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Research Article

Pricing and Production Decisions for New and Remanufactured Products

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Remanufacturing widely exists in production activities. Two different game models are involved while considering reverse channels: (1) In Model P, the manufacturer provides new and remanufactured products to two retailers. New products are sold through an online platform (retailer R1), while remanufactured products are sold in offline physical stores (retailer R2) in a decentralized scenario. (2) In Model C, the manufacturer provides new and remanufactured units to only one retailer (retailer R) that operates both online and offline channels in a centralized scenario. This research showed that a manufacturer's profitability and industry profits in Model P were higher than those in Model C from the perspective of economic performance; the sum of the profits of both retailers in Model P was worse than the profits of the retailer in Model C. Moreover, Model P was found to be greener than Model C from the perspective of environmental sustainability. From a social viewpoint, Model P had a higher consumer surplus than Model C; the higher the cost of distributing a remanufactured unit, the more disadvantageous the model to the consumers.

1. Introduction

Recently, the environmental burden has increased because of unsustainable spending and a high reliance on natural resources. Metal and glass packaging (totally, 12 million tons of glass bottles and glass jars were recovered) ranked the second and third with a recovery rate of 78.3% and 74.1%, respectively. If not handled properly, this causes environmental pollution, wastes a considerably high amount of materials, and is harmful to our physical health. The reuse of waste paper, waste iron, computers, mobile phones, and LED energy-saving lamps is a common economic phenomenon in production and operations, which is considered an environmentally friendly method of operation. The reduction of resource consumption accelerates the awareness of product reuse rather than a "one-way" economy.

To protect the environment and product recycling, governments encourage people to enjoy an ecological life. For example, Japan attaches considerable importance to environmental protection, resource conservation, and sustained economic development. In 1994, Japan issued the Programme of Action for the 21st Century, which is an effort to harmonize environmental protection with economic development to minimize the reliance on nonrenewable resources and develop renewable energy. Faced with ecological and environmental problems, the United States formulated a series of sustainable development strategies, such as improving environmental management systems, encouraging companies to recycle packaging materials, and labeling recycled materials. Similarly, China undertook a series of measures including vigorously promoting a cyclic economy and improving the cyclic use of major wastes. In particular, in September 2015, the United Nations Development Summit approved and adopted the "2030 Agenda for Sustainable Development," which proposed 17 sustainable development goals (SDGs) covering three major areas, namely, economy, society, and environment. Whether it is environmental protection or energy conservation, it is necessary to further explore.

Remanufacturing has been recognized as a profitable strategy for firms in a reverse supply chain as it can be beneficial for the recycling of waste products and consumes less energy than the original manufacturing process. Furthermore, it can considerably reduce environmental pollution as it generally requires only 15% of the energy used in production [1]. In October 2012, a report titled "Remanufactured Goods: An Overview of the US and Global Industries, Markets, and Trade" was released, which stated that the US remanufacturing industry is concentrated on aerospace, automotive parts, machinery, medical equipment, electrical equipment, and used tires. From 2009 to 2011, this industry created 180,000 full-time jobs, and the value created by remanufacturing in the US increased by 15%, reaching at least \$43 billion. In the 1990s, Japan promoted the implementation of the 3R policy (i.e., reduce, reuse, and resource). By combining remanufacturing with the 3R policy, Japan has achieved the combined goal of reducing pollution emissions and promoting resource conservation.

Although the promotion of environmental sustainability has attracted more attention to "remanufacturing" in the past decades, in practice, remanufacturing involves retailers' marketing related to distribution channels as well as operations management. For example, an internationally well-known company, Hewlett-Packard Development Company (HP, https://hp.com), recycles used computers and printers and resells them after processing. HP sells both new and remanufactured products through independent distributors, similar to Lenovo, Apple, Canon, and Panasonic. Haier Group, a large household appliance brand in China, sells new products such as water heaters, refrigerators, air conditioners, and washing machines through its online website (https://haier.com), as well as second-hand appliances (i.e., remanufactured products) in brick-and-mortar stores. According to the 2017 US "Green Friday" campaign, Amazon's "frustration-free packaging" is expected to save 181,000 tons of packaging materials and 307 million transport containers in the next decade. "Worry-Free Packaging" reduces waste throughout the supply chain with a focus on reducing the environmental impact of packaging and driving the sustainability of packaging. Similarly, according to the emission reduction plan, Walmart is expected to combine energy conservation measures with the use of 50% renewable energy to achieve the target of reducing emissions by 18% by 2025. Walmart stores will be equipped with light-emitting diode (LED) energy-saving lamps, air conditioning energy-saving upgrades, and thermal energy recovery systems. By 2025, Walmart is expected to use 100% recyclable packaging for its own-brand goods. In such a circumstance, how a downstream competition affected all the players' strategic decisions was explored, which in turn affected the environment and society.

In response to these cases, the objective of this study was to compare the economic, environmental, and social effects of decentralized and centralized scenarios and elaborate on them from different perspectives.

In particular, the following fundamental research issues were addressed:

(1) From the viewpoint of economic performance, how does the competition of retailers affect economic performance? Thus, it is important to know how marketing strategies should be formulated in a market.

(2) From the viewpoint of environmental sustainability, how does the competition of retailers affect the environment concerning the marketing of remanufactured products?

(3) From the viewpoint of social performance, will retailers' competition have an impact on consumer surplus?

From an economic perspective, our analysis indicated that when compared with Model C, Model P improved the manufacturer's financial performance and industry profits, while cutting into the retailers' profits. From a social viewpoint, our results showed that in terms of consumer surplus, the decentralized scenario (Model P) was superior to the centralized scenario (Model C). The latter reduced consumer surplus and caused a social loss, which was detrimental to consumers. From the viewpoint of environmental sustainability, Model P was greener than Model C. From the manufacturers' perspective, if they are concerned about economic performance and social development, some measures had to be taken to limit the competition of retailers in marketing.

