect CLSC operations?

1.2. Novelty of Research Work

The network externality of remanufactured product, the sales effort, and sales channel structure cannot be ignored in CLSC management. Previous studies on sales effort in CLSC did not focus on the differential pricing decision for new and remanufactured products in a dual-channel structure. However, consumers have lower willingness to pay for remanufactured products than new ones, so it is necessary for CLSC members to provide differential pricing for new and remanufactured products. In addition, the remanufactured products have the inherent characteristic of strong network externalities, but fewer works have discussed the impact of network externalities on CLSC management. In summary, no studies have discussed the differential pricing strategy for new and remanufactured ones and the sales effort decision in the dual sale-channels CLSC, considering the network externalities characteristic of remanufactured product and sales effort exerted by the CLSC chain members.

To fill the research gaps, in the presence of network externality of remanufactured ones, our paper investigates the optimal pricing and sales effort decisions for chain members in a dual-channel CLSC.

1.3. Flow of Study

To answer the above questions, this paper constructs a Stackelberg game model considering network externality and sales effort. We first obtain the optimal solutions of the models under three scenarios, i.e., Model N, Model R and Model M. Then, we compare the CLSC members' performance in the three models and examine the CLSC members' strategy selection for sales effort. Finally, we explore more complex scenarios by numerical examples.

The paper is organized as follows. In the next section, we briefly review the previous works. In Section 3, we introduce the model overview. In Section 4, we present the model formulation and solution. In Section 5, we provide model analysis. Additional numerical experiments are presented in Section 6. Finally, Section 7 presents the conclusion. All proofs are provided in Appendix A.

2. Literature Review

In this section, the related literature are reviewed across four research streams: (1) differential pricing for the new and remanufactured products in CLSCs, (2) network externality in supply chains (CLs), (3) sales effort in CLSCs, and (4) dual sales channel in CLSCs.

2.1. Differential Pricing for New and Remanufactured Products in CLSCs

Lots of previous studies assume that there is no distinction between the new and remanufactured products, and they are sold in the market with the same price [11–14]. However, due to quality concerns regarding remanufactured products by consumers, their willingness to pay for remanufactured products is relatively lower than new ones [15]. With respect to differential pricing in CLSCs, Huang et al. [16] analyzed the influence of consumers' strategic behaviors and remanufacturing costs on pricing and production decisions in three remanufacturing scenarios. Zhao et al. [17] developed the decision models of pricing, service, and recycling of CLSCs with three different remanufacturing modes and they showed that remanufacturing by retailers paying fixed technology authorization fees can improve the retailer's product service level and promote the third-party to improve recovery rate. Zhao et al. [18] investigated the impact of three government subsidy scenarios on the unit wholesale price, retail price and profit of the new and remanufactured products. They indicated that the government subsidy can enhance the market demand of remanufactured product. Ma et al. [19] introduced the reference price effects and reference quality effects into the remanufacturing decision-making game model, and investigated the impact of dual reference parameters and government incentive policy on pricing strategy, profits of supply chain members and consumer surplus. Zhang et al. [20] analyzed the manufacturer remanufacturing and the retailer remanufacturing modes under government fund policy. They showed that the manufacturer chooses to remanufacture by itself without government fund policy while the retailer remanufacturing mode benefits the CLSC members under government fund policy. As mentioned above, we also consider the new and remanufactured products that are sold at different prices in the market. Then, we examine the optimal pricing and sales effort decisions for CLSC members.

2.2. Network Externality in SCs

When consumers purchase products, they are not only affected by the factors of the product itself, but also by the number of consumers who buy the product, that is, the product network externality. Katz and Shapiro [21] defined the network externality as the phenomenon that the increased value of a product is affected by the number of those who use similar or compatible products. Subsequently, some scholars focused on the operation management of enterprises under the characteristic of product network externality. Candogan et al. [22] discussed a monopolist's optimal pricing strategies in the presence of positive network externality. Liu et al. [23] analyzed the sales channel and versioning strategy under the network externality. Xu et al. [24] analyzed retailers' return strategy when network externality exists in the market and found that the policies depend on consumer initial return and network-externality return. Xu et al. [25] investigated the impact of product network externalities on firms' optimal profits in a duopolistic information product market and identified the conditions in which each marketing strategy prevails. They showed that sufficiently strong network externality can enhance the profit of the firm. Wang et al. [26] studied the manufacturer's carbon emission reduction strategy considering network externalities and altruistic preferences. They concluded that network externalities and altruistic preferences can efficiently increase the manufacturer's profit and carbon emission reduction level. Similarly, the remanufactured products also have the obvious characteristic of network externality [8]. That is to say, when more consumers buy the remanufactured products, the potential consumers' value evaluation of the remanufactured products will be improved. For instance, Zhou et al. [8] introduced the theory of network externality to explore the impact of government subsidy with or without budget constraint on OEM decision making. Xie et al. [27] examined the impact of network externality on CLSC members decision making with different waste recycling channel strategies considering consumers' dual preference for product quality and environmental friendliness. They found that the demands of both new and remanufactured products with network externalities are greater than those of products without network externalities.

However, the above works consider network externality in the traditional supply chain, and few studies focus on the network externality characteristic of remanufactured products, except for Zhou et al. [8] and Xie et al. [27]. Differing from the above-mentioned studies, our paper examines the problems of CLSC members' optimal differential pricing and sales effort decisions considering the network externality of remanufactured product.

2.3. Sales Effort in CLSCs

Many scholars have discussed the effects of sales effort on pricing decisions and operational performance of closed-loop supply chains. Gao et al. [28] studied the influence of retailers' sales efforts on CLSC pricing decisions under different power structures. They showed that demand expansion, effectiveness of collection rate of used products and sales effort play important roles in the supply chain. Ma et al. [29] discussed the optimal decision and performance of the CLSC members considering marketing effort-dependent demand and the retailer's fairness concerns. Zerang et al. [30] investigated optimal decisions in a three-echelon CLSC model with sales effort exerted by the retailer and they found that from the perspective of remanufacturing process and consumers' welfare, the manufacturer-led structure is often the most effective scenario in CLSC. Taleizadeh et al. [31] explored the effect of marketing effort on a dual-channel CLSC by considering different models when the manufacturer/retailer exerts sales effort. They showed that the effect of sales effort investment depends on consumers' channel preference and a two-part tariff can coordinate the supply chain only when the manufacturer is the investor. Mondal and Giri [7] analyzed the impact of sales effort and green innovation effort on the decision making of the CLSC recycling channel. The above studies [7,28–31] on sales effort of CLSC assumed that new and remanufactured products are sold at the same price. Scholars have also studied the differential pricing of new and remanufactured products under sales effort. For example, Li and Wang [32] developed a CLSC decision-making model considering sales effort under government subsidy. They showed that government subsidy and sales effort can efficiently improve the demand for remanufactured product. Further, based on the government subsidy policy, Li and Wang [33] discussed the influence of retailers' service level and fairness concern behavior on CLSC decision making.

The above literature hold a common assumption that the new and remanufactured products are sold at the same price and the product is purchased by the consumer only through a single sales channel. Li and Wang [32] and Li and Wang [33] considered differential pricing for the new and remanufactured products, but they did not focus on dual-sales channel. Then, we take the critical issue into account in this paper. We investigate the optimal pricing and sales effort decisions considering differential pricing for the new and remanufactured products with a dual-sales channel.

2.4. Dual Sales Channel in CLSCs

Based on the research achievements of a sales channel in a traditional supply chain [34–36], many scholars have studied the dual sales channel issues in CLSC. Regarding the problem of sales channel difference in a CLSC, Zheng et al. [1] studied pricing, collection and coordination decisions of a dual-channel CLSC under different channel power structures, and exerted a two-part contract to coordinate the supply chain. Giri et al. [37] focused on the revenue management aspect for remanufactured products in the CLSC by considering dual channels for both the forward and reverse supply chain. Gan et al. [38] investigated pricing decisions for new and differentiated remanufactured products in a CLSC in which the new product is sold by traditional retail stores and the remanufactured product is sold by the manufacturer's direct channel. They revealed that implementing a separate channel can improve the entire CLSC's profit compared to the single-channel approach. Alizadeh-Basban and Taleizadeh [39] developed game models in a dual-channel supply chain that consists of a distributor and a manufacturer to consider sales effort, delivery time and hybrid remanufacturing under different game structures, and they showed that the Stackelberg in the manufacturer-led case is the best game structure to maximize the profit of the green supply chain. Liu et al. [6] examined a two-period model for a CLSC with a manufacturer and a retailer to decide the optimal pricing and production strategies for new and remanufactured products with consideration to the production costs and the channel selling costs. Han and Chen [40] investigated whether the manufacturer adopts the online sales channel and how to choose the optimal product portfolios in a CLSC. They concluded that the manufacturer will always adopt the online sales channel and it is harmful to the retailer. Pal and Sana [41] explored the optimal sales prices, rewards for obsolete items and green innovation levels in a dual-channel CLSC under different frameworks.

Many research studies about dual-sales channels assume that the new and remanufactured products are sold at the same price and few studies have introduced network externality or sales effort into dual-channel issues in CLSCs. Differing from above studies, this paper considers a dual sales-channel CLSC with differential pricing for new and remanufactured products.

Table 1 shows the difference between our study and existing related works.

Table 1. Comparison of our work with the related literature.

Research Paper	Discriminating Prices	Network Externality	Sales Effort	Dual Sales Channel	Game Theory
Zhou et al. [8]	✔	✔			Stackelberg
Xie et al. [27]	✔	✔			Stackelberg
Taleizadeh et al. [31]			✔	✔	Stackelberg
Gao et al. [28]			✔		Stackelberg/Nash
Ma et al. [29]			✔		Stackelberg
Li and Wang [32]	✔		✔		Stackelberg
Liu et al. [6]	✔			✔	Stackelberg
Zheng et al. [1]				✔	Stackelberg
Alizadeh-Basban and Taleizadeh [39]			✔	✔	Stackelberg/Nash
This paper	✔	✔	✔	✔	Stackelberg

Differing from the above papers, based on consumers' differing willingness to pay for new and remanufactured products and the network externality of remanufactured products, this paper considers that the retailer sells both new and remanufactured products through its retail channel, and the OEM only sells remanufactured products directly to consumers. Then, we construct game models under three scenarios, namely Model N, Model R and Model M. The influence of network externality and sales effort on CLSC operations are investigated. This paper provides references for the optimization decision of CLSC with differential pricing considering sales effort investment.

3. Model Description, Notations, Assumptions and Demand Functions

3.1. Problem Description

In this paper, we consider a CLSC with an OEM and a retailer. The OEM produces new products with raw materials and then sells the new products to consumers through the retail channel. Simultaneously, the OEM collects the end-of-life products from consumers to remanufacture the recycled products, then sells the remanufactured products through both the retail channel and its direct channel. We investigate three models, namely, no sales effort (Model N), the retailer exerting sales effort (Model R) and the OEM exerting sales effort (Model M). The OEM is the Stackelberg leader of the CLSC and the retailer is the follower.

3.2. Notations

Table 2 presents the notations used in this paper.

Table 2. Notations and definitions.

Notations	Definitions
Indices	
i	Index of the product types (subscript): $i = n$ (new product), $i = t$ (remanufactured product in retail channel), $i = d$ (remanufactured product in direct channel) and $i = r$ (remanufactured product in both channels)
j	Index of the CLSC members (subscript): $j = M$ (OEM), $j = R$ (retailer) and $j = SC$ (the entire CLSC)
l	Index of models (superscript): $l = N$(no sales effort), $l = R$ (retailer exerting sales effort) $l = M$ (OEM exerting sales effort)
Parameters	
c	Unit production cost for a new product
Q	The market size
θ	Consumer's perceived value of a new product, a uniform distribution with the supporting range $[0, Q]$
α	Consumer's acceptance level of the remanufactured product sold by retail channel
β	Consumer's acceptance level of the remanufactured product sold by direct channel
k_j	Sales effort cost coefficient when j exerts sales effort ($j = R, M$)
λ	The strength of network externality
ε_j	Consumers' sensitivity of sales effort when j exerts sales effort ($j = R, M$)
q_i^l	The demand of product i under Model l ($i = n, t, d, r$, $l = N, R, M$)
Π_j^l	The profit of j under Model l ($j = R, M, SC$, $l = N, R, M$)
Decision variables	
y^l	Sales effort level under Model l ($l = R, M$)
ω_i^l	Wholesale price of the product i under Model l ($i = n, t$, $l = N, R, M$)
p_i^l	Sales price of product i under Model l ($i = n, t, d$, $l = N, R, M$)

3.3. Assumptions

The assumptions of the models are as follows.

(1) We normalize the unit remanufacturing cost to 0 [6,42];
(2) Each consumer only buys, at most, one copy of the product [43];
(3) There are enough end-of-life products available for remanufacturing, and the decisions of the OEM and the retailer are not limited by the quantity of end-of-life products recycled [44];
(4) The consumers' sensitivity of sales effort level which we assume to be equal in two channels. As the advertising process in two channels is very similar and almost

the same, we consider in this paper the scenario in which the sales effort effects on customers in the two channels are equal [31]. That is, $\varepsilon_M = \varepsilon_R = \varepsilon$;

(5) When the OEM or the retailer exerts sales effort, their investments are $\frac{k_M y^{M2}}{2}$ and $\frac{k_R y^{R2}}{2}$, respectively. For simplicity, we assume $k_M = k_R = k$ [31,45] and k is large enough to ensure the existence of the optimal solution of the models [46];

(6) For the simplicity of subsequent analysis, we assume that the market size Q is much larger than other parameters, except k [47];

(7) Though the functionalities of new and remanufactured products may be the same, consumers always have a lower perceived value for the remanufactured products because they have been used and returned before [6,48];

(8) The customer values the online direct channel less than the traditional retail channel [6,49], we assume $\alpha > \beta$.

