

Optimal Product Pricing and Recovery Strategies in a Two-period Model for Manufacturers with Core Classification and Trade-In-for-New/Reman Policies

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Abstract: Motivated by the recent policy initiative of the Central Financial and Economic Affairs Commission to promote a new round of equipment upgrading and consumer-goods trade-in programs, we develop a two-period game-theoretic model for a manufacturer endowed with remanufacturing capability. In period 1, the market is partitioned into new and remanufactured products, and the initial market structure is determined by their respective demand shares. In period 2, consumers' trade-in/-for-remanufacturing behavior is disentangled; utility theory is employed to derive demand functions under alternative scenarios. The manufacturer then chooses the sales prices of both new and remanufactured products together with the buy-back price of used new products so as to maximize its total profit. Key findings are as follows. (1) The new-product demand share, the trade-in discount for remanufactured items, and the product's circular value are the three pivotal drivers of pricing strategy. In particular, when the new-product demand share is low, the circular value is high, or the remanufactured-product trade-in discount is large, the optimal buy-back price of new products equals the selling price of remanufactured products. (2) The sales prices of new/remanufactured products and the buy-back price increase with the remanufacturing trade-in discount and consumers' perceived-value discount, decrease with the circular value, and rise with the new-product production cost. (3) The impact of the new product's circular value on pricing depends on the market structure: only when the new-product demand share is high, the trade-in discount is low, and the circular value itself is small will an increase in circular value raise all prices. (4) Under a high remanufactured-product pricing strategy, the buy-back price is U-shaped in the new-product demand share; under a low pricing strategy it increases monotonically. (5) Manufacturer profit increases with the remanufacturing trade-in discount, the circular value, and the perceived-value discount, but decreases with the remanufacturing circular value. A lower new-product demand share and higher production cost reduce total profit; however, once the cost exceeds a critical threshold, profit rebounds. We recommend that manufacturers dynamically adjust pricing, invest in remanufacturing technology, and enhance recovery incentives. Meanwhile, governments should underpin green consumption and the circular economy through supportive policies and effective oversight.

Keywords: Product Segmentation; Trade-in-for-New; Trade-in-for-Reman; Pricing Strategy; Remanufacturing

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1.Introduction

Remanufacturing refers to the process of restoring discarded products or components to their original performance and quality levels through repair, upgrading, and reassembly, thereby extending their service life and reintroducing them to the market^[1]. Remanufacturing not only protects the environment and improves resource reuse efficiency but also reduces production costs and enhances economic benefits, thus achieving sustainable development. Consequently, the remanufacturing market is experiencing rapid growth. Taking the automotive-parts remanufacturing market as an example, the global market value is expected to increase from approximately USD 61.8 billion in 2023 to USD 119.5 billion by 2032, with a compound annual growth rate of about 9 %^a. As consumers' environmental awareness and acceptance of remanufactured products rise, more and more manufacturers are introducing remanufacturing and establishing remanufactured-product lines to further expand market share. For instance, SAIC Volkswagen has set up its own power-train remanufacturing plant, and Caterpillar, a world-leading construction and mining equipment manufacturer, also provides remanufacturing services for engineering machinery^b. However, substitutability between remanufactured and new products creates a cannibalization effect that forces manufacturers to adjust their pricing strategies. Therefore, how manufacturers should design product-pricing strategies under new-versus-reman product competition is the key question addressed in this paper.

To stimulate consumption of both new and remanufactured products, the Chinese government has launched trade-in-for-new and trade-in-for-reman policies. 'Trade-in-for-new' allows consumers to return an old unit and receive a discount on the purchase of a new product^[2]. Apple, for example, promotes trade-in programs that encourage consumers to return old devices to authorized dealers, thereby boosting sales of new products. Data show that, compared with 2018, Apple's sales in 2019 quadrupled thanks to the trade-in policy^c. 'Trade-in-for-reman' refers to consumers trading in an old unit for a discount on a remanufactured product. Remanufactured products are also called officially refurbished products. Huawei, for instance, offers officially refurbished Mate40 Pro 5G phones on its official website, all of which have passed strict remanufacturing processes to ensure performance comparable to new devices. The trade-in-for-reman policy greatly promotes sales of remanufactured products. According to market-research agency Counterpoint, global shipments of second-hand smartphones—including officially refurbished phones—reached 282.6 million units, an increase of 11.5 % year-on-year^d. In practice, an increasing number of firms have adopted trade-in-for-new and trade-in-for-reman policies as sales strategies to stimulate consumer purchasing behavior. Yet previous studies on new-versus-reman sales strategies rarely consider the coexistence of both incentive policies. Therefore, the first objective of this paper is to uncover how these two sales incentives influence consumer purchasing behavior under new-versus-reman competition.

The introduction of trade-in-for-new/reman policies significantly affects consumer purchasing behavior. Under these policies, strategic consumers care not only about future prices of new and remanufactured products but also about the residual value of their used units and the utility derived from continuing to use them. Consumers' purchasing decisions thus become inherently multi-period dynamic problems. Faced with such complex consumer behavior, manufacturers find it more difficult to set prices for new and remanufactured products. Moreover, the multiplicity of sources for trade-in cores further complicates pricing. Existing studies usually assume that cores come only from originally sold new products, ignoring used remanufactured products. Currently, large quantities of remanufactured products are already in circulation, and firms in practice recycle both used new and used remanufactured units. For example, Apple's AppleCare+ trade-in service allows users to trade in old devices—including officially refurbished ones—toward the purchase of new devices^e. Therefore, the second objective of this paper is to investigate manufacturers' dynamic pricing strategies that simultaneously account for the impacts of trade-in-for-new/reman policies on consumer behavior, the multiplicity of core sources, and product competition.

a <https://www.custommarketinsights.com/report/automotive-parts-remanufacturing-market/>

b <https://www.caterpillar.com/>

c <https://www.qianzhan.com/analyst/detail/329/210205-838290ce.html>

d https://www.thepaper.cn/newsDetail_forward_24934009

e https://www.thepaper.cn/newsDetail_forward_24934009

In summary, this paper simultaneously considers consumers' multi-period purchasing behavior, trade-in-for-new/reman policies, and multiple core sources to study a manufacturer's multi-period dynamic optimal sales-pricing and collection strategies. We construct a two-product, two-period pricing model in which the manufacturer maximizes total profit. Consumers choose between a new and a remanufactured product in period 1; in period 2, consumers who purchased in period 1 may either participate in trade-in-for-new, trade-in-for-reman, or keep their old units. Building on this complex consumer behavior, we construct consumer utility functions that incorporate the remanufactured-product perceived-value discount and collection-price differentials, derive the corresponding demand functions, and solve the model under KKT conditions to obtain optimal pricing decisions under various scenarios. We then conduct sensitivity analyses with respect to key parameters such as the remanufactured-product perceived discount, the proportion of different core types, and the remanufactured-product collection-price discount, and complement the analytical results with numerical simulations. Compared with previous studies, this paper makes several important contributions. First, in a competitive-product setting, we simultaneously consider both trade-in-for-new and trade-in-for-reman policies and explore how these two sales incentives influence consumer purchasing behavior. Second, we account for the multiplicity of core sources—namely, originally sold new and remanufactured products—and examine how different core-mix proportions affect manufacturers' sales and collection pricing when implementing trade-in-for-new and trade-in-for-reman programs. Finally, based on consumers' multi-period dynamic purchasing behavior, we derive optimal pricing strategies under both policies, thereby extending the literature on dynamic collection pricing. The main research questions are as follows:

- (1) How do product competition and core classification affect consumer purchasing behavior under trade-in-for-new/reman policies?
- (2) How should a manufacturer set sales and collection prices for new and remanufactured products when accounting for the combined effects of trade-in-for-new/reman policies on consumer behavior, product competition, and core sources?
- (3) How do key factors such as the proportion of different core types, the remanufactured-product collection-price discount, and consumers' perceived discount on remanufactured products influence the manufacturer's optimal sales and collection pricing strategies and profit?

The remainder of the paper is organized as follows. Section 2 reviews the literature, Section 3 describes the problem and basic assumptions, Section 4 establishes and solves the manufacturer's two-period sales-and-collection pricing model, Section 5 conducts sensitivity analyses of sales and collection pricing strategies, Section 6 provides numerical simulations and supplementary discussions, and Section 7 concludes.

2. Literature Review

Literature closely related to this study can be grouped into three main streams: consumer purchase behavior, product remanufacturing, and sales-incentive strategies.

2.1 Consumer Purchase Behavior

Studies investigating the determinants of consumer purchase behavior toward remanufactured products provide abundant empirical evidence. Some scholars focus on cognitive factors. Wang and Hazen^[4] employ structural equation modeling to examine how cost, quality, and environmental knowledge affect purchase intention; their results show that perceived value positively influences intention, whereas perceived risk exerts a negative effect. Using the theory of planned behavior (TPB), Wang et al.^[5] analyze Chinese consumers and find that attitude, subjective norm, and perceived behavioral control are the main drivers, with perceived inconvenience and perceived risk being negative. Others concentrate on attitudes and behaviors: Wang et al.^[6] demonstrate that attitude, perceived behavioral control, and perceived risk significantly shape remanufactured-product purchase intention. Singhal et al.^[7] corroborate via meta-analysis that attitude, subjective norm, perceived green benefit, and perceived behavioral control are positively related to intention, while perceived risk is negatively related. Product characteristics also matter. Khor and Hazen^[8] apply TPB to Malaysian consumers and reveal a preference for energy-saving remanufactured products. Jun et al.^[9] show that similarity between remanufactured and new products negatively affects new-product purchase intention, with brand reputation moderating this link. Regarding non-economic factors, Alyahya et al.^[10] use fuzzy-set qualitative comparative analysis (FsQCA) and identify moral responsibility as an important

antecedent of remanufactured-product purchase behavior. Collectively, these studies underscore the complexity of consumers' remanufactured-product purchase intention.