In response to these issues, a game model for the analysis in the decentralized and centralized contexts is constructed. This article makes three contributions to the existing knowledge of selling concepts in a sustainable marketing strategy. First, although previous scholars have explored the relationship of competition among retailers, there is limited existing literature on the competition of retailers in the remanufacturing industry. To address this gap, an alternative approach to discussing how the competition of retailers affected both parties' profitability and industrial outputs is considered. This is an important novelty for the article. Second, even though the question of retailer's competition has been studied in depth, limited information is known about the effect of the competition of retailers on the economy, environment, and society. We analyzed the effects of competition on these aspects in the remanufacturing industry. We further discussed the impact of manufacturer's operations on the environment and consumer surplus. This is the most important novelty of the article. Finally, the analytical modeling results provided several managerial insights, which would be beneficial for game players to develop reasonable channel strategies and provide a theoretical basis for the supply chain participants.

The rest of this article is organized as follows. Section 2 reviews the existing literature in this field, while Section 3 discusses the model assumptions. The model formulation and the analysis of the two models are presented in Sections 4 and 5, respectively. Sections 6 and 7 provide numerical examples and managerial implications. Section 8 concludes this paper and presents ideas for further research. All the relevant proofs have been moved to an online supplement.

2. Literature Review

The efficient operation of enterprises needs to consider the sustainable development of economy and environment. Sustainability is one of the important issues in operations management, which aims at building harmony and a win-win scenario for society, economy, and nature. Esenduran et al. [2] were concerned about the influence of environmental regulations on the manufacturer's profits and consumer surplus and showed that consumers benefit from buying remanufactured products because of the competition and low cost of remanufacturing in an environmentally regulated marketplace. Cao et al. [3] underscored that environmentally friendly regulation by the governments motivates firms to engage in remanufacturing activities and considered extended producer responsibility (EPR) principles to achieve a breakthrough in the remanufacturing industry. Bittar [4] discussed whether the purchase of remanufactured products by consumers is related to environmental consciousness by using empirical methods. Taleizadeh et al. [5] comprehensively considered carbon reduction and return policy in a supply chain to achieve sustainable development of enterprises. They found that a higher refund price has a positive impact on the supply chain profits and carbon emission reduction. Chetan et al. [6] adopted a two-stage mechanism to analyze the cost functions. The optimal scoring function is designed to maximize its utility. Pazoki et al. [7] addressed environmental performance issues and proposed a decision-making system to set up environmental regulations to recycle as many products as possible. Based on consumer utility, Zhang et al. [8] studied a centralized system for selling short-life-cycle products in which green remanufactured products are remarketed at an appropriate price in the second period. They found that improving the quality and informing consumers of the benefits of remanufactured units are considered environmental benefits. Huang et al. [9] analyzed the impact of government subsidy on the environment and game players' profits. They found that regardless of which subsidy pattern the government adopts, it benefits both manufacturer and collector. It is also beneficial to environmental sustainability. Yang et al. [10] considered the cap-and-trade regulation to construct game models with and without remanufacturing. The research results showed that remanufacturing can increase profit and improve the level of carbon emission reduction. When a manufacturer is subject to strict emission controls, the total amount of carbon emissions under third-party collection mode is always the lowest. Li et al. [11] discussed the impact of low-carbon manufacturing in a closed-loop supply chain (CLSC) and constructed a CLSC model. They further analyzed the impact of emission reduction effort on supply chain performance and stated that recycling benefits the utility of low-carbon consumers but damages the profit of CLSC due to the high investment cost of recycling. Zheng et al. [12] explored the influence of the design for the environment (DfE) on firms' remanufacturing strategies. A theoretical model is constructed to demonstrate the impact on game decisions. Although a DfE can help reduce the environmental impact, a high level of DfE may harm the environment by substantially increasing total sales. Yang et al. [13] studied the environmental impacts of a flexible versus simple trade-in strategy considering carbon tax policies and established a hoteling model. An appropriate carbon tax on green products could lead businesses to adopt a more environmentally friendly trade-in strategy. Giri et al. [14] discussed product quality and return policy under two strategies, which play an increasing role in environmental protection, and assumed that the manufacturer is the Stackelberg leader. The retailer sets the retail price and provides a return policy in the first period only. Mondal et al. [15] investigated greening strategies and pricing for the green supply chain. As the greening cost increases, the greening level and wholesale price decrease. The green level of the products can be improved by a cost-sharing mechanism. Cao et al. [16] analyzed pricing decisions under carbon tax policy (CTP) and remanufacturing subsidy policy (RSP). The social welfare under RSP is greater than that under CTP when the environmental cost coefficient is low. Deng [17] looked at environmental performance and remanufacturing model selection under the influence of consumers' risk aversion. For environmental performance, the supplier tends to choose either the NR (no remanufacturing) model or the SR (remanufacturing is carried out by the supplier) model. Both the environment and supplier will benefit from the SR model. Chung et al. [18] presented a sustainable remanufacturing model in a dynamic supply chain. The disposal of environmental pollutants caused by defective items is considered. Niu et al. [19] discussed the influence of retail link on coordination of social welfare and profit. The social welfare levels are compared in the models of bundled outsourcing and individual outsourcing. A similar approach can be found in Wei et al. [20]. Most of the above studies consider environmental issues related to operation management, but few consider the issue of consumer surplus. This paper makes up for this gap and compares the channel selection strategies of game players.