3.4. Demand Functions

According to the above assumptions, the demand functions in the models are derived based on utility theory. In Model N, the demands for the new and remanufactured products are

$$q_n^N = \int_{\frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha}}^{Q} f(\theta)d\theta = Q - \frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha}, \tag{1}$$

$$q_t^N = \int_{\frac{p_t^N - p_d^N}{\alpha-\beta}}^{\frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha}} f(\theta)d\theta = \frac{(1-\alpha)p_d^N - (1-\beta)p_t^N + (\alpha-\beta)(p_n^N + \lambda q_r^N)}{(1-\alpha)(\alpha-\beta)}, \tag{2}$$

$$q_d^N = \int_{\frac{p_d^N - \lambda q_r^N}{\beta}}^{\frac{p_t^N - p_d^N}{\alpha-\beta}} f(\theta)d\theta = \frac{\beta p_t^N - \alpha p_d^N + \lambda(\alpha-\beta)q_r^N}{\beta(\alpha-\beta)}. \tag{3}$$

In Model R, the demands for the new and remanufactured product in Model R are

$$q_n^R = \int_{\frac{p_n^R - p_t^R + \lambda q_r^R + \varepsilon y^R}{1-\alpha}}^{Q} f(\theta)d\theta = Q - \frac{p_n^R - p_t^R + \lambda q_r^R + \varepsilon y^R}{1-\alpha}, \tag{4}$$

$$q_t^R = \int_{\frac{p_t^R - p_d^R - \varepsilon y^R}{\alpha-\beta}}^{\frac{p_n^R - p_t^R + \lambda q_r^R + \varepsilon y^R}{1-\alpha}} f(\theta)d\theta = \frac{(1-\alpha)p_d^R - (1-\beta)(p_t^R - \varepsilon y^R) + (\alpha-\beta)(p_n^R + \lambda q_r^R)}{(1-\alpha)(\alpha-\beta)}, \tag{5}$$

$$q_d^R = \int_{\frac{p_d^R - \lambda q_r^R}{\beta}}^{\frac{p_t^R - p_d^R - \varepsilon y^R}{\alpha-\beta}} f(\theta)d\theta = \frac{(\alpha-\beta)\lambda q_r^R + \beta(p_t^R - \varepsilon y^R) - \alpha p_d^R}{\beta(\alpha-\beta)}. \tag{6}$$

In Model M, the demands for the new and remanufactured product in Model M are

$$q_n^M = \int_{\frac{p_n^M - p_t^M + \lambda q_r^M}{1-\alpha}}^{Q} f(\theta)d\theta = Q - \frac{p_n^M - p_t^M + \lambda q_r^M}{1-\alpha}, \tag{7}$$

$$q_t^M = \int_{\frac{p_t^M - p_d^M + \varepsilon y^M}{\alpha-\beta}}^{\frac{p_n^M - p_t^M + \lambda q_r^M}{1-\alpha}} f(\theta)d\theta = \frac{(1-\alpha)(p_d^M - \varepsilon y^M) - (1-\beta)p_t^M + (\alpha-\beta)(p_n^M + \lambda q_r^M)}{(1-\alpha)(\alpha-\beta)}, \tag{8}$$

$$q_d^M = \int_{\frac{p_d^M - \lambda q_r^M - \varepsilon y^M}{\beta}}^{\frac{p_t^M - p_d^M + \varepsilon y^M}{\alpha-\beta}} f(\theta)d\theta = \frac{(\alpha-\beta)\lambda q_r^M - \alpha(p_d^M - \varepsilon y^M) + \beta p_t^M}{\beta(\alpha-\beta)}. \tag{9}$$

4. Model Formulation and Solution

In this section, the optimal pricing strategies are derived for the OEM and the retailer in the Stackelberg game for three Models, $l = \{N, R, M\}$.

4.1. Model N (No Sales Effort)

In Model N, neither the OEM nor the retailer exert sales effort. The dynamic decision process between the OEM and the retailer is as follows: (1) the OEM determines the wholesale prices of both new and remanufactured products ω_n^N, ω_t^N, and the sales price of remanufactured products in direct channel p_d^N; (2) then, the retailer determines the sales prices of both new and remanufactured products in retail channel p_n^N and p_t^N after observing the OEM's decisions. The profit functions of the OEM and the retailer are, respectively

$$\Pi_M^N = \left(\omega_n^N - c\right)q_n^N + p_d^N q_d^N + \omega_t^N q_t^N, \tag{10}$$

$$\Pi_R^N = \left(p_n^N - \omega_n^N\right)q_n^N + \left(p_t^N - \omega_t^N\right)q_t^N. \tag{11}$$

Then, using backward induction to solve the game, we can obtain Proposition 1.

Proposition 1. *In Model N, under the conditions that $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, the optimal wholesale and sales prices of the new and remanufactured products are*

$$\omega_n^{N*} = \frac{c+Q}{2}, \tag{12}$$

$$\omega_t^{N*} = \frac{\alpha Q}{2}, \tag{13}$$

$$p_n^{N*} = \frac{(c+3Q)(\beta-\lambda) - \beta^2 Q}{4(\beta-\lambda)}, \tag{14}$$

$$p_t^{N*} = \frac{Q(3\alpha-\beta)}{4}, \tag{15}$$

$$p_d^{N*} = \frac{\beta Q}{2}. \tag{16}$$

With prices in Proposition 1, we can derive the optimal demands of both new and remanufactured products and the optimal profits of CLSC members and the entire supply chain as:

$$q_n^{N*} = \frac{Q[(1-\alpha)(\beta-\lambda) - \lambda\beta] - c(\beta-\lambda)}{4[(1-\alpha)(\beta-\lambda) - \lambda\beta]}, \tag{17}$$

$$q_t^{N*} = \frac{c(\beta-\lambda)}{4[(1-\alpha)(\beta-\lambda) - \lambda\beta]}, \tag{18}$$

$$q_d^{N*} = \frac{\beta Q}{4(\beta-\lambda)} + \frac{\lambda c(\beta-\lambda)}{4(\beta-\lambda)[(1-\alpha)(\beta-\lambda) - \lambda\beta]}, \tag{19}$$

$$\Pi_M^{N*} = \frac{Q[(1-\alpha)(\beta-\lambda) - \lambda\beta]\left[(Q-2c)(\beta-\lambda) + \beta^2 Q\right] + c^2(\beta-\lambda)^2}{8(\beta-\lambda)[(1-\alpha)(\beta-\lambda) - \lambda\beta]}, \tag{20}$$

$$\Pi_R^{N*} = \frac{Q[(1-\alpha)(\beta-\lambda) - \lambda\beta]\left[(Q-2c)(\beta-\lambda) - \beta^2 Q\right] + c^2(\beta-\lambda)^2}{16(\beta-\lambda)[(1-\alpha)(\beta-\lambda) - \lambda\beta]}, \tag{21}$$

$$\Pi_{SC}^{N*} = \frac{3Q[(1-\alpha)(\beta-\lambda) - \lambda\beta]\left[(Q-2c)(\beta-\lambda) + \beta^2 Q\right] + 3c^2(\beta-\lambda)^2}{16(\beta-\lambda)[(1-\alpha)(\beta-\lambda) - \lambda\beta]}. \tag{22}$$

4.2. Model R (Retailer Exerting Sales Effort)

Different from Model N, the retailer exerts sales effort to stimulate the sales of remanufactured products in Model R. The dynamic decision process between the OEM and the retailer is as follows: (1) the OEM determines the wholesale prices of both new and remanufactured products ω_n^R, ω_t^R and the sales price of remanufactured products in direct channel p_d^R; (2) then, the retailer determines the sales prices of both new and remanufactured products in retail channel p_n^R, p_t^R, and sales effort level y^R. In Model R, the profit functions of the OEM and the retailer are, respectively

$$\Pi_M^R = \left(\omega_n^R - c\right)q_n^R + p_d^R q_d^R + \omega_t^R q_t^R, \tag{23}$$

$$\Pi_R^R = \left(p_n^R - \omega_n^R\right)q_n^R + \left(p_t^R - \omega_t^R\right)q_t^R - \frac{ky^{R2}}{2}. \tag{24}$$

Similarly, backward induction is used to solve this game, and thus we obtain Proposition 2.

Proposition 2. *In Model R, under the conditions $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, the optimal wholesale and sales prices of the new and remanufactured products and the optimal sales effort level exerted by the retailer are*

$$\omega_n^{R*} = \frac{c+Q}{2}, \tag{25}$$

$$\omega_t^{R*} = \frac{\alpha Q}{2}, \tag{26}$$

$$p_d^{R*} = \frac{\beta Q}{2}, \tag{27}$$

$$p_n^{R*} \frac{(c+3Q)(\beta-\lambda) - \beta^2 Q}{4(\beta-\lambda)}, \tag{28}$$

$$p_t^{R*} = \frac{2kQ(\alpha-\beta)(3\alpha-\beta)A - \varepsilon^2\{Q(3\alpha-\beta)B - c(\alpha-\beta)(\beta-\lambda)\}}{8k(\alpha-\beta)A - 4\varepsilon^2[\beta(1-\beta)-\lambda]}, \tag{29}$$

$$y^{R*} = \frac{\varepsilon c(\alpha-\beta)(\beta-\lambda)}{4k(\alpha-\beta)A - 2\varepsilon^2 B}. \tag{30}$$

With optimal solutions in Proposition 2, we can derive the optimal demands of both new and remanufactured products and the optimal profits of CLSC members and the entire supply chain as:

$$q_n^{R*} = \frac{2k(\alpha-\beta)\{QA - c(\beta-\lambda)\} - \varepsilon^2\{QB - c(\beta-\lambda)\}}{8k(\alpha-\beta)A - 4\varepsilon^2 B}, \tag{31}$$

$$q_t^{R*} = \frac{ck(\alpha-\beta)(\beta-\lambda)}{4k(\alpha-\beta)A - 2\varepsilon^2 B}, \tag{32}$$

$$q_d^{R*} = \frac{2k(\alpha-\beta)[\beta QA + \lambda c(\beta-\lambda)] - \beta\varepsilon^2\left[(c+Q)(\beta-\lambda) - \beta^2 Q\right]}{4(\beta-\lambda)[2k(\alpha-\beta)A - \varepsilon^2 B]}, \tag{33}$$

$$\Pi_M^{R*} = \frac{Q\left[(Q-2c)(\beta-\lambda) + \beta^2 Q\right]\left[2k(\alpha-\beta)A - \varepsilon^2 B\right] + c^2(\beta-\lambda)^2\left[2k(\alpha-\beta) - \varepsilon^2\right]}{8(\beta-\lambda)[2k(\alpha-\beta)A - \varepsilon^2 B]}, \tag{34}$$

$$\Pi_R^{R*} = \frac{Q\left[(Q-2c)(\beta-\lambda) - \beta^2 Q\right]\left[2k(\alpha-\beta)A - \varepsilon^2 B\right] + c^2(\beta-\lambda)^2\left[2k(\alpha-\beta) - \varepsilon^2\right]}{16(\beta-\lambda)[2k(\alpha-\beta)A - \varepsilon^2 B]}, \tag{35}$$

$$\Pi_{SC}^{R*} = \Pi_M^{R*} + \Pi_R^{R*} = \frac{Q\left[3(Q-2c)(\beta-\lambda) + \beta^2 Q\right]\left[2k(\alpha-\beta)A - \varepsilon^2 B\right] + 3c^2(\beta-\lambda)^2\left[2k(\alpha-\beta) - \varepsilon^2\right]}{16(\beta-\lambda)[2k(\alpha-\beta)A - \varepsilon^2 B]}. \tag{36}$$

For notational convenience, let $A = (1-\alpha)(\beta-\lambda) - \lambda\beta > 0$, $B = [\beta(1-\beta) - \lambda] > 0$.

4.3. Model M (OEM Exerting Sales Effort)

In this model, the OEM exerts sales effort to stimulate the sales of remanufactured products. The dynamic decision process between the OEM and the retailer is as follows: (1) the OEM determines the wholesale prices of both new and remanufactured products ω_n^M, ω_t^M, the sales price of remanufactured product in direct channel p_d^M and sales effort level y^M; (2) then, the retailer determines the sales prices of both new and remanufactured products in retail channel p_n^M, p_t^M. In Model M, the profit functions of the OEM and the retailer are, respectively

$$\Pi_M^M = \left(\omega_n^M - c\right)q_n^M + p_d^M q_d^M + \omega_t^M q_t^M - \frac{ky^{M2}}{2}, \tag{37}$$

$$\Pi_R^M = \left(p_n^M - \omega_n^M\right)q_n^M + \left(p_t^M - \omega_t^M\right)q_t^M. \tag{38}$$

Using backward induction to solve the game, we can obtain Proposition 3.

