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Differential Pricing Decision and Coordination of Green Electronic Products from the Perspective of Service Heterogeneity

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Abstract: Consumers focus on level of service while purchasing electronic products. This study focuses on consumer buying behavior. We determine the Stackelberg outcome for a market when a durable electronic product has three different forms: new product, remanufactured product and refurbished product. Under the dynamic game model, the optimal differential pricing strategy is implemented, and the double marginal effect is coordinated through a revenue-sharing contract and two toll contracts to increase the system's revenue capacity. Our research shows that as the degree of consumer preference increases, the service differentiation of the three products is reduced. A lower level of consumer preference affects the pricing decision of new products and significantly affects the pricing of remanufactured products and refurbished products.

Keywords: remanufacturing; closed-loop supply chain; Stackelberg game; differential pricing

1. Introduction

Electronic waste has significant value in recycling and remanufacturing, while causing environmental pollution. For example, the International Telecommunications Union (ITU) studies show that electronic waste generated in 2016 contained 55 billionworth of recyclable raw materials [1]. Among them, the most common way to reuse is to remanufacture used products as remanufactured products or refurbished products in the market to obtain the residual value of the products. After the recycling and remanufacture of electronic waste, remanufactured products and refurbished products save 70% of materials compared with new products, save energy by 60%, save costs by 50% and reduce pollutants by more than 80% [2]. While increasing corporate profits, the environmental hazards of electronic waste are greatly reduced. Currently, well-known manufacturers and retail companies such as Kodak, Hewlett-Packard, Wal-Mart and Apple have successfully implemented closed-loop supply chain management and obtained huge commercial profits for their respective companies.

Product remanufacture is a process in which waste electronic products are used as raw material for production, and specialized repairs and technological refurbishment of used electronic product components are performed such that the remanufactured product meets or achieves the same quality and performance as the original product. Raw material-production-sales-consumption-recycling-remanufacturing is a closed-loop supply chain (CLSC) management model for product remanufacture. Compared with the traditional supply chain production model, the closed-loop supply chain management model can effectively use the residual value of electronic waste, thereby improving resource utilization and reducing environmental pollution. In particular, in the field of consumer remanufacturing, electronic products have unique characteristics due to their short life cycle, which is different from other closed-loop supply chain models for consumer goods: for example, in the United States,

“Post-consumer carpets” are recycled for the extraction of recyclable materials and the creation of new products outside the new carpet [3,4]. This paper focuses on the internal cycle remanufacturing of electronic products and studies the closed-loop supply chain operation mode.

Closed-loop supply chain pricing decisions directly affect the consumer market capacity. Obviously, when new products, remanufactured products and refurbished products emerge in the market, adopting a non-discriminating pricing strategy for the three will inevitably lead to a disordered CLSC management model. Implementing differential pricing strategies has become one of the key measures for companies to improve profitability. For example, Apple will sell remanufactured products with the “Apple certified” logo to consumers through a 50–70% discount on new products through online sales channels, thereby achieving the dual optimization of social and economic benefits. This shows that the differential pricing model has important and practical significance for CLSC management. Currently, the optimal pricing of remanufactured products has drawn academic attention: Savaskan et al. [5] considered manufacturers and retailers as recyclers to discuss the selection of recycling channels and product pricing strategies; Dekker et al. [6] emphasized the reverse supply chain. The coordination problem of pricing decision in China resulted in a qualitative analysis of the key factors of the CLSC coordination; Han Xiaohua [7] discussed the adjustment of the pricing strategy under the condition of cost perturbation; Klaussner [8] studied the optimal recovery cost. Liu L et al. [9], based on the recovery competition between dual recycling channels and original equipment manufacturers, studied the optimal selection of recycling cores under the three selection models. Regarding the impact of manufacturers, Liang [10] discussed the impact of the recycling rate of discarded electronic products on the optimal pricing strategy of remanufacturers; Ferrer [11] and others constructed a double for the manufacturer-oriented Stackelberg game model. Regarding the cycle and single-cycle pricing models, Zhu Xiaodong [12] and others, based on the dual-channel model, analyzed the impact of the recycling channel competition coefficient on the profit level of CLSC and effectively solved model defects through recycling coordination contracts; for the influence of each member’s decision making, the advantages and disadvantages of the degree of fair concern and the increase or decrease in profit under differential pricing decisions were discussed by Yao Fengmin et al. [13]. According to Sun Hao et al. [14], in the competitive environment between the original manufacturer and the remanufacturer, the profitability of different decision models is not influenced by the competition model of the patent licensing mechanism; Sheu et al. [15] considered the changes in the market demand of short life-cycle electronic products for the supply chain binary and found perturbations in the collaborative relationship between members.

However, most of the studies in the literature only consider the impact of various member companies within the supply chain on the pricing model and ignore the impact of consumer behavior on the CLSC. According to research in behavioral economics, consumers focus on service levels while purchasing products, such as unconditional refunds and free after-sales maintenance services (high-technology electronic products industries) within a limited period, which plays an important role in consumers’ purchase strategy choices. Simultaneously, with the expansion of remanufacturing production requirements, many companies adopt the “new-for-new” model to increase the service factor while increasing the recycling scale. For example, for a specific user group, DJI Innovation provides DJICARE services for new products. For the loss caused by accidents or abnormal performance of products, consumers can replace the used products and utilize the official warranty service. Therefore, the service level not only affects the pricing decision of the company, but also affects the overall efficiency of the CLSC system. Xu Lei et al. [16] evaluated the impact of 32 pressures on the industry based on the impact of the GSCM and used two independent assumptions to test the nature of the impact and the extent of impact differences. Guo Junhua [17] studied pricing decisions and coordination mechanisms in closed-loop supply chains based on the differentiated willingness of consumers to pay for products (willingness to pay). Xu Maozeng [18] further expanded the consumer utility function of Debo [19] and obtained a differential pricing model in the context of consumer preferences for new products and remanufactured products. Yan Rongfang [20] studied the

uncertain demanding manufacturers’ pricing strategies and service cooperation problems; however, Bin [21] and others have found that product prices are closely related to customer sensitivity coefficients and used sales compensation-service cost sharing contracts to optimize the product service supply chain profits. However, for further improvement, the following questions arise: How does consumer preference influence service level decision making? From the perspective of government subsidies and consumer preferences, how does retreading affect the pricing of new and remanufactured products and the choice of service strategies? These problems have become the issues that need to be considered urgently in the real management practices of enterprises and decision makers.

To summarize, based on the existing research, this paper considers the consumer preference for green remanufacturing products (remanufactured products, refurbished products) and discusses the issues of differential pricing and coordination decision making of CLSCs from the perspective of dynamic gaming. The structure of the paper is as follows: First, based on the premise that the market has new products and green electronic products simultaneously, Debo’s consumer utility function model is expanded [19]. Subsequently, a game model is used to build a decision model and a comprehensive analysis of the different differential pricing under different models. A comparative analysis of the product pricing strategy is performed in terms of the best selling price, best wholesale price and best service level. Second, based on the study of Cachon et al. [22], revenue-sharing contracts are used to coordinate the M-R decision making model led by manufacturers, and two toll contracts are used to coordinate the R-M decision making models followed by retailers. Finally, the numerical simulation shows the effect of the coordination mechanism on the supply-chain system.

2. Problem Description and Related Assumptions

2.1. Problem Description

This paper considers a single-phase CLSC system consisting of a manufacturer and a retailer, where both the manufacturer and retailer are risk-neutral and fully rational (Figure 1). In this system, the manufacturer is responsible for manufacturing, remanufacturing and recycling a single product and setting the wholesale price. The retailer is responsible for selling the product and setting the retail price. In addition, new products, remanufactured products and refurbished products (remanufactured products and refurbished products are treated with the same quality and function as the new products) with certain durable electronic products in the market are considered. The following discussion focuses on the following: a centralized decision model (manufacturers and retailers form a whole and make decisions); the manufacturer and retailer belong to the Stackelberg game model, but a manufacturer is used as the leader (MR decentralized decision model), as well as the retail business (RM decentralized decision model).