The second set of literature is related to the remanufacturing industry and focuses on saving resources, reducing energy consumption, reducing product costs, and improving the competitiveness of enterprises. Yan et al. [21] found optimal pricing policies for new and remanufactured units while considering the inventory level, which is inversely proportional to the price of the remanufactured products, but directly proportional to the price difference. Shu et al. [22] investigated game models with three different structures in remanufacturing supply chains. The results show that the dominant player gets higher profits and the players will take the initiative to strive for market leadership. However, there is a cost to pay for market leadership. Wu et al. [23] studied pricing strategy and competitive remanufacturing problems under different scenarios. They analyzed how the contrast effect and assimilation effect influence the pricing strategy of original equipment manufacturers (OEMs). If OEMs sell remanufactured products, this will weaken consumers' perceived value of new products. Zhao et al. [24] developed a decision model considering technology authorizations in a closed-loop supply chain. The results show that fixed technology authorization fees in remanufacturing mode can enable a retailer to improve service levels and improve the recovery rate of the third party. Shi et al. [25] studied divisional conflict and channel choice in remanufacturing the supply chain. The firm sells new and remanufactured products through a direct or indirect channel (through an independent retailer). The study showed that when compared with a direct channel, a decentralized firm achieved higher profit and more consumer demand from an indirect channel. Jin et al. [26] analyzed optimal warranty policy using a game-theoretic model. They argued that the optimal warranty policy depends on the cost structure. Interestingly, higher warranty fees may induce manufacturers to adopt a warranty policy. In some cases, mandatory warranty provisions can be harmful. Xiang et al. [27] discussed the influence of technological innovation and Big Data marketing on the decision making of game players in remanufacturing the supply chain. It is shown that an Internet recycling platform is conducive to manufacturers but hurts suppliers' profits. On the contrary, efficient technological innovation and Big Data marketing weaken the initiative of the manufacturer. Wang et al. [28] analyzed the influence of consumer behavior and the trade-in remanufacturing policy on remanufacturer decisions by using a consumer utility model. The trade-in policy raised brand prices and increased corporate profits and consumer surplus. Jia et al. [29] considered a closed-loop supply chain, including e-retailers platform service and self-operated store, which provide upstream manufacturers with options for selling new and remanufactured products. From an environmental point of view, selling new products through an e-retailer and selling a remanufactured product online are optimal choices. Han et al. [30] discussed the manufacturer's optimal recovery strategy for handling used products. Government subsidies would reduce environmental impact and increase consumer surplus. Interestingly, a manufacturer with higher product quality tends to choose remanufacturing products instead of recycling materials. Xu et al. [31] explored the coordination mechanism of collection rate and pricing in the remanufacturing industry. It has been demonstrated that lower competitive intensity and saving production costs encourage the manufacturer to remanufacture products. A two-part tariff contract can achieve Pareto improvement. Huang et al. [32] studied pricing decisions considering technology licensing and strategic consumers. With an increase in strategic consumers, the demand for remanufactured products increases, and the demand for new products decreases. When a manufacturer authorizes a third party to remanufacture products, it suffers a profit loss. Li et al. [33] explored the issues of remanufacturing construction and demolition waste. They showed that retailer fairness concerns cut into the manufacturers' profits and led to a lower wholesale price of building materials. Rahmani et al. [34] focused on horizontal and vertical cooperation in two reverse supply chains and analyzed quality improvement competition. It has been demonstrated that in decentralized decision making, the remanufacturers who cooperate horizontally will cut down the collector's profits. The multiple-link two-part tariff is applied to coordinate each player. Wang et al. [35] considered a manufacturer who acquired core materials through either outsourcing or self-remanufacturing under yield uncertainty. The distribution bounds determine the manufacturer's strategic choice under a random recovery rate. Kleber et al. [36] considered two-sided competition in both acquisition and sales in remanufacturing. It has been demonstrated that the market advantage is much stronger than the acquisition advantage. Zhang et al. [37] explored a competitive closed-loop supply chain, and authorization mode and outsourcing mode were considered. When per-unit new product production cost is low, the duopoly third-party remanufacturers (TPRs) will select an outsourcing strategy. Raz et al. [38] explored codevelopment at the product level and the influence of outsource manufacturing/process innovation. Outsourcing must include options for codevelopment on specific activities and product innovations. Different from the above literature, this paper makes a comparative analysis of the sales quantity, profit, environmental impact, and consumer surplus, which enriches the theoretical research on channel competition.

Thus far, few researchers have studied the integration of sustainability and remanufacturing. To bridge this gap in this article, instead of outsourcing remanufactured products to third-party manufacturers, it is assumed that all of the used products are recycled by the manufacturer [39]. Moreover, none of the existing studies focused on the effects of retailers' competition on the environment and consumer surplus. On the contrary, the effects of competition on the economy, environment, and society concerning the sale of remanufactured products are demonstrated. The results of this study will be beneficial to game players in developing operations management and marketing strategies, which will enhance economic, environmental, and social sustainability.

3. Model Assumptions and Notations

In this study, how different distribution channels of retailers affect sustainable development in the remanufacturing industry is explored. Consequently, based on business practices, two models have been developed for investigating the effects of a competition involving two retailers: (1) The manufacturer provides new and remanufactured products to two retailers (retailer 1, retailer 2) respectively, in a decentralized scenario (i.e., Model P). (2) In a centralized scenario, the manufacturer provides new and remanufactured units to only one retailer (retailer R) (i.e., Model C). See Table 1 for more detailed notations and explanations

Table 1: Detailed notations and explanations.