To delve deeper into the decision mechanism, researchers construct consumer utility functions that incorporate behavioral traits and preferences to quantify utility levels across purchase options. Christensen and Manser^[11] adopt direct and indirect translog utility functions to derive budget-share equations, demonstrating flexibility and consistency with utility-maximization theory and concluding that the translog form is well suited for preference modeling. Grounded in perceived-risk theory, consumers form distinct initial value expectations when facing product choices. Wang et al.^[12] and Esenduran et al.^[13] build utility functions that capture the choice between new and remanufactured products, noting that remanufactured products suffer a consumer value discount relative to new ones. Dong and Lei^[14] design a two-period utility function that portrays the effects of continuing to use, collecting a rebate, or upgrading to a new product, but their setting considers only new products and ignores the option to buy remanufactured products. Therefore, drawing on prior work, this paper constructs a two-period utility function that simultaneously encompasses three options—buying new, buying remanufactured, and keeping the old unit—and explicitly incorporates the remanufactured-product consumer value discount and collection price, thereby capturing consumers' complex purchase behavior.

2.2 Product Remanufacturing

As remanufacturing has gradually become a key component of firms' product portfolios, the competitive relationship between new and remanufactured products in the marketplace and their pricing have attracted extensive attention. Sun et al.^[15] construct a differentiated-competition model involving a manufacturer, a remanufacturer, and a retailer, and employ theoretical and numerical analyses to examine the impact of third-party remanufacturing on market competition; they point out that consumers' different sensitivities toward new and remanufactured products play a critical role in equilibrium decisions. Guide and Li^[16] use auction experiments to propose a willingness-to-pay model and investigate the self-cannibalization problem when new and remanufactured products are sold simultaneously, showing that commercial products face high cannibalization risk. Abbey et al.^[17] develop a consumer-preference-based pricing model between a new-product manufacturer and a third-party remanufacturer, and study price competition between new and remanufactured products; they find that when remanufactured products enter the market, appropriately raising the new-product price helps reduce profit erosion. Wang et al.^[18] propose a price-and-service competition model involving a traditional manufacturer, a remanufacturer, and a retailer, and explore optimal profits of new and remanufactured products under different game structures. Wu^[19] designs a supply-chain competition model composed of a new-product manufacturer, a remanufacturer, and a retailer, investigates price and service competition between new and remanufactured products, and reveals the equilibrium characteristics of the remanufacturer's effort level as well as its price and service decisions. Although single-period pricing strategies have been well studied, research on multi-period pricing of new and remanufactured products remains scarce^[20, 21].

To reduce the difficulty of remanufacturing, the value and quality of collected used cores have likewise received increasing attention^[22-24]. Fan et al.^[25] provide useful managerial insights into the relationships among a firm's channel choice, consumer acceptance of the direct channel, and the value of used products. Li et al.^[26] propose three collection strategies based on consumers' quality perceptions, examine how the quality-decay coefficients of used and refurbished products and the value of new products affect the choice of collection mode, and offer optimal decisions for collection platforms. Yin et al.^[27] further build a system-dynamics simulation model to compare the impacts of different graded collection mechanisms on used-core collection quality and remanufacturer profit. Van et al.^[28] analyze the economic conditions for remanufacturing based on used-core quality and derive optimal collection strategies under general settings. However, existing studies have not adequately considered how sales and collection strategies are affected when cores originate from both new and remanufactured products. Therefore, this paper incorporates the issue of core sources in trade-in-for-new/reman programs and thoroughly investigates two-period sales and collection pricing strategies.

2.3 Sales-Incentive Strategies

Sales-incentive strategies are key instruments for firms to stimulate product sales, covering pre-sale services, after-sale rebates^[29], subsidies^[30], and celebrity live-streaming sales^[31]. Among new-product promotions, trade-in-for-new has been

widely adopted and studied, and has demonstrated significant effectiveness. Wan et al.^[32] propose three trade-in schemes and examine how quality differences affect collection mode and sales price, showing that trade-in raises the collection rate of used products in many scenarios. Xu et al.^[33] analyze the joint decisions of online/offline channel expansion and logistics choice through a two-period dynamic model, pointing out that trade-in-for-new critically influences corporate strategic choices. Liu et al.^[34] explore a manufacturer's use of a third-party information platform to implement trade-in-for-new, finding that under certain conditions the strategy markedly increases manufacturer profit. Shi et al.^[35] investigate the strategy in the presence of informal recycling competition and show that it improves market share and profit. Researchers have also delved into different trade-in service modes. Wang et al.^[36] employ a manufacturer–retailer game to examine who should offer trade-in under different e-commerce modes; they identify conflicting interests under the reselling mode but a win–win outcome under the agency mode. Tang et al.^[37] use a duopoly-retailer model to study how brand loyalty affects exclusive versus non-exclusive trade-in strategies, showing that the exclusive strategy performs better in markets with low brand loyalty. Yang et al.^[38] compare self-built versus cooperative trade-in modes from an omnichannel perspective and find that the cooperative mode enhances social welfare when consumer waiting costs are low.

Besides trade-in-for-new, trade-in-for-reman has attracted attention as a means to promote remanufactured-product sales. Ma et al.^[39] show that when firms introduce trade-in-for-reman, the reference-quality effect cannot be ignored given quality differences in remanufactured products. Sun and Xu^[40] study pricing decisions in closed-loop supply chains, propose four trade-in-for-reman models, and reveal how firm power, collection channel, and product durability affect profit and market share. Gao and Ding^[41] segment consumers and develop five demand structures and five decision models, concluding that the manufacturer's optimal strategy depends on market structure. Wan and Zou^[42] examine government influence and find that properly set sales subsidies can effectively promote the end-of-life vehicle-remanufacturing industry. Han et al.^[43] investigate how firms use trade-in-for-reman to develop the remanufactured-product market and identify product remanufacturability and government subsidy as key determinants. A few studies simultaneously consider both trade-in-for-new and trade-in-for-reman^[1, 44, 45], but they do not differentiate core sources. Therefore, this paper incorporates both policies and further classifies returned cores into originally sold new products and previously remanufactured products.

2.4 Literature Summary

Extant studies have thoroughly addressed trade-in-for-new, and research on trade-in-for-reman is gradually increasing. However, the foregoing review reveals that further investigation is needed in the following areas.

- (1) Most existing work concentrates on either trade-in-for-new or trade-in-for-reman alone; studies examining both strategies simultaneously are scarce, indicating an insufficient characterization of consumers' complex purchase behavior under combined incentives. Therefore, this paper incorporates the remanufactured-product perceived-value discount and collection-price differentials into the consumer utility function to explore how the two sales incentives jointly influence purchase behavior.
- (2) In used-product collection, few studies classify cores by source. Different core types affect operational management, and although some scholars have considered quality and value, they have not distinguished whether cores originated from new or previously remanufactured products. Hence, this paper examines how the proportion of different core sources influences manufacturers' sales and collection pricing when implementing trade-in-for-new and trade-in-for-reman policies.
- (3) Single-period pricing strategies are well developed, yet multi-period pricing of new and remanufactured products remains under-explored. Accordingly, this paper investigates two-period trade-in-for-new and trade-in-for-reman pricing strategies based on consumers' inherently multi-period dynamic purchase behavior, thereby extending the literature on collection pricing.

3. Problem Description and Basic Assumptions

We consider a manufacturer who possesses both manufacturing and remanufacturing capabilities, produces new and remanufactured products, and offers consumers who already own its products either a trade-in-for-new or a trade-in-for-reman service. New and remanufactured products are indexed by subscripts n and r , respectively. The unit production cost of a new product is c_n , and that of a remanufactured product is c_r . Because remanufacturing saves raw-material input relative to

new production^[46, 47], we have $c_r < c_n$. Consequently, $c_n - c_r$ captures the cost advantage of remanufacturing^[48, 49]. To simplify computations without loss of generality, we set $c_r = 0$ ^[50, 51]. The circular values of new and remanufactured products are denoted by s_n and s_r , respectively, with $c_n > s_n > s_r > 0$ ^[32, 52]. The unit selling prices of new and remanufactured products are p_r and p_n , and the unit buy-back prices are r_r and r_n , satisfying $\phi r_n = r_r$. To ease calculations, let $\phi \in (0, 1)$ denote the buy-back price discount the manufacturer offers consumers for remanufactured products relative to new ones; a larger ϕ implies a higher remanufactured-product buy-back price. In line with reality, unit buy-back prices never exceed unit selling prices, $r_n \leq p_r < p_n$. To guarantee a positive selling price for remanufactured products, we assume $0 < s_r < \min \left\{ s_n, \alpha \frac{1 + (1 - \beta)(1 - \phi)}{(1 - \beta)(1 - \phi)} \right\}$. Both new and remanufactured products last two periods;

within one period, each consumer buys at most one product. Consumers' willingness-to-pay for a new product is v , uniformly distributed on $[0, 1]$ ^[53-55]; their willingness-to-pay for a remanufactured product is αv , where $\alpha \in (0, 1)$ is the perceived-value discount factor representing the value gap consumers perceive. Empirical studies show that this gap stems mainly from consumers' loss-aversion toward remanufactured products.

