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Research Article

Pricing and Collection Rate for Remanufacturing Industry considering Capacity Constraint in Recycling Channels

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This paper explores the decision-making and coordination mechanism of pricing and collection rate in a closed-loop supply chain with capacity constraint in recycling channels, which consists of one manufacturer and one retailer. On the basis of game theory, the equilibriums of decisions and profits in the centralized and decentralized scenarios are obtained and compared. Through the performance analysis of a different scenario, a higher saving production cost and lower competition intensity trigger the members to engage in remanufacturing. Furthermore, we try to propose a two-part tariff contract through bargaining to coordinate supply chain and achieve a Pareto improvement. The results show that when the capacity constraints in recycling channels exceed a threshold, the decisions and profit will change. Additionally, for closed-loop supply chain, the selling price is more susceptible to the influence of capacity constraint in recycling channel than the members' profit.

1. Introduction

In recent years, the Considering Capacity Constraint in Recycling Channels closed-loop supply chain (CLSC) is a hot topic in the field of logistics and supply chain management, which has been attracting extensive attention from the industrial and theoretical circles. According to the viewpoint of the whole life cycle, products have been manufactured, wholesaled, retailed and used. Then, the end-of-life products are eliminated by consumers, which are classified, cleaned, and disassembled by the collectors; meanwhile, the valuable parts are implemented in the process of remanufacturing [1]. Remanufacturing increases the time of material utilization, and makes it more energy-saving and environmentally friendly. Studies have shown that recycling and reuse of core components can save about 40%–60% of the cost [2, 3]. Therefore, many famous enterprises like Xerox, Robert Bosch, and Hewlett-Packard improve the performance through remanufacturing. However, many companies still have doubts about whether the manufacturing can bring profit. Thus, it is of great significance to quantitatively explore the economics of remanufacturing and give some managerial guidance to collection and remanufacturing strategy for promoting the development of the remanufacturing industry and improving the level of closed-loop supply chain management.

However, the closed-loop supply chain should simultaneously consider operations of forward and reverse flow. The recycling channels of closed-loop supply chain have their corresponding infinite recycling capacity; otherwise, it goes against the realistic conditions like warehouse, routing, and staff. Under these circumstances, the relationship between capacity constraint and supply chain performance has been unpredictable. The remanufacturing capacity of Benz-cummins, an automobile-engine remanufacturer, only 3000 per year for Cummins, Doitz, and Mercedes-Benz. Further, Wuxi diesel-engine factory is located in Jiangsu Province with an annual capacity of 5000 modified vehicles. Obviously, the development strategies of both companies are affected by the production capacity, so they cannot meet the market demand. In other words, if the recycling capacity is reduced at a certain threshold, the capacity constraint results in a huge influence of decision and profit [4, 5]. In general, the less recycling capacity tends to decrease the collection ability in the reverse channel. Note that this situation may result in a phenomenon, which undercuts corporate profit aggravate environmental harm [6–9]. Furthermore, based on managerial insight, realistically, the imposing capacity constraints will change the manufacturing and remanufacturing process. Managers; should also take the recycling capacity into account when they decide the strategies. Thus, the limitation in the recycling capacity impacting the supply chain performance is a major challenge for the operation management era.

Therefore, the behavior of collection and remanufacturing for end-of-life products is crucial to our environment and economic. According to the Stackelberg game, we establish a centralized and decentralized model to obtain the decision of pricing and collection rate in a closed-loop supply chain. Furthermore, we adopt the Nash bargaining theory to propose an improved coordinated contract and discuss the performance of optimal profits and decisions. Different from the above, we mainly fill in the research gap with the influence of the capacity in recycling channel on optimal profits and decisions. In addition, we focus on the design of coordination mechanism in a closed-loop supply chain with a manufacturer recycling channel and a retailer recycling channel to achieve a perfect Pareto improvement. The rest of this paper is organized as follows. Section 2 reviews the relative literature of closed-loop supply chain management and coordinated mechanism. In Section 3, the notation and assumption are provided. We formulate the mathematical model and decision analysis in Section 4. Further, we present the numerical analysis to obtain some managerial insights in Section 5. Section 6 provides the conclusions and suggestions for future research.

2. Literature Review

The Several relevant literature should be reviewed here to clarify the need for our paper. In order to demonstrate in detail the contributions, we explore the literature spanning across two subsections. In Section 2.1, we focus on the management of a closed-loop supply chain, which contains network design, collection competition and recycling constraint. Then, we address the coordination mechanism for members to improve the performance and achieve improvement in Section 2.2.

2.1. Closed-Loop Supply Chain Management. Many scholars discussed the remanufacturing strategy in a closed-loop supply chain, including recycling mode and channel choice, which is an academic problem and achieve an efficient decision. Savaskan et al. [10] based on the game theory to establish three recycling channels to compare the differences among manufacturer collection retailer collection and third-party collection. Then, Savaskan et al. [11] took one manufacturer and two competitive retailers into consideration in determining the decisions of pricing and collection. On this basis, Wu [12] introduced the price and service decisions into a two-stage Stackelberg game, which consists of one manufacturer, one remanufacturer, and one retailer. In addition, this model was extended to a dual-channel recycling model in a closed-loop supply chain between retailer and third-party recycling competition [13]. Zhang and Ren [14] discussed differences in optimal decision and profit in the centralized and decentralized closed-loop supply chain, as well as analyzed the influences of channel preference and sales service on performance. Morteza et al. [15] proposed a fuzzy two-objective model with the random interruptions, which is a price-dependent demand, to construct a closed-loop network between the manufacturer and the retailer. Taleizadeh et al. [16] combined pricing, quality, and collection in a closed-loop supply chain, besides explore the impact of channel structure on decision and profit. From the above, previous studies seldom considered the impacts of competitive intensity on different recycling models.