Proposition 3. *In Model M, under the conditions that $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, the optimal wholesale and sales prices of the new and remanufactured products and the optimal sales effort level exerted by OEM are*

$$\omega_n^{M*} = \frac{c+Q}{2}, \tag{39}$$

$$\omega_t^{M*} = \frac{\alpha Q}{2}, \tag{40}$$

$$p_n^{M*} = \frac{4k(\alpha-\beta)(\beta-\lambda)A\left[(c+3Q)(\beta-\lambda)-\beta^2 Q\right] - \varepsilon^2\left\{QE - c(\beta-\lambda)\left[2\alpha^2+\beta-\alpha(2+\beta)+\lambda\right]\right\}}{4(\beta-\lambda)[4k(\alpha-\beta)A-\varepsilon^2 D]}, \tag{41}$$

$$p_t^{M*} = \frac{4kQ(\beta-\lambda)\left(3\alpha^2-4\alpha\beta+\beta^2\right)A - \varepsilon^2\{\lambda c(\alpha-\beta)(\beta-\lambda)+2\alpha\beta Q(1-\alpha)(3\alpha-2\beta)+F\}}{16k(\alpha-\beta)(\beta-\lambda)A-4\varepsilon^2 D}, \tag{42}$$

$$p_d^{M*} = \frac{(\beta-\lambda)\left\{4\beta kQ(\alpha-\beta)A - \varepsilon^2\{\beta Q[\alpha(1-\alpha)-\lambda]-\lambda c(\alpha-\beta)\}\right\}}{8k(\alpha-\beta)(\beta-\lambda)A-2\varepsilon^2 D}, \tag{43}$$

$$y^{M*} = \frac{\varepsilon(\alpha-\beta)\{\beta Q[\alpha(1-\alpha)-\lambda]+\lambda c(\beta-\lambda)\}}{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D}. \tag{44}$$

Substituting these values in Equations (7)–(9), (37) and (38), we can get the optimal demands of both new and remanufactured products and the optimal profits of CLSC members and the entire supply chain as:

$$q_n^{M*} = (\beta-\lambda)\frac{4k(\alpha-\beta)[QA-c(\beta-\lambda)] - \varepsilon^2\left\{Q\left[2\alpha^2+\beta^2-\alpha(2+\beta)+\lambda\right]-c(2\alpha-\beta-\lambda)\right\}}{16k(\alpha-\beta)(\beta-\lambda)A-4\varepsilon^2 D}, \tag{45}$$

$$q_t^{M*} = \frac{4kc(\alpha-\beta)(\beta-\lambda)^2 - \varepsilon^2\{c(2\alpha-\beta)(\beta-\lambda)+\beta Q[\alpha(1-\alpha)-\lambda]\}}{16k(\alpha-\beta)(\beta-\lambda)A-4\varepsilon^2 D}, \tag{46}$$

$$q_d^{M*} = \frac{k(\alpha-\beta)[\beta QA+\lambda c(\beta-\lambda)]}{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D}, \tag{47}$$

$$\Pi_M^{M*} = \frac{4k(\alpha-\beta)G + c\varepsilon^2(\beta-\lambda)\{c(2\alpha-\beta-\lambda)-2Q[(1-\alpha)(2\alpha-\beta)-\lambda]\} - \varepsilon^2 Q^2\left\{D+\beta^2[\alpha(1-\alpha)-\lambda]\right\}}{32k(\alpha-\beta)(\beta-\lambda)A-8\varepsilon^2 D}, \tag{48}$$

$$\Pi_R^{M*} = \left(p_n^{M*} - \omega_n^{M*}\right)q_n^{M*} + \left(p_t^{M*} - \omega_r^{M*}\right)q_t^{M*}, \tag{49}$$

$$\Pi_{SC}^{M*} = \Pi_M^{M*} + \Pi_R^{M*}. \quad (50)$$

For notational convenience, let $D = \beta(1-\alpha)(2\alpha-\beta) - \lambda[2\alpha(1-\alpha) + \beta(2\alpha-\beta)] + \lambda^2$, $E = \beta(1-\alpha)[\alpha(6-\beta) - 3\beta] + 2\lambda[3\alpha^2 + 2\beta^2 - 3\alpha(1+\beta)] + 3\lambda^2$, $F = \lambda Q[(1-7\alpha)\alpha\beta + \beta^2(1+3\alpha) - 6\alpha^2(1-\alpha)] + \lambda^2 Q(3\alpha-\beta)$ and $G = QA[(Q-2c)(\beta-\lambda) + \beta^2 Q] - c^2(\beta-\lambda)^2$.

5. Model Analysis

In this section, we make a comparison of the optimal results of above models and analyze the effects of key parameters on optimal decisions.

Proposition 4. *The optimal wholesale and sales prices of both new and remanufactured products in different models are as follows:* $\omega_n^{N*} = \omega_n^{R*} = \omega_n^{M*}$, $\omega_t^{N*} = \omega_t^{R*} = \omega_t^{M*}$, $p_n^{M*} < p_n^{N*} = p_n^{R*}$, $p_t^{M*} < p_t^{N*} < p_t^{R*}$, $p_d^{N*} = p_d^{R*} < p_d^{M*}$.

Proposition 4 demonstrates that, (1) the sales effort behavior does not affect the OEM's decisions about wholesale prices of new and remanufactured products. (2) The sales effort behavior affects the sales prices of both two products. The sales prices of the new and remanufactured products in the retail channel are lowest in Model M, that is, the sales effort exerted by the OEM damages the unit profit of new and remanufactured products. The reason is that when the OEM exerts sales effort, the retailer decreases the sales prices to alleviate the competition from the direct channel. (3) In Model R, the sales effort makes remanufactured products in the retail channel more competitive. Therefore, compared to Model N, the retailer increases the sales price of remanufactured product due to consumers' higher valuation for it and the sales effort investment increasing, while the retailer does not change the sales price of new product in Model R. (4) Similarly, the OEM charges the highest sales price for the remanufactured product in direct channel in Model M.

Proposition 5. *The optimal demands of both new and remanufactured products and sales effort level in different models are as follows:*

(1) $q_n^{N*} > q_n^{M*} > q_n^{R*}$;
(2) If $\beta(1-\alpha) > \lambda$, then $q_t^{R*} > q_t^{N*} > q_t^{M*}$, otherwise, $q_t^{M*} > q_t^{R*} > q_t^{N*}$;
(3) If $\beta(1-\alpha)(2\alpha-\beta) - \lambda[2\alpha(1-\alpha) + \beta(2\alpha-\beta)] + \lambda^2 > 0$, $q_d^{M*} > q_d^{R*}$, if $\beta(1-\alpha) > \lambda$, $q_d^{N*} > q_d^{R*}$, if $\beta^2(1-\alpha-\lambda) + 2\lambda\alpha(1+\beta) - 2\alpha(\beta - \alpha\beta + \lambda\alpha) - \lambda^2 > 0$, $q_d^{M*} < q_d^{N*}$, otherwise, the marks are opposite;
(4) $q_r^{M*} > q_r^{R*} > q_r^{N*}$;
(5) $q_{SC}^{M*} > q_{SC}^{R*} > q_{SC}^{N*}$;
(6) $y^{R*} < y^{M*}$.

Proposition 5 states that, (1) the sales effort behavior is helpful for remanufactured product to cannibalize the new product market, and the cannibalization effect is more significant in Model R. (2) When the condition $\beta(1-\alpha) > \lambda$ is satisfied, the sales effort exerted by the retailer induces an increase in the demand of remanufactured product in the retail channel, while it is harmful to that in Model M. On the contrary, Model M is more conducive for the retailer's remanufactured product sales than Model R. (3) The comparison of the demand of remanufactured product through a direct channel depends on the relationship of parameters such as consumer's acceptance level of the remanufactured product sold through a retail/direct channel and the strength coefficient of network externality of remanufactured product. (4) It is clear that it is beneficial to the remanufactured product sales when the OEM exerts sales effort. In other words, Model M performs better than Model R to stimulate the total demand of remanufactured product. (5) With respect to the total demand of products, since the reducing volume of new product sales is less than the increasing volume of remanufactured product sales, the sales effort can effectively expand the market, and the OEM's sales effort performs better. (6) As the leader of the CLSC, the OEM is motivated to exert more sales effort to obtain higher profit.

Proposition 6. *The optimal profits of OEM, the retailer and entire CLSC in different models are as follows:* $\Pi_M^{N*} < \Pi_M^{R*} < \Pi_M^{M*}$, $\Pi_R^{M*} < \Pi_R^{N*} < \Pi_R^{R*}$, $\Pi_{SC}^{N*} < \Pi_{SC}^{R*} < \Pi_{SC}^{M*}$.

Proposition 6 implies that, (1) compared with no sales effort, no matter who exerts sales effort, the behavior can always improve the profits of the OEM and entire CLSC. For the retailer, it can obtain the highest profit in Model R. It means that OEM exerting sales effort behavior can cause a loss for the retailer. (2) The OEM obtains more profits in Model M, and the retailer obtains more profits in Model R. Therefore, the best choices for the OEM or the retailer are to exert sales effort by themselves. (3) OEM exerting sales effort is beneficial to improve the total profit of the whole supply chain.

Proposition 7. *Impact of the increase in λ on the optimal decisions under Model R and Model M.*

(1) Same effects: $\frac{\partial p_n^*}{\partial \lambda} < 0$, $\frac{\partial q_n^*}{\partial \lambda} < 0$, $\frac{\partial q_t^*}{\partial \lambda} > 0$, $\frac{\partial q_d^*}{\partial \lambda} > 0$, $\frac{\partial q_{SC}^*}{\partial \lambda} > 0$, $\frac{\partial \Pi_M^*}{\partial \lambda} > 0$, $\frac{\partial \Pi_R^*}{\partial \lambda} < 0$, $\frac{\partial \Pi_{SC}^*}{\partial \lambda} > 0$, $\frac{\partial y^*}{\partial \lambda} > 0$.

(2) Different effects: $\frac{\partial p_t^{R*}}{\partial \lambda} > 0$, $\frac{\partial p_t^{M*}}{\partial \lambda} < 0$; $\frac{\partial p_d^{R}}{\partial \lambda} = 0$, $\frac{\partial p_d^{M*}}{\partial \lambda} > 0$.

Proposition 7 states that when the network externality strength coefficient (λ) increases, (1) the retailer implements a markdown pricing for new products, and the stronger network externality exacerbate the cannibalization of remanufactured product to the new product market. (2) The demand for remanufactured product in dual sales channels and the whole market demand all get improved. That is to say, the stronger network externality can stimulate more consumers to purchase remanufactured products. (3) As the increasing sales volume of remanufactured products can offset the market loss of new products, market expansion effect exists. The reason is that the consumer's utility of purchasing a remanufactured product becomes higher with an increasing λ and consumers are more willing to purchase remanufactured products. Meanwhile, a proportion of consumers who purchase new products turn to buy remanufactured products. (4) The profits of the OEM and the entire CLSC increase, but the profit of the retailer decreases. Thus, the OEM is more motivated to improve the network externality of remanufactured products, while the retailer is contrary to that. (5) Differently, the sales price of remanufactured product in the retail channel increases in Model R, while decreasing in Model M. Though the network externality can improve consumers' valuation of purchasing remanufactured products, the retailer has to decrease the sales price of remanufactured product to deal with the competition from direct channel when the OEM exerts sales effort. (6) With respect to the sales price of remanufactured product in the direct channel, the coefficient λ has no effect on that in Model R, while it increases with an increasing λ in Model M.

Proposition 8. *Impact of the increase in ε on the optimal decisions under Model R.*

(1) $\frac{\partial p_n^{R*}}{\partial \varepsilon} = 0$, $\frac{\partial p_t^{R*}}{\partial \varepsilon} > 0$, $\frac{\partial p_d^{R*}}{\partial \varepsilon} = 0$;

(2) $\frac{\partial q_n^{R*}}{\partial \varepsilon} < 0$; $\frac{\partial q_t^{R*}}{\partial \varepsilon} > 0$; if $\beta(1-\alpha) > \lambda$, then $\frac{\partial q_d^{R*}}{\partial \varepsilon} < 0$, otherwise, $\frac{\partial q_d^{R*}}{\partial \varepsilon} > 0$; $\frac{\partial q_{SC}^{R*}}{\partial \varepsilon} > 0$;

(3) $\frac{\partial \Pi_M^{R*}}{\partial \varepsilon} > 0$, $\frac{\partial \Pi_R^{R*}}{\partial \varepsilon} > 0$, $\frac{\partial \Pi_{SC}^{R*}}{\partial \varepsilon} > 0$;

(4) $\frac{\partial y^{R*}}{\partial \varepsilon} > 0$.

Proposition 8 implies that in Model R, when consumers' sensitivity of sales effort (ε) increases, (1) ε has no effect on the optimal pricing decisions for both new and remanufactured products in the direct channel. Since the sales effort can greatly improve consumers' utility valuation for the remanufactured product in retail channel, the retailer increases the sales price of remanufactured product in the retail channel with ε increasing. That is to say, the cost of a retailer exerting sales effort can be compensated by increasing its sales price of remanufactured product. (2) The sales volume of remanufactured product in the retail channel also gets increased, while conversely the sales volume of new product decreases. Namely, the enhancement of ε can also exacerbate the cannibalization of remanufactured product to the new product market. However, the total demand of CLSC gets expanded. As for the demand of remanufactured product in the direct channel, when the condition $\beta(1-\alpha) > \lambda$ is satisfied, it decreases; otherwise, it increases. (3) The increasing consumers' sensitivity of sales effort is beneficial for the OEM/retailer/CLSC to obtain more profit. (4) The more sensitive the consumers are to sales effort, the more motivated the retailer is to improve the sales effort level.

Proposition 9. *Impact of the increase in ε on the optimal decisions under Model M.*

(1) $\frac{\partial p_n^{M*}}{\partial \varepsilon} < 0$, $\frac{\partial p_t^{M*}}{\partial \varepsilon} < 0$, $\frac{\partial p_d^{M*}}{\partial \varepsilon} > 0$;

(2) $\frac{\partial q_n^{M*}}{\partial \varepsilon} < 0$; if $\beta(1-\alpha) < \lambda$, then $\frac{\partial q_t^{M*}}{\partial \varepsilon} < 0$, otherwise, $\frac{\partial q_t^{M*}}{\partial \varepsilon} > 0$; if $\beta(1-\alpha)(2\alpha-\beta) - \lambda[2\alpha(1-\alpha)+\beta(2\alpha-\beta)] + \lambda^2 < 0$, then $\frac{\partial q_d^{M*}}{\partial \varepsilon} < 0$, otherwise, $\frac{\partial q_d^{M*}}{\partial \varepsilon} > 0$; $\frac{\partial q_{SC}^{M*}}{\partial \varepsilon} > 0$;

(3) $\frac{\partial \Pi_M^{M*}}{\partial \varepsilon} > 0$, $\frac{\partial \Pi_R^{M*}}{\partial \varepsilon} < 0$, $\frac{\partial \Pi_{SC}^{M*}}{\partial \varepsilon} > 0$;

(4) $\frac{\partial y^{M*}}{\partial \varepsilon} > 0$.