Notation	Explanation
w_n^j/w_r^j	The wholesale price of new/remanufactured product in Model j, $j \in (P, C)$
c_n/c_r	Unit cost for distributing new/remanufactured product
p_n^j/p_r^j	New/remanufactured product price in Model j, $j \in (P, C)$
q_n^j/q_r^j	Quantity of new/remanufactured product in Model j, $j \in (P, C)$
c	Unit cost for making a new product
δ	Consumer value discount for remanufactured products
e_n/e_u	Per-unit environmental impact of a new/remanufactured product
π_k^j	Profits of player k in Model j, $j \in (P, C)$, $k \in (R1, R2, R, M, T)$

[40]. Considering the framework involved, these assumptions about the manufacturer, retailer, product, and consumers can be described as follows.

Assumption 1. Game decision making is taken into account in a steady-state period with the following consequences: First, the manufacturer claims the wholesale price for both products (w_n, w_r). Second, the retailer maximizes its profits by responding with the optimal quantity of products (q_n, q_r).

This is a common practice in the existing literature, where new and remanufactured products are repeatedly sold, and each product is sold only once in the business market, which is referred to as the steady-state period. According to the principal-subordinate game theory, the manufacturer is the Stackelberg leader and the retailer is the follower. The equilibrium solution is obtained by backward induction method.

Assumption 2. Compared to the new product, the primary consumers' willingness to pay for the remanufactured product is a ratio of the value discount $\delta \in (0, 1)$.

Here, consumers believe that the value of remanufactured products is lower; that is, $\delta \in (0, 1)$. Similar to existing pieces of literature, Assumption 2 implies a vertical differentiation model with an agreed order for the consumers' valuation; that is, consumers are more inclined to buy new products rather than remanufactured ones. Note that a consumer has a valuation of v for the new product and δv for the remanufactured unit.

Assumption 3. For a new product, the consumers' valuation (v) is heterogeneous and the number of consumers is considered to be constant, which follows a uniform distribution in the market that is normalized to 1; that is, $v \sim U[0, 1]$.

This conforms to the relevant literature, and the market size is normalized to 1. Most notably, the cannibalization problem of both new and remanufactured units should be considered because of the consumer value discount (δ). Note that if $\delta = 0$, consumers will not buy the remanufactured product, which is regarded as a low-quality product, but if $\delta = 1$, consumers believe that the remanufactured product can completely replace the new product and thus pay the same amount for either product. Based on Assumptions 2 and 3, the linear inverse demand functions [41] are obtained as follows:

$$
\begin{aligned}
p_n &= 1 - q_n - \delta q_r, \\
p_r &= \delta (1 - q_n - q_r).
\end{aligned}
\tag{1}
$$

Assumption 4. The unit cost for distributing a new product is c_n, and the unit cost for distributing a remanufactured product is c_r.

In both models, it is assumed that the distribution costs of new products and remanufactured products are different. According to the relevant pieces of literature (e.g., Taleizadeh et al. [5], Wu et al. [23]), the remanufacturing cost is divided into two parts, namely, the cost of producing and marketing the remanufactured product.

Assumption 5. The unit cost for remanufacturing a used product (c_m) is less than that of manufacturing a new product, c_p (i.e., $c_p = c > c_m = 0$).

To develop a circular economy, used products are recycled to save resources and protect the environment. In order to confirm the rationality of employing a remanufacturing scenario, it is assumed that remanufacturing is lower in cost than production, which is the consensus in the existing literature (e.g., Wu et al. [23], Jia et al. [29]). Without any loss of generality, c_m is normalized to zero $(c_m = 0)$, and it is assumed that $c_p = c > c_m$. In particular, the focus is on the cost of marketing by controlling the cost of producing and remanufacturing, and thus the focus is mainly on the marketing issues related to competition among retailers.

4. Model Formulation and Solution

From the perspective of circular economy, the strategy of online and offline sales channel selection of new products and remanufactured products is discussed, and the impact of unit new products and remanufactured products on the environment is quantitatively described. New products and remanufactured products are sold online and offline by retailer R. It makes up for the lack of combining online and offline channel marketing of new products with remanufactured products in the existing literature. In Model P and Model C, the game order of the events is as follows: The manufacturer first announces the wholesale price for both products (w_n, w_r). Then, to make more profits, the retailer sets the optimal quantity of the two products (q_n, q_r). Note that π_k^j represents the profits of the player k in Model j, where $k \in (R1, R2, R, M, T)$ denote the retailers, the manufacturer, and the total supply chain, respectively, and $j \in (P, C)$ represents Model P and Model C, respectively.

4.1. Decentralized Model (Model P). In this scenario, both products are sold to different retailers. The manufacturer's optimization problem can be expressed as follows:

$$\max_{w_n, w_r} \pi_M^P = (w_n - c)q_n + w_r q_r. \quad (2)$$

From the viewpoint of the wholesale price (w_n^{P*}), retailer 1's optimization problem can be expressed as follows:

$$\max_{q_n} \pi_{R1}^P = (p_n - w_n - c_n)q_n. \quad (3)$$

From the viewpoint of the wholesale price (w_r^{P*}), retailer 2's optimization problem can be expressed as follows:

$$\max_{q_r} \pi_{R2}^P = (p_r - w_r - c_r)q_r. \quad (4)$$

The total profits of the supply chain can be calculated as follows:

$$\pi_T^{P*} = \pi_M^{P*} + \pi_{R1}^{P*} + \pi_{R2}^{P*}. \quad (5)$$

Using the backward induction method, the equilibrium decisions are determined and the important outcomes are summarized as follows.