But beyond that, the other branch is recycling competition. Feng et al. [17] introduced consumer preference in establishing a dual-channel collection model for a closed-loop supply chain, which discuss the recycling competition and recycling configuration between the manufacturer and the recycler. He et al. [18] discussed competitive collection in a closed-loop supply chain, which investigated remanufacturing efficiency and consumer acceptance with channel inconvenience. Further, Liu et al. [6] proposed a price- and quality-dependent competition model between the formal and informal recyclers to explore the impact of governmental policy on the four competitive scenarios. Liu et al. [19] introduced the recycling competition into the decisions of pricing and reverse channel choice and also compared three different dual-channel recycling models. Wang et al. [20] combined the Stackelberg game to obtain the pricing strategies for the three individual collection models with the competitive collection market and demand market. From the above, these literature on the remanufacturing strategy in a two-period Stackelberg game is derived by backward induction. Yet, the remanufacturing behavior can be affected by some realistic factors, which lead to a capacity constraint in recycling channel. How to analyze the impact of capacity constraint on the performance in a closed-loop supply chain is an urgent problem.

Capacity constraint in decision-making is becoming increasingly crucial in real-life scenarios. Sereno and Efthimiadis [21] investigated the investment of firms whether to add the capacity or not, besides discussing how capacity constraints and incentive schemes influence firms' strategies. This is especially circumstance in closed-loop supply chain. Fischetti et al. [22] adopted Benders' decomposition without separability to design an algorithm and conduct a numerical analysis in deriving the capacitated facility location problems. Mota et al. [23] proposed a multi-objective MIP model, which combines the demand uncertainty and capacity restriction, to guarantee the sustainable development of a closed-loop supply chain through locating the facility. Further, Wang et al. [24] and Dominguez et al. [25] discussed respectively the influences of capacity constraint on low-carbon and closed-loop supply chain. Meanwhile, Zhen et al. [26] and Ljubic and Moreno [27] optimized the network of a closed-loop supply chain from the perspective of capacity constraint to demonstrate several decisions, such as capacity locations, network design and technology allocation. However, they mainly focused on the capacity constraint in distribution centers, which ignores the restriction in recycling channels.

2.2. Coordinated Mechanism in Closed-Loop Supply Chain. The topic of coordinated mechanism in the supply chain has received great attention in the existing literature. From the view of cost and revenue sharing, Cachon and Lariviere [28] compared the revenue-sharing contract, buyback contract, and wholesale price contract to conclude that the optimal coordinated mechanism. Mafakheri and Nasiri [29] focused on the extracting value from end-of-life products to investigate the distribution of revenue sharing in a closed-loop supply chain. Hu and Feng [30] analyzed the revenue-sharing contract in a supplier buyer supply chain under the demand and supply uncertainties. Beyond that, some scholars provided the buyback contract [12, 31] and, discount schemes [32, 33], and lead time incentive mechanisms [34, 35]. Different from the traditional supply chain, Heydari and Ghasemi [36] proposed a coordinated model in a reverse supply chain based on the uncertainty for member's risk, which considered the random remanufacturing capacity, to achieve a win–win situation. Further, Li et al. [37] emphatically analyzed the efficiency of a revenue-sharing contract with the perspective of recycling cost as an extra value for the collector. Zhao and Zhu [38] designed a revenue-sharing mechanism to coordinate the manufacturer and retailer considering the uncertainties of remanufacturing rate and market demand. In addition, Xie et al. [39] compared the performance in the centralized and decentralized supply chain, which indicated the influence of channel conflict in a reverse supply chain scenario, to get a revenue-sharing coordinated mechanism. Therefore, for the members in the closed-loop supply chain, eliminating double-marginalization and ensuring profit-maximization has been a urgently problem.

In the coordinated mechanism, profit distribution between the manufacturer and retailer is more and more becoming a hot topic in the field of operation management [7]. Shi and Wu [40] adopted the fuzzy decision theory to the Shapley value for profit distribution, which considered the risk influence and capital appreciation ratio. Dai and Chen [41] designed the mechanism of profit distribution for supplier, manufacturer, and retailer to improve the traditional Shapley value. Zhang and Geng [42] demonstrated a profit allocation model in the evolutionary game model and discussed the impact of relative parameters on the member's cooperation and performance. Chen et al. [43] compared the different coordinated mechanisms with price- and time-dependent demand, as well as proposed the allocation of individual income for all participants. Wu et al. [44] combined the fairness concern into the coordinated mechanism to incentive the members' participation in energy saving. Wang et al. [45] proposed a mixed integer-programming model, which combined the transportation expansion, vehicle time, and collection routing to improve the Shapley value to balance the profits.

Outside of this, in order to improve the efficiency of supply chain coordination, some scholars investigated the contract with several methods. Zhang and Ren [14] provided a coordinated contract to balance the manufacturer and the retailer, which contained revenue sharing and cost sharing. Xie et al. [46] discussed the coordinated mechanism with service effect and sale effect based on the perspectives of revenue and expenditure. In total, there are limited points of previous studies, which didn't achieve perfectly the coordination in a closed-loop supply chain.