Proposition 9 states that in Model M, with increasing ε (1) the sales prices of new and remanufactured products in the retail channel both decrease, while the sales price of remanufactured product in the direct channel increases. Similarly, the OEM's cost of exerting sales effort can be compensated by increasing its sales price of remanufactured product. (2) The same as in Model R, the demand for new product decreases while the total market demand increases with ε in Model M. (3) With the enhancement of consumers' sensitivity to sales effort, the profits of the OEM and the entire CLSC can be improved while the profit of the retailer decreases. (4) Obviously, as consumers are more sensitive to sales effort, the OEM exerts more sales effort.

6. Numerical Analysis

In practice, the performance efficiency of sales effort is different within the retail or direct channels. In this section, we investigate the CLSC performance difference when the OEM and the retailer have different sales effort cost and the consumers have different sensitivity to the OEM/retailer exerting sales effort.

The value of parameters in each model are set as follows: $c = 5$, $Q = 400$, $\alpha = 0.8$, $\beta = 0.6$, $\lambda = 0.1$, $k = 1000$, $\varepsilon = 0.5$.

6.1. Comparison of Profits and Sales Effort Level When the OEM and Retailer with Different Sales Effort Cost Coefficient

Next, extend to the scenario when the OEM/retailer exerts sales effort with different cost. Then, we introduce a parameter δ that means the cost advantage of the retailer exerting sales effort compared to OEM exerting sales effort. Further, the sales effort cost coefficient of the OEM is still denoted as k, so the sales effort cost coefficient of the retailer is δk. Here, we assume the parameter δ changes within $[0, 2]$.

In this subsection, the optimal sales effort level and profit of OEM/retailer/CLSC in Model R are as follows:

$$y^{R(k_M \neq k_R)*} = \frac{\varepsilon c(\alpha-\beta)(\beta-\lambda)}{4\delta k(\alpha-\beta)A - 2\varepsilon^2 B}, \tag{51}$$

$$\Pi_M^{R(k_M \neq k_R)*} = \frac{Q\left[(Q-2c)(\beta-\lambda)+\beta^2 Q\right]\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right] + c^2(\beta-\lambda)^2\left[2\delta k(\alpha-\beta)-\varepsilon^2\right]}{8(\beta-\lambda)\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right]}, \tag{52}$$

$$\Pi_R^{R(k_M \neq k_R)*} = \frac{Q\left[(Q-2c)(\beta-\lambda)-\beta^2 Q\right]\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right] + c^2(\beta-\lambda)^2\left[2\delta k(\alpha-\beta)-\varepsilon^2\right]}{16(\beta-\lambda)\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right]}, \tag{53}$$

$$\Pi_{SC}^{R(k_M \neq k_R)*} = \frac{Q\left[3(Q-2c)(\beta-\lambda)+\beta^2 Q\right]\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right] + 3c^2(\beta-\lambda)^2\left[2\delta k(\alpha-\beta)-\varepsilon^2\right]}{16(\beta-\lambda)\left[2\delta k(\alpha-\beta)A-\varepsilon^2 B\right]}. \tag{54}$$

Additionally, the optimal sales effort level and profit of OEM/retailer/CLSC in Model N and Model M do not change, so they are still Equations (14), (20)–(22) and (48)–(50). Then, the profits and sales effort level under the scenario with different sales effort cost is shown in Figure 1.

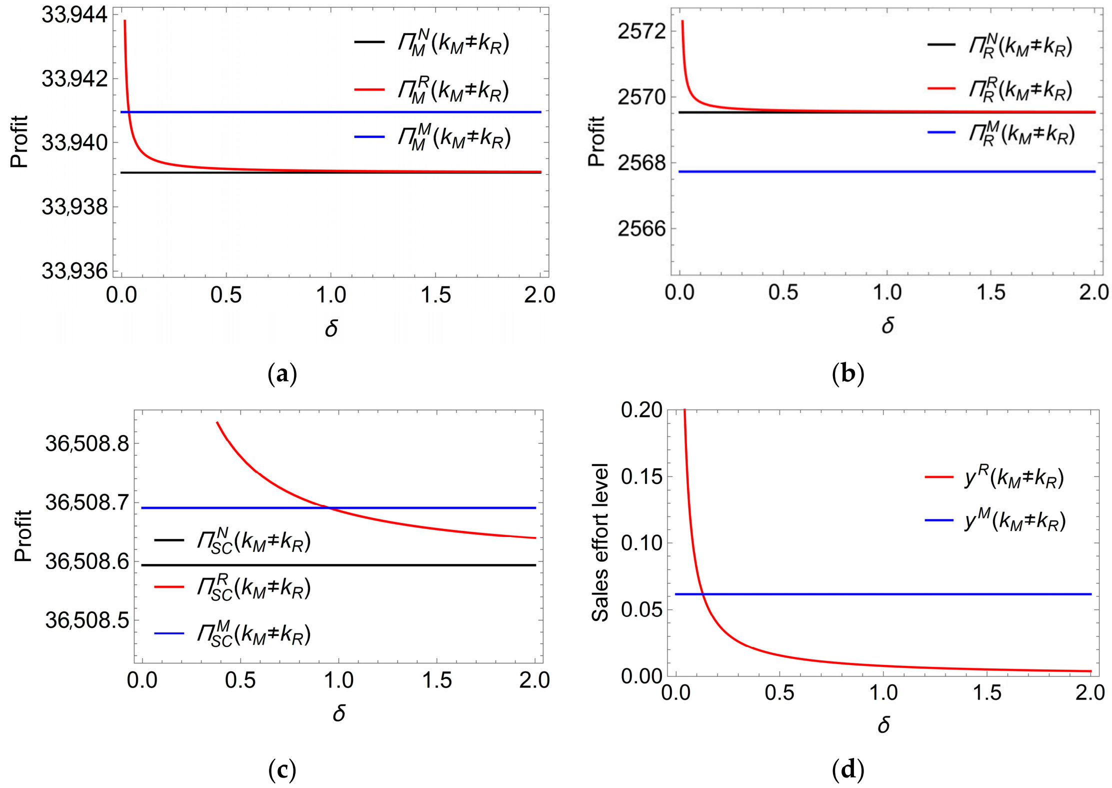


Figure 1. Profits and sales effort level under the scenario with different sales effort cost: (**a**) the OEM's profit; (**b**) the retailer's profit; (**c**) the entire CLSC's profit; (**d**) the sales effort level.

From Figure 1a, we find that: no matter who exerts sales effort, the behavior can always increase OEM's profit. Further, only when the parameter δ is extremely small ($0 < \delta < 0.034$), the retailer has the great cost advantage of exerting sales effort, meaning that the OEM can obtain more profit in Model R than in Model M. That is to say, when the efficiency of retailer's sales effort is extremely effective, the OEM's profit can also be greatly improved in Model R. On the contrary, the OEM prefers to exert sales effort by itself. As in Figure 1b, for the retailer, it can obtain higher profit when the retailer is exerting sales effort, so especially when the retailer has a great cost advantage of exerting sales effort, its profit can be increased significantly. With the increasing of the retailer's sales effort cost, the improvement of the retailer's profit is not significant. However, the OEM exerting sales effort hurts the retailer's profit. As in Figure 1c, no matter who exerts sales effort, the sales effort behavior could always improve the performance of CLSC. When the advantage of the retailer's sales effort cost is obvious ($0 < \delta < 0.95$), the retailer exerting sale effort is more favorable to the whole supply chain. On the contrary, the OEM exerting sales effort is more profitable for the CLSC. From Figure 1d, when the retailer has a great cost advantage of exerting sales effort ($0 < \delta < 0.129$), the retailer exerts more sales effort than the OEM. In other cases, the OEM exerts more sales effort.

6.2. Comparison of Profits and Sales Effort Level When Consumers with Different Sensitivity of Sales Effort to the OEM/Retailer Exerting Sales Effort

Extend to the scenario when the consumers with different sensitivity of sales effort to the OEM/retailer exerting sales effort. Then, we introduce a parameter γ that means the consumers have different sensitivity to retailer's sales effort compared to that of OEM's sales effort. The consumers' sensitivity of OEM's sales effort is still denoted as ε, so the consumers' sensitivity of retailer's sales effort is $\gamma\varepsilon$. Here, we set the parameter γ changes within $[0, 2]$.

In this subsection, the optimal sales effort level and profit of OEM/retailer/CLSC in Model R are as follows:

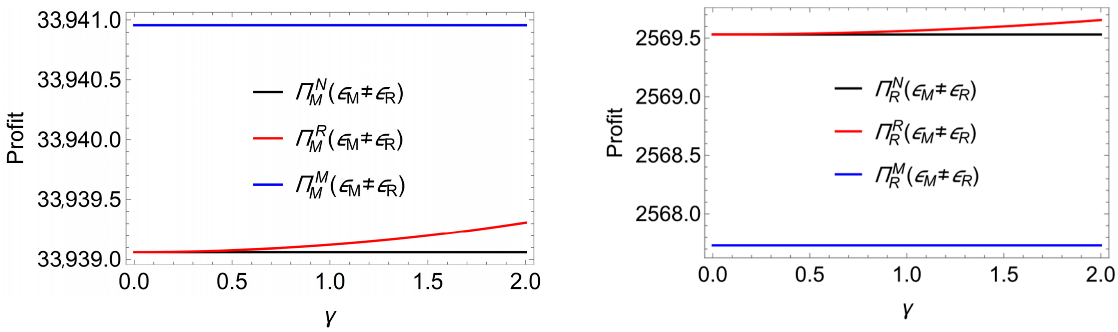
$$y^{R(\varepsilon_M \neq \varepsilon_R)*} = \frac{\gamma\varepsilon c(\alpha-\beta)(\beta-\lambda)}{4k(\alpha-\beta)A - 2(\gamma\varepsilon)^2 B}, \tag{55}$$

$$\Pi_M^{R(\varepsilon_M \neq \varepsilon_R)*} = \frac{Q\left[(Q-2c)(\beta-\lambda)+\beta^2 Q\right]\left[2k(\alpha-\beta)A-(\gamma\varepsilon)^2 B\right]+c^2(\beta-\lambda)^2\left[2k(\alpha-\beta)-(\gamma\varepsilon)^2\right]}{8(\beta-\lambda)\left[2k(\alpha-\beta)A-(\gamma\varepsilon)^2 B\right]}, \tag{56}$$

$$\Pi_R^{R(\varepsilon_M \neq \varepsilon_R)*} = \frac{Q\left[(Q-2c)(\beta-\lambda)-\beta^2 Q\right]\left[2k(\alpha-\beta)A-\varepsilon^2 B\right]+c^2(\beta-\lambda)^2\left[2k(\alpha-\beta)-(\gamma\varepsilon)^2\right]}{16(\beta-\lambda)\left[2k(\alpha-\beta)A-(\gamma\varepsilon)^2 B\right]}, \tag{57}$$

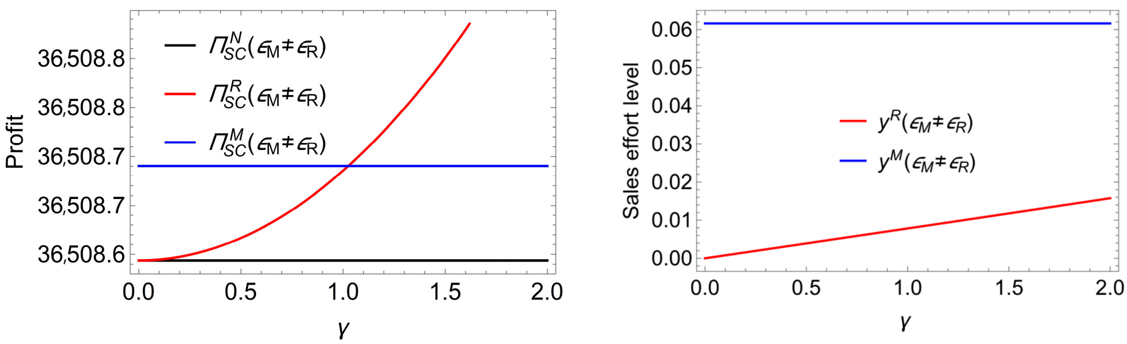
$$\Pi_{SC}^{R(\varepsilon_M \neq \varepsilon_R)*} = \frac{Q\left[3(Q-2c)(\beta-\lambda)+\beta^2 Q\right]\left[2k(\alpha-\beta)A-(\gamma\varepsilon)^2 B\right]+3c^2(\beta-\lambda)^2\left[2k(\alpha-\beta)-(\gamma\varepsilon)^2\right]}{16(\beta-\lambda)\left[2k(\alpha-\beta)A-(\gamma\varepsilon)^2 B\right]}. \tag{58}$$

Further, the optimal sales effort level and profit of OEM/retailer/CLSC in Model N and Model M also do not change. Then, the profits and sales effort level under the scenario with consumers' different sensitivity to sales effort to the OEM/retailer exerting sales effort, as shown in Figure 2.



(**a**) (**b**)

Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. Profits and sales effort level under the scenario with different consumers' sensitivity of sales effort level: (**a**) the OEM's profit; (**b**) the retailer's profit; (**c**) the entire CLSC's profit; (**d**) the sales effort level.