Based on the above, we construct a two-period consumer-utility model. In period 1, each consumer chooses to buy either a new or a remanufactured product. Total period-1 demand is normalized to 1^[51, 56]; letting β denote the fraction of consumers who buy new, the fraction buying remanufactured is $1 - \beta$. In period 2, consumers who bought new in period 1 face three options: (i) trade in the period-1 new product for another new one (labelled S_n^n), (ii) trade it in for a remanufactured one (labelled S_n^r), or (iii) continue using it. Likewise, consumers who bought remanufactured in period 1 choose among: (i) trade in the period-1 remanufactured product for a new one (labelled S_r^n), (ii) trade it in for another remanufactured one (labelled S_r^r), or (iii) keep using it. In notation S_i^j , i stands for the period-1 purchase choice, j for the period-2 purchase choice, and $\{i, j\} \in \{n, r\}$. Consumers keep the used unit only if the utilities of both trade-in-for-new and trade-in-for-reman are negative.

Accordingly, period-1 demands for new and remanufactured products are $D_n = \beta$ and $D_r = 1 - \beta$, respectively. If a consumer bought new in period 1, the period-2 utility functions for buying new, buying remanufactured, and continuing to use are $v - p_n + r_n$, $\alpha v - p_r + r_n$ and 0. If the consumer bought remanufactured in period 1, the corresponding utilities are $v - p_n + \phi r_n$, $\alpha v - p_r + \phi r_n$ and 0. The period-2 demand function for new products under consumer behavior S_n^n is then derived as:

$$D_n^n = \beta \int_{\frac{p_n - p_r}{1 - \alpha}}^1 dv = \beta \left(1 - \frac{p_n - p_r}{1 - \alpha} \right) \quad (1)$$

The period-2 demand function for remanufactured products under consumer behavior S_n^r is:

$$D_n^r = \beta \int_{\frac{p_r - r_n}{\alpha}}^{\frac{p_n - p_r}{1 - \alpha}} dv = \beta \left(\frac{p_n - p_r}{1 - \alpha} - \frac{p_r - r_n}{\alpha} \right) \quad (2)$$

The period-2 demand function for new products under consumer behavior S_r^n is:

$$D_r^n = (1 - \beta) \int_{\frac{p_n - p_r}{1 - \alpha}}^1 dv = (1 - \beta) \left(1 - \frac{p_n - p_r}{1 - \alpha} \right) \quad (3)$$

The period-2 demand function for remanufactured products under consumer behavior S_r^r is:

$$D_r^r = (1 - \beta) \int_{\frac{p_r - \phi r_n}{\alpha}}^{\frac{p_n - p_r}{1 - \alpha}} dv = (1 - \beta) \left(\frac{p_n - p_r}{1 - \alpha} - \frac{p_r - \phi r_n}{\alpha} \right) \quad (4)$$

Based on consumers' complex purchasing behavior, this paper takes the unit selling price of new products, the unit selling price of remanufactured products, and the unit buy-back price of new products as decision variables, aims at maximizing the total profit over two periods, and investigates sales and collection pricing strategies for new and remanufactured products.

The sequence of the game is shown in Figure 1. Table 1 summarizes the main parameters and symbols.

Figure 1 Sequence of the Two-period Game

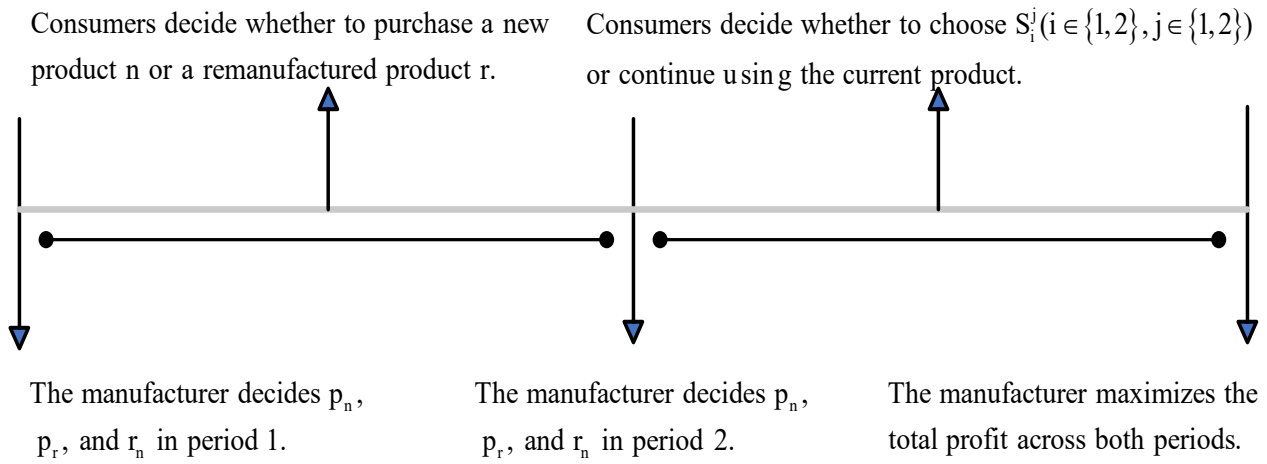


Table 1 Glossary of Symbols

Symbol	Definition
ϕ	Discount ratio of remanufactured product collection price
β	Proportion of consumers who purchased new products in period 1
s_n, s_r	Circular value of new/remanufactured products
p_n, p_r	Unit selling price of new/remanufactured products
c_n	Unit production cost of new products
α	Perceived value discount ratio of remanufactured products
r_n	Unit collection price of new products
D_i	Demand for product i in period 1, $i \in \{n, r\}$
S_i^j	Consumers holding product i from period 1 trade in for product j in period 2, $i \in \{n, r\}, j \in \{n, r\}$
D_i^j	Demand function for product j under consumer behavior S_i^j in period 2, $i \in \{n, r\}, j \in \{n, r\}$

4. Model Construction and Solution Analysis

This section formulates a two-period game-theoretic pricing model for the manufacturer under the trade-in-for-new / trade-in-for-reman policy. The manufacturer maximizes total profit over both periods, taking the unit selling prices and unit buy-back prices as decision variables. The optimal unit selling prices of new and remanufactured products and the optimal unit buy-back price of new products under various scenarios are derived by applying the Karush–Kuhn–Tucker (KKT) conditions.

The manufacturer's first-period profit function is expressed as:

$$\max_{\{p_n, p_r, r_n\}} \pi_1 = (p_n - c_n) D_n + p_r D_r \quad (5)$$

The manufacturer's second-period profit function can be expressed as:

$$\begin{aligned} \max_{\{p_n, p_r, r_n\}} \pi_2 = & (p_n - c_n - r_n + s_n) D_n^n + (p_r - r_n + s_n) D_n^r \\ & + (p_n - c_n - \phi r_n + s_r) D_r^n + (p_r - \phi r_n + s_r) D_r^r \end{aligned} \quad (6)$$

Therefore, the manufacturer's total profit over the two periods is:

$$\max_{\{p_n, p_r, r_n\}} \pi = (p_n - c_n)D_n + p_r D_r + (p_n - c_n - r_n + s_n)D_n^n + (p_r - r_n + s_n)D_n^r \quad (7)$$

$$+ (p_n - c_n - \phi r_n + s_r)D_r^n + (p_r - \phi r_n + s_r)D_r^r$$

$$s.t. 0 < r_n \leq p_r < p_n \quad (8)$$

In Equation (7), the first, second, third and fourth terms represent the profits that the manufacturer earns under consumer behaviors S_n^n , S_n^r , S_r^n and S_r^r , respectively. Constraint (8) ensures that the remanufactured product's selling price is lower than the new product's selling price and that the buy-back price does not exceed the selling price. Applying the Lagrangian multiplier method based on the KKT conditions yields Proposition 1.

Proposition 1 Under the trade-in-for-new/reman strategy, the manufacturer has two distinct optimal policy options: the high remanufactured-product pricing strategy A and the low remanufactured-product pricing strategy B , as shown in Table 2. The corresponding optimal sales and buy-back prices and the manufacturer's profits under strategies A and B are given in Table 3.

Table 2 Manufacturer's Optimal Strategy Choices under the Trade-in-for-New/Reman Policy

Range			Strategy
$0 < \beta \leq \beta_L$			low pricing strategy B
$\beta_L < \beta < 1$	$0 < \phi < \frac{1}{2}$	$s_r < s_n \leq \alpha(1 - \frac{\beta_L}{\beta})$	high pricing strategy A
		$\alpha(1 - \frac{\beta_L}{\beta}) < s_n < c_n$	low pricing strategy B
	$\frac{1}{2} \leq \phi < 1$		low pricing strategy B