Different from the existing literature, this paper focuses on the decision and coordination of a closed-loop supply chain with a manufacturer recycling channel and a retailer recycling channel to obtain managerial insights from the perspective of capacity constraint in recycling channels. The main contributions of this paper are characterized by three fields. The first is to examine the impacts of competitive intensity for recycling channel on optimal decision and profit. The second is to discuss the effectiveness conditions of capacity constraint in recycling channels for optimal decisions and profits. Finally, we propose a two-part tariff contract through bargaining to coordinate closed-loop supply chain and achieve a Pareto improvement.

Table 1: Notations and explanations.

Notation	*Explanation*
c_m	The production cost manufactured the new product via raw materials
c_r	The production cost manufactured the manufactured product via used products
s	The saving production cost between the new and the remanufactured product
k	The scaling parameter for collection cost in a recycling channel
γ	The competition intensity between two collection channels
b	The transfer price from manufacturer to retailer to collect used product
z_m	The available capacity constraint in the manufacturer's recycling channel
z_r	The available capacity constraint in the retailer's recycling channel
p	The retailer's selling price for unit product
w	The manufacturer's wholesale price for unit product
τ_m	The manufacturer's collection rate for used production
τ_r	The retailer's collection rate for used production
π_{sc}	The profit function for supply chain
π_m	The profit function for manufacturer
π_r	The profit function for retailer
θ_m	The bargaining power for manufacturer
θ_r	The bargaining power for retailer

3. Problem Description and Assumption

In this paper, we investigate the decision and coordination of a closed-loop supply chain, which consists of one-single manufacturer and one-single retailer under capacity constraints in recycling channel. In the forward channel, the manufacturer sells a certain type of product through the retailer to consumers. Further, the manufacturer and the retailer collect used products in the reverse channel. Since the recycling channels for used products can differ, the demands are divided into two types from both the manufacturer and retailer, which are affected by the competition intensity between the two recycling channels. To discuss the decision behavior and coordination mechanism under capacity constraints in recycling channels, we suppose that the manufacturer follows the "lot-for-lot" policy, which is applied in the existing literature. Notation and explanations are listed in Table 1.

In addition, the following assumptions are considered in our mathematical models under the capacity constraints.

Table 2: Decisions with different strategies in the centralized scenario.

Strategy	*Optimal decisions* $(p, \tau_m,$ *and* $\tau_r)$
N-N-P	$p = \dfrac{k(a+c) - 2as^2(1-\gamma)}{2[k - s^2(1-\gamma)]}, \tau_m = \dfrac{s(1-\gamma)(a-c)}{2[k - s^2(1-\gamma)]}, \tau_r = \dfrac{s(1-\gamma)(a-c)}{2[k - s^2(1-\gamma)]}$
N-N-F	$p = \dfrac{a+c-s}{2}, \tau_m = \dfrac{1}{2}, \tau_r = \dfrac{1}{2}$
Y-N-P	$p = \dfrac{k(a+c-s\cdot z_r) - as^2(1-\gamma)}{2k - s^2(1-\gamma)}, \tau_m = \dfrac{s(1-\gamma)(a-c+s\cdot z_r)}{2k - s^2(1-\gamma)}, \tau_r = z_r$
Y-N-F	$p = \dfrac{a+c-s}{2}, \tau_m = 1 - z_r, \tau_r = z_r$
N-Y-P	$p = \dfrac{k(a+c-s\cdot z_m) - as^2(1-\gamma)}{2k - s^2(1-\gamma)}, \tau_m = z_m, \tau_r = \dfrac{s(1-\gamma)(a-c-s\cdot z_m)}{2k - s^2(1-\gamma)}$
N-Y-F	$p = \dfrac{a+c-s}{2}, \tau_m = z_m, \tau_r = 1 - z_m$
Y-Y-P	$p = \dfrac{a+c-s(z_m+z_r)}{2}, \tau_m = z_m, \tau_r = z_r$
Y-Y-F	$p = \dfrac{a+c-s}{2}, \tau_m = z_m, \tau_r = z_r$

Assumption 1. Following the existing literature and many others [10, 18, 47], we suppose that there is no significant difference between new and remanufactured product and the market demand is a linear function $D = a - p$, which shows a trend of monotonically decreasing and continuous with respect to the selling price.

Assumption 2. Comparing the new and remanufactured product, we adopt c and $c - s$ to characterize the production cost for two types of products, where the average production cost $\bar{c} = c(1 - \tau_m - \tau_r) + (c - s)(\tau_m + \tau_r)$ represents the saving production cost between the new and the remanufactured product. Thus, we derive the relationship $s < \bar{c} < c$ and $0 < b < s$, which ensure the collection behavior is profitable.

Assumption 3. Considering the recycling competition between manufacturer and retailer, we introduce the competition intensity into our research, which reflects the competition level between two channels in collecting used products. Therefore, the larger the competition intensity is, the more fierce the collection is. Consistent with Zou et al. [48], Xu et al. [49] and Jerbia et al. [50], we get a symmetric influence between two channels. We suppose there exists competition between the two collection channels. This paper refers to the competition intensity between two collection channels and it reflects intense competition level between two collection agents in collecting used products. The collection investments for both the manufacturer and the retailer are a quadratic functions with the collection rate, $k(\tau_m^2 + \gamma\tau_r^2)/2(1-\gamma^2)$ and $k(\gamma\tau_m^2 + \tau_r^2)/2(1-\gamma^2)$, which is widely used in the literature [13, 19, 51].