With an increasing γ in Figure 2a, we find that the sales effort behavior improves the OEM's profit regardless of who exerts sales effort, and the OEM exerting sales effort is more effective to increase OEM's profit. From Figure 2b, the retailer exerting sales effort benefits the retailer, and its profit grows significantly, especially when consumers' sensitivity to the retailer's sales effort is higher than OEM's. So, the OEM exerting sales effort can cause a loss for the retailer. From Figure 2c, no matter who exerts sales effort, the sales effort behavior can improve CLSC's profit. With the increasing consumers' sensitivity to retailer's sales effort, when the retailer exerts sales effort, the CLSC's profit increases significantly. When consumers are more sensitive to OEM's sales effort ($0 < \gamma < 1.026$), the OEM exerting sales effort is more effective to improve CLSC's profit; on the contrary, the retailer exerting sales effort is more profitable for CLSC. From Figure 2d, the OEM always exerts a higher sales effort level than the retailer. With the increasing consumers' sensitivity to retailer's sales effort, the retailer exerts more sales effort.

7. Conclusions and Managerial Insights

7.1. Conclusions

This paper simultaneously introduces sales effort and network externality into the CLSC, and establishes Stackelberg game models between the OEM and the retailer with dual sales channel under three scenarios, i.e., Model N, Model R and Model M (no sales effort, the retailer exerting sales effort and the OEM exerting sales effort). We obtain the optimal pricing and sales effort decisions for the CLSC members and compare the three models. Finally, we extend our study to more complex scenarios through numerical analysis. The conclusions we get are as follows.

(1) Compared with no sales effort, regardless of who exerts sales effort, the sale effort behavior can always improve the profits of the OEM and the entire CLSC. For the retailer, it can obtain more profit in Model R, so the OEM exerting sales effort can cause a loss for the retailer. Moreover, the sales effort can promote the sales of remanufactured products but cannibalize the new product market;

(2) OEM exerting sales effort is more favorable to improve the profits of the OEM and the entire CLSC, while the retailer prefers Model R. That is, the OEM and the retailer both prefer to exert sales effort by themselves. As the leader of the CLSC, OEM exerts higher sales effort level and Model M is more beneficial for remanufactured product sales and total market sales;

(3) The stronger network externality of remanufactured product increases the sales of remanufactured product in both retail and direct channels, yet exacerbates the cannibalization to the new product market. The network externality can significantly improve the OEM and the entire CLSC's profits, but is not beneficial to the retailer. The OEM is more motivated to exert more sales efforts with the increase in network externality;

(4) The increase in consumers' sensitivity of sales effort improves the total sales volume of the CLSC and causes less market volume of the new product. As the consumer's sensitivity of sales effort becomes more intensive, the profits of the OEM and the entire CLSC can be improved. For the retailer, the impact of the consumer's sensitivity of sales effort on its profit is correlated with the identity of who exerting the sales effort. With the consumer's sensitivity of sales effort increasing, the retailer's profit can be increased when the retailer exerts sales effort, but can be decreased when OEM exerts sales effort. In addition, the CLSC members would exert more sales effort with the increasing of the consumers' sensitivity of sales effort;

(5) Only when the cost advantage of the retailer exerting sales effort is much more obvious can OEM obtain higher profit when the retailer exerts sales effort, rather than OEM exerting sales effort. When consumers are more sensitive to a retailer's sales effort, the retailer exerting sales effort is more effective at improving CLSC's profit, while, on the contrary, the OEM exerting sales effort is beneficial for CLSC.

7.2. Theoretical and Practical Contributions

(1) Theoretical Contributions

This study enriches the CLSC management research by constructing a dual sales-channel CLSC pricing decision model that considers the network externality of remanufactured product and sales effort investment. In addition, this paper shows how the sales price, demand and profit are affected by the network externality of remanufactured product, consumers' sensitivity of sales effort and sales effort cost. Moreover, this study also contributes to the CLSC members' sales effort strategy to optimize their own profit and the sales of remanufactured product by comparing the CLSC operations in three models, i.e., no sales effort, the retailer exerting sales effort and the OEM exerting sales effort. The results show that the OEM and the retailer both prefer to exert sales effort by themselves and the OEM exerting sales effort is more beneficial to the sales of remanufactured product. Therefore, this study provides a research model which can be extended to conduct further studies.

(2) Practical Contributions

The results also provide significant managerial insights for enterprises that are involved in the CLSC:

a. Since the network externality of remanufactured product can improve the profits of the OEM/CLSC and promote the sales of remanufactured product, the OEM is motivated to improve the network externality of remanufactured product, thereby attracting more consumers to purchase remanufactured ones. For instance, the OEM can take advantage of consumers' group psychology and Internet technology to improve the network externality of remanufactured product.
b. The OEM should exert sales effort to attract more consumers to purchase remanufactured products, and then the OEM's profit can be improved. For instance, the OEM can increase publicity by advertising, hiring green brand spokespeople, etc., to increase consumers' environmental awareness and help them understand the benefits of remanufacturing activities.

7.3. Limitations

There are also some limitations in our study. This paper only considers the CLSC composed of one OEM and one retailer, but does not consider the market competition of more enterprises. In the section of numerical analysis, we briefly analyze the results under different sales effort cost and we can use theoretical analysis to examine that in the future. In addition, this paper considers deterministic demand, so further research can be performed by introducing stochastic demand.

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Appendix A

Derivation of demand functions in Section 3.4. According to the assumptions, the demand functions in the models are derived based on utility theory.

In model N, the consumer can buy the new product through the retail channel or buy the remanufactured products through either the retail channel or the direct channel. The utilities can be presented as: $\mu_n^N = \theta - p_n^N$, $\mu_t^N = \alpha\theta - p_t^N + \lambda q_r^N$, $\mu_d^N = \beta\theta - p_d^N + \lambda q_r^N$. The consumer will buy a new product through the retail channel when $\mu_n^N \geq 0$, $\mu_n^N \geq \mu_t^N$ and $\mu_n^N \geq \mu_d^N$, which give $\theta \geq p_n^N$, $\theta \geq \frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha}$, and $\theta \geq \frac{p_n^N - p_d^N + \lambda q_r^N}{1-\beta}$, respectively. The consumer will buy a remanufactured product through the retail channel when $\mu_t^N \geq 0$, $\mu_t^N \geq \mu_n^N$ and $\mu_t^N \geq \mu_d^N$, which give $\theta \geq \frac{p_t^N - \lambda q_r^N}{\alpha}$, $\theta \leq \frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha}$ and $\frac{p_t^N - p_d^N}{\alpha-\beta}$, respectively. The consumer will buy a remanufactured product through the direct channel when $\mu_d^N \geq 0$, $\mu_d^N \geq \mu_n^N$, $\mu_d^N \geq \mu_t^N$, which give $\theta \geq \frac{p_d^N - \lambda q_r^N}{\beta}$, $\theta \leq \frac{p_n^N - p_d^N + \lambda q_r^N}{1-\beta}$, $\theta \leq \frac{p_t^N - p_d^N}{\alpha-\beta}$. To ensure that the demands for the new and remanufactured products in two channels are non-negative, it is required that $\frac{p_d^N - \lambda q_r^N}{\beta} \leq \frac{p_t^N - p_d^N}{\alpha-\beta} \leq \frac{p_n^N - p_t^N + \lambda q_r^N}{1-\alpha} \leq Q$. Thus, the demands for the new and remanufactured products in Model N are obtained as Equations (1)–(3).

Similarly, in Model R, the utilities of the consumer buying the new product through the retail channel or buy the remanufactured products through either the retail channel or the direct channel can be presented as: $\mu_n^R = \theta - p_n^R$, $\mu_t^R = \alpha\theta - p_t^R + \lambda q_r^R + \varepsilon y^R$ and $\mu_d^R = \beta\theta - p_d^R + \lambda q_r^R$. To ensure that the demands for the new and remanufactured product in two channels are non-negative, it is required that $\frac{p_d^R - \lambda q_r^R}{\beta} \leq \frac{p_t^R - p_d^R - \varepsilon y^R}{\alpha-\beta} \leq \frac{p_n^R - p_t^R + \lambda q_r^R + \varepsilon y^R}{1-\alpha} \leq Q$. Thus, the demands for the new and remanufactured product in Model R are obtained as Equations (4)–(6).

Then, in Model M, the utilities of the consumer buying the new product through the retail channel or buying the remanufactured products through either the retail channel or the direct channel can be presented as: $\mu_n^M = \theta - p_n^M$, $\mu_t^M = \alpha\theta - p_t^M + \lambda q_r^M$ and $\mu_d^M = \beta\theta - p_d^M + \lambda q_r^M + \varepsilon y^M$. To ensure that the demands for the new and remanufactured product in two channels are non-negative, it is required that $\frac{p_d^M - \lambda q_r^M - \varepsilon y^M}{\beta} \leq \frac{p_t^M - p_d^M + \varepsilon y^M}{\alpha-\beta} \leq \frac{p_n^M - p_t^M + \lambda q_r^M + \varepsilon y^M}{1-\alpha} \leq Q$. Thus, the demands for the new and remanufactured product in Model M are obtained as Equations (7)–(9).

The derivation of demand functions is completed.

Proof of Proposition 1. The first-order derivatives of Π_R^N to p_n^N and p_t^N can be shown as:

$$\frac{\partial \Pi_R^N}{\partial p_n^N} = \frac{Q[(1-\alpha)(\beta-\lambda)-\lambda\beta](\beta-\lambda)\left(2p_t^N - 2p_n^N\right) + \lambda\left(p_d^N - \omega_n^N + \omega_t^N\right) + \beta\left(\omega_n^N - \omega_t^N\right)}{(1-\alpha)(\beta-\lambda)-\lambda\beta}, \tag{A1}$$

$$\frac{\partial \Pi_R^N}{\partial p_t^N} = \frac{[\beta(1-\alpha)-\lambda]p_d^N - [\beta(1-\beta)-\lambda]\left(2p_t^N - \omega_t^N\right) + (\alpha-\beta)(\beta-\lambda)\left(2p_n^N - \omega_n^N\right)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}. \tag{A2}$$

The Hessian matrix of Π_R^N is

$$HN = \begin{bmatrix} -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} \\ \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{-2[\beta(1-\beta)-\lambda]}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} \end{bmatrix}. \tag{A3}$$

Since $|HN_1| = -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta}$, $|HN| = \frac{4(\beta-\lambda)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, the mark of $|HN_1|$ is opposite to the mark of $|HN|$. So, Π_R^N is jointly concave in p_n^N and p_t^N. Furthermore, by setting $\frac{\partial \Pi_R^N}{\partial p_n^N} = 0$ and $\frac{\partial \Pi_R^N}{\partial p_t^N} = 0$, we can obtain as follows:

$$p_n^{N*}\left(\omega_n^N, p_d^N\right) = \frac{Q[\beta(1-\beta)-\lambda] + \beta p_d^N + (\beta-\lambda)\omega_n^N}{2(\beta-\lambda)}, \tag{A4}$$

$$p_t^{N*}\left(p_d^N, \omega_t^N\right) = \frac{Q(\alpha-\beta) + p_d^N + \omega_t^N}{2}. \tag{A5}$$

Next, substitute Equations (A4) and (A5) into Equation (10). Then, taking the first-order derivatives of Π_M^N with respect to ω_n^N, p_d^N and ω_t^N, we obtain

$$\frac{\partial \Pi_M^N}{\partial \omega_n^N} = \frac{Q[(1-\alpha)(\beta-\lambda)-\lambda\beta] + 2\lambda p_d^N - (\beta-\lambda)\left[2\left(\omega_n^N - \omega_t^N\right) - c\right]}{2[(1-\alpha)(\beta-\lambda)-\lambda\beta]}, \tag{A6}$$

$$\frac{\partial \Pi_M^N}{\partial p_d^N} = \frac{(\alpha-\beta)\left\{\beta QA + \lambda(\beta-\lambda)\left(2\omega_n^N - c\right)\right\} + 2(\beta-\lambda)[\beta(1-\alpha)-\lambda]\omega_t^N - 2p_d^N D}{2(\alpha-\beta)(\beta-\lambda)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}. \tag{A7}$$

$$\frac{\partial \Pi_M^N}{\partial \omega_t^N} = \frac{2[\beta(1-\alpha)-\lambda]p_d^N + (\alpha-\beta)(\beta-\lambda)\left(2\omega_n^N - c\right) - 2[\beta(1-\beta)-\lambda]\omega_t^N}{2(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}. \tag{A8}$$

The Hessian matrix of Π_M^N is

$$MN = \begin{bmatrix} \frac{-(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{\beta-\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta} \\ \frac{\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{\lambda(\beta-\lambda)+\lambda\beta(\alpha-\beta)-(2\alpha-\beta)(1-\alpha)(\beta-\lambda)}{(\alpha-\beta)(\beta-\lambda)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} & \frac{\beta(1-\alpha)-\lambda}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} \\ \frac{\beta-\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{\beta(1-\alpha)-\lambda}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} & -\frac{\beta(1-\beta)-\lambda}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} \end{bmatrix}. \tag{A9}$$

We can know, $|MN_1| = -\frac{\beta-\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta}$, $|MN_2| = \frac{2\alpha-\beta-\lambda}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, $|MN| = -\frac{2}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$. Under the condition $(\beta-\lambda)(2\alpha-\beta-\lambda) > 0$, the mark of $|MN_1|$ is opposite to the mark of $|MN_2|$ and same to the mark of $|MN|$, then Π_M^N is jointly concave in ω_n^N, p_d^N and ω_t^N.

Furthermore, let Equations (A6) and (A8) be 0, and the optimal wholesale prices of both new and remanufactured products and the sales price of remanufactured product in direct channel can be derived as follows:

$$\omega_n^{N*} = \frac{c+Q}{2}, \tag{A10}$$

$$\omega_t^{N*} = \frac{\alpha Q}{2}, \tag{A11}$$

$$p_d^{N*} = \frac{\beta Q}{2}. \tag{A12}$$

Substituting Equations (A10)–(A12) to relative functions, we can obtain the optimal sales prices of both new and remanufactured products in the retail channel.