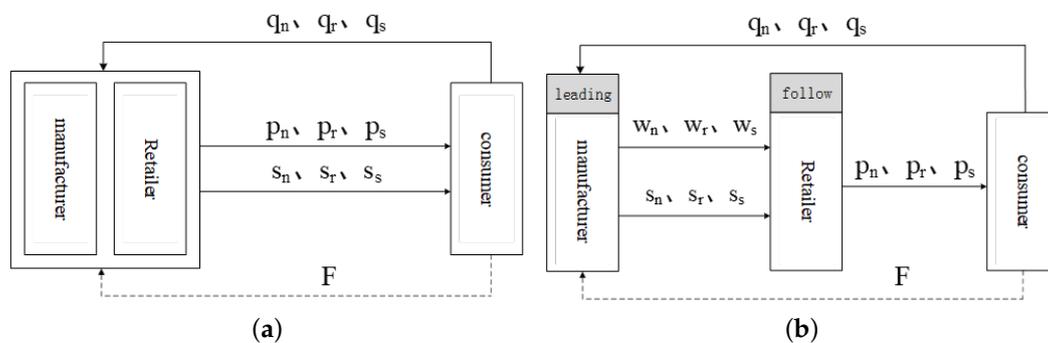


Figure 1. Cont.

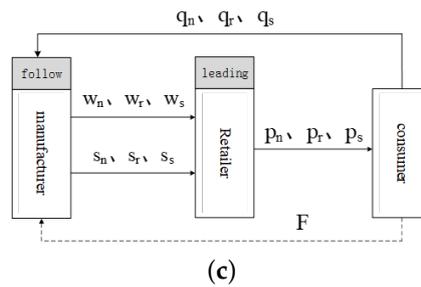


Figure 1. (a) Centralized decision model. (b) Decentralized M-R decision model. (c) Decentralized R-M decision model.

2.2. Symbol Introduction

Assumption 1. The unit manufacturing cost of the new product is c ; Δ_1 is the remanufactured product unit cost savings; Δ_2 is the renewal product unit cost savings. Among them, $c > (c - \Delta_1) > (c - \Delta_2), \frac{(c - \Delta_1)}{c} \in [40\%, 60\%]$.

Assumption 2. The wholesale price of refurbished products, remanufactured products and new products is ω_i ; the sales price is p_i ; the quantity of demand (i.e., production) is $q_i, i \in \{n, r, s\}$; n indicates a new product; r indicates remanufactured products; s indicates renovated products. The profit function is $\Pi_j, j \in \{S, R, M\}$; S is the overall system; R is the retailer; M is the manufacturer.

Assumption 3. Let the product recovery and remanufacturing cost be F .

Assumption 4. According to the study by Tsay et al. [23], the “services” that express the ability to satisfy random demands are quantified as the primary indicators for measuring customer satisfaction. Let s_i be the service level; subsequently, the service cost is expressed as $\frac{1}{2}\eta s_i, i \in \{n, r, s\}$ where η represents the service cost influencing factors.

Assumption 5. The revenue-sharing ratio is δ , and the channel fee is set to S .

Assumption 6. Assuming a constant market size of Q , consumers will pay for a new product and obey the uniform distribution of $U \in \{0, 1\}$. Let the consumer’s preference coefficient be $\theta, \theta \in (0, 1)$; the willingness of the consumer to pay for remanufactured products is $\alpha_n\theta_1$, and the willingness to pay for refurbished products is $\alpha_r\theta_2$. In addition to price and service levels, government policy subsidies also affect consumer demand. The government is designed to subsidize consumers to purchase refurbished products. The subsidy value is g .

According to Moorthy et al. [24], when new products, remanufactured products and refurbished products are simultaneously present in the market, consumers will use self-selection models to compare the magnitude of consumer utility and decide which products to buy (Figure 2). For example: Let $\theta_1 = \theta_2$ to obtain the consumer’s utility function for new products as $\mu_n = \alpha_n - p_n$, and the utility function for remanufactured products and refurbished products is $\mu_i = \theta\alpha_i - p_i, (i \in \{r, s\})$. Hence, we can obtain the distribution map of the consumers’ needs under different strategies.

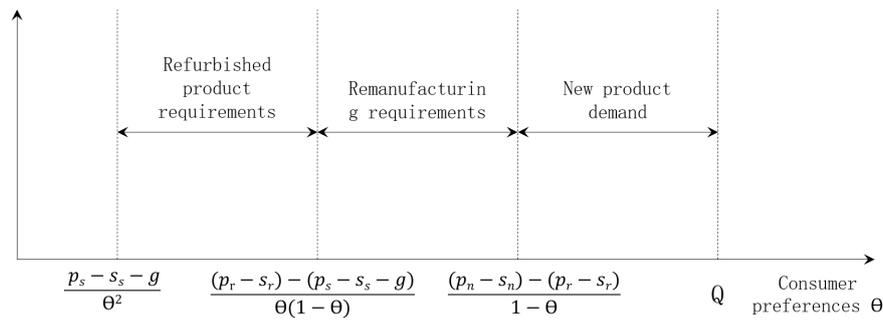


Figure 2. Consumer utility floating range.

According to the literature, when satisfied,

$$\begin{cases} p_n - (1 - \theta) < p_r < \theta p_n \\ p_n - (1 - \theta^2) < p_s < \theta^2 p_n \end{cases} \quad (1)$$

meaning new product, remanufactured product and refurbished product requirements exist in the market. The consumer demand function can be expressed as:

$$q_n = \int_{\frac{(p_n - s_n) - (p_r - s_r)}{1 - \theta}}^Q 1 \, d\alpha \quad (2)$$

$$q_r = \int_{\frac{(p_r - s_r) - (p_s - s_s - g)}{\theta(1 - \theta)}}^{\frac{(p_n - s_n) - (p_r - s_r)}{1 - \theta}} 1 \, d\alpha \quad (3)$$

$$q_s = \int_{\frac{p_s - s_s - g}{\theta^2}}^{\frac{(p_r - s_r) - (-g + p_s - s_s)}{\theta(1 - \theta)}} 1 \, d\alpha \quad (4)$$

The superscript “c” represents a centralized decision model; “d1” represents a decentralized M-R decision model; “d2” represents a decentralized R-M decision model; “r1” represents a coordination mechanism M-R decision model; “r2” represents a coordination mechanism R-M decision model; and “*” indicates the optimal decision. To simplify the model display, we define: $\lambda = c + Q$, $\phi = \theta - 1$, $\gamma = 16\eta^2\theta^2\phi^2$.