Lemma 1. *Considering Model P, the quantities, wholesale price, and profits can be calculated as follows:*

$$\begin{aligned}
w_n^{P*} &= \frac{1}{2}(c - c_n + 1), \\
w_r^{P*} &= \frac{1}{2}(\delta - c_r), \\
q_n^{P*} &= \frac{2 - 2c - 2c_n + c_r - \delta}{8 - 2\delta}, \\
q_r^{P*} &= \frac{2c_r - \delta(1 + c + c_n)}{2\delta(\delta - 4)}, \\
\pi_M^{P*} &= \frac{\delta(c + c_n - 1)^2 + (c_r - \delta)[c_r - \delta(c + c_n)]}{2\delta(4 - \delta)}, \\
\pi_{R1}^{P*} &= \frac{(-2 + 2c + 2c_n - c_r + \delta)^2}{4(\delta - 4)^2}, \\
\pi_{R2}^{P*} &= \frac{(-2c_r + \delta + c\delta + \delta c_n)^2}{4\delta(\delta - 4)^2}, \\
\pi_T^{P*} &= \frac{1}{4\delta(-4 + \delta)^2}\Big[\delta(-2 + 2c + 2c_n - c_r + \delta)^2 \\
&\quad + (-2c_r + \delta + c\delta + \delta c_n)^2 - 2(\delta - 4)\Big((c + c_n - 1)^2\delta + (c_r - \delta)(c_r - c\delta + \delta c_n)\Big)\Big].
\end{aligned} \quad (6)$$

4.2. Centralized Model (Model C). In this scenario, both products are sold to a retailer R, and the manufacturer's optimization problem can be expressed as follows:

$$\max_{w_n, w_r} \pi_M^M = (w_n - c)q_n + w_r q_r. \quad (7)$$

Given the wholesale price (w_n^{M*} and w_r^{M*}), the downstream end-product market became a monopoly market. In other words, retailers R1 and R2 merged into a more powerful retailer R, who was one of the two retailers when the competition took place. The retailer R's problem could be optimized as follows:

$$\max_{q_n, q_r} \pi_R^M = (p_n - w_n - c_n)q_n + (p_r - w_r - c_r)q_r. \quad (8)$$

The total profits of the supply chain can be calculated as follows:

$$\pi_T^{M*} = \pi_M^{M*} + \pi_R^{M*}. \quad (9)$$

Using the backward induction method, the important outcomes are summarized as follows.

Lemma 2. *Considering Model C, the quantities, wholesale price, and profits can be calculated as follows:*

$$\begin{aligned}
w_n^{M*} &= \frac{1}{2}(1 + c - c_n),\\
w_r^{M*} &= \frac{1}{2}(\delta - c_r),\\
q_n^{M*} &= \frac{-1 + c + c_n - c_r + \delta}{4(\delta - 1)},\\
q_r^{M*} &= \frac{c_r - \delta(c + c_n)}{4\delta(\delta - 1)},\\
\pi_M^{M*} &= \frac{(-1 + c + c_n)^2\delta + (c_r - \delta)(c_r + \delta - 2c\delta - 2\delta c_n)}{8\delta(1 - \delta)},\\
\pi_M^{M*} &= \frac{(-1 + c + c_n)^2\delta + (c_r - \delta)(c_r + \delta - 2c\delta - 2\delta c_n)}{8\delta(1 - \delta)},\\
\pi_T^{M*} &= \frac{3\left[(c + c_n - 1)^2\delta + (c_r - \delta)(c_r + \delta - 2c\delta - 2\delta c_n)\right]}{16\delta(1 - \delta)}.
\end{aligned} \tag{10}$$

To ensure that the players distribute a certain quantity of the two products in the market, the following condition had to be imposed: $q_n > q_r > 0$.

Lemma 3. *Considering both scenarios, the unit cost of distributing a remanufactured product needs to satisfy the following condition:*

$$\frac{-\delta + 3c\delta + 3c_n\delta + \delta^2}{2 + \delta} < c_r < c\delta + c_n\delta. \tag{11}$$

This lemma shows that the manufacturer is engaged in remanufacturing; that is, $q_r > 0$. Therefore, the marketing cost would not be very high: $c_r < c\delta + c_n\delta$. In contrast, if the retailer distributes an adequate quantity of the new product, which is the source of the remanufacturing cores (i.e., $q_n > q_r$), the following is required: $-\delta + 3c\delta + 3c_n\delta + \delta^2/2 + \delta < c_r$.

5. Model Analysis

In this part, the competition between economic performance and green sustainability in the remanufacturing industry is discussed, and some interesting insights are derived. The differences between the two scenarios are discussed, and subsequently the sustainability of the economy, environment, and society based on Lemmas 1 and 2 is discussed to make the following observations.

5.1. Comparison of Economic Sustainability. According to Lemmas 1 and 2, some insightful results were obtained in different scenarios. In particular, we first consider the question posed at the beginning of the article: From the viewpoint of economic performance, how does the competition of retailers affect economic performance? The differences between the decentralized and centralized cases are highlighted to clarify the managerial implications.

Proposition 1. *The manufacturer benefits more in Model P than in Model C; that is,* $\pi_M^{P*} > \pi_M^{C*}$.

Note that a competition of downstream retailers can lead to economic losses for manufacturers. The focus is on the impact when competition occurs, rather than optimal decisions of the supply chain partners in the remanufacturing industry. Further explaining the managerial insight, in Model P, competition among downstream retailers reduces the sales price but increases the quantity, which allows the manufacturer to wholesale more products to obtain more revenue. Therefore, such competition is beneficial to a manufacturer in a decentralized scenario; that is, $\pi_M^{P*} > \pi_M^{C*}$. Furthermore, as it controls the reverse channel, when compared with that in Model C, the number of remanufactured products in Model P is determined by the manufacturer ($q_r^{P*} > q_r^{C*}$). As a result, the quantity of the remanufactured product decreases and the profits for the upstream manufacturer decrease when such competition occurs. In other words, the proposition shows that yield from the remanufactured units in Model P is sufficient to compensate for the loss of new product sales.

Proposition 2. *The sum of the profits of both retailers in Model P is always worse than that in Model C; that is,* $\pi_{R1}^{P*} + \pi_{R2}^{P*} < \pi_R^{C*}$.