Table 3 Manufacturer's Optimal Solutions under Different Strategies

Optimal solution	high pricing strategy	low pricing strategy
p_n	$G + \frac{(1+\beta)(\alpha + (1-\alpha)\beta) - \beta(s_n - c_n)}{2\beta}$	$M + \frac{1}{2}((1+\beta)(1-\alpha) + c_n)$
p_r	$G + \frac{\alpha(1+\beta) - \beta s_n}{2\beta}$	M
r_n	$G + \frac{\alpha}{2\beta(1-\phi)}$	M
D_n^n	$\frac{\beta((1-\beta)(1-\alpha) - c_n)}{2(1-\alpha)}$	$\frac{\beta((1-\beta)(1-\alpha) - c_n)}{2(1-\alpha)}$
D_n^r	$\frac{1}{2}\beta\left(\beta + \frac{c_n}{1-\alpha} + \frac{\phi}{\beta(1-\phi)} + \frac{s_n}{\alpha}\right)$	$\frac{1}{2}\beta\left(1 + \beta + \frac{c_n}{1-\alpha}\right)$
D_r^n	$\frac{1}{2}(1-\beta)\left(1 - \beta - \frac{c_n}{1-\alpha}\right)$	$\frac{1}{2}(1-\beta)\left(1 - \beta - \frac{c_n}{1-\alpha}\right)$
D_r^r	$\frac{1}{2}\left((1-\beta)\left(\beta + \frac{c_n}{1-\alpha} + \frac{s_r}{\alpha}\right) - \frac{1}{1-\phi}\right)$	$\frac{1}{2}\left((1-\beta)\left(\beta + \frac{c_n}{1-\alpha} + \frac{s_r}{\alpha}\right) - \frac{1}{1-\phi}\right)$
π	$\frac{1}{4}\left(N + \alpha\left(2 - \beta(2+\beta) + \frac{\beta + (1-\beta)\phi^2}{(1-\beta)\beta(1-\phi)^2}\right) + \frac{2\phi s_n}{1-\phi} + \frac{\beta s_n^2}{\alpha}\right)$	$\frac{1}{4}\left(N + \frac{\alpha(3 - 2(\beta(1-\phi) + \phi))}{(1-\beta)(1-\phi)^2} - \alpha\beta(3 + \beta) + 2\beta s_n\right)$

In Table 3, $N = (1 + \beta)(1 + \beta - 2c_n) + \frac{c_n^2}{1 - \alpha} + 2\beta s_n - \frac{2(\beta + \phi(1 - \beta))s_r}{1 - \phi} + \frac{(1 - \beta)s_r^2}{\alpha}$, $M = \frac{\alpha}{2(1 - \beta)(1 - \phi)^2} + \frac{\alpha - s_r}{2(1 - \phi)}$,

$$\beta_L = \frac{\phi}{1 - \phi}, \quad G = \frac{\alpha}{2(1 - \beta)\beta(1 - \phi)^2} - \frac{2\alpha - \beta(s_n - s_r)}{2\beta(1 - \phi)}.$$

The proof is provided in Appendix A.

High remanufactured-product pricing strategy A refers to the case where the remanufactured product's selling price is higher than the new-product buy-back price; low remanufactured-product pricing strategy B means the remanufactured product's selling price equals the new-product buy-back price and is higher than the remanufactured-product buy-back price. Notably, under the low pricing strategy every consumer who bought new in period 1 participates in trade-in-for-new/reman in period 2. Proposition 1 shows that the manufacturer's choice between the two strategies depends on the proportion of consumers who bought new products in period 1 β , the remanufactured-product buy-back price discount ϕ , and the circular value of new products r_n .

When the proportion of consumers who bought new products in period 1 is small, i.e., $0 < \beta \leq \beta_L$, the manufacturer adopts the low remanufactured-product pricing strategy B . At this time market acceptance of remanufactured products is relatively high. By pushing the remanufactured selling price down to the new-product buy-back price, the manufacturer on the one hand attracts more consumers to remanufactured products and enlarges period-2 demand ($(D_n^r + D_r^r)|_{p_r^B > r_n^B} < (D_n^r + D_r^r)|_{p_r^B = r_n^B}$), and on the other hand effectively converts the remanufactured option into a “free upgrade” that eliminates the possibility of keeping the original unit: the utility of continuing to use the period-1 new product is lower than the net surplus of trading it in for reman, so every unit is returned ($D_n^r + D_n^r = \beta$). This maximizes the collection rate and guarantees sales opportunities for remanufactured products in period 2, creating a profit model that compensates low margin with high volume.

When the proportion of consumers who bought new products in period 1 is large and the remanufactured buy-back discount is also large, i.e., $\beta_L < \beta < 1$ and $0 < \phi < \frac{1}{2}$, the optimal strategy hinges on the circular value of new products s_n . If the

circular value is low ($s_r < s_n \leq \alpha(1 - \frac{\beta_L}{\beta})$), the manufacturer chooses the high remanufactured-product pricing strategy

A ; if the circular value is high ($s_n > \alpha(1 - \frac{\beta_L}{\beta})$), the low pricing strategy B is preferred. When new products dominate

period-1 market share and the remanufactured buy-back price is far below the new buy-back price, the firm must balance the high margin of new products with the cost-saving potential of remanufacturing. A low circular value encourages the manufacturer to maintain a high remanufactured selling price to protect profit, while offering a high new-product buy-back price to stimulate trade-in-for-new. Conversely, a high circular value makes it attractive to lower the remanufactured price to induce trade-in-for-reman, exploit the low-cost remanufacturing opportunity, expand the remanufactured market, and ultimately increase profit.

When the proportion of consumers who bought new products in period 1 is large but the remanufactured buy-back discount is small, i.e., $\beta_L < \beta < 1$ and $\frac{1}{2} \leq \phi < 1$, the manufacturer again adopts the low remanufactured-product pricing strategy B .

With a sufficiently high share of new-product buyers, the manufacturer uses the low reman price to steer these consumers toward trade-in-for-reman instead of trade-in-for-new, preventing new products from cannibalizing the reman market and enlarging remanufactured demand. Simultaneously, a low discount (or high buy-back price) ensures that all period-1 new-product buyers return their units, forcing every used product into the collection system, securing ample remanufacturing cores, and lowering collection costs through economies of scale.

Thus, the manufacturer's pricing strategy always revolves around consumers' trade-in behavior and the circular value of used products: low-price strategies drive market penetration and collection, whereas high-price strategies balance cost and margin; the level of circular value and collection cost determines whether remanufactured products can achieve sustainable

profitability through scale effects.

5.Sensitivity Analysis under Different Pricing Strategies

This section examines how changes in key parameters affect the manufacturer's optimal pricing decisions and profit under the two remanufactured-product pricing strategies.

Proposition 2 reports the sensitivity of the optimal sales prices of new and remanufactured products and the optimal buy-back price of new products to parameter changes under the low and high remanufactured-product pricing strategies; the results are summarized in Table 4, where the symbols $+$, $-$, 0 and indicate an increase, a decrease, and no change, respectively, in the optimal prices.

Table 4 Sensitivity Analysis of Optimal Unit Sales Prices of New and Remanufactured Products under Different Strategies

Parameter	Strategy A			Strategy B	
	p_n^A	p_r^A	r_n^A	p_n^B	$p_r^B (r_n^B)$
ϕ	+	+	+	+	+
α	+	+	+	+	+
s_n	+	+	+	0	0
s_r	-	-	-	-	-
β	+	+	$\pm^*$	+	+
c_n	+	0	0	+	0

Note: $\pm^*$: If $\beta < \frac{\sqrt{\phi}}{1+\sqrt{\phi}}$, then $-$, else $+$.

Proof is provided in Appendix B.

Under the high remanufactured-product pricing strategy A, the selling prices p_n^A and buy-back price r_n^A of new products and the selling prices of remanufactured products p_r^A all increase with the remanufactured-product buy-back discount ratio ϕ , the remanufactured-product perceived-value discount ratio α , and the circular value of new products s_n , but decrease with the circular value of remanufactured products s_r . A higher remanufactured-product buy-back discount ratio and a higher perceived-value discount ratio imply higher collection costs and higher market acceptance of remanufactured products, which push up both the selling and buy-back prices of remanufactured products. A higher remanufactured-product buy-back price also raises the buy-back price of new products and, in turn, the selling price of new products. A higher circular value of new products increases the selling and buy-back prices of new products, which then lifts the buy-back price of remanufactured products and ultimately the selling price of remanufactured products. Notably, when the circular value of remanufactured products increases, the manufacturer earns more from remanufactured-product collection, but because consumers are loss-averse toward remanufactured products, the manufacturer lowers the unit selling price of remanufactured products to stimulate sales and simultaneously reduces the buy-back price to ease upfront cost pressure. This also lowers the buy-back price of new products, and to protect the market share of new products, the unit selling price of new products is reduced as well.

The selling price of new products p_n^A increases with the proportion of consumers c_n who bought new products in the first period β , indicating that stronger demand for new products encourages the manufacturer to charge a higher price, which also drives up the selling price of remanufactured products p_r^A . The buy-back price of new products r_n^A first decreases and then increases with the proportion of first-period new-product buyers. When this proportion is small (i.e., $\beta < \frac{\sqrt{\phi}}{1+\sqrt{\phi}}$), the incremental demand for new products gives the manufacturer more options in collection, so the buy-back price of new products falls. When the proportion is large (i.e., $\beta > \frac{\sqrt{\phi}}{1+\sqrt{\phi}}$), demand for remanufactured products is relatively low, so

the manufacturer raises the unit buy-back price of remanufactured products to incentivize consumers to choose remanufactured products, which in turn increases the buy-back price of new products. In addition, a higher unit production cost of new products c_n raises their selling price p_n^A , consistent with intuition. However, the unit selling price of remanufactured products p_r^A and the buy-back price of new products r_n^A are independent of the production cost of new products c_n , meaning that changes in this cost do not affect the manufacturer's pricing decisions for remanufactured-product selling or buy-back prices.

Under the low remanufactured-product pricing strategy B , the monotonicity of p_n^B and p_r^B with respect to ϕ , β , s_n , and α is the same as in strategy A . Because the unit selling price of remanufactured products p_r^B equals the unit buy-back price of new products r_n^B in this strategy, their sensitivity results are identical. Unlike the high-pricing strategy, the unit selling prices of both new and remanufactured products are independent of circular values s_n . This is because the buy-back price of new products has already reached its maximum; the manufacturer cannot earn additional trade-in surplus from consumers' a behavior, so changes in the circular value of new products have no impact on the unit selling prices of either new or remanufactured products.