Assumption 4. In addition, the recycling quantities from the manufacturer and the retailer are set at a level much lower than the actual levels in collecting used products [5, 52, 53]. To some extent, this is intuitively consistent with reality since the actual conditions often incur a drop recycling quantity. Hence, we adopt $0 \le \tau_m \le z_m$, $0 \le \tau_r \le z_r$ and $0 \le \tau_m + \tau_r \le 1$ as the relationship to characterize the collection rates of manufacturer and retailer.

Assumption 5. According to Zhao and Zhu [38], Wang et al., [54], and Zhao and Zhu [55], we consider a symmetric-information Stackelberg game led by the manufacturer and followed by the retailer in closed-loop supply chain, in which the bargaining power of the retailer is limited compared with that of the manufacturer.

4. Model Equilibrium

In this section, we explore the decisions of pricing and collection rate for a closed-loop supply chain in the centralized scenario and decentralized scenario. Considering the capacity constraint, the manufacturer and the retailer have two options "*N*" or "*Y*," which mean that the quantities of used products from different recycling channels exceed the capacity constraint or not. Further, we denote "*P*" or "*F*" to illustrate that a part of used products or full of used products from the manufacturer and the retailer turns remanufacturing. We discuss eight strategies to obtain equilibriums in the centralized scenario and decentralized scenario.

4.1. Centralized Scenario. Initially, we establish a centralized model for a closed-loop supply chain and get the decisions of pricing and collection rate with capacity constraint in the recycling channel. Under this structure, the manufacturer and the retailer as a system aim to maximize the total profit. Therefore, the profit function for a supply chain is given as follows

$$\begin{aligned} \pi_{sc} &= [p - c + s(\tau_m + \tau_r)](a - p) - \tfrac{k(\tau_m^2 + \tau_r^2)}{2(1-\gamma)} \\ \text{s.t.} &\quad \tau_m \le z_m, \tau_r \le z_r, \tau_m + \tau_r \le 1. \end{aligned} \tag{1}$$

Table 3: Decisions with different strategies in the decentralized scenario.

Strategy	*Optimal decisions* $(p, \tau_m,\ and\ \tau_r)$
N-N-P	$p = \frac{k(3a+c) - a \cdot s^2(3-\gamma)(1-\gamma^2)}{4k - 3s^2(3-\gamma)(1-\gamma^2)}, w = \frac{2k(a+c) - s^2(2a - \gamma a + c)(1-\gamma^2)}{4k - 3s^2(3-\gamma)(1-\gamma^2)}, \tau_m = \frac{s(a-c)(1-\gamma^2)}{4k - 3s^2(3-\gamma)(1-\gamma^2)}, \tau_r = \frac{s(a-c)(1-\gamma^2)}{4k - 3s^2(3-\gamma)(1-\gamma^2)}$
N-N-F	$p = \frac{k(3a+c-2s) + as^2(1-\gamma)(1+\gamma)^2}{4k + s^2(1-\gamma)(1+\gamma)^2}, w = \frac{2k(a+c-2s) - s^2(1-\gamma^2)(2a+\gamma a - c + 2s)}{4k + s^2(1-\gamma)(1+\gamma)^2}, \tau_m = \frac{4k - s(1-\gamma^2)[a - c + s(1-\gamma)]}{4k + s^2(1-\gamma)(1+\gamma)^2}, \tau_r = \frac{s(1-\gamma^2)(a - c + 2s)}{4k + s^2(1-\gamma)(1+\gamma)^2}$
Y-N-P	$p = \frac{k(3a + c - s \cdot z_r) - as^2(1-\gamma^2)}{4k - s^2(1-\gamma^2)}, w = \frac{2k(a + c + s \cdot z_r) - s^2(1-\gamma^2)(a + s \cdot z_r)}{4k - s^2(1-\gamma^2)}, \tau_m = \frac{s(1-\gamma^2)(a - c + s \cdot z_r)}{4k - s^2(1-\gamma^2)}, \tau_r = z_r$
Y-N-F	$p = \frac{3a + c - s}{4}, w = \frac{a + c - s(1 - 2z_r)}{2}, \tau_m = 1 - z_r, \tau_r = z_r$
N-Y-P	$p = \frac{k(3a + c - s \cdot z_m) - as^2(2-\gamma)(1-\gamma^2)}{4k - s^2(2-\gamma)(1-\gamma^2)}, w = \frac{2k(a + c - s \cdot z_m) - s^2(1-\gamma^2)(a - \gamma a - c + s \cdot z_m)}{4k - s^2(2-\gamma)(1-\gamma^2)}, \tau_m = z_m, \tau_r = \frac{s(1-\gamma^2)(a - c + s \cdot z_m)}{4k - s^2(2-\gamma)(1-\gamma^2)}$
N-Y-F	$p = \frac{as(1-\gamma^2) - k(1 - z_m)}{s(1-\gamma^2)}, w = \frac{s(1-\gamma^2)[a + s(1 - z_m)] - 2k(1 - z_m)}{s(1-\gamma^2)}, \tau_m = z_m, \tau_r = 1 - z_m$
Y-Y-P	$p = \frac{3a + c - s(z_m + z_r)}{4}, w = \frac{a + c - s(z_m - z_r)}{2}, \tau_m = z_m, \tau_r = z_r$
Y-Y-F	$p = \frac{3a + c - s}{4}, w = \frac{a + c - s(1 - 2z_r)}{2}, \tau_m = z_m, \tau_r = z_r$

Table 4: Optimal decisions and profits in different scenarios.