3. Closed-Loop Supply Chain Decision

3.1. Centralized Decision

Under the centralized decision making model, manufacturers and retailers form an overall joint decision (for example: Gree electric manufacturing-sales model), whose profit function is expressed as:

$$\begin{aligned} \max_{p_n, p_r, p_s, s_n, s_r, s_s} \Pi_s^c &= \int_{\frac{p_n - s_n - p_r + s_r}{1 - \theta}}^Q (p_n - c) \, d\alpha + \int_{\frac{g + p_r - p_s - s_r + s_s}{\theta(1 - \theta)}}^{\frac{p_n - s_n - p_r + s_r}{1 - \theta}} (p_r - (c - \Delta_1)) \, d\alpha \\ &+ \int_{\frac{-g + p_s - s_s}{\theta^2}}^{\frac{g + p_r - p_s - s_r + s_s}{\theta(1 - \theta)}} (p_s - (c - \Delta_2)) \, d\alpha - F - \frac{1}{2}\eta (s_n^2 + s_r^2 + s_s^2) \end{aligned} \quad (5)$$

Solving Proposition 1 according to first-order linear conditions:

Proposition 1. The optimal sales prices of new products, remanufactured products and refurbished products under CLSC decisions p_i^{c*} and the optimal service level s_i^{c*} are:

$$p_n^{c*} = \frac{2c\eta^2\theta\phi (2\theta^2(\eta\phi + 1) + \theta) + \eta\theta (2\Delta_1\eta\theta^2\phi + \Delta_2\theta) + \eta (g\theta^2 + Q (2\eta (2\eta\theta^2\phi^2 + \theta^4) + \theta^3))}{4\eta\theta^2(\eta\phi + 1)(2\eta\theta\phi + 1)} \tag{6}$$

$$p_r^{c*} = \frac{c\theta^2 + 2c + \theta^2 (2\Delta_2\eta\phi - 4\Delta_1\eta^2\theta\phi^2) + 4\eta^2\theta^3\lambda\phi^2 + 2\eta\theta\phi (\theta(g + \lambda) + \theta^2\lambda + Q) + \theta^3Q}{4\eta\theta\phi (2\theta^2(\eta\phi + 1) + 1)} \tag{7}$$

$$p_s^{c*} = \frac{4c\eta^3\theta^3\mu - \Delta_2\eta\theta (4\eta^2\theta^2\mu + \theta) + 2\Delta_1\eta^2\theta^2\phi + \eta\theta^2 (4g\eta^2\theta\mu + \theta Q (4\eta^2\theta^2\mu + \theta))}{4\eta^2\theta^2\phi(2\eta\theta\phi + 1)} \tag{8}$$

$$s_n^{c*} = \frac{2\eta\theta (2\Delta_1\eta\theta^2\phi + \Delta_2\theta) + 2g\eta\theta^2 + Q (4\eta^2\theta^3\mu + 2\eta (\theta^3 - 1) \theta)}{8\eta^2\theta^3\phi(\eta\phi + 1)} \tag{9}$$

$$s_r^{c*} = \frac{2c\eta\phi + 4\Delta_2\eta^2\theta^2\phi + 4\Delta_1\eta^2 (\theta^2 - 1) \theta^2 + 2\eta\theta^2(2g\eta\phi + \theta Q\phi) + \theta Q}{4\eta\theta^2 (2\eta\theta^2 + 1) (\eta\phi + 1)} \tag{10}$$

$$s_s^{c*} = \frac{4c\eta^2\theta\mu + 4\Delta_1\eta^2\theta^2\phi - 4\Delta_2\eta^2\theta\phi + \Delta_2 - 4g\eta^2\theta\phi + g + \theta^2Q}{8\eta^3\theta^3\phi^2} \tag{11}$$

The objective function model is explained in Table 1.

Table 1. Objective function model interpretation.

Parameter Determined by the Formula	Formula
New product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (p_n - c) d\alpha$
Remanufactured product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (p_r - (c - \Delta_1)) d\alpha$
Refurbished product sales profit	$\int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (p_s - (c - \Delta_2)) d\alpha$
Total service cost	$\frac{1}{2}\eta (s_n^2 + s_r^2 + s_s^2)$
Recycling and remanufacturing fixed costs	F

It is proven that the Hessian matrix of the objective function under a centralized decision can be determined as negative by Equation (5). That is, the target profit function is a strictly concave function about p_n, p_r and p_s , and an optimal solution exists. The first-order partial derivatives of p_n, p_r and p_s are solved for Equation (5) and set to zero. The simultaneous equations can subsequently be solved optimally.

Conclusion 1: Under the centralized decision:

- p_n^{c*}, s_n^{c*} decreases as the consumption preference increases;
- $p_r^{c*}, p_s^{c*}, s_r^{c*}, s_s^{c*}$ increase with the increase in consumer preference;
- p_s^{c*}, q_s^{c*} increase with the increase in government subsidy degree g ; at this time, the producer surplus and consumer surplus increase.

Inference 1: With the increase in consumer preferences, remanufactured products and refurbished products erode the new product market share; however, the overall profit of the CLSC systems has increased. With the increase in government subsidies, the surplus of producers and the increase in consumer surplus occur.

3.2. Decentralized Decision

Under the decentralized decision making, manufacturers and retailers respectively pursue their own interests in the market. Two situations exist:

1. Manufacturer as leader, and retailer as follower;
2. Retailer as leader, and manufacturer as follower.

3.2.1. M-R Decision

In the M-R decision model, the manufacturer as a leader first considers the retailer’s optimal reaction function to determine the wholesale prices $(\omega_n, \omega_r, \omega_s)$ and service levels (s_n, s_r, s_s) . Subsequently, the retailer determines its sales price according to the manufacturer’s decision, i.e., p_n, p_r, p_s , (e.g., Apple Inc. and its affiliates). The decision model is:

$$\begin{aligned} \max_{\omega_n, \omega_r, \omega_s, s_n, s_r, s_s} \Pi_M^d = & \int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (\omega_n - c) d\alpha + \int \frac{\frac{p_n - s_n - p_r + s_r}{1 - \theta}}{g + p_r - p_s - s_r + s_s} (\omega_r - (c - \Delta_1)) d\alpha \\ & + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (\omega_s - (c - \Delta_2)) d\alpha - F - \frac{1}{2}\eta (s_n^2 - s_r^2 - s_s^2) \end{aligned} \tag{12}$$

$$\begin{aligned} s.t. \quad p_n, p_r, p_s \in \operatorname{argmax} \Pi_R = & \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (p_r - \omega_r) d\alpha \\ & + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (p_s - \omega_s) d\alpha + \int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (p_n - \omega_n) d\alpha \end{aligned} \tag{13}$$

The objective function model is explained in Table 2.

Table 2. Objective function model interpretation.

Game Party	Parameter Determined by the Formula	Formula
Manufacturer (Leadership)	New product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (\omega_n - c) d\alpha$
	Remanufactured product sales profit	$\int \frac{\frac{p_n - s_n - p_r + s_r}{1 - \theta}}{g + p_r - p_s - s_r + s_s} (\omega_r - (c - \Delta_1)) d\alpha$
	Refurbished product sales profit	$\int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (\omega_s - (c - \Delta_2)) d\alpha$
	Total service cost	$\frac{1}{2}\eta (s_n^2 + s_r^2 + s_s^2)$
	Recycling and remanufacturing fixed costs	F

Table 2. Cont.

Game Party	Parameter Determined by the Formula	Formula
Retailer (following status)	New product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (p_r - \omega_r) d\alpha$
	Remanufactured product sales profit	$\int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (p_s - \omega_s) d\alpha$
	Refurbished product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (p_n - \omega_n) d\alpha$

To solve Equations (12) and (13), we introduce Proposition 2:

Proposition 2. Under the M-R decision, the optimal selling prices of new products, remanufactured products and refurbished products under the CLSC p_i , optimal wholesale price ω_i and optimal service level s_i are:

$$p_n^{d1*} = \frac{c\eta\theta(\gamma + \theta) + 3\eta\theta(4\Delta_1\eta\theta^2\phi + \Delta_2\theta) + 3\eta(g\theta^2 + Q(\gamma\theta + 4\eta(\theta^4 - 1)\theta + \theta^4 + \theta^2))}{64\eta^3\theta^3\phi^2} \tag{14}$$

$$p_r^{d1*} = \frac{c\eta\theta(\gamma + \theta) - \Delta_1\eta\theta(\gamma + 4\theta) + 12\Delta_2\eta^2\theta^2\phi + 3\eta\theta(4g\eta\theta\phi + \theta Q(\gamma + \theta^2))}{64\eta^3\theta^3\phi^2} \tag{15}$$

$$p_s^{d1*} = \frac{c\eta\theta(\gamma + 5\theta) - 16\Delta_2\eta^3\theta^3\phi^2 + 12\Delta_1\eta^2\theta^2\phi + \Delta_2 + 3\eta\theta^2(16g\eta^2\theta\phi^2 + \theta Q(\gamma + \theta))}{64\eta^3\theta^3\phi^2} \tag{16}$$

$$\omega_n^{d1*} = \frac{\theta(c + g) + 4c\eta\phi + 8\eta^2\theta^2\phi^2(c + 2Q) + \theta(4\Delta_1\eta\theta\phi + \Delta_2) + Q(4\eta(\theta^4 - 1) + \theta^3 + \theta)}{32\eta^2\theta^2\phi^2} \tag{17}$$

$$\omega_r^{d1*} = \frac{c(\gamma + \theta) + \Delta_1(\gamma + 2\theta) + 4\Delta_2\eta\theta\phi + 4g\eta\theta\phi + \theta Q(\gamma + \theta^2)}{32\eta^2\theta^2\phi^2} \tag{18}$$

$$\omega_s^{d1*} = \frac{\Delta_2(2\eta\theta(\gamma + \theta)) + 2\eta\theta(c(\gamma + \theta) + 4\Delta_1\eta\theta\phi + \theta^2(16g\eta^2\phi^2 + \theta Q(8\eta\theta\phi(2\eta\phi + 1))))}{64\eta^3\theta^3\phi^2} \tag{19}$$

$$s_n^{d1*} = \frac{-c + 4\eta\theta^2(4\Delta_1\eta\theta\phi + \Delta_2) + 4\eta\theta(g\theta + Q(4\eta\theta^2\phi^2 + \theta^3 - 1))}{64\eta^3\theta^3\phi^2} \tag{20}$$

$$s_r^{d1*} = \frac{4\eta\phi(c + \theta^2(4g\eta + \theta Q)) + 16\eta^2\theta^2(\Delta_1(\theta^2 - 1) + \Delta_2\phi) + \theta Q}{4\eta\theta\phi(16\eta^2\theta^2\phi - 1)} \tag{21}$$

$$s_s^{d1*} = \frac{\theta(16c\eta^2\phi^2 + \theta Q) + 16\eta^2\theta\phi(\Delta_1\theta - \Delta_2) + \Delta_2 - 16g\eta^2\theta\phi + g}{64\eta^3\theta^3\phi^2} \tag{22}$$

Proof. According to the Stackelberg game model, manufacturers as the market leader first determine their wholesale prices $\omega_n, \omega_r, \omega_s, s_n, s_r, s_s$; for retailers as followers, the manufacturer’s decision model is referred to in order to determine the sales price p_n, p_r, p_s . □

From Equation (13), the Hessian matrix of the retailer’s profit function for p_n, p_r and p_s is negatively determined. In other words, the retailer’s profit function is a strictly concave function for p_n, p_r and p_s . There is a unique optimal solution.

Next, we solve the first-order partial derivatives of p_n, p_r and p_s separately for Equation (13) and set it to zero:

$$\frac{\partial \Pi_R}{\partial p_n} = -\frac{p_n - \omega_n}{1 - \theta} - \frac{p_n - s_n - p_r + s_r}{1 - \theta} + \frac{p_r - \omega_r}{1 - \theta} + Q = 0 \tag{23}$$

$$\begin{aligned} \frac{\partial \Pi_R}{\partial p_r} = & -\frac{g + p_r - p_s - s_r + s_s}{(1 - \theta)\theta} + \frac{p_n - \omega_n}{1 - \theta} + \frac{p_n - s_n - p_r + s_r}{1 - \theta} \\ & + \left(-\frac{1}{(1 - \theta)\theta} - \frac{1}{1 - \theta} \right) (p_r - \omega_r) + \frac{p_s - \omega_s}{(1 - \theta)\theta} = 0 \end{aligned} \tag{24}$$

$$\begin{aligned} \frac{\partial \Pi_R}{\partial p_s} = & \frac{g + p_r - p_s - s_r + s_s}{(1 - \theta)\theta} - \frac{-g + p_s - s_s}{\theta^2} + \frac{p_r - \omega_r}{(1 - \theta)\theta} \\ & + \left(-\frac{1}{\theta^2} - \frac{1}{(1 - \theta)\theta} \right) (p_s - \omega_s) = 0 \end{aligned} \tag{25}$$

The vertical type for Equations (23)–(25) is as follows:

$$p_n = \frac{1}{2} (s_n + \omega_n + Q) \tag{26}$$

$$p_r = \frac{1}{2} (\theta Q + s_r + \omega_r) \tag{27}$$

$$p_s = \frac{1}{2} (g + \theta^2 Q + \omega_s + s_s) \tag{28}$$

Substituting Equations (26)–(28) into Equation (12) solves the first-order partial derivative of Π_M^d for $\omega_n, \omega_r, \omega_s, s_n, s_r$ and s_s . By setting them to zero:

$$\frac{\partial \Pi_M}{\partial \omega_n} = \frac{\Delta_1 + s_n - 2\omega_n - \theta Q + Q - s_r + 2\omega_r}{2 - 2\theta} = 0 \tag{29}$$

$$\frac{\partial \Pi_M}{\partial \omega_r} = \frac{\Delta_1 - \Delta_2 + g + \theta (\Delta_1 - 2\omega_n + 2\omega_r) + \theta s_n - (\theta + 1)s_r + 2\omega_r - 2\omega_s + s_s}{2(\theta - 1)\theta} = 0 \tag{30}$$

$$\frac{\partial \Pi_M}{\partial \omega_s} = -\frac{c(-\theta) + c - \Delta_2 + g + \theta (\Delta_1 - s_r + 2\omega_r) - 2\omega_s + s_s}{2(\theta - 1)\theta^2} = 0 \tag{31}$$

$$\frac{\partial \Pi_M}{\partial s_n} = \frac{\Delta_1 - 2\eta(\theta - 1)s_n - \omega_n + \omega_r}{2(\theta - 1)} = 0 \tag{32}$$

$$\frac{\partial \Pi_M}{\partial s_r} = \frac{-\Delta_1(\theta + 1) + \Delta_2 + \theta\omega_n - \theta\omega_r - 2\eta(\theta - 1)\theta s_r - \omega_r + \omega_s}{2(\theta - 1)\theta} = 0 \tag{33}$$

$$\frac{\partial \Pi_M}{\partial s_s} = -\frac{c(\theta - 1) + \Delta_2 - \theta (\Delta_1 + \omega_r) + 2\eta(\theta - 1)\theta^2 s_s + \omega_s}{2(\theta - 1)\theta^2} = 0 \tag{34}$$

The simultaneous solution for Equations (29)–(34) can be obtained from the optimal solution of Proposition 2.

Conclusion 2: Under the decentralized M-R decision, the optimal sales price of new products, remanufactured products and refurbished products under CLSC decisions p_i^{c*} and the optimal service level s^{c*}_i are:

1. p_n, ω_n, s_n decrease with the increase in θ ;
2. p_r, ω_r, s_r increase with the increase in θ ;
3. p_s, ω_s, s_s increase with the increase in θ ;

Conclusion 3: Under the decentralized M-R decision, the optimal sales price of new products, remanufactured products and refurbished products under CLSC decisions p_i^{c*} and the optimal service level s^{c*}_i are:

1. $p_n^{c*} < p_n^{d1*}; p_r^{c*} < p_r^{d1*}; p_s^{c*} < p_s^{d1*};$
2. $s_n^{c*} > s_n^{d1*}; s_r^{c*} > s_r^{d1*}; s_s^{c*} > s_s^{d1*};$
3. $\Pi_M^{d1*} + \Pi_R^{d1*} < \Pi_S^{c*}.$

Inference 2:

1. With the increase in consumer acceptance of remanufactured products and new products, the best selling price, the best wholesale price and the optimal service level should be increased, and new products should be reduced accordingly;
2. In the manufacturer-dominated Stackelberg game model, the manufacturer’s gain Π_M^{d1*} and the optimal sales price for new products, remanufactured products and refurbished products are greater than those under centralized decision making. Further, the optimal service level is less than that under centralized decision making. The CLSC presents a double marginal effect, and the supply chain is non-optimal.