Note that the merging retailer earns higher profits because of a higher retail price, which reduces the competitive intensity between the retailers and hurts the upstream manufacturer by lowering its profits (see Proposition 1). The power of the players can be interpreted as follows: according to the economic theory of competition, a downstream competition can enhance the power of downstream retailers by reducing the number of companies in the market, thus hurting the profits of upstream enterprises. Similarly, such competition can reduce the supply chain profits in the remanufacturing market. The competition between downstream firms is beneficial to the merging firm, which is one of them when the competition takes place.

The industry performance of a sustainable supply chain is the driving force for maintaining the well-being of the economy (see Tajbakhsh et al. [42] for more details). Most notably, the focus was on economic significance in market competition according to Lemmas 1 and 2, and the following observation was made.

Proposition 3. *The competition among retailers is always detrimental to the industry; that is,* $\pi_T^{P*} > \pi_T^{C*}$.

Most notably, the equilibrium profits of the industry in the decentralized scenario (Model P) are higher than those in the centralized scenario (Model C), and the merging firm benefits because it alleviates the double marginalization problem (described in Proposition 2). As described in Proposition 1, due to the fierce competition led by mergers and acquisitions in downstream retailers, the manufacturer benefits from the competition, and thus its sales strategies are affected.

5.2. Comparison of Environmental Sustainability. In this section, the focus is on environmental implications in the remanufacturing industry. We answer the second question posed in the introduction of this article: From the viewpoint of environmental sustainability, how does the competition of retailers affect the environment concerning the marketing of remanufactured products?

Environmental sustainability of the decentralized and centralized cases is highlighted to provide managerial inspiration. In these models, it is assumed that the per-unit disposal impact of a new/remanufactured product was e_n/e_u, respectively. Remanufacturing consumes less energy and materials than producing new units in a traditional industry; therefore, the following assumption is necessary.

Assumption 6. The environmental impact per unit of a new product is larger than that of a remanufactured unit with essentially $e_n > e_u$.

Based on this assumption and Lemmas 1 and 2, E^P/E^C indicates the environmental impact for Model P/C, respectively. The difference in environmental sustainability can be summarized as follows.

Proposition 4. *In terms of the environmental impact, Model P is always greener than Model C; that is,* $E^P < E^C$.

Note that the total disposal impact of a new and remanufactured product is $E_n = e_n(q_n - q_r)$ and $E_u = e_u q_r$, respectively. Not only new products but also remanufactured products can have an impact on the environment. As discussed in the optimal quantity comparative analysis, retailer 1 sells fewer units of new products in the decentralized scenario (i.e., $q_n^{P*} < q_n^{C*}$), which indicates the lower environmental impact of new products. In addition, although there are more remanufactured products in Model P (i.e., $q_r^{P*} > q_r^{C*}$), their environmental impact is insufficient to compensate for the environmental damage caused by the new products in Model C. In other words, $q_n^{C*} > q_n^{P*} > q_r^{P*} > q_r^{C*}$. Therefore, Model P is beneficial in terms of environmental sustainability, as stated in Proposition 4.

From a broader viewpoint, if the retailers focus on economic performance, the competitive strategy is conducive to the firms' development; conversely, if they care more about environmental sustainability, some measures should be implemented to prevent competition among retailers in marketing.

5.3. Comparison of Social Sustainability. The focus is now on the consumer surplus of remanufacturing in a market. We can answer the final question posed in the introduction of this article: From the viewpoint of social performance, will retailers' competition have an impact on consumer surplus?

To evaluate the social performance of the retailers' competition strategy in a reverse channel, the following formula is used for calculating the consumer surplus, which included the consumers' willingness to pay for both products:

$$CS = \int_{1-q_n-q_r}^{1-q_n} (\delta u - p_r)\mathrm{d}u + \int_{1-q_n}^{1} (u - p_n)\mathrm{d}u. \tag{12}$$

Let CS^P/CS^C indicate the consumer surplus of Model P/C, respectively. The difference in social sustainability can be summarized as follows.

Proposition 5. *In terms of the consumer surplus, Model P always has a higher surplus than Model C with essentially* $CS^P > CS^C$.

Consumer surplus measures the extra benefits that buyers feel they are getting in a particular market. The above proposition implies that a decentralized scenario (i.e., Model P) is more attractive to consumers and brings more utility to them in marketing. In Model C, there is a lower consumer surplus than in Model P because of the higher prices after the competition, which is a common phenomenon in a business market. In contrast, note that retailers are very concerned about the competitive strategy because it leads to better financial performance in Model C (Proposition 2). In general, a downstream competition benefits a merging firm at the expense of the consumers and partner firms. From a social perspective, increasing the consumer surplus and meeting the demand of the consumers to enhance their economic welfare are a central part of ensuring long-term economic growth.

6. Numerical Example

To better present how parameter changes affect sustainable performance, a numerical simulation analysis of the equilibrium decisions and the environmental, economic, and social outputs was conducted.

To illustrate the influence of remarketing costs (c_r) on the supply chain members, the distribution cost of the new product is set as $c_n = 0.4$, and it is reasonable for the marketing cost to be between 20% and 60%. Previous studies have pointed out that the per-unit cost of manufacturing of the manufacturers could not be ignored; therefore, a scenario where the manufacturing cost per unit was $c = 0.1$ was considered. Note that the consumer value discount of the remanufactured product ranged between 45% and 90% (e.g., Esenduran et al. [43]). Thus, $\delta = 0.8$ was set for the numerical analysis. From production to remanufacturing, products are accompanied by energy consumption. Based on Esenduran et al. [43], the environmental impact of disposal of a new/remanufactured product per unit is set to 240 MJ (i.e., $e_n = 240$) and 138 MJ (i.e., $e_u = 138$), respectively. Based on Lemma 3, by using the constraint condition $q_n^{j*} > q_r^{j*} > 0$, the range of the unit cost for distributing a remanufactured product is obtained as $-\delta + 3c\delta + 3c_n\delta + \delta^2/2 + \delta < c_r < c\delta + c_n\delta$, and after substituting the numerical values, it is calculated as $0.371 < c_r < 0.4$. All these figures reflected the extent to which the change c_r affected both models.