	θ_m	F	p	w	τ_m	τ_r	π_m	π_r	π_{sc}
Centralized scenario	—	—	5.703	—	0.462	0.45	—	—	16.146
Decentralized scenario	—	—	7.843	6.062	0.313	0.313	7.947	4.105	12.052
Coordination contract	0.5	6.725	—	5.703	0.462	0.45	10.567	5.579	16.146
	0.6	6.430	—	5.703	0.462	0.45	10.861	5.285	16.146
	0.7	6.135	—	5.703	0.462	0.45	11.156	4.990	16.146
	0.8	5.840	—	5.703	0.462	0.45	11.451	4.695	16.146
	0.9	5.545	—	5.703	0.462	0.45	11.746	4.400	16.146
	1.0	5.250	—	5.703	0.462	0.45	12.041	4.105	16.146

Proposition 1. *In the centralized scenario, the equilibrium can be expressed as in Table* 2.

Proof of Proposition 1 is in supplementary materials (available here). Proposition 2 demonstrates the following results: (1) neither the manufacturer's nor retailer's collection rates are not affected by the capacity constraints under the conditions $k > \max(k_1, k_2)$, where $k_1 = s(1-\gamma)\,(a-c+2s\cdot z_m)/2z_m$ and $k_2 = s(1-\gamma)(a-c+2s\cdot z_r)/2z_r$; (2) both the manufacturer's and the retailer's collection rates are closely associated with the capacity constraints under the conditions $k < \min(k_3, k_4)$, where $k_3 = s(1-\gamma)\ [a-c+s(z_m+z_r)]/2z_m$ and $k_4 = s(1-\gamma)$ $[a-c+s(z_m+z_r)]/2z_r$; (3) only the manufacturer's collection rate is affected by the capacity constraints under the condition $k_1 < k < k_3$; (4) only the retailer's collection rate is affected by the capacity constraints under the conditions $k_2 < k < k_4$.

4.2. Decentralized Scenario. Next, we consider the manufacturer and the retailer are independent, with the aim of maximizing one's profit. According to the Stackelberg game, the manufacturer first determines the wholesale price and collection rate. Then the retailer decides the selling price and collection rate. Therefore, the profit functions for the manufacturer and the retailer are respectively given as follows:

$$\pi_m = [w-c+s(\tau_m+\tau_r)-b\tau_r](a-p)-\frac{k\left(\tau_m^2+\gamma\tau_r^2\right)}{2\left(1-\gamma^2\right)}. \quad (2)$$

$$\begin{aligned}\pi_r &= (p-w+b\tau_r)(a-p)-\frac{k\left(\gamma\tau_m^2+\tau_r^2\right)}{2\left(1-\gamma^2\right)}\\ \text{s.t.}\quad &\tau_m \le z_m, \tau_r \le z_r, \tau_m+\tau_r \le 11\end{aligned} \quad (3)$$

Proposition 2. *In the decentralized scenario, the equilibrium can be expressed as in Table* 3.

Proof of Proposition 2 is in supplementary materials (available here). Proposition 2 demonstratesthe following results: (1) neither the manufacturer's nor retailer's collection rates are not affected by the capacity constraints under the conditions $k > \max(k_5, k_6)$, where $k_5 = s\left(1-\gamma^2\right)[a-c+sz_m(3-\gamma)](4z_m)$ and $k_6 = s\left(1-\gamma^2\right)[a-c+sz_r(3-\gamma)]/4z_r$; (2) both the manufacturer's and retailer's collection rates are closely associated with the capacity constraints under the conditions $k < \min(k_7, k_8)$, where $k_7 = s\left(1-\gamma^2\right)[1-c+s(z_m+z_r)]/4$ z_m and $k_8 = s\left(1-\gamma^2\right)[a-c+s(z_m+z_r)]/4z_r$; (3) only the manufacturer's collection rate is affected by capacity constraints under the condition $k_5 < k < k_7$; (4) only the retailer's collection rate is affected by capacity constraints under the conditions $k_6 < k < k_8$.

Next, we compare the equilibriums in the decentralized scenario and centralized scenarios to investigate the differences in optimal performance.

Proposition 3. *From the above equilibrium, the following orders can be obtained:* $p^C \le p^D, \tau_m^C \ge \tau_m^D, \tau_r^C \ge \tau_r^D$ *and* $\pi_{sc}^C \ge \pi_{sc}^D$.

This relationship can be derived through algebraic comparison. From the above, it indicates that the centralized scenario results in a lower selling price and a higher collection rate, while the minimal total profit occurs under the decentralized scenario without coordination and the maximal total profit occurs under the centralized scenario. Further, a higher saving production cost *s and lower competition intensity* k trigger the manufacturer and the retailer to engage in remanufacturing. In addition, the centralized supply chain is hard to be carried out due to the independence for the manufacturer and the retailer to promote the maximization of supply chain profit. Therefore, the gaps between the optimal performances provide a substantial motivation to coordinate the members. Hence, we will propose a contract to solve the effect of double marginalization in the supply chain, which is caused by profit conflict. The collection strategy adopted by manufacturer and the retailer depends on the values of capacity constraint in the centralized and decentralized scenarios.

4.3. Coordinated Contract. In reality, it is difficult to make an agreement possible to be accepted by both the manufacturer and the retailer, which is explained that the upstream and downstream as an independent entity cannot transfer their own decision-making authority and execute centralized scenario. In this section, we provide a side-payment self-enforcing contract to coordinate the members with capacity constraint in recycling channels. The condition for a closed-loop supply chain to achieve the performances of a centralized scenario is negotiated in an agreement, which makes the allocation of profit fair and reasonable [7, 56, 57].