3.2.2. R-M Decision

In the RM decision model, the retailer, as the market leader (e.g., Wal-Mart), first determines the sales price p_n, p_r and p_s according to its own objective function and the manufacturer’s optimal reaction function. Subsequently, the manufacturer, according to its own objective function and the retailer’s decision, determines the wholesale prices $(\omega_n, \omega_r, \omega_s)$ and service levels (s_n, s_r, s_s) .

The decision model is:

$$\max_{p_n, p_r, p_s} \Pi_R^d = \int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (p_n - \omega_n) d\alpha + \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (p_r - \omega_r) d\alpha + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (p_s - \omega_s) d\alpha \tag{35}$$

$$s.t. = \begin{cases} \max_{\omega_n, \omega_r} \Pi_M^d = \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (\omega_r - (c - \Delta_1)) d\alpha \\ + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (\omega_s - (c - \Delta_2)) d\alpha \\ + \int \frac{p_n - s_n - p_r + s_r}{1 - \theta} (\omega_n - c) d\alpha - F - \frac{1}{2} \eta s_n s_n - \frac{1}{2} \eta s_r s_r - \frac{1}{2} \eta s_s s_s \\ p_n = \omega_n + A \\ p_r = \omega_r + B \\ p_s = \omega_s + M \end{cases} \tag{36}$$

Among them, the constraints $p_n = \omega_n + A, p_r = \omega_r + B, p_s = \omega_s + M$ imply that the retailer sales price is more significant than or equal to the manufacturer wholesale price.

The objective function model is explained in Table 3.

Table 3. Objective function model interpretation.

Game Party	Parameter Determined by the Formula	Formula
Retailer (following status)	New product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (p_r - \omega_r) d\alpha$
	Remanufactured product sales profit	$\int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (p_s - \omega_s) d\alpha$
	Refurbished product sales profit	$\int_0^Q \frac{p_n - s_n - p_r + s_r}{1 - \theta} (p_n - \omega_n) d\alpha$
Manufacturer (Leadership)	New product sales profit	$\int_0^Q \frac{p_n - s_n - p_r + s_r}{1 - \theta} (\omega_n - c) d\alpha$
	Remanufactured product sales profit	$\int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} \frac{1 - \theta}{\theta(1 - \theta)} (\omega_r - (c - \Delta_1)) d\alpha$
	Refurbished product sales profit	$\int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1 - \theta)}{\theta^2} (\omega_s - (c - \Delta_2)) d\alpha$
	Total service cost	$\frac{1}{2} \eta (s_n^2 + s_r^2 + s_s^2)$
	Recycling and remanufacturing fixed costs	F

Next, Equations (35) and (36) are solved and the proposition obtained.

Proposition 3. For the proposition R-M decision under the CLSC of new products, remanufactured products and refurbished products, we obtain the best sales price p_i , the best wholesale price ω_i and the optimal service level s_i as follows:

$$p_n^{d2*} = \frac{4\eta^2\theta\phi^2(c + 3Q) + c + 2\Delta_1\eta\theta\phi + \Delta_2 + g + Q(\theta(2\eta(\theta(\theta + 4) - 2) + \theta) + 3)}{16\eta^2\theta\phi^2} \tag{37}$$

$$p_r^{d2*} = \frac{\eta\theta^2(4\eta^2\theta\phi^2(c + 3\theta Q) + c - 2\Delta_1(2\eta^2\theta\phi^2 + 1) + 2\Delta_2\eta\phi + 2g\eta\phi + \theta(\theta + 2)Q)}{2(2\eta\theta\phi + 1)(2\eta(2\theta^2(\eta\phi + 1) + 1) - 1)} \tag{38}$$

$$p_s^{d2*} = \frac{\eta\theta^2(4\eta^2\theta\phi^2 + 1)(c + 3(g + \theta^2Q)) - \eta\theta^2(2\eta\phi(2\Delta_2\eta\theta\phi - \Delta_1) + \Delta_2) + \Delta_2}{16\eta^3\theta^3\phi^2} \tag{39}$$

$$\omega_n^{d2*} = \frac{16\eta^2\theta\phi^2(3c + Q) + 3c + 4\Delta_1\eta\theta\phi + \Delta_2 + g + Q(4\eta(\theta^3 + 1) + \theta^2 + 2)}{64\eta^2\theta\phi^2 + 4} \tag{40}$$

$$\omega_r^{d2*} = \frac{\theta(c(48\eta^2\theta\phi^2 + 3) + 4\eta\phi(\Delta_2 - 12\Delta_1\eta\theta\phi) + 4\eta\phi(g + \theta(2\theta + 1)Q) + Q(\gamma + \theta^2))}{4(\gamma + \theta)} \tag{41}$$

$$\omega_s^{d2*} = \frac{\theta(16\eta^2\theta\phi^2(3c + g) + 24c\eta\theta\phi + c + 8\eta\phi(\Delta_1 - 6\Delta_2\eta\theta\phi) - 3\Delta_2 + \theta Q(\gamma + \theta))}{4(\gamma + \theta)} \tag{42}$$

$$s_n^{d2*} = \frac{-c + 2\eta\theta^2 (4\Delta_1\eta\theta\phi + \Delta_2) + 2\eta\theta^2 (g + Q (4\eta\theta\phi^2 + \theta^2 + 1))}{2\eta\theta(\gamma + \theta)} \tag{43}$$

$$s_r^{d2*} = \frac{4c\eta\phi + 8\eta^2\theta^2 (\Delta_1 (\theta^2 - 1) + \Delta_2\phi) + \theta(2\eta\theta\phi(4g\eta + \theta Q) + Q)}{2\eta\theta^2(8\eta\theta\phi(2\eta\phi + 1) + 1)} \tag{44}$$

$$s_s^{d2*} = \frac{\theta (16c\eta^2\phi^2 + \theta Q) + 16\eta^2\theta\phi (\Delta_1\theta - \Delta_2) + \Delta_2 - 16g\eta^2\theta\phi + g}{4\eta\theta(\gamma + \theta)} \tag{45}$$

Proof. According to the Stackelberg game model, retailers, as market leaders, first determine their retail prices p_n, p_r and p_s ; manufacturers as followers, according to the retailer decision model, determine their sales prices $(\omega_n, \omega_r, \omega_s)$ and service levels (s_n, s_r, s_s) . □

Next, we substitute $p_n = \omega_n + A, p_r = \omega_r + B$ and $p_s = \omega_s + M$ into Π_M^{d2} and obtain the first-order partial derivatives of $\omega_n, \omega_r, \omega_s$. After including the human intervention, we set the first derivative be zero and solve the simultaneous equations. The group can obtain the unique optimal solution, by substituting the optimal wholesale prices $\omega_n, \omega_r, \omega_s$ of new products, remanufactured products and refurbished products into Π_R^{d2} . According to the reverse induction method, the optimal decision result in the proposition can be obtained.