First, Figure 1 reports the results of the economic sustainability before and after the competition in a market. From Figures 1(a), 1(b), and 1(c), it can be concluded that the profits of the manufacturer, retailers, and entire system decreased with an increase in the value of c_r. Furthermore, Figures 1(a) and 1(c) imply that the profitability of the manufacturer and industry in the decentralized scenario was higher than that in the centralized scenario. However, from

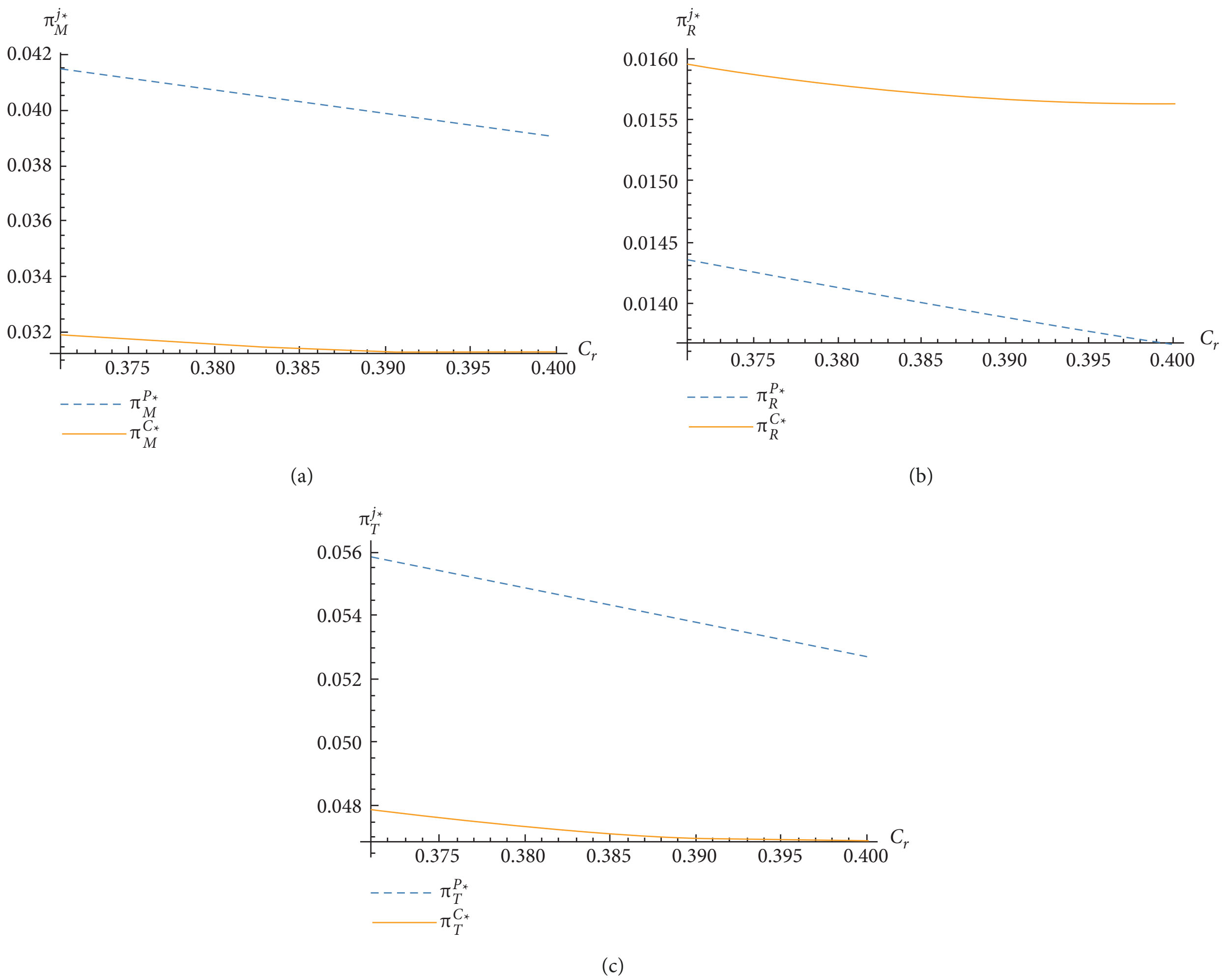

FIGURE 1: Economic outcomes: (a) effects of c_r on π_M^{j*}; (b) effects of c_r on π_R^{j*}; (c) effects of c_r on π_T^{j*}.

Figure 1(b), it is inferred that the sum of the profits of retailers 1 and 2 in Model P (π_R^{P*}) was always less than the profits of retailer R in Model C (π_R^{C*}). As a result, competition in the retail industry is widespread as they result in a better financial performance of the merging retailer. Figures 1(a), 1(b), and 1(c) show that economic sustainability was in line with the theoretical prediction discussed in Propositions 1–3.

Second, Figure 2 illustrates the impact of both models on environmental sustainability. Model P had a lower destructive impact on the environment than Model C. That is, Model P was greener than Model C (see Proposition 4). In addition, the environmental impact increased with an increase in c_r in both the decentralized and centralized scenarios.