In a coordinated contract, we design a two-part tariff contract through bargaining to achieve a Pareto improvement and eliminate the effect of double marginalization. According to the above, we assume that the retailer sells products with the wholesale price set by the manufacturer and the sub-game

Table 5: Sensitivity analysis for the performances considering capacity constraints.

Fluctuation of γ	−50%	−37.5%	−25%	−12.5%	0%	12.5%	25%	37.5%	50%
Centralized scenario	Case 2	Case 2	Case 5	Case 5	Case 5	Case 1	Case 1	Case 1	Case 1
p	5.65	5.65	5.662	5.683	5.703	5.737	5.778	5.819	5.859
τ_m	0.579	0.55	0.529	0.496	0.462	0.428	0.393	0.359	0.326
τ_r	0.45	0.45	0.45	0.45	0.45	0.428	0.393	0.359	0.326
π_{sc}	16.704	16.579	16.442	16.298	16.146	15.988	15.831	15.678	15.527
λ_1	0	0	+	+	+	0	0	0	0
λ_2	0	0	0	0	0	0	0	0	0
λ_3	+	+	0	0	0	0	0	0	0
Decentralized scenario	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
p	7.809	7.815	7.823	7.832	7.843	7.856	7.868	7.883	7.898
w	6.039	6.043	6.049	6.055	6.062	6.070	6.079	6.088	6.099
τ_m	0.352	0.344	0.335	0.325	0.313	0.300	0.285	0.269	0.252
τ_r	0.352	0.344	0.335	0.325	0.313	0.300	0.285	0.269	0.252
π_m	8.137	8.095	8.042	8.036	7.947	7.892	7.835	7.775	7.715
π_r	4.259	4.224	4.286	4.146	4.105	4.063	4.020	3.976	3.933
π_{sc}	12.396	12.319	12.328	12.182	12.052	11.955	11.855	11.751	11.648
λ_1	0	0	0	0	0	0	0	0	0
λ_2	0	0	0	0	0	0	0	0	0
λ_3	0	0	0	0	0	0	0	0	0

equilibrium is equivalent to that in the centralized scenario. Further, the manufacturer pays a fixed fee F to the retailer, which is negotiated by the members' bargaining powers to supply chain coordination. The bargaining powers for manufacturer and retailer are θ_m and θ_r. Therefore, the model can be characterized as follows

$$\pi_m = \left[w - c_m + c_s(\tau_m + \tau_r) - b\tau_r\right](a - w) - \frac{k\left(\tau_m^2 + \gamma\tau_r^2\right)}{2\left(1 - \gamma^2\right)} - F. \tag{4}$$

$$\begin{aligned} &\pi_r = F - \tfrac{k\left(\gamma\tau_m^2+\tau_r^2\right)}{2\left(1-\gamma^2\right)} \\ \text{s.t.}\quad &\tau_m \le z_m, \tau_r \le z_r, \tau_m + \tau_r \le 1. \end{aligned} \tag{5}$$

Proposition 4. *In this coordinated contract, the fixed fee should be satisfied as* $F = \theta_m\left[\pi_r^D + C(\tau_r^*)\right] + \theta_r\left(\pi_{sc}^C - \pi_m^D\right)$.

Proof of Proposition 4 is in supplementary materials (available here) discusses the two-part tariff contract coordinates effectively the performances in the decentralized scenario to achieve the best in the centralized scenario. Meanwhile, it also obtains a Pareto improvement, which indicates that the individual members' profits with the improved two-part tariff contract will be improved.

Proposition 5. *The two-part tariff contract through bargaining can effectively coordinate the decentralized closed-loop supply chain and achieves the performances similar to that in the centralized supply chain as follows* $w^T = p^C$, $\tau_m^T = \tau_m^C$, $\tau_r^T = \tau_r^C$ *and* $\pi_{sc}^T = \pi_{sc}^C$.

Proposition 5 indicates that the two-part tariff can improve the performances of a closed-loop to that of a centralized scenario. The manufacturer and the retailer negotiate the fixed fee F which should ensure the members' profits are not lower than those in the decentralized scenario. From the retailer's and manufacturer's profit function, the retailer benefits from the manufacturer's payment and the manufacturer covers the input in saving the production cost. Further, the lower the selling price is, the more consumers purchase the more products. In addition, it implies the two-part tariff contract through bargaining is beneficial for economic development and environmental protection in the sustainable operation of a closed-loop supply chain.

5. Numerical Analysis

In this section, we provide a numerical example to discuss theoretical results in managerial insights and analyze the influence of relevant parameters on optimal performance. Considering the values of coefficients used in the existing literature [13, 18, 58–60], we suppose that: $a = 10$, $\gamma = 0.35$, $c = 2.5$, $s = 1.2$, $k = 7.25$, $z_m = 0.6$, and $z_r = 0.45$.

5.1. Case Analysis. According to the above analysis, the optimal decisions and profits for each effective case in the centralized and decentralized scenarios are shown in Table 4.