Conclusion 4: Under the decentralized R-M decision,

1. p_n, ω_n, s_n decrease with the increase in θ ;
2. p_r, ω_r, s_r increase with the increase in θ ;
3. p_s, ω_s, s_s increase with the increase in θ ;

Conclusion 5: Under the decentralized R-M decision,

1. $p_n^{c*} < p_n^{d2*}; p_r^{c*} < p_r^{d2*}; p_s^{c*} < p_s^{d2*};$
2. $s_n^{c*} > s_n^{d2*}; s_r^{c*} > s_r^{d2*}; s_s^{c*} > s_s^{d2*};$
3. $\Pi_M^{d1*} + \Pi_R^{d1*} < \Pi_S^*.$

Inference 3:

1. With the increase in consumer acceptance, remanufactured products and new products, the best selling price, best wholesale price and optimal service level should be increased, and new products should be reduced accordingly;
2. Under the retailer-led Stackelberg game model, the retailer’s gain Π_R^{d2} is more significant than the manufacturer’s gain Π_M^{d2} , and the optimal selling price of new products, remanufactured products and refurbished products is more significant than the centralized decision. The optimal service level is less than the centralized decision making, and the CLSC presents a double marginal effect. The supply chain is non-optimal.

4. Coordination Mechanism Design

Owing to the dual marginal effects of decentralized M-R and R-M decisions, the systems are not optimal. Therefore, for the M-R model, we designed a revenue-sharing contract optimization model; for the R-M model, we designed two toll contracts to improve the model defects.

4.1. M-R Decision: Revenue Sharing Contract

According to Cachon et al. [19], the revenue-sharing contract is superior to other contracts and can significantly increase the overall benefit of the supply chain system. Its decision model is:

$$\begin{aligned} \max_{\omega_n, \omega_r} \Pi_M^{r1} = & \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} (\omega_r - (c - \Delta_1)) d\alpha + \int \frac{g + p_r - p_s - s_r + s_s}{\theta(1-\theta)} (\omega_s - (c - \Delta_2)) d\alpha \\ & + \int \frac{p_n - s_n - p_r + s_r}{1-\theta} (\omega_n - c) d\alpha - F + (1-\delta) \left(p_r \left(\int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} 1 d\alpha \right) \right) \\ & + p_s \left(\int \frac{g + p_r - p_s - s_r + s_s}{-\theta} \frac{\theta(1-\theta)}{g + p_s - s_s} 1 d\alpha \right) + p_n \left(\int \frac{p_n - s_n - p_r + s_r}{1-\theta} 1 d\alpha \right) - \frac{1}{2} \eta (s_n^2 + s_r^2 + s_s^2) \end{aligned} \tag{46}$$

$$s.t. p_n, p_r \in \operatorname{argmax}_{\omega_n, \omega_r} \Pi_R^{r1} = \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} (\delta p_r - \omega_r) d\alpha \tag{47}$$

$$+ \int \frac{g + p_r - p_s - s_r + s_s}{-\theta} \frac{\theta(1-\theta)}{g + p_s - s_s} (\delta p_s - \omega_s) d\alpha + \int \frac{p_n - s_n - p_r + s_r}{1-\theta} (\delta p_n - \omega_n) d\alpha$$

$$\Pi_R^r \geq \Pi_R^d, \Pi_M^r \geq \Pi_M^d \tag{48}$$

When $\delta = 1$, no cooperation exists between the manufacturers and retailers. At this time, they return to the M-R decision making model of the CLSC. Manufacturers obtain all the benefits, and the revenue-sharing contract is invalid.

Proposition 4. The optimal sales price p_i for the CLSC new products, remanufactured products and refurbished products under a revenue-sharing contract is:

$$p_n^{r1*} = \frac{-c + 2\eta\theta^2 (2\Delta_1\eta\theta\phi + \Delta_2) + 2\eta\theta (g\theta + 2\eta\theta^2\phi^2(2\eta\lambda + Q) + (\theta^3 - 1) Q)}{16\eta^3\theta^3\phi^2} \tag{49}$$

$$p_r^{r1*} = \frac{1}{2} \left(\frac{2\eta\phi (c + \theta^2(2g\eta + \theta Q)) + 4\eta^2\theta^2 (\Delta_1 (\theta^2 - 1) + \Delta_2\phi) + \theta Q}{8\eta^3\theta^3\phi^2} + c - \Delta_1 + \theta Q \right) \tag{50}$$

$$p_s^{r1*} = \frac{1}{2} \left(\frac{\theta(4c\eta\phi(\eta\phi + 1) + \theta Q) + 4\eta^2\theta\phi (\Delta_1\theta - \Delta_2) + \Delta_2 - 4g\eta^2\theta\phi + g}{8\eta^3\theta^3\phi^2} + c - \Delta_2 + g + \theta^2 Q \right) \tag{51}$$

Proposition 5. Under the coordination of the revenue-sharing contract model, the necessary and sufficient conditions for the M-R game model to constitute the optimal decision are $\omega_n = c\delta, \omega_r^{r1*} = \delta(c - \Delta_1)$ and $\omega_s^{r1*} = \delta(c - \Delta_2)$. At this time, $s_n^{r1*} = s_n^{c*}, s_r^{r1*} = s_r^{c*}$ and $s_s^{r1*} = s_s^{c*}$.

Proof. To achieve the M-R supply chain coordination, it is necessary to perform equal decisions under both the decentralized and centralized decision making. The following must be met:

$$\begin{cases} p_n^{r1*} = p_n^{c*} \\ p_r^{r1*} = p_r^{c*} \\ p_s^{r1*} = p_s^{c*} \end{cases} \tag{52}$$

□

The first-order partial derivatives of p_n, p_r and p_s are obtained from Π_R and are equal to the centralized decision making pricing strategy.

$$\frac{\partial \Pi_R}{\partial p_n} = -\frac{-\delta s_n - \omega_n + \delta(-Q)}{2\delta} = p_n^{c*} \tag{53}$$

$$\frac{\partial \Pi_R}{\partial p_r} = -\frac{\delta\theta(-Q) - \delta s_r - \omega_r}{2\delta} = p_r^{c*} \tag{54}$$

$$\frac{\partial \Pi_R}{\partial p_s} = -\frac{-\delta g + \delta\theta^2(-Q) - \delta s_s - \omega_s}{2\delta} = p_s^{c*} \tag{55}$$

The propositions are solved according to Equations (53)–(55). Substituting w_n, w_r, w_s into Equation (22) yields p_n, p_r, p_s and the retailer’s and manufacturer’s optimal profit Π_R^{1*}, Π_M^{1*} . Finally, according to the constraint condition $\Pi_R^r \geq \Pi_R^d, \Pi_M^r \geq \Pi_M^d$, the value range of δ^* (gain sharing interval) can be obtained.

4.2. R-M Decision: Two Charge Contracts

Under decentralized R-M decision making, large-scale retail enterprises are dominant, possess strong bargaining advantage and will charge manufacturers a certain amount of fixed fees (passage fees S), thereby strengthening retailers’ profit margins. From the extension Savaskan et al. [6], the decision model is:

$$\begin{aligned} \max_{p_n, p_r, p_s} \Pi_R^{r2} = & \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} (p_r - \omega_r) d\alpha + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1-\theta)}{\theta^2} (p_s - \omega_s) d\alpha \\ & + \int \frac{p_n - s_n - p_r + s_r}{1-\theta} (p_n - \omega_n) d\alpha - S \end{aligned} \tag{56}$$

$$\text{s.t.} = \begin{cases} (\omega_n, \omega_r, \omega_s, s_n, s_r, s_s) \in \text{argmax} \Pi_M^{r2} = \int \frac{p_n - s_n - p_r + s_r}{1-\theta} (\omega_n - c) d\alpha \\ + \int \frac{p_n - s_n - p_r + s_r}{g + p_r - p_s - s_r + s_s} (\omega_r - (c - \Delta_1)) d\alpha \\ + \int \frac{g + p_r - p_s - s_r + s_s}{-g + p_s - s_s} \frac{\theta(1-\theta)}{\theta^2} (\omega_s - (c - \Delta_2)) d\alpha - F - \frac{1}{2}\eta (s_n^2 + s_r^2 + s_s^2) + S \\ p_n = \omega_n + A \\ p_r = \omega_r + B \\ p_s = \omega_s + M \\ \Pi_M^{r2} \geq \Pi_M^{d2} \end{cases} \tag{57}$$