According to the conditions that the demand of products is non-negative when deriving the demand function, we can obtain the optimal solutions when parameters satisfy $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$.

The proof of Proposition 1 is completed. □

Proof of Proposition 2. The first-order derivatives of Π_R^R to p_n^R, p_t^R and y^R can be shown as:

$$\frac{\partial \Pi_R^R}{\partial p_n^R} = \frac{QA + (\beta-\lambda)\left(2p_t^R - 2p_n^R + \omega_n^R - \omega_t^R - \varepsilon y^R\right) + \lambda p_d^R}{(1-\alpha)(\beta-\lambda) - \lambda\beta}, \tag{A13}$$

$$\frac{\partial \Pi_R^R}{\partial p_t^R} = \frac{(\alpha-\beta)(\beta-\lambda)\left(2p_n^R - \omega_n^R\right) + [\beta(1-\alpha)-\lambda]p_d^R - [\beta(1-\beta)-\lambda]\left(2p_t^R - \omega_t^R - \varepsilon y^R\right)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}, \tag{A14}$$

$$\frac{\partial \Pi_R^R}{\partial y^R} = \varepsilon\frac{[\beta(1-\beta)-\lambda]\left(p_t^R - \omega_t^R\right) - (\alpha-\beta)(\beta-\lambda)\left(p_n^R - \omega_n^R\right)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} - ky^R. \tag{A15}$$

The Hessian matrix of Π_R^R is

$$RR = \begin{bmatrix} -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & -\frac{\varepsilon(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} \\ \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{-2[\beta(1-\beta)-\lambda]}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} & \frac{\varepsilon[\beta(1-\beta)-\lambda]}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} \\ -\frac{\varepsilon(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{\varepsilon[\beta(1-\beta)-\lambda]}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} & -k \end{bmatrix}. \tag{A16}$$

Since $|RR_1| = -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta}$, $|RR_2| = \frac{4(\beta-\lambda)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, $|RR| = -\frac{2(\beta-\lambda)\left\{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}}{(\alpha-\beta)^2[(1-\alpha)(\beta-\lambda)-\lambda\beta]^2}$, the mark of $|RR_1|$ is opposite to the mark of $|RR_2|$ and same to the mark of $|RR|$. So, Π_R^R is jointly concave in p_n^R, p_t^R and y^R.

Furthermore, by setting Equations (A13) = 0, (A14) = 0 and (A15) = 0, we can obtain as follows:

$$p_n^{R*}\left(\omega_n^R, p_d^R\right) = \frac{Q[\beta(1-\beta)-\lambda] + \beta p_d^R + (\beta-\lambda)\omega_n^R}{2(\beta-\lambda)}, \tag{A17}$$

$$p_t^{R*}\left(\omega_n^R, p_d^R, \omega_t^R\right) = \frac{2k(\alpha-\beta)A\left[Q(\alpha-\beta) + p_d^R + \omega_t^R\right] - \varepsilon^2\left\{(\alpha-\beta)\left[\beta p_d^R - (\beta-\lambda)\omega_n^R\right] + BQ(\alpha-\beta) + 2\omega_t^R\right\}}{4k(\alpha-\beta)A - 2\varepsilon^2[\beta(1-\beta)-\lambda]}, \tag{A18}$$

$$y^{R*}\left(\omega_n^R, p_d^R, \omega_t^R\right) = \frac{\varepsilon\left\{[\beta(1-\alpha)-\lambda]p_d^R - [\beta(1-\beta)-\lambda]\omega_t^R + (\alpha-\beta)(\beta-\lambda)\omega_n^R\right\}}{2k(\alpha-\beta)A - \varepsilon^2[\beta(1-\beta)-\lambda]}. \tag{A19}$$

Next, substitute Equations (A17)–(A19) into Equation (23). Then, taking the first-order derivatives of Π_M^R with respect to ω_n^R, p_d^R and ω_t^R, we obtain

$$\frac{\partial \Pi_M^R}{\partial \omega_n^R} = \frac{2k(\alpha-\beta)\left\{QA - (\beta-\lambda)\left[2\left(\omega_n^R - \omega_t^R\right) - c\right] + 2\lambda p_d^R\right\} - \varepsilon^2\left\{Q[\beta(1-\beta)-\lambda] - (\beta-\lambda)\left(2\omega_n^R - c\right) + 2\beta p_d^R\right\}}{4k(\alpha-\beta)A - 2\varepsilon^2[\beta(1-\beta)-\lambda]}, \tag{A20}$$

$$\frac{\partial \Pi_M^R}{\partial p_d^R} = \frac{\begin{array}{c} 2k\left\{(\alpha-\beta)\left[\beta QA + \lambda(\beta-\lambda)\left(2\omega_n^R - c\right)\right] + 2(\beta-\lambda)[\beta(1-\alpha)-\lambda]\omega_t^R - 2p_d^R\left(D + 4\lambda\alpha^2\right)\right\} \\ -\varepsilon^2\left\{\left(2p_d^R - \beta Q\right)B + (\beta-\lambda)\left(2p_d^R + \beta c - 2\beta\omega_n^R\right)\right\} \end{array}}{2(\beta-\lambda)\{2k(\alpha-\beta)A - \varepsilon^2[\beta(1-\beta)-\lambda]\}}, \tag{A21}$$

$$\frac{\partial \Pi_M^R}{\partial \omega_t^R} = \frac{k\left\{2[\beta(1-\alpha)-\lambda]p_d^R + (\alpha-\beta)(\beta-\lambda)\left(2\omega_n^R - c\right) - 2[\beta(1-\beta)-\lambda]\omega_t^R\right\}}{2k(\alpha-\beta)A - \varepsilon^2[\beta(1-\beta)-\lambda]}. \tag{A22}$$

The Hessian matrix of Π_M^R is

$$MR = \begin{bmatrix} \frac{-(\beta-\lambda)\left[2k(\alpha-\beta)-\varepsilon^2\right]}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} & \frac{2\lambda k(\alpha-\beta)-\beta\varepsilon^2}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} & \frac{2k(\alpha-\beta)(\beta-\lambda)}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} \\ \frac{2\lambda k(\alpha-\beta)-\beta\varepsilon^2}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} & \frac{2k\left\{\beta(1-\alpha)(2\alpha-\beta)+\lambda\left[2\alpha^2+\beta^2-2\alpha(1+\beta)\right]+\lambda^2\right\}-\varepsilon^2[\beta(2-\beta)-2\lambda]}{-(\beta-\lambda)\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}} & \frac{2k[\beta(1-\alpha)-\lambda]}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} \\ \frac{2k(\alpha-\beta)(\beta-\lambda)}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} & \frac{2k[\beta(1-\alpha)-\lambda]}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} & \frac{-2k[\beta(1-\beta)-\lambda]}{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]} \end{bmatrix}. \tag{A23}$$

We can know, $|MR_1| = -\frac{(\beta-\lambda)\left[2k(\alpha-\beta)-\varepsilon^2\right]}{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]}$, $|MR_2| = \frac{2[k(2\alpha-\beta-\lambda)-\varepsilon^2]}{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]}$, $|MR| = -\frac{4k}{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]}$. Under the condition $\beta-\lambda>0$, the mark of $|MR_1|$ is opposite to the mark of $|MR_2|$ and same to the mark of $|MR|$, then Π_M^R is jointly concave in ω_n^R, p_d^R and ω_t^R.

Furthermore, let Equations (A6)–(A8) be 0, and the optimal wholesale prices of both new and remanufactured products and the sales price of remanufactured product in the direct channel can be derived as follows:

$$\omega_n^{R*} = \frac{c+Q}{2}, \tag{A24}$$

$$\omega_t^{R*} = \frac{\alpha Q}{2}, \tag{A25}$$

$$p_d^{R*} = \frac{\beta Q}{2}. \tag{A26}$$

Substituting Equations (A24)–(A26) to relative functions, we can obtain the optimal sales prices of both new and remanufactured products in the retail channel.

According to the conditions that the demand of products is non-negative when deriving the demand function, we can obtain the optimal solutions when parameters satisfy $\beta>\lambda$ and $(1-\alpha)(\beta-\lambda)>\lambda\beta$.

The proof of Proposition 2 is completed. □

Proof of Proposition 3. The first-order derivatives of Π_R^M to p_n^M and p_t^M can be shown as:

$$\frac{\partial\Pi_R^M}{\partial p_n^M} = \frac{QA+(\beta-\lambda)\left(2p_t^M-2p_n^M+\omega_n^M-\omega_t^M\right)+\lambda\left(p_d^M-\varepsilon y^M\right)}{(1-\alpha)(\beta-\lambda)-\lambda\beta}, \tag{A27}$$

$$\frac{\partial\Pi_R^M}{\partial p_t^M} = \frac{(\alpha-\beta)(\beta-\lambda)\left(2p_n^M-\omega_n^M\right)+[\beta(1-\alpha)-\lambda]\left(p_d^M-\varepsilon y^M\right)-[\beta(1-\beta)-\lambda]\left(2p_t^M-\omega_t^M\right)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}. \tag{A28}$$

The Hessian matrix of Π_R^M is

$$RM = \begin{bmatrix} -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} \\ \frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta} & \frac{-2[\beta(1-\beta)-\lambda]}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} \end{bmatrix}. \tag{A29}$$

Since $|RM_1| = -\frac{2(\beta-\lambda)}{(1-\alpha)(\beta-\lambda)-\lambda\beta}$, $|RM| = \frac{4(\beta-\lambda)}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, the mark of $|RM_1|$ is opposite to the mark of $|RM|$. Thus, Π_R^M is jointly concave in p_n^M and p_t^M.

Furthermore, by setting Equations (A27) = 0 and (A28) = 0, we can obtain as follows:

$$p_n^{M*}\left(\omega_n^M, p_d^M, y^M\right) = \frac{Q[\beta(1-\beta)-\lambda]+\beta\left(p_d^M-\varepsilon y^M\right)+(\beta-\lambda)\omega_n^M}{2(\beta-\lambda)}, \tag{A30}$$

$$p_t^{M*}\left(p_d^M, \omega_t^M, y^M\right) = \frac{Q(\alpha-\beta)+p_d^M+\omega_t^M-\varepsilon y^M}{2}. \tag{A31}$$

Next, substitute Equations (A30) and (A31) into Equation (37). Then, taking the first-order derivatives of Π_M^M with respect to ω_n^M, p_d^M, ω_t^M and y^M, we obtain

$$\frac{\partial\Pi_M^M}{\partial\omega_n^M} = \frac{QA-(\beta-\lambda)\left[2\left(\omega_n^M-\omega_t^M\right)-c\right]+\lambda\left(2p_d^M-\varepsilon y^M\right)}{2[(1-\alpha)(\beta-\lambda)-\lambda\beta]}, \tag{A32}$$

$$\frac{\partial\Pi_M^M}{\partial p_d^M} = \frac{\beta QA(\alpha-\beta)-D\left(2p_d^M-\varepsilon y^M\right)+\lambda(\alpha-\beta)(\beta-\lambda)\left(2\omega_n^M-c\right)+2(\beta-\lambda)[\beta(1-\alpha)-\lambda]\omega_t^M}{2(\alpha-\beta)(\beta-\lambda)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}, \tag{A33}$$

$$\frac{\partial \Pi_M^M}{\partial \omega_t^M} = \frac{(\alpha-\beta)(\beta-\lambda)\left(2\omega_n^M - c\right) + [\beta(1-\alpha)-\lambda]\left(2p_d^M - \varepsilon y^M\right) - 2[\beta(1-\beta)-\lambda]\omega_t^M}{2(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}, \tag{A34}$$

$$\frac{\partial \Pi_M^M}{\partial y^M} = \frac{\varepsilon p_d^M D - \varepsilon(\beta-\lambda)\left\{\lambda(\alpha-\beta)\left(\omega_n^M - c\right) + [\beta(1-\alpha)-\lambda]\omega_t^M\right\}}{2(\alpha-\beta)(\beta-\lambda)[(1-\alpha)(\beta-\lambda)-\lambda\beta]} - ky^M. \tag{A35}$$

The Hessian matrix of Π_M^M is

$$MM = \begin{bmatrix} \frac{-(\beta-\lambda)}{A} & \frac{\lambda}{A} & \frac{\beta-\lambda}{A} & \frac{-\varepsilon\lambda}{2A} \\ \frac{\lambda}{A} & \frac{\beta(1-\alpha)(2\alpha-\beta)+\lambda\left[2\alpha^2+\beta^2-2\alpha(1+\beta)\right]+\lambda^2}{-(\alpha-\beta)(\beta-\lambda)A} & \frac{\beta(1-\alpha)-\lambda}{(\alpha-\beta)A} & \frac{\varepsilon(1-\alpha)(\beta-\lambda)(2\alpha-\beta)+\lambda\varepsilon\left[\beta^2-\beta(1+\alpha)\right]+\lambda}{2(\alpha-\beta)(\beta-\lambda)A} \\ \frac{\beta-\lambda}{A} & \frac{\beta(1-\alpha)-\lambda}{(\alpha-\beta)A} & -\frac{\beta(1-\beta)-\lambda}{(\alpha-\beta)A} & \frac{-\varepsilon[\beta(1-\alpha)-\lambda]}{2(\alpha-\beta)A} \\ \frac{-\varepsilon\lambda}{2A} & \frac{\varepsilon(1-\alpha)(\beta-\lambda)(2\alpha-\beta)+\lambda\varepsilon\left[\beta^2-\beta(1+\alpha)\right]+\lambda}{2(\alpha-\beta)(\beta-\lambda)A} & \frac{-\varepsilon[\beta(1-\alpha)-\lambda]}{2(\alpha-\beta)A} & -k \end{bmatrix}. \tag{A36}$$

We can know, $|MM_1| = -\frac{\beta-\lambda}{(1-\alpha)(\beta-\lambda)-\lambda\beta}$, $|MM_2| = \frac{2\alpha-\beta-\lambda}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, $|MM_3| = -\frac{2}{(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]}$, $|MM| = \frac{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2\left\{\beta(1-\alpha)(2\alpha-\beta)-\lambda[2\alpha(1-\alpha)+\beta(2\alpha-\beta)]+\lambda^2\right\}}{2(\beta-\lambda)(\alpha-\beta)^2[(1-\alpha)(\beta-\lambda)-\lambda\beta]^2}$. Under the condition $\beta - \lambda > 0$, the mark of $|MM_1|$ is opposite to the marks of $|MR_2|$ and $|MM|$ and same to the mark of $|MM_3|$, then Π_M^M is jointly concave in ω_n^M, p_d^M, ω_t^M and y^M.