From Table 4, we can obtain that:

(1) In the centralized supply chain, the optimal profit is obtained when $\lambda_1 > 0$, $\lambda_2 = 0$, and $\lambda_3 = 0$ since the KKT conditions should be satisfied. The supply chain can achieve maximal profit when the manufacturer's collection rate does not exceed the capacity constraint in the recycling channel and the retailer's collection rate exceeds the capacity constraint in the recycling channel. The optimal collection strategy is to collect the used product through the manufacturer since the capacity constraint from the manufacturer is greater

Table 6

(a) Sensitivity analysis for z_m on the optimal decision and profit.

Fluctuation of z_m	−60%	−45%	−30%	−15%	0%	15%	30%	45%	60%
Centralized scenario	Case 3	Case 7	Case 7	Case 5	Case 5	Case 5	Case 5	Case 5	Case 5
p	5.837	5.782	5.728	5.703	5.703	5.703	5.703	5.703	5.703
τ_m	0.24	0.33	0.42	0.462	0.462	0.462	0.462	0.462	0.462
τ_r	0.448	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
π_{sc}	15.888	16.055	16.137	16.146	16.146	16.146	16.146	16.146	16.146
λ_1	0	+	+	+	+	+	+	+	+
λ_2	+	+	+	0	0	0	0	0	0
λ_3	0	0	0	0	0	0	0	0	0
Decentralized scenario	Case 3	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
p	7.867	7.843	7.843	7.843	7.843	7.843	7.843	7.843	7.843
w	6.106	6.062	6.062	6.062	6.062	6.062	6.062	6.062	6.062
τ_m	0.24	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313
τ_r	0.310	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313
π_m	7.929	7.947	7.947	7.947	7.947	7.947	7.947	7.947	7.947
π_r	4.069	4.105	4.105	4.105	4.105	4.105	4.105	4.105	4.105
π_{sc}	12.098	12.052	12.052	12.052	12.052	12.052	12.052	12.052	12.052
λ_1	0	0	0	0	0	0	0	0	0
λ_2	+	0	0	0	0	0	0	0	0
λ_3	0	0	0	0	0	0	0	0	0

(b) Sensitivity analysis for z_r on the optimal decision and profit.

Fluctuation of z_r	−60%	−45%	−30%	−15%	0%	15%	30%	45%	60%
Centralized scenario	Case 5	Case 5	Case 5	Case 5	Case 5	Case 1	Case 1	Case 1	Case 1
p	5.876	5.832	5.789	5.746	5.703	5.694	5.694	5.694	5.694
τ_m	0.444	0.448	0.453	0.458	0.462	0.463	0.463	0.463	0.463
τ_r	0.18	0.248	0.315	0.383	0.45	0.463	0.463	0.463	0.463
π_{sc}	15.731	15.906	16.033	16.113	16.146	16.147	16.147	16.147	16.147
λ_1	+	+	+	+	+	0	0	0	0
λ_2	0	0	0	0	0	0	0	0	0
λ_3	0	0	0	0	0	0	0	0	0
Decentralized scenario	Case 5	Case 5	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
p	7.893	7.962	7.843	7.843	7.843	7.843	7.843	7.843	7.843
w	6.182	6.221	6.062	6.062	6.062	6.062	6.062	6.062	6.062
τ_m	0.293	0.296	0.313	0.313	0.313	0.313	0.313	0.313	0.313
τ_r	0.18	0.248	0.313	0.313	0.313	0.313	0.313	0.313	0.313
π_m	7.734	7.857	7.947	7.947	7.947	7.947	7.947	7.947	7.947
π_r	3.810	3.774	4.105	4.105	4.105	4.105	4.105	4.105	4.105
π_{sc}	11.544	11.631	12.052	12.052	12.052	12.052	12.052	12.052	12.052
λ_1	+	+	0	0	0	0	0	0	0
λ_2	0	0	0	0	0	0	0	0	0
λ_3	0	0	0	0	0	0	0	0	0

than that of the retailer. However, in the decentralized scenario, the collection rates from the manufacturer and the retailer are equal because of the value of the capacity constraint in the two channels.

(2) Compared with the decentralized scenario, the centralized supply chain can result in improved performances. From this point, the selling price is lower in the centralized scenario than that in the decentralized scenario, whereas the collection rates and profit are higher. Hence, this means that the centralized system can help to enhance the overall efficiency of the supply chain. In addition, the contract can coordinate the members in the profit's distribution, which means that the profits of the manufacturer and the retailer are higher than those of the decentralized supply chain, and the selling price is lower and the collection rates are higher.

(3) The two-part tariff contract through bargaining has a significant implication for improving the economic performance and environmental benefit. Therefore, the optimal profits are improved to achieve the performance of a centralized scenario and create a win–win situation for the manufacturer and the retailer through the coordinated contract if the incentive compatibility constraint is guaranteed. Moreover, the profit of supply chain in the coordinated contract is constant. When the manufacturer and the retailer integrate as a whole system, the fluctuations of bargaining powers do not influence the total profit. However, under this coordinated contract, the manufacturer's profit and retailer's profit increase as the one's own bargaining power increases. Intuitively, we find that the capacity of recycling channel plays a critical role in the decision and coordination from the above case analysis. From a managerial viewpoint, we suggest that the closed-loop supply chain can integrate the capacity constraints in both recycling channels, to fulfill consumers' demand with a cost-effective method.

5.2. Sensitivity Analysis. To illustrate the effects of competitive intensity in a recycling channel on optimal performance, we provide the impact of competitive intensity on performance. Therefore, we assume that the maximal fluctuation of γ is ±50% of the baseline values, the results of which are presented in Table 5.