Proposition 3 The sensitivity of the manufacturer's optimal profit to ϕ , β , s_n and c_n under the low and high remanufactured-product pricing strategies is reported in Table 5, where symbols $+$ and $-$ indicate an increase and a decrease in optimal profit, respectively.

Table 5 Sensitivity Analysis of Manufacturer's Total Profit under Different Strategies

Parameter	π^A	π^B
ϕ	+	+
β	$\pm^{**}$	$\pm^{***}$
s_n	+	+
c_n	$\pm^{****}$	$\pm^{****}$
$\pm^{**}$: If $c_n < c_{n1}$, then $+$, else $-$. $\pm^{***}$: If $c_n < c_{n2}$, then $+$, else $-$. $\pm^{****}$: If $c_n < c_{n3}$, then $-$, else $+$.		

In table 5, $c_{n1} = \frac{\alpha(2\beta-1)}{2(1-\beta)^2\beta^2(1-\phi)^2} + \frac{\alpha}{\beta^2(1-\phi)} - \frac{\alpha}{2\beta^2} + (1+\beta)(1-\alpha) + \frac{(s_n-s_r)(2\alpha+s_n+s_r)}{2\alpha}$, $c_{n3} = (1+\beta)(1-\alpha)$,

$$c_{n2} = \frac{\alpha}{2(1-\beta)^2(1-\phi)^2} + \frac{\alpha(2-3\alpha+2(1-\alpha)\beta+4s_n)-2\alpha s_r-s_r^2}{2\alpha}.$$

Proof is provided in Appendix C.

Proposition 3 shows that, in every scenario, an increase in the remanufactured-product buy-back discount ratio ϕ or in the circular value of new products s_n —by pushing up the selling and buy-back prices of both new and remanufactured products—improves the manufacturer's total profit. The unit production cost of new products c_n can also be viewed as an inverse indicator of the remanufacturing cost advantage. When this cost is low (i.e., the remanufacturing advantage is weak), profit is generated mainly from new products, so total profit rises with the proportion of consumers who bought new products in period 1 c_n ; conversely, when the cost is high (i.e., the remanufacturing advantage is strong), profit comes mainly from remanufactured products, and total profit falls as the proportion of period-1 new-product buyers β increases. The difference between strategy A and strategy B in the monotonicity of profit with respect to β lies only in the location of the critical threshold. Under either strategy, changes in the new-product production cost c_n affect only the unit selling price of new products, so total profit first decreases and then increases with this cost at the same threshold value. Because the monotonicity of profit with respect to the circular value of remanufactured products s_r and the perceived-value discount ratio α is too complex for analytical presentation, it is examined numerically in Section 5.

6. Numerical Verification and Analysis

This section uses extensive numerical examples to simulate the optimal sales-and-collection pricing outcomes and the sensitivity analyses under the two strategies. First, it supplements the sensitivity of the manufacturer's total profit with respect to the remanufactured-product circular value s_r and the consumer perceived-value discount ratio α . Second, it verifies the correctness of the sensitivity results stated in Propositions 2–4. Following related studies^[52, 57, 58], we set the unit production cost of new products $c_n = 0.3$, the remanufactured-product perceived-value discount ratio $\alpha = 0.6$, and the circular value of new products $s_n = 0.2$. The remaining parameters are fixed at $\beta = 0.8$ and $s_r = 0.1$. Because manufacturers must choose the optimal sales-and-collection pricing strategy according to different market conditions, we construct two scenarios that fit strategy and strategy : in the scenario for strategy A , ϕ is 0.3, whereas in the scenario for strategy B , ϕ is 0.6.

6.1 Impact of remanufactured-product circular value and perceived value discount ratio on total profit

Figures 2 and 3 show that, under either strategy A or strategy B , the manufacturer's total profit always decreases as the remanufactured-product circular value s_r rises and increases with the remanufactured-product perceived-value discount ratio α . Together with Proposition 4—total profit increases with the circular value of new products—this indicates that changes in the circular values of remanufactured and new products move total profit in opposite directions. A higher remanufactured-product circular value may erode the new-product market and reduce new-product sales, thereby lowering profit. In addition, greater consumer acceptance of remanufactured products is beneficial for profit growth, so manufacturers should actively promote the advantages of remanufactured products.

Figure 2 Impact of s_r on Manufacturer's Total Profit under Different Strategies

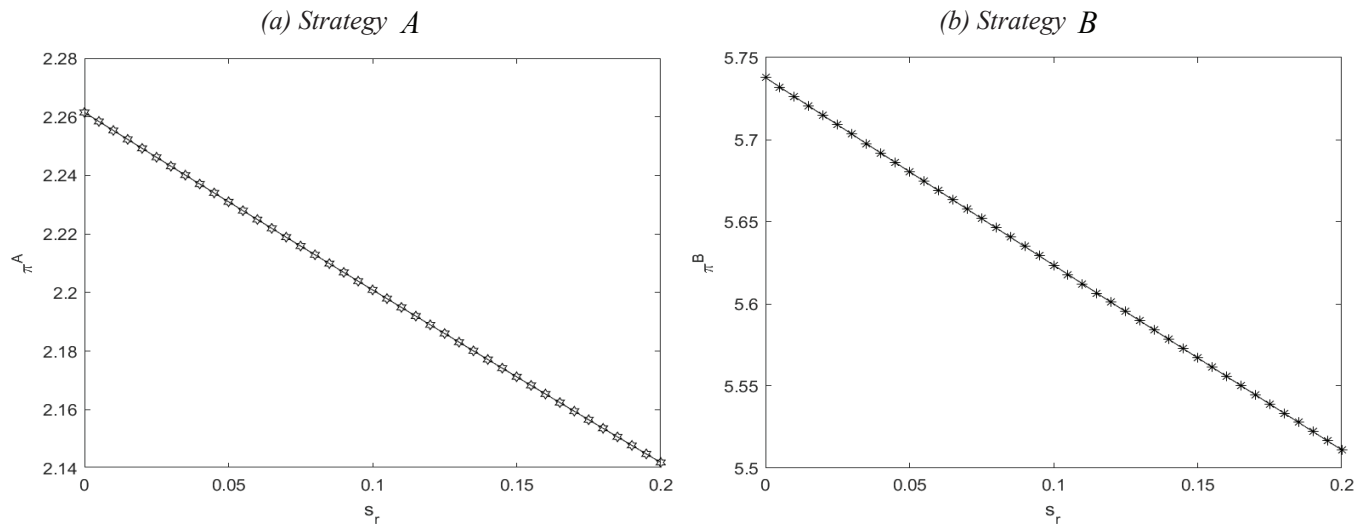
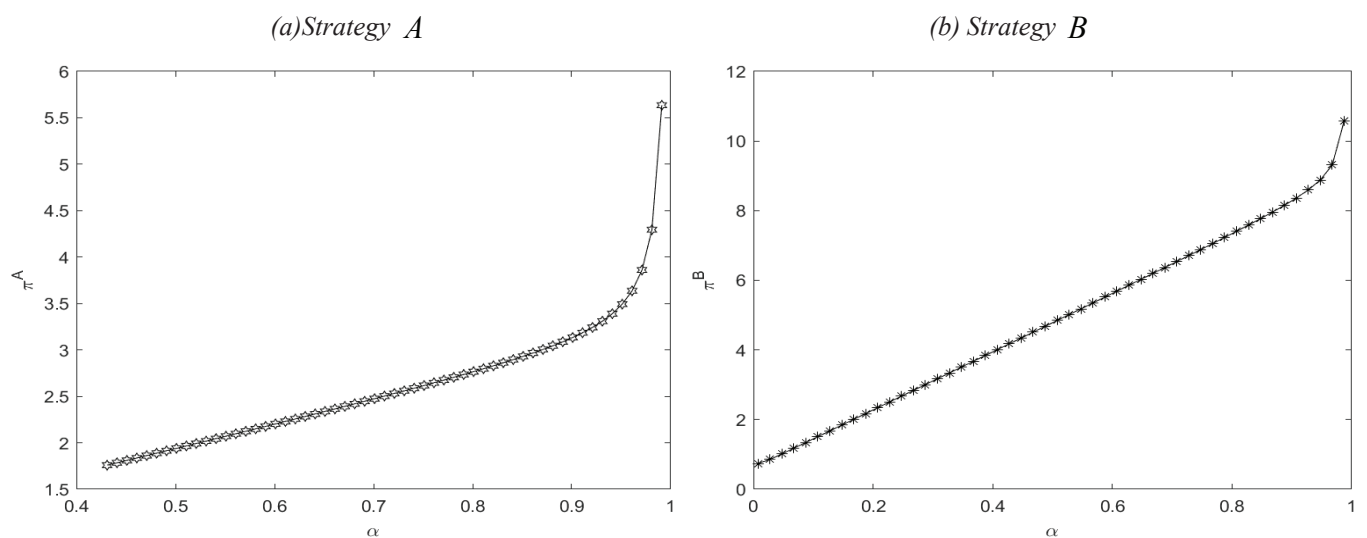


Figure 3 Impact of α on Manufacturer's Total Profit under Different Strategies



6.2 Numerical verification of the sensitivity results in each proposition

We first verify the sales- and collection-pricing sensitivities stated in Propositions 2 and 3. Figures 4–13 show that the simulation outcomes are consistent with the analytical results and always satisfy $0 < r_n \leq p_r \leq p_n$. To demonstrate the two theoretical cases, in Figure 5(a) we set $\phi = 0.009$, when $\beta < 0.087$, r_n^A decreases with β , whereas when $\beta > 0.087$, r_n^A increases with β . In Figure 11(a) we set $c_n = 6$, when $\beta < 0.661$, π^A decreases with β , whereas when $\beta > 0.661$, π^A increases with β . The same parameter is used in Figure 11(b), when $\beta < 0.413$, π^B decreases with β , whereas when $\beta > 0.413$, π^B increases with β . In Figure 13, when $c_n < 0.72$, both π^A and π^B decrease with c_n , and when $c_n > 0.72$, both π^A and π^B still decrease with c_n .