The available propositions are solved:

Proposition 6. *The channel fee charged by the retailer to the manufacturer under the coordination of the two-toll contracts is:*

$$S^* = \frac{2\eta (\Delta_2\eta (2c\phi + \Delta_2) + \Delta_1\theta (2\Delta_2\eta + 2g\eta + \theta Q)) + \phi (\theta Q (\eta\theta^3 Q - c) - c\phi (-2c\eta + 4g\eta))}{8\eta^2\theta^2\phi} \tag{58}$$

Proof. Research shows that the necessary and sufficient conditions for the utility of the two-toll contracts are the following: $p_n^{r2*} = p_n^{c*}, p_r^{r2*} = p_r^{c*}, p_s^{r2*} = p_s^{c*}$. According to Π_M^r , the manufacturer’s optimal response function for retailer decision can be obtained as $\omega_i^{r2*}(p_i), s_i^{r2*}(p_i)$, and p_n, p_r, p_s

can be substituted into the manufacturer's optimal response function. Using Equation (27), the optimal solution can be obtained. \square

5. Numerical Simulation

In the following, a mobile phone is used as a simulation case to perform the numerical simulation analysis on the settings of the model above to yield the relevant parameters: $c = 100, Q = 1000, \eta = 25, \Delta_1 = 50, \Delta_2 = 25$. Using Mathematica 11 programming, the pricing decision and coordination model under different models are obtained.

5.1. Closed-Loop Supply Chain Differential Pricing Decision

1. When $\theta \in [0.7, 0.9], g = 50$, the optimal retail price, optimal wholesale price and optimal service level of new products, remanufactured products and retreaded products change with θ under centralized and decentralized decision making. The situation is shown in Figure 3. Numerical examples show that with the increase in the consumer preference coefficient, the retail price and wholesale price of remanufactured products and refurbished products will increase, and the pricing level of new products will decrease accordingly. It shows that remanufactured products and refurbished products erode the market share of new products, resulting in lower pricing decisions for new products.

Simultaneously, as the consumer preference coefficient increases, the service differentiation between new products and remanufactured products or refurbished products decreases, indicating that as consumers favor the remanufactured products and refurbished products, the service strategies of the supply-chain member companies are adjusted accordingly. At this time, the degree of polarization of customer satisfaction is reduced.

In addition, lower consumer preferences affect new product pricing decisions and significantly affect remanufactured goods and refurbishment product pricing decisions. This shows that with the increase in consumer preference, the total market demand increases.

2. When $\theta = 0.7$ and $g \in [50, 100]$, the optimal retail price, optimal wholesale price and optimal service level of new products, remanufactured products and refurbished products change with g in the centralized and decentralized decision making. This scenario is illustrated in Figure 4. The numerical example shows that with the increase in the government subsidy coefficient, the retail price, wholesale price, service level and market demand of the refurbished products have increased, indicating that under the conditions of government subsidies, the surplus of producers and the increase in consumer surplus, the overall supply chain profits rise.
3. When $\theta \in [0.7, 0.9]$ and $g \in [50, 100]$, the total profit of the supply chain under centralized decision making, decentralized R-M decision making and decentralized M-R decision making is shown in Table 4. Numerical examples show that with the increase in consumer preferences θ and government subsidies g , the total profits of all members of the supply chain and the supply chain increase, and the profits obtained by the leading ones are higher; the total profit of the supply chain under the R-M decision and M-R decision, individually, is lower than the concentration. Further, decision making shows a double marginal effect, and the supply chain is non-optimal.

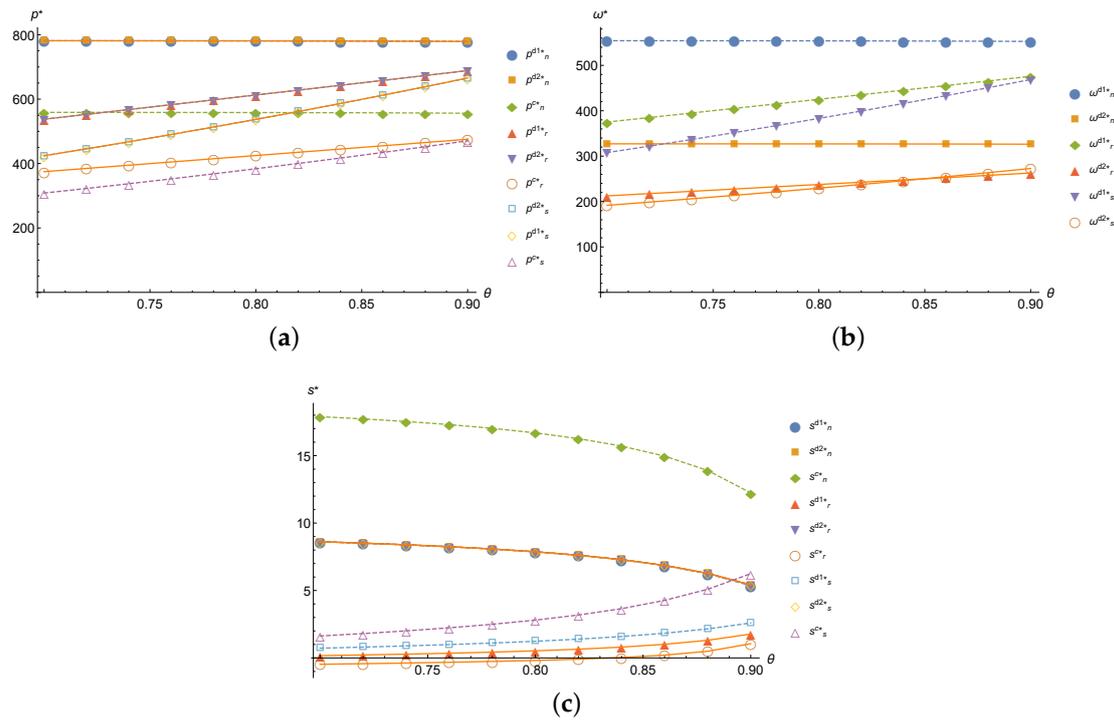


Figure 3. (a) Changes in optimal selling prices with consumer preferences. (b) Changes in optimal wholesale price with consumer preferences. (c) Changes in optimal service levels with consumer preferences.