From Table 5, we can conclude that:

(1) In the centralized scenario, changes in the optimal decisions and profit are larger (more than 3.6% and 7.2%) when the value of γ fluctuates in the range of $[-50\%, 50\%]$. This means that the selling price and collection rate are sensitive to the competitive intensity in the centralized scenario. Moreover, the selling price appears as monotonic increasing trend and the profits show a monotonic decreasing trend with the competitive intensity in recycling channels. However, the difference in the collection rates for members first increases and then decreases with competitive intensity increasing.

(2) In the decentralized scenario, the difference between the collection rates for the manufacturer and the retailer is more insensitive to the fluctuation of γ, which shows that the manufacturer and the retailer achieve the same collection rates. This is because, compared with the recycling channels in a no competitive situation, the larger the competition intensity is, the more expanse in collection has been invested in to obtain a same collection rate. Therefore, the decreasing collection rate with the competition intensity increasing results in a rise in the production cost, which directly leads to the higher wholesale price and selling price.

Comparing the above situations, we evaluate how the effect of competitive intensity determines the operational performance of the whole supply chain system by measuring the capacity constraint of recycling channels. Interestingly, due to the double marginal effect, the centralized supply chain is more adaptable to the changes in capacity constraints. In other words, centralized supply is more conducive to the improvement of performance between the manufacturer and the retailer to achieve a higher profit. Further, we demonstrate the effect of capacity constraint in recycling channel on the optimal decisions and profits in closed-loop supply chain and give a sensitivity analysis for the capacity constraint. Considering the maximal fluctuations of z_m and z_r are respectively ±60% of the baseline values, the calculation results are as presented in Table 6.

From Table 6, we can obtain that:

(1) In the centralized scenario, when z_m decreases by 30%, the total profit for the supply chain drops by at most 1.6% and the selling price rises by at most 2.3%, the collection rates decrease by at most 49.1% and 0.6% respectively. Meanwhile, the total profit for the supply chain drops by at most 2.6% and the selling price rises by at most 3.1%, and the collection rates decreases by at most 4.3% and 61.3% when z_r decreases by 30%. Obviously, this means that the selling price is more sensitive than the total profit for the supply chain to capacity constraint in recycling channels. Further, the manufacturer's collection rate is more affected and the retailer's collection rate is not much affected by z_m, whereas the situation in the change of z_r demonstrates the opposite. Additionally, the optimal decisions and profits will change if the capacity constraint in recycling channels exceeds a certain threshold.

(2) In the decentralized scenario, when $\lambda_1 = 0, \lambda_2 = 0$, and $\lambda_3 = 0$, the optimal decision and profit are not affected by the change of z_m and z_r. However, the collection rate for the manufacturer shows a significant declining trend and the collection rate for the retailer is negligible with the value of z_m when $\lambda_1 = 0$, $\lambda_2 > 0$ and $\lambda_3 = 0$; this situation is the contrary with the change of z_r when $\lambda_1 = 0$, $\lambda_2 > 0$ and $\lambda_3 = 0$. It indicates that the members in the decentralized scenario result in a double marginalization effect, that is, the members determines a higher selling price and a lower collection rate. Therefore, only if the capacity constraint in recycling channels has a huge reduction can the decision and profit be effected. This indicates that the government should provide a more attention to ensure the recycling capacity for members in closed-loop supply chain. Specifically, the capacity constraints in recycling channels may cause a smoothing effect in the fabrication of both the manufacturing ability and the market demand.

6. Conclusions

This paper studies the decision and coordination in a closed-loop supply chain considering capacity constraints in recycling channels, which the manufacturer and retailer should determine the optimal selling prices and collection rate to balance their profits. Comparing the performances in the centralized scenario and decentralized scenario, we obtain the following results; (1) The centralized scenario results in a lower selling price and a higher collection rate, while the minimal profit occurs under the decentralized scenario without coordination and the maximal profit occurs under the centralized scenario. (2) A higher saving production cost and lower competition intensity trigger the manufacturer and the retailer to engage in remanufacturing. To coordinate closed-loop supply chain, we propose a two-part tariff contract and combine the bargain theory to achieve a Pareto improvement. In addition, the numerical analysis discussed the following managerial insights; (1) The optimal decisions and profits will change when the capacity constraint in recycling channel exceeds a certain threshold. Further, the selling price is more sensitive than the total profit for supply chain to capacity constraint in recycling channels. Hence, the closed-loop supply chain should find ways, through environmental propaganda and remanufacturing technologies to expand the capacity of recycling channels. (2) The optimal collection strategy is to collect the used product through the manufacturer since the capacity constraint from the manufacturer is greater than that of the retailer. Moreover, the difference in the centralized scenario between the collection rates from the manufacturer and the retailer are not equal to that of the centralized scenario because of the value of the capacity constraint in the two channels. Obviously, it is significantly important that the cooperation between the manufacturer and the retailer avoids the double marginal effect. (3) Specifically, the capacity constraints in recycling channels create a smoothing effect in the fabrication of both the manufacturing ability and market demand. Further, the two-part tariff contract through bargaining has a significant implication for improving the economic performance and environmental benefit, which improves the optimal profit to achieve the performance of centralized scenario and make a win–win situation for members via the coordinated contract if the incentive compatibility constraint is guaranteed.

This paper does not consider the uncertainty of market demand and asymmetric information, which are the future research to explore the equilibrium of a closed-loop supply chain with capacity constraints. In addition, introducing the insight of government into the decision and coordination for a closed-loop supply chain is another significant topic.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

The proof for propositions. (*Supplementary Materials*)

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