Furthermore, let Equations (A32)–(A35) be 0, the optimal wholesale prices of both new and remanufactured products and the sales price of remanufactured product in the direct channel can be derived as follows:

$$\omega_n^{M*} = \frac{c+Q}{2}, \tag{A37}$$

$$\omega_t^{M*} = \frac{\alpha Q}{2}, \tag{A38}$$

$$p_d^{M*} = \frac{(\beta-\lambda)\left\{4\beta kQ(\alpha-\beta)A - \varepsilon^2\{\beta Q[\alpha(1-\alpha)-\lambda] - \lambda c(\alpha-\beta)\}\right\}}{8k(\alpha-\beta)(\beta-\lambda)A - 2\varepsilon^2 D}, \tag{A39}$$

$$y^{M*} = \frac{\varepsilon(\alpha-\beta)\{\beta Q[\alpha(1-\alpha)-\lambda] + \lambda c(\beta-\lambda)\}}{4k(\alpha-\beta)(\beta-\lambda)A - \varepsilon^2 D}. \tag{A40}$$

Substituting Equations (A37)–(A40) to Equations (A30) and (A31), we can obtain the optimal sales prices of both new and remanufactured products in the retail channel.

According to the conditions that the demand of products is non-negative when deriving the demand function, we can obtain the optimal solutions when parameters satisfy $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$.

The proof of Proposition 3 is completed. □

Proof of Proposition 4. The comparison of optimal wholesale and sales prices of both new and remanufactured products in different models are as follows:

It is clear that $\omega_n^{N*} = \omega_n^{R*} = \omega_n^{M*}$, $\omega_t^{N*} = \omega_t^{R*} = \omega_t^{M*}$, $p_n^{N*} = p_n^{R*}$ and $p_d^{N*} = p_d^{R*}$.

According to assumption 5 and assumption 6, and the conditions $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, we obtain the following results.

$p_n^{R*} - p_n^{M*} = \frac{\beta\varepsilon^2(\alpha-\beta)[\beta QA+\lambda c(\beta-\lambda)]}{4(\beta-\lambda)\left\{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right\}} > 0$, $p_t^{N*} - p_t^{M*} = \frac{\varepsilon^2(\alpha-\beta)[\beta QA+\lambda c(\beta-\lambda)]}{16k(\alpha-\beta)(\beta-\lambda)A-4\varepsilon^2 D} > 0$, $p_t^{N*} - p_t^{R*} = -\frac{c\varepsilon^2(\alpha-\beta)(\beta-\lambda)}{8k(\alpha-\beta)A-4\varepsilon^2[\beta(1-\beta)-\lambda]} < 0$, $p_d^{R*} - p_d^{M*} = -\frac{\varepsilon^2(\alpha-\beta)\{\beta Q[(1-\alpha)(\beta-\lambda)-\lambda\beta]+\lambda c(\beta-\lambda)\}}{8k(\alpha-\beta)(\beta-\lambda)A-2\varepsilon^2 D} < 0$.

From the above results, we can obtain $p_n^{M*} < p_n^{N*} = p_n^{R*}$, $p_t^{M*} < p_t^{N*} < p_t^{R*}$ and $p_d^{N*} = p_d^{R*} < p_d^{M*}$.

The proof of Proposition 4 is completed. □

Proof of Proposition 5. The comparison of optimal demands of both new and remanufactured products and sales effort level in different models are as follows:

According to assumption 5 and assumption 6 about k and Q, and the conditions $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, we obtain the following results.

$q_n^{R*} - q_n^{M*} = -\frac{\alpha-\beta}{4} * \frac{2k(\alpha-\beta)\left[\lambda\beta QA - c(\beta-\lambda)\left(2\beta^2-4\lambda\beta+\lambda^2\right)\right] - \varepsilon^2\left\{\lambda\beta QB + c(\beta-\lambda)\left[\beta^2-2\alpha(\beta-\lambda)\right]\right\}}{4k(\alpha-\beta)(\beta-\lambda)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2 D} < 0$,

$q_n^{N*} - q_n^{M*} = \frac{\lambda\varepsilon^2(\alpha-\beta)[\beta QA + c(\beta-\lambda)]}{4A[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D]} > 0$, so $q_n^{N*} > q_n^{M*} > q_n^{R*}$.

$q_t^{R*} - q_t^{M*} = \varepsilon^2 \frac{2k(\alpha-\beta)\left\{\beta QA[\beta(1-\alpha)-\lambda] - c(\beta-\lambda)\left[\lambda\beta(3+\alpha-2\beta)-2\beta^2(1-\beta)-\lambda^2\right]\right\} - \varepsilon^2 B\{c(2\alpha-\beta)(\beta-\lambda)+\beta Q[\beta(1-\alpha)-\lambda]\}}{4\left[4kA(\alpha-\beta)(\beta-\lambda)-\varepsilon^2 D\right]\left\{2kA(\alpha-\beta)-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}} > 0$, if $\beta(1-\alpha) > \lambda$, $q_t^{R*} > q_t^{M*}$, otherwise, $q_t^{R*} < q_t^{M*}$,

$q_t^{N*} - q_t^{M*} = \frac{\varepsilon^2[\beta(1-\alpha)-\lambda][\beta QA + \lambda c(\beta-\lambda)]}{4A\left\{4kA(\alpha-\beta)(\beta-\lambda)-\varepsilon^2 D\right\}}$, if $\beta(1-\alpha) > \lambda$, $q_t^{N*} > q_t^{M*}$, otherwise, $q_t^{N*} < q_t^{M*}$, $q_t^{N*} - q_t^{R*} = -\frac{c\varepsilon^2(\beta-\lambda)[\beta(1-\beta)-\lambda]}{4A[2kA(\alpha-\beta)-\varepsilon^2[\beta(1-\beta)-\lambda]]} < 0$, so, when the condition satisfies $\beta(1-\alpha) > \lambda$, $q_t^{R*} > q_t^{N*} > q_t^{M*}$, otherwise, $q_t^{M*} > q_t^{R*} > q_t^{N*}$.

$q_d^{R*} - q_d^{M*} = -\frac{2k(\alpha-\beta)\varepsilon^2\left\{\beta QAD - c(\beta-\lambda)\left\{\begin{array}{c}\lambda\beta^2(7-5\alpha-\lambda)+\lambda^2[2\alpha(1-\alpha)+\lambda] \\ -2\beta^3(1-\alpha)-2\lambda\beta[\alpha(1-\alpha-2\lambda)]+3\lambda\end{array}\right\}\right\} - \beta\varepsilon^4 D\left[(c+Q)(\beta-\lambda)-\beta^2 Q\right]}{4(\beta-\lambda)\left[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right]\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}}$, if $D = \beta(1-\alpha)(2\alpha-\beta) - \lambda[2\alpha(1-\alpha)+\beta(2\alpha-\beta)] + \lambda^2 > 0$, $q_d^{R*} < q_d^{M*}$, otherwise, $q_d^{R*} > q_d^{M*}$.

$q_d^{N*} - q_d^{R*} = \frac{c\varepsilon^2(\beta-\lambda)[\beta(1-\alpha)-\lambda]}{4[(1-\alpha)(\beta-\lambda)-\lambda\beta]\left\{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}}$, if $\beta(1-\alpha) > \lambda$, $q_d^{N*} > q_d^{R*}$, $q_d^{N*} < q_d^{R*}$.

$q_d^{N*} - q_d^{M*} = \frac{\varepsilon^2\left\{\beta^2(1-\alpha-\lambda)+2\lambda\alpha(1+\beta)-2\alpha(\beta-\alpha\beta+\lambda\alpha)-\lambda^2\right\}\{\beta Q[(1-\alpha)(\beta-\lambda)-\lambda\beta]+c(\beta-\lambda)\}}{4(\beta-\lambda)A\left\{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2\left\{\beta(1-\alpha)(2\alpha-\beta)-\lambda[2\alpha(1-\alpha)+\beta(2\alpha-\beta)]+\lambda^2\right\}\right\}}$, if $\beta^2(1-\alpha-\lambda) + 2\lambda\alpha(1+\beta) - 2\alpha(\beta-\alpha\beta+\lambda\alpha) - \lambda^2 > 0$, $q_d^{N*} > q_d^{M*}$, otherwise, $q_d^{N*} < q_d^{M*}$.

$q_r^{N*} - q_r^{R*} = -\frac{\varepsilon^2\beta c(\alpha-\beta)(\beta-\lambda)}{4A[2k(\alpha-\beta)A-\varepsilon^2 B]} < 0$,

$q_r^{R*} - q_r^{M*} = -\varepsilon^2(\alpha-\beta)\frac{\begin{array}{c}2k(\alpha-\beta)\{\beta QA[2(1-\alpha)(\beta-\lambda)-\lambda\beta] - c(\beta-\lambda)\left[2\beta^3-2\lambda\beta(1+2\beta-\alpha)+\lambda^2(2-2\alpha+3\beta)\right]\} \\ -\varepsilon^2\{\beta QB[2(1-\alpha)(\beta-\lambda)-\lambda\beta] + c(\beta-\lambda)\left[\beta^3+2\lambda\beta(1-\beta)-2\lambda^2-2\alpha\beta(\beta-\lambda)\right]\}\end{array}}{4(\beta-\lambda)\left[2k(\alpha-\beta)A-\varepsilon^2 B\right]\left[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right]}$ < 0, so, $q_r^{M*} > q_r^{R*} > q_r^{N*}$.

$q_{SC}^{R*} - q_{SC}^{N*} = \frac{\lambda c\varepsilon^2(\alpha-\beta)(\beta-\lambda)}{4A[2k(\alpha-\beta)A-\varepsilon^2 B]} > 0$,

$q_{SC}^{R*} - q_{SC}^{M*} = -\varepsilon^2(\alpha-\beta)\frac{2k(\alpha-\beta)\left\{\beta QA\left(2A+\lambda^2\right) - \lambda c(\beta-\lambda)\left[\lambda^2-2(\beta-\lambda)(1-\alpha-\beta)\right]\right\} - \varepsilon^2\left\{\beta QB\left(2A+\lambda^2\right) + \lambda c(\beta-\lambda)\left[2(1-\alpha)(\beta-\lambda)-\beta^2\right]\right\}}{4(\beta-\lambda)\left[2k(\alpha-\beta)A-\varepsilon^2 B\right]\left[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right]} < 0$, so $q_{SC}^{M*} > q_{SC}^{R*} > q_{SC}^{N*}$.

$y^{R*} - y^{M*} = -\varepsilon(\alpha-\beta)\frac{4k(\alpha-\beta)A\{\beta QA - c(\beta-2\lambda)(\beta-\lambda)\} - 2\varepsilon^2\beta QAB - c\varepsilon^2(\beta-\lambda)\left\{\lambda\left[2\alpha(1-\alpha)+2\beta(1+\alpha)-3\beta^2\right]-\beta(1-\alpha)(2\alpha-\beta)-3\lambda^2\right\}}{2\left[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right]\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}} < 0$.

Based on assumption 5 and assumption 6, the conditions $\beta > \lambda$ and $(1-\alpha)(\beta-\lambda) > \lambda\beta$, we can obtain the above results.

The proof of Proposition 5 is completed. □

Proof of Proposition 6. The comparison of optimal profits of the OEM, retailer and the entire CLSC in different models are as follows:

$\Pi_M^{N*} - \Pi_M^{R*} = -\frac{c^2\varepsilon^2(\alpha-\beta)(\beta-\lambda)^2}{8A[2kA(\alpha-\beta)-\varepsilon^2 B]} < 0$,

$\Pi_M^{R*} - \Pi_M^{M*} = (\alpha-\beta)\varepsilon^2\frac{-2k(\alpha-\beta)\left\{2\lambda\beta cQA(\beta-\lambda)+\beta^2Q^2A^2-c^2(\beta-\lambda)^2\left(2\beta^2-4\lambda\beta+\lambda^2\right)\right\}+\varepsilon^2\left\{2\lambda\beta cQB(\beta-\lambda)+\beta^2Q^2AB+c^2(\beta-\lambda)^2\left[\beta^2-2\alpha(\beta-\lambda)\right]\right\}}{(\beta-\lambda)\left[2kA(\alpha-\beta)-\varepsilon^2 B\right]\left[4kA(\alpha-\beta)(\beta-\lambda)-\varepsilon^2 D\right]}$ < 0, so $\Pi_M^{M*} > \Pi_M^{R*} > \Pi_M^{N*}$.

$\Pi_R^{N*} - \Pi_R^{R*} = -\frac{c^2\varepsilon^2(\alpha-\beta)(\beta-\lambda)^2}{16A[2kA(\alpha-\beta)-\varepsilon^2 B]} < 0$,

$\Pi_R^{N*} - \Pi_R^{M*} = \frac{\varepsilon^2(\alpha-\beta)[\beta QA + c(\beta-\lambda)]}{16} *$

$$\frac{\begin{array}{c}8k(\alpha-\beta)(\beta-\lambda)A[\beta QA - c(\beta-\lambda)] - \varepsilon^2\beta QA\{\beta(1-\alpha)(4\alpha-\beta) - \lambda[4\alpha(1-\alpha)+2\beta(1-\alpha)-\beta^2]+3\lambda^2\} \\ +\varepsilon^2\lambda c(\beta-\lambda)\{\beta(1-\alpha)(4\alpha-3\beta) - \lambda[4\alpha(1-\alpha)+3\beta(2\alpha-\beta)-2\beta]+\lambda^2\}\end{array}}{(\beta-\lambda)A\{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\}^2}$$

> 0, so $\Pi_R^{R*} > \Pi_R^{N*} > \Pi_R^{M*}$.