Figure 4 Impact of ϕ on Manufacturer's Sales and Collection Pricing under Different Strategies

(a) Strategy A

(b) Strategy B

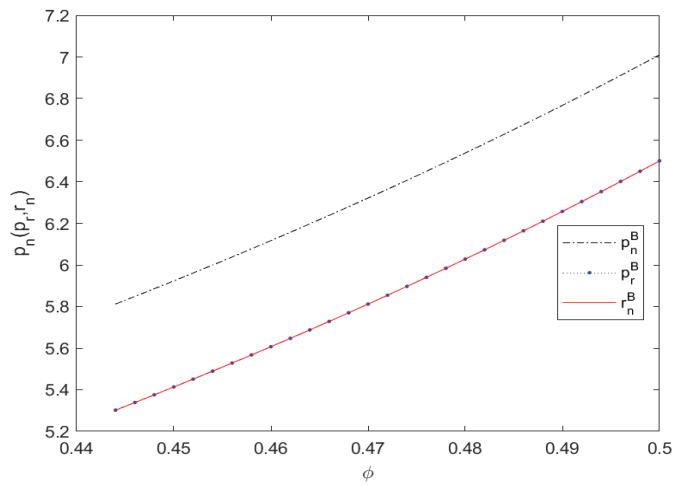
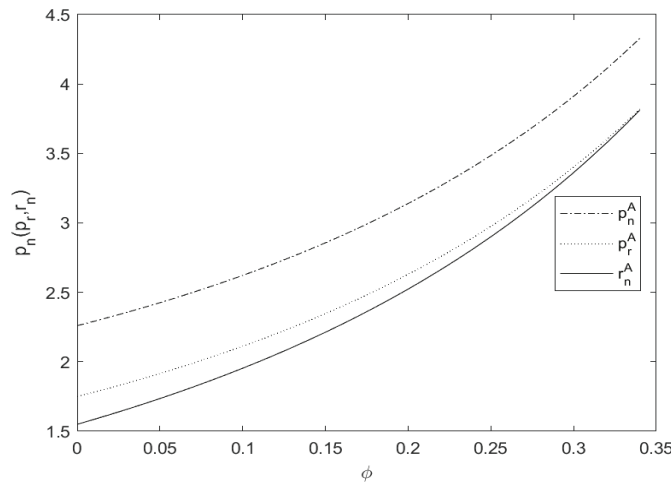


Figure 5 Impact of β on Manufacturer's Sales and Collection Pricing under Different Strategies

(a) Strategy A

(b) Strategy B

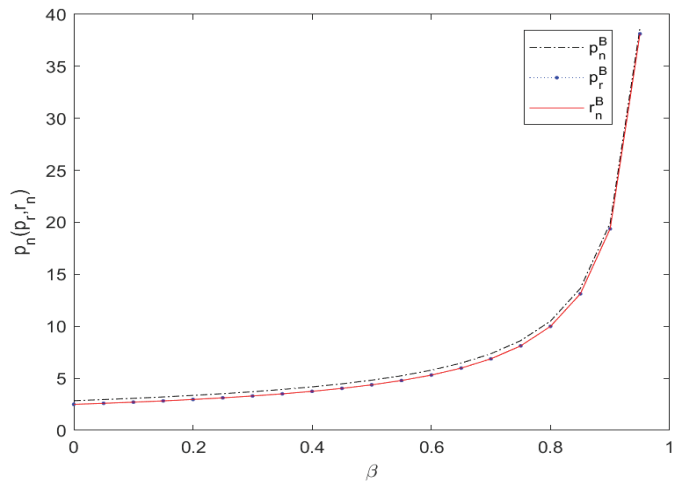
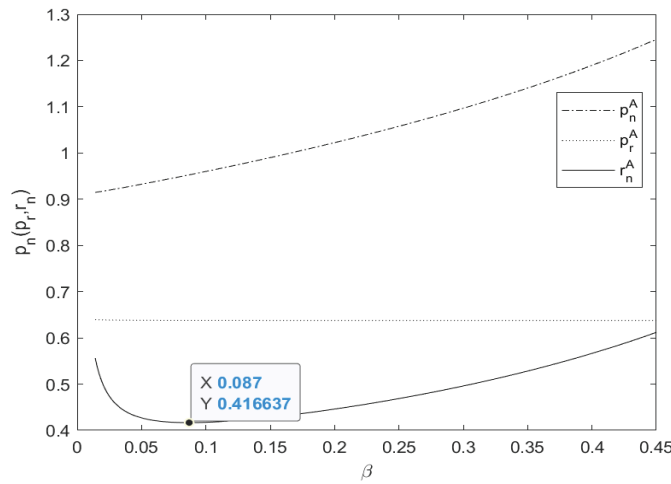


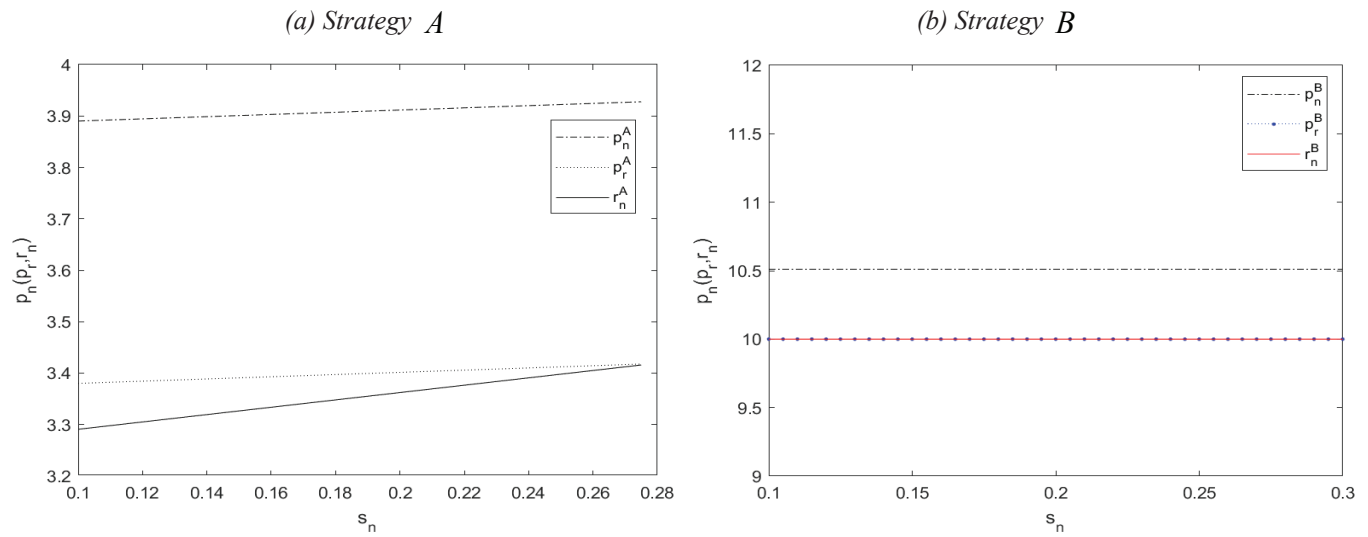
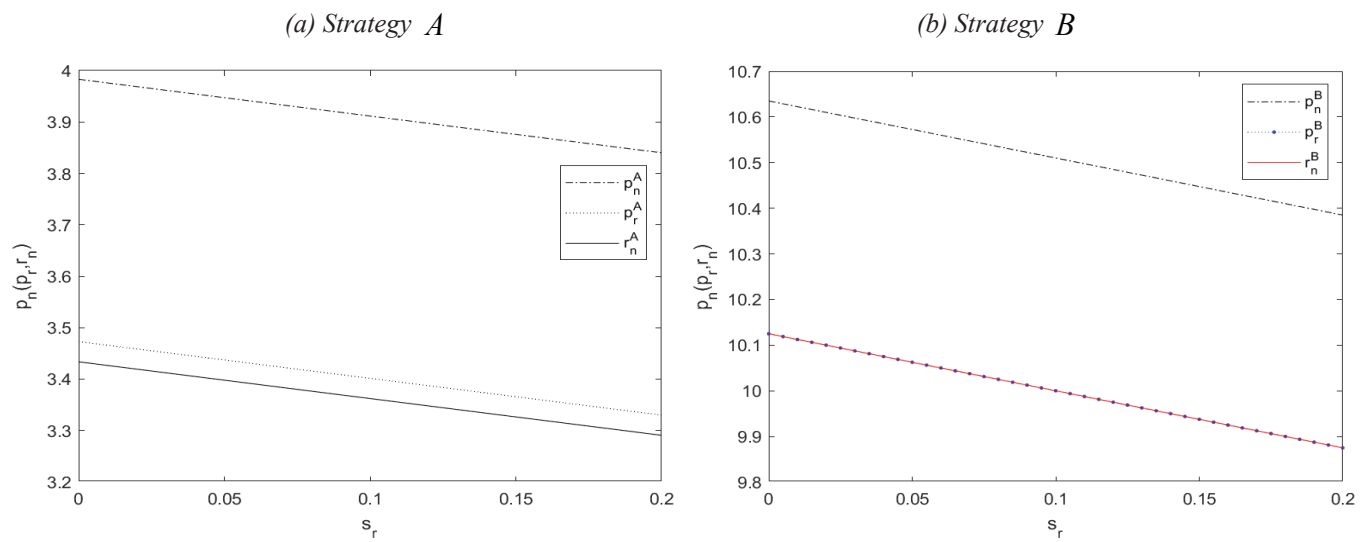
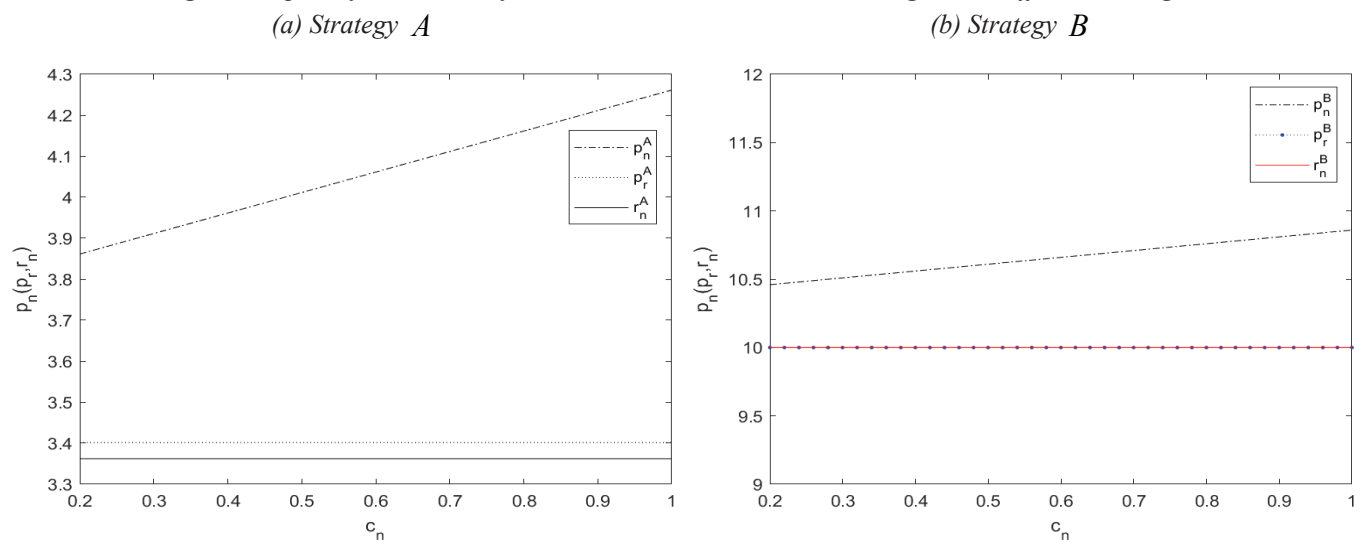
Figure 6 Impact of S_n on Manufacturer's Sales and Collection Pricing under Different StrategiesFigure 7 Impact of S_r on Manufacturer's Sales and Collection Pricing under Different StrategiesFigure 8 Impact of C_n on Manufacturer's Sales and Collection Pricing under Different Strategies