Finally, the focus is now on social sustainability in both models. As shown in Figure 3, consumer surplus in Model P was larger than that in Model C ($CS^P > CS^C$), which was consistent with Proposition 5. Furthermore, consumer surplus in both models decreased as the value c_r increased; in other words, when the cost of remarketing was higher, the corresponding product was more disadvantageous to consumers.

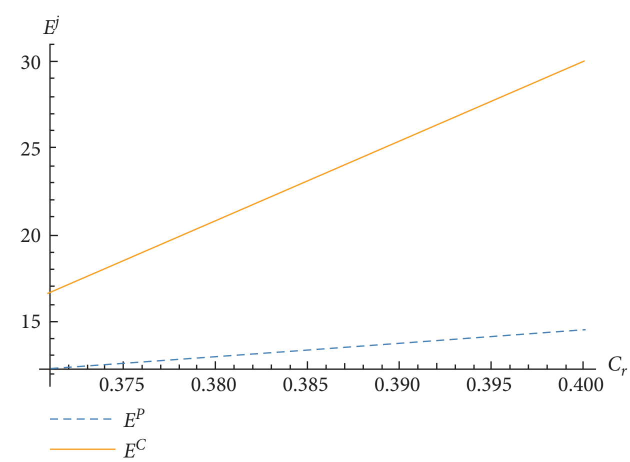

FIGURE 2: Environmental outcomes: effects of c_r on E^j.

7. Managerial Implications

Based on the above analysis, the managerial insights for marketing remanufacturing products involving a reverse channel were summarized, and some interesting

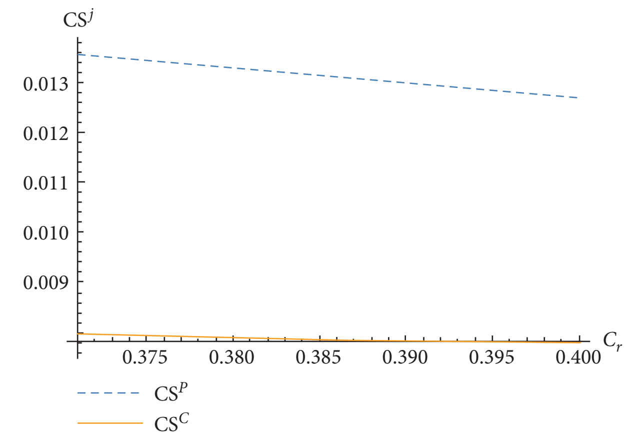

Figure 3: Social outcomes: effects of c_r on CS^j.

observations were derived. Specifically, this summary was divided into the following three aspects:

First, from the viewpoint of economic performance, the manufacturer's profitability and industry profits in the decentralized scenario were always higher than in the centralized scenario. However, the merging retailer earned higher profits than the retailers in Model P. Thus, if manufacturer wants to achieve more performance, it should cooperate with multiple retailers. For retailer, choosing a dual-channel model will bring more performance.

Second, from the viewpoint of environmental sustainability, the decentralized scenario was always greener than the centralized scenario; that is, Model P was beneficial for the environment when the competition took place. For manufacturers, the production process needs to consider environmental pollution and formulate action plans to reduce pollution, for example, adopting technologies to reduce carbon emissions and optimizing production processes.

Last, from the viewpoint of social performance, Model P was always better than Model C in terms of the consumer surplus. Consumer surplus, which measures the extra benefits that buyers feel they are getting, is an important factor influencing which business model to adopt. Sustainable operations management needs to maintain a balance of economy, society, and environment.

In brief, our findings provide some practical implications for business managers. The most significant contribution is that our research helps to develop channel selection strategies and environmental sustainability in the remanufacturing industry.

8. Conclusion

With the maturity of remanufacturing technology, an increasing number of manufacturers are motivated to produce new and remanufactured products simultaneously. The end-of-life products from consumers are collected by manufacturers for remarketing, which forms a reverse supply chain that reduces environmental pollution. Developing a circular economy in the future has become one of the objectives of modern enterprise operations and management.

Although a considerable amount of literature has investigated competitive strategy and channel selection in the remanufacturing industry, to the best of our knowledge, closed-loop supply chains in the decentralized and centralized contexts have been rarely studied, which represents a gap in the theory. However, in practice, the importance of both marketing strategies and environmental sustainability of the supply chain has been recognized in recent years, and the selection of the appropriate environment for an enterprise ecosystem is more complicated from the viewpoint of operations management. Moreover, none of these studies focused on how retailers' competition affects the environment and consumer surplus. To address this gap, two theoretical models were constructed where a manufacturer collected the used products to produce the remanufactured products, which can be viewed as green products: (1) Model P, which is in a decentralized scenario; (2) Model C, which is in a centralized scenario.

The following three results are beneficial for managers in developing pricing and channel selection strategies. First, the economic benefit of the manufacturer in Model P was higher than that in Model C. The sum of profits of retailer R1 and retailer R2 in Model P was lower than that of retailer *R* in Model C. Second, for environmental protection, Model P was found to be greener than Model C. Last, from a social viewpoint, Model P had a higher consumer surplus than Model C, because of the higher prices when such a competition occurs.

In this paper, some valuable managerial insights were presented, but it is also acknowledged that some limitations deserve further study. First, the competition of downstream retailers was analyzed without considering the vertical competition between the upstream and downstream retailers. A vertical competition will have different effects on the firm's business strategy, which is one of the directions that can be investigated in the future. Second, it is assumed that there was a monopolistic manufacturer in the model. In reality, remanufacturing can be outsourced to a third-party remanufacturer or other agents such as retailers. Third, to pay close attention to sustainability, other factors, such as information asymmetry, network externality, and used product quality, were abstracted, which can potentially impact sustainable operations in a supply chain where such competition occurs.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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