$\Pi_{SC}^{N*} - \Pi_{SC}^{R*} = -\frac{3c^2\varepsilon^2(\alpha-\beta)(\beta-\lambda)^2}{16A[2kA(\alpha-\beta)-\varepsilon^2 B]} < 0$,

$$\Pi_{SC}^{M*}-\Pi_{SC}^{R*}=\frac{\varepsilon^2(\alpha-\beta)}{16}*$$

$$\frac{2k\left\{\begin{array}{c} k\left[16\lambda\beta QcA^2(\alpha-\beta)^2(\beta-\lambda)^2-8c^2A(\alpha-\beta)^2(\beta-\lambda)^3\left(3\beta^2-6\lambda\beta+\lambda^2\right)\right] \\ -\varepsilon^2\beta^2Q^2A^2(\alpha-\beta)\left[2\lambda\beta(1-\alpha)-\beta^2(1-\alpha-\lambda)-\lambda^2\right]-2\lambda\beta Qc\varepsilon^2A(\alpha-\beta)(\beta-\lambda)\left[\beta^2-4\beta^3+\alpha\beta(4+3\beta-6\lambda)-4\lambda\alpha-6\lambda\beta+7\lambda\beta^2+5\lambda^2-4\alpha^2(\beta-\lambda)\right] \\ +c^2\varepsilon^2(\alpha-\beta)(\beta-\lambda)^2\left\{12\beta^3(1-\alpha)(2\alpha-\beta)-12\lambda\beta^2[6\alpha(1-\alpha)-\beta(2-4\alpha+\beta)]+\lambda^2\beta\left[64\alpha(1-\alpha)+\beta(55\alpha-3)-16\beta^2\right]-\lambda^3\left[16\alpha(1-\alpha)+2\beta(5+7\alpha)+\beta^2\right]+\lambda^4\right\} \end{array}\right\} \begin{array}{c} +\varepsilon^4\beta^2Q^2AB\left[2\lambda\beta(1-\alpha)-\beta^2(1-\alpha-\lambda)-\lambda^2\right]+2\lambda\beta Qc\varepsilon^4B(\beta-\lambda)\left\{\beta(1-\alpha)(4\alpha-3\beta)-\lambda\left[4\alpha(1-\alpha)-2\beta+6\alpha\beta-3\beta^2\right]+\lambda^2\right\} \\ -c^2\varepsilon^4(\beta-\lambda)^2\left\{3\beta^2(1-\alpha)(2\alpha-\beta)^2+3\lambda\beta(2\alpha-\beta)\left[4\alpha^2+\beta^2-2\alpha(2+\beta)\right]+\lambda^2\left[12\alpha^2(1+\beta-\alpha)+4\alpha\beta(1-\beta)-\beta^2(1+2\beta)\right]-2\lambda^3(2\alpha+\beta)\right\} \end{array}}{(\beta-\lambda)[2kA(\alpha-\beta)-\varepsilon^2B]\{4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D\}^2}>0,$$

so $\Pi_{SC}^{M*}>\Pi_{SC}^{R*}>\Pi_{SC}^{N*}$.

Based on assumption 5 and assumption 6, the conditions $\beta>\lambda$ and $(1-\alpha)(\beta-\lambda)>\lambda\beta$, we can obtain the above results.

The proof of Proposition 6 is completed. □

Proof of Proposition 7. The impact of the increase in λ on the optimal decisions under Model R and Model M.

In Model R, $\frac{\partial p_n^{R*}}{\partial\lambda}=-\frac{\beta^2Q}{4(\beta-\lambda)^2}<0$, $\frac{\partial p_d^{R*}}{\partial\lambda}=0$,

$\frac{\partial p_t^{R*}}{\partial\lambda}=\frac{\beta^2\varepsilon^2c(\alpha-\beta)\left[2k(\alpha-\beta)-\varepsilon^2\right]}{4\left\{2k(\alpha-\beta)[(1-\alpha)(\beta-\lambda)-\lambda\beta]-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}^2}>0$, $\frac{\partial q_n^{R*}}{\partial\lambda}=-\frac{\beta^2c\left[2k(\alpha-\beta)-\varepsilon^2\right]^2}{4\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}^2}<0$, $\frac{\partial q_t^{R*}}{\partial\lambda}=\frac{\beta^2ck(\alpha-\beta)\left[2k(\alpha-\beta)-\varepsilon^2\right]}{2\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}^2}>0$, $\frac{\partial q_d^{R*}}{\partial\lambda}=\frac{\beta Q}{4(\beta-\lambda)^2}+\frac{\beta c\left\{2k(\alpha-\beta)\left[2k(1-\alpha)(\alpha-\beta)-\varepsilon^2(2-\alpha)\right]+\varepsilon^4\right\}}{4\left\{2k(\alpha-\beta)A-\varepsilon^2[\beta(1-\beta)-\lambda]\right\}^2}>0$,

$\frac{\partial q_r^{R*}}{\partial\lambda}=\frac{\beta Q}{4(\beta-\lambda)^2}+\frac{\beta c\left[2k(1-\alpha+\beta)(\alpha-\beta)-\varepsilon^2\right]\left[2k(\alpha-\beta)-\varepsilon^2\right]}{4[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$,

$\frac{\partial q_{SC}^{R*}}{\partial\lambda}=\frac{\beta c(\beta-\lambda)^2\left[2k(\alpha-\beta)-\varepsilon^2\right]\left\{2k(\alpha-\beta)(1-\alpha)-\varepsilon^2(1-\beta)\right\}+\beta Q\left[2k(\alpha-\beta)A-\varepsilon^2B\right]^2}{4(\beta-\lambda)^2[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$,

$\frac{\partial\Pi_M^{R*}}{\partial\lambda}=\frac{\beta^2Q^2}{8(\beta-\lambda)^2}+\frac{\beta^2c^2\left[2k(\alpha-\beta)-\varepsilon^2\right]^2}{8[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$, $\frac{\partial\Pi_{SC}^{R*}}{\partial\lambda}=\frac{\beta^2Q^2}{16(\beta-\lambda)^2}+\frac{3\beta^2c^2\left[2k(\alpha-\beta)-\varepsilon^2\right]^2}{16[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$,

$\frac{\partial\Pi_R^{R*}}{\partial\lambda}=-\beta^2\frac{Q^2\left[2k(\alpha-\beta)A-\varepsilon^2B\right]^2-\left\{c(\beta-\lambda)\left[2k(\alpha-\beta)-\varepsilon^2\right]\right\}^2}{16(\beta-\lambda)^2[2k(\alpha-\beta)A-\varepsilon^2B]^2}<0$, $\frac{\partial y^{R*}}{\partial\lambda}=\frac{\beta^2\varepsilon c(\alpha-\beta)\left[2k(\alpha-\beta)-\varepsilon^2\right]}{2\left[2k(\alpha-\beta)A-\varepsilon^2B\right]^2}>0$.

The proof in Model M is similar to Model R, thus we omit the details here.

The proof of Proposition 7 is completed. □

Proof of Proposition 8. The impact of the increase in ε on the optimal decisions under Model R.

It is clear that $\frac{\partial p_n^{R*}}{\partial\varepsilon}=0$ and $\frac{\partial p_d^{R*}}{\partial\varepsilon}=0$.

$\frac{\partial p_t^{R*}}{\partial\varepsilon}=\frac{\varepsilon ckA(\alpha-\beta)^2(\beta-\lambda)}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$, $\frac{\partial q_n^{R*}}{\partial\varepsilon}=-\frac{\varepsilon ck(\alpha-\beta)^2(\beta-\lambda)^2}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}<0$, $\frac{\partial q_t^{R*}}{\partial\varepsilon}=\frac{\varepsilon ck(\alpha-\beta)(\beta-\lambda)B}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$,

$\frac{\partial q_d^{R*}}{\partial\varepsilon}=-\frac{\varepsilon ck(\alpha-\beta)(\beta-\lambda)[\beta(1-\alpha)-\lambda]}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}$, if $\beta(1-\alpha)>\lambda$, $\frac{\partial q_d^{R*}}{\partial\varepsilon}<0$, otherwise, $\frac{\partial q_d^{R*}}{\partial\varepsilon}>0$,

$\frac{\partial q_{SC}^{R*}}{\partial\varepsilon}=\frac{\varepsilon ck(\alpha-\beta)^2(\beta-\lambda)}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$, $\frac{\partial\Pi_M^{R*}}{\partial\varepsilon}=\frac{\varepsilon c^2k(\alpha-\beta)^2(\beta-\lambda)^2}{[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$, $\frac{\partial\Pi_R^{R*}}{\partial\varepsilon}=\frac{\varepsilon c^2k(\alpha-\beta)^2(\beta-\lambda)^2}{4[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$,

$\frac{\partial y^{R*}}{\partial\varepsilon}=\frac{c(\alpha-\beta)(\beta-\lambda)\left[2kA(\alpha-\beta)+\varepsilon^2B\right]}{2[2k(\alpha-\beta)A-\varepsilon^2B]^2}>0$.

The proof of Proposition 8 is completed. □

Proof of Proposition 9. The impact of the increase in ε on the optimal decisions under Model M.

$\frac{\partial p_n^{M*}}{\partial\varepsilon}=-\frac{2\beta\varepsilon k(\alpha-\beta)^2A[\beta QA+\lambda c(\beta-\lambda)]}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}<0$, $\frac{\partial p_t^{M*}}{\partial\varepsilon}=-\frac{2\varepsilon k(\alpha-\beta)^2(\beta-\lambda)A[\beta QA+\lambda c(\beta-\lambda)]}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}<0$,

$\frac{\partial p_d^{M*}}{\partial\varepsilon}=\frac{16\varepsilon k(\alpha-\beta)^2(\beta-\lambda)A[\beta QA+\lambda c(\beta-\lambda)]}{[8k(\alpha-\beta)(\beta-\lambda)A-2\varepsilon^2D]^2}>0$, $\frac{\partial q_n^{M*}}{\partial\varepsilon}=-\frac{2\lambda\varepsilon k(\alpha-\beta)^2(\beta-\lambda)A[\beta QA+\lambda c(\beta-\lambda)]}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}$ <0,

$\frac{\partial q_t^{M*}}{\partial\varepsilon}=-\frac{2\varepsilon k(\alpha-\beta)(\beta-\lambda)[\beta(1-\alpha)-\lambda][\beta QA+\lambda c(\beta-\lambda)]}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}$, if $\beta(1-\alpha)>\lambda$, $\frac{\partial q_t^{M*}}{\partial\varepsilon}<0$, otherwise, $\frac{\partial q_t^{M*}}{\partial\varepsilon}>0$, $\frac{\partial q_d^{M*}}{\partial\varepsilon}=\frac{2\varepsilon k(\alpha-\beta)(\beta-\lambda)D[\beta QA+\lambda c(\beta-\lambda)]}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}$, if $D=\beta(1-\alpha)(2\alpha-\beta)-\lambda[2\alpha(1-\alpha)+\beta(2\alpha-\beta)]+\lambda^2<0$, then $\frac{\partial q_d^{M*}}{\partial\varepsilon}<0$, otherwise, $\frac{\partial q_d^{M*}}{\partial\varepsilon}>0$,

$\frac{\partial q_{SC}^{M*}}{\partial\varepsilon}=\frac{2\varepsilon k(\alpha-\beta)^2[\beta QA+\lambda c(\beta-\lambda)]\left(2A+\lambda^2\right)}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}>0$, $\frac{\partial\Pi_M^{M*}}{\partial\varepsilon}=\frac{\varepsilon k(\alpha-\beta)^2[\beta QA+\lambda c(\beta-\lambda)]^2}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2D]^2}>0$,

$$\frac{\partial \Pi_R^{M*}}{\partial \varepsilon} = -\frac{2\varepsilon k(\alpha-\beta)^2(\beta-\lambda)A[\beta QA+\lambda c(\beta-\lambda)]\{2k(\alpha-\beta)[\beta QA+\lambda c(\beta-\lambda)]-\varepsilon^2\{\beta Q[\alpha(1-\alpha)-\lambda]-\lambda c(\alpha-\beta)\}\}}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D]^3} < 0,$$

$$\frac{\partial \Pi_{SC}^{M*}}{\partial \varepsilon} = \frac{\varepsilon k(\alpha-\beta)^2[\beta QA+\lambda c(\beta-\lambda)]\left\{\begin{array}{c}\lambda c(\beta-\lambda)\left\{8k(\alpha-\beta)(\beta-\lambda)A+\varepsilon^2\left[\beta(1-\alpha)(4\alpha-3\beta)+\lambda\left(4\alpha^2-4\alpha+2\beta-6\alpha\beta+3\beta^2\right)+\lambda^2\right]\right\}\\ +\varepsilon^2\beta QA\left[\beta(1-\alpha)(\beta-2\lambda)-\lambda\left(\beta^2-\lambda\right)\right]\end{array}\right\}}{\left[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D\right]^3}$$

$$> 0, \frac{\partial y^{M*}}{\partial \varepsilon} = \frac{(\alpha-\beta)[\beta QA+\lambda c(\beta-\lambda)]\{4k(\alpha-\beta)(\beta-\lambda)A+\varepsilon^2 D\}}{[4k(\alpha-\beta)(\beta-\lambda)A-\varepsilon^2 D]^2} > 0.$$

Hence, the proof of Proposition 9 is completed. □

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