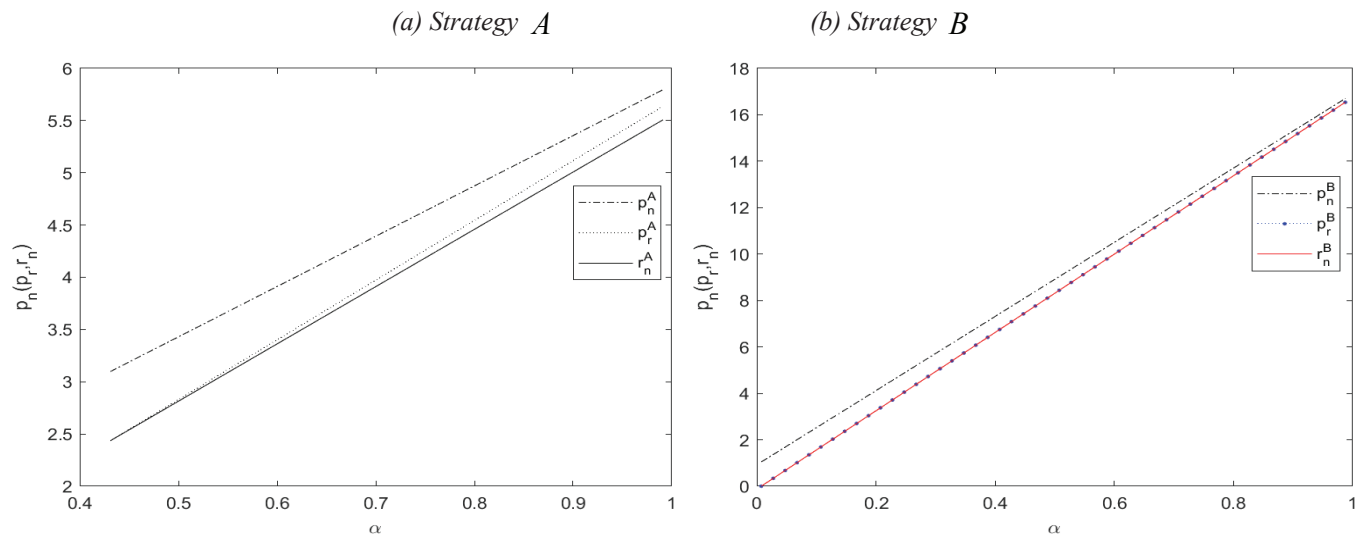
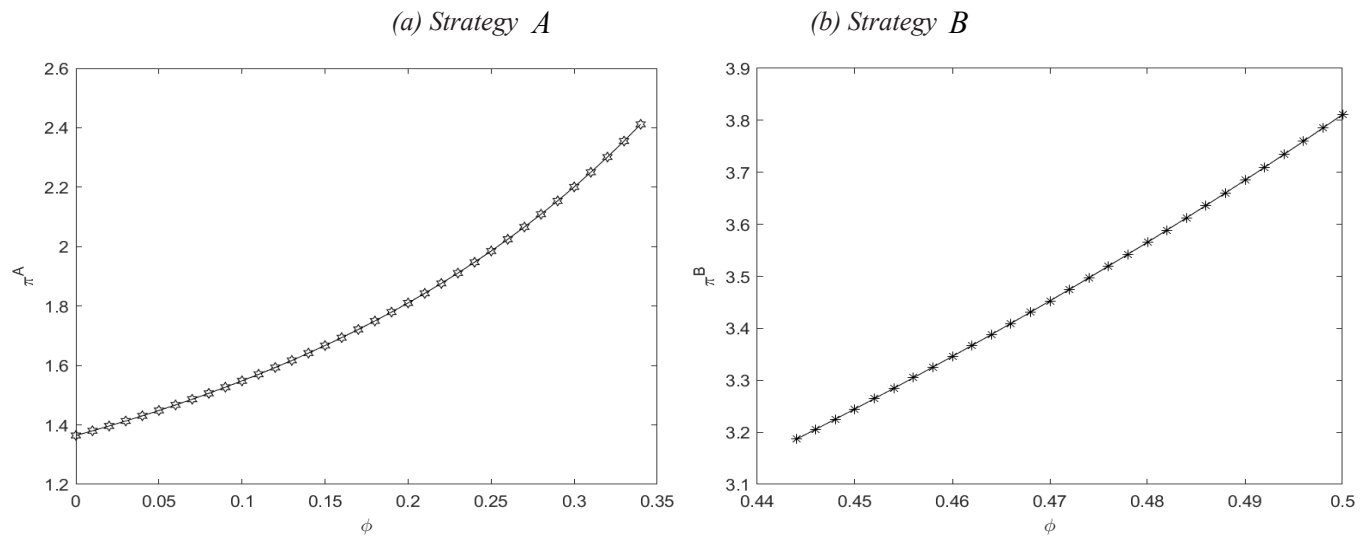
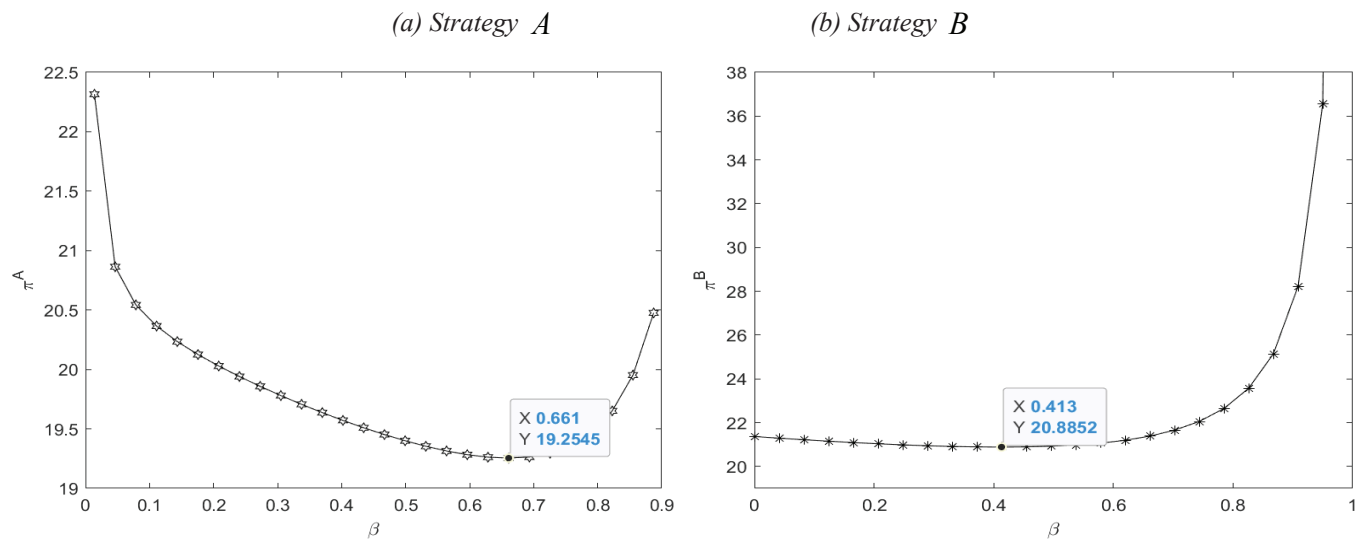
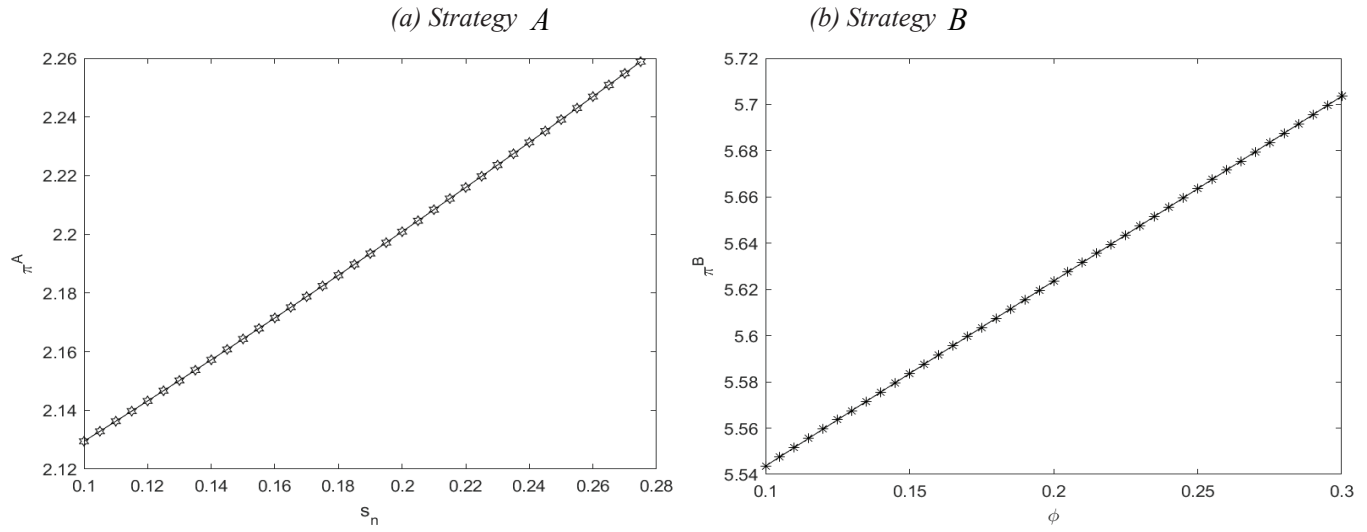
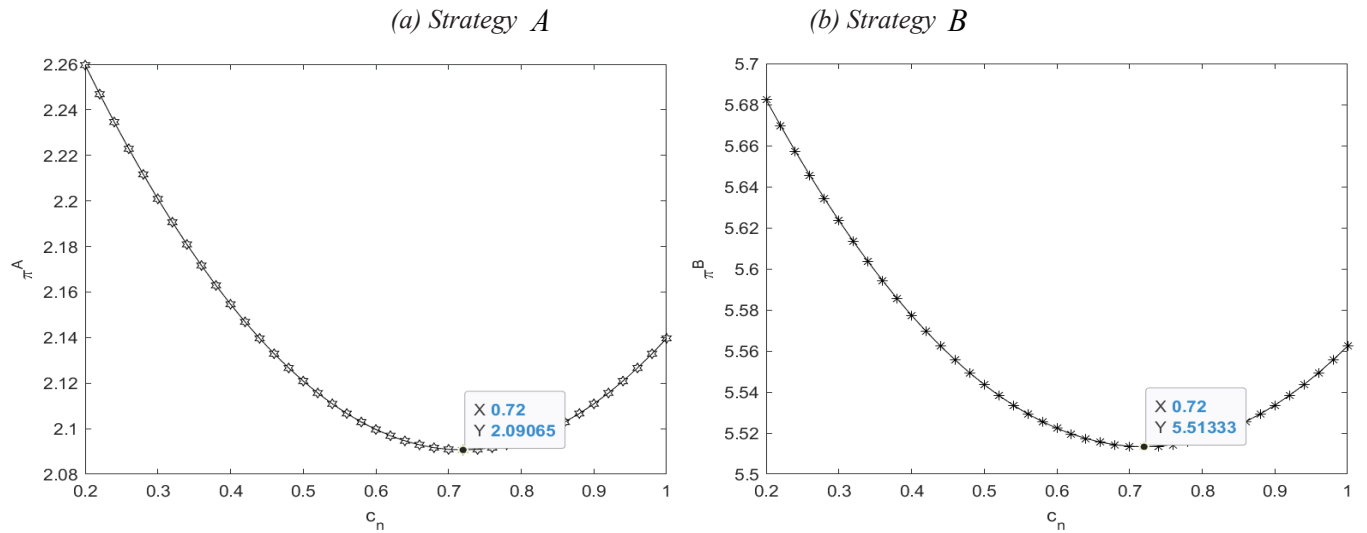
Figure 9 Impact of α on Manufacturer's Sales and Collection Pricing under Different StrategiesFigure 10 Impact of ϕ on Manufacturer's Sales and Collection Pricing under Different StrategiesFigure 11 Impact of β on Manufacturer's Total Profit under Different Strategies