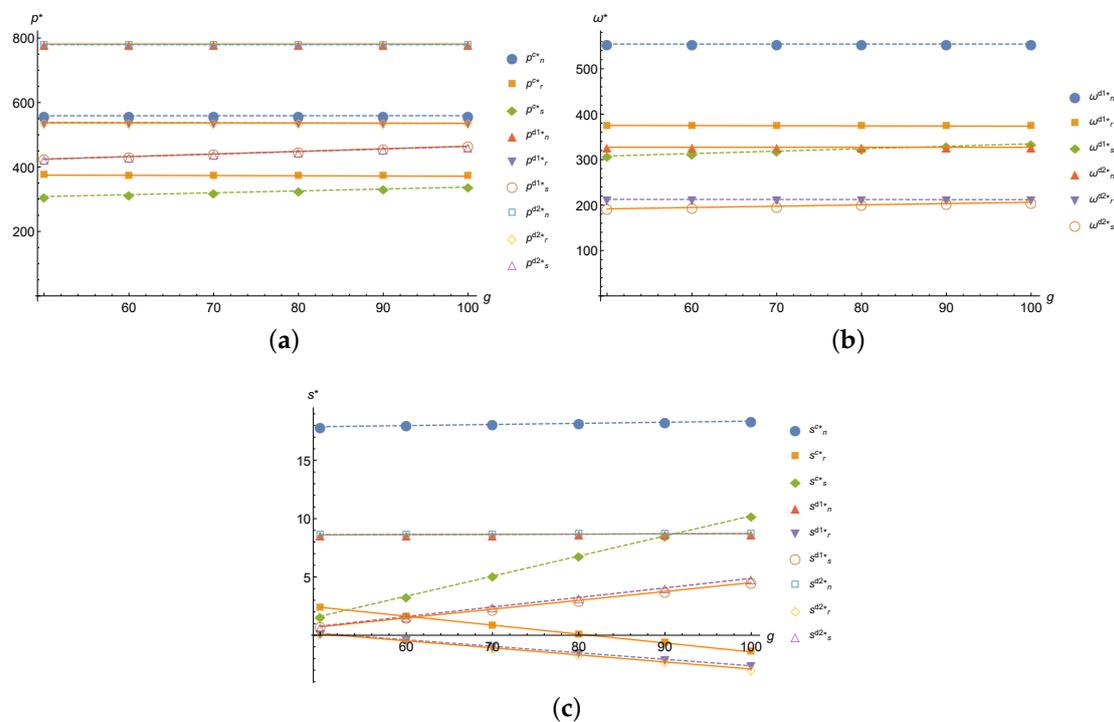


Figure 4. (a) Changes in optimal sales price with government subsidies. (b) Changes in optimal wholesale prices due to government subsidies. (c) Changes in optimal service levels with government subsidies.

Table 4. Effect of the change of parameters g and θ on the optimal model.

θ	g	Centralized Decision	Decentralized M-R Decision			Decentralized R-M Decision		
		Π_S^*	Π_R^{d1*}	Π_M^{d1*}	$\Pi_R^{d1*} + \Pi_M^{d1*}$	Π_R^{d2*}	Π_M^{d2*}	$\Pi_R^{d2*} + \Pi_M^{d2*}$
0.7	50	196,896	51,706.1	92,477.6	144,183.7	103,413	40,778.2	144,191.2
	70	198,570	52,113.7	93,217.5	145,331.2	104,237	41,166.8	145,403.8
	90	201,967	52,944.9	94,715.9	147,660.8	105,918	41,947.5	147,865.5
0.8	50	197,552	51,865.4	92,934.7	144,800.1	103,733	41,089.3	144,822.3
	70	200,028	52,459.9	94,002.2	146,462.1	104,941	41,658.1	146,599.1
	90	204,650	53,574.5	95,969.5	149,544	107,210	42,685.3	149,895.3
0.9	50	200,153	52,517.9	94,553.7	147,071.6	105,040	42,133.7	147,173.7
	70	205,857	53,762	96,659.2	150,421.2	107,686	43,323.1	151,009.1
	90	216,724	56,086	100,384	156,470	112,660	45,279.8	157,939.8

5.2. Closed-Loop Supply Chain Differential Pricing Coordination

Let $\theta = 0.8, g = 50$, and substitute them into the decentralized M-R and R-M decision models, respectively.

5.2.1. M-R Decision: Revenue-Sharing Contract

From the proposition result of Section 5.2, the optimal profit result can be obtained (Figure 5), where the abscissa is the revenue-sharing ratio δ . When $\Pi_R^{r1*} = \Pi_R^{d1*} = 51,865.4, \delta = 0.249$; when $\Pi_M^{r1*} = \Pi_M^{d1*} = 92,934.7, \delta = 0.512$, i.e., when the revenue-sharing interval $\delta \in [0.249, 0.512]$, the revenue-sharing contract is valid.

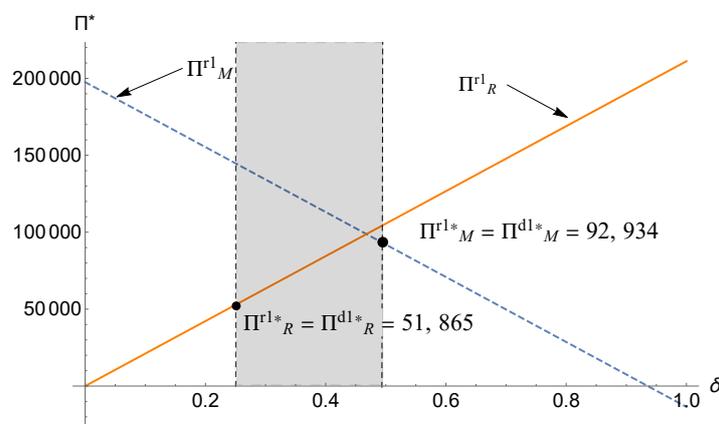


Figure 5. Change in optimal profit of manufacturers and retailers under changing income-sharing intervals.

5.2.2. R-M Decision: Two Charge Contracts

From the proposition results of Section 4.2, the optimal value of S^* is obtained. At this time, under the two-toll contracts, $\Pi_M^{r2*} = 156,663$ and $\Pi_R^{r2*} = 410,893$. This shows that the retailer who is the leading player of the Stackelberg game obtains the full profits of the coordination of the two toll contracts, while the manufacturer retains the pre-coordinated optimal returns. The overall revenue capacity of the system is expanded.

6. Conclusions

We herein assumed three forms of e-waste recycling and remanufacturing market: new products, remanufactured products and refurbished products. Under the influence of factors such as government subsidies, consumer preferences and other factors, the CLSC pricing and service level decision, as well as coordination issues were studied. In the modeling process, a combination of symbolic model

construction and numerical simulation was used to construct a pricing model based on consumer preferences. The optimal solutions under different models were determined, and a revenue-sharing contract and two toll-making contracts were proposed to coordinate the CLSC pricing model. Based on the findings, we can conclude that consumer preferences have a positive correlation with the overall return of the CLSC system; as the degree of consumer preference increases, the service differentiation of new products, remanufactured products and refurbished products decreases. Government subsidies can effectively increase the surplus of producers, and the consumer surplus improves the overall profitability of the supply chain system. Under the dynamic game model, the dominant player achieves higher returns through bargaining advantages, but causes the decentralized M-R decision making and R-M decision to have double marginal effects, thereby producing a non-optimal system. The revenue-sharing contract and the two charge contract coordination models constructed herein can effectively mitigate the contradiction caused by the double marginal effect, which is embodied in the following: (1) In order to stimulate the retailer's sales volume, the manufacturer will transfer some of the proceeds to achieve the effect of small profits, but quick turnover. At this point, how to determine the revenue-sharing ratio δ is especially critical (extremely, when the revenue-sharing ratio $\delta = 1$, the manufacturer does not cooperate with the retailer). (2) Retailers in a strong position tend to charge manufacturers a certain amount of access fee to achieve the retailers' goal in capitalizing their markets.

The Stackelberg game model proposed in this paper provides theoretical reference and practical guidance for the differential pricing and service level decision making and coordination of real enterprises. Centralized decision making is applicable to the integrated decision making of manufacturers and retailers, achieving optimal profit through cooperation and win-win; the manufacturer-led decision making model is applicable to the dominant manufacturers in the supply chain (for example: Apple in the U.S. and its affiliates) vendors; retailer-led decision making models are applicable to strong retailers in the supply chain (e.g., Jingdong Mall in China, etc.). In addition to price and service level factors, corporate location models, sales channel models, etc., will also affect consumer purchasing decisions. Future studies on this model should address other aspects not covered in this study. First, the model assumes that the market demand is constant at Q , but the market demand is unstable due to the disturbance of many factors; and the enterprise remanufacturing ability and recovery efforts influence the production demand. The relationship between market demand and pricing strategy will be investigated in a future study. Second, this study considers new products, remanufactured products and refurbished products that exist in the market simultaneously and assumed that they have the same product utility. However, in actual operations, product replacements often occur, and new products have a higher level of product utility. In future studies on consumer's utility, the issue of strategic coordination in the context of product upgrading will be investigated. Third, this study only considers the provision of services by manufacturers; the provision of services by retailers or by both manufacturers and retailers (cooperative services) should be considered in future studies.

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