Figure 12 Impact of S_n on Manufacturer's Total Profit under Different StrategiesFigure 13 Impact of C_n on Manufacturer's Total Profit under Different Strategies

6. Conclusions

This paper divides the market in the first period into new and remanufactured products, determines their demand shares, and then, in the second period, segments consumers holding different used units according to their trade-in choices. Utility-maximizing consumers yield demand functions for every scenario, and a two-period game-theoretic pricing model is built from the perspective of manufacturer profit maximization. The optimal sales prices for new and remanufactured products and the optimal buy-back price for new products are derived. The impacts of the proportion of consumers who bought new products in the first period, the remanufactured-product buy-back discount ratio, the unit production cost of new products, the remanufactured-product perceived-value discount ratio, and product circular values on sales and collection prices are examined, and the trends of total profit with respect to these key parameters are explored. The results show that: (1) When choosing the optimal pricing strategy, the manufacturer should jointly consider new-product demand, the remanufactured-product buy-back discount ratio, and the circular value of new products. In particular, when the proportion of consumers who bought new products in the first period is small ($0 < \beta \leq \beta_L$), or the circular value of new products is high ($(\alpha(1 - \frac{\beta_L}{\beta}) < s_n < c_n)$), or the remanufactured-product buy-back discount is large ($\frac{1}{2} \leq \phi < 1$), the manufacturer should set the unit buy-back price paid to consumers for returning used new products equal to the sales price of remanufactured products to maximize profit. (2) In every scenario, the unit sales prices of new and remanufactured products and the unit buy-back price of new products increase with the remanufactured-product buy-back discount ratio and the remanufactured-

product perceived-value discount ratio, but decrease with the circular value of remanufactured products. (3) An increase in the proportion of consumers who bought new products in the first period raises the sales prices of both new and remanufactured products; its effect on buy-back prices depends on the manufacturer's pricing strategy. Under the high-pricing strategy, the buy-back price first decreases and then increases with this proportion; otherwise, it increases continuously. (4) An increase in the production cost of new products only raises their sales price. The impact of the circular value of new products on sales and buy-back prices is market-dependent: if the proportion of consumers who bought new products in the first period is large, the remanufactured-product buy-back discount is small, and the circular value of new products is low, then an increase in this circular value raises all prices; otherwise, it has no effect. (5) Manufacturer profit increases with the remanufactured-product buy-back discount ratio, the circular value of new products, and the remanufactured-product perceived-value discount ratio, but decreases with the circular value of remanufactured products; profit first increases and then decreases with the production cost of new products. An increase in the proportion of consumers who bought new products in the first period raises profit, yet once the production cost of new products exceeds a critical threshold, total profit declines.

Based on these findings, managerial insights are offered. Manufacturers should flexibly adjust pricing strategies by integrating demand, cost, and circular-value considerations for both new and remanufactured products to maximize profit. They should also increase R&D investment in remanufacturing technology to improve remanufacturing efficiency and product quality, thereby enhancing consumer trust in remanufactured products. In addition, manufacturers can optimize collection channels and incentive mechanisms to encourage consumer participation in product returns and improve resource recycling rates. For governments, stronger policy support for the remanufacturing industry is needed, including tax incentives, fiscal subsidies, and R&D funding to lower remanufacturing costs and promote sustainable industrial development. Governments should also improve relevant regulations and standards, strengthen supervision of product quality and the collection market, and protect consumer rights. Meanwhile, public education campaigns can raise awareness and acceptance of remanufactured products, foster green consumption, and advance circular-economy development across the entire supply chain.

This study has limitations. It ignores the existence of a secondary market and assumes zero remanufacturing cost. Future research will incorporate the complex impact of remanufacturing costs and further investigate sales and collection pricing strategies for new and remanufactured products when a secondary market is present.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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