

Research Article

Coordination of Closed-Loop Supply Chain with Dual-Source Supply and Low-Carbon Concern

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Considering the impact of dual-source supply and low-carbon manufacturing on a closed-loop supply chain (CLSC) system, this article constructs a CLSC model with two competitive dominant upstream suppliers and one following a downstream (re-) manufacturer, then coordinates supply chain through cost-sharing contract. Based on the industrial case in the area of power battery, we analyze the optimal strategies under competition, cooperation, and coordination structures separately and then investigate the influences of emission reduction effort and collection efficiency on supply chain performance. The results reveal that collection of used products can positively affect the (re-)manufacturer's profit but has opposite impact on the new component supplier. Besides, recycling is beneficial to both low-carbon consumers' utility and social welfare, but hurts the total profit of CLSC because of the high investment cost of collection. Therefore, the paper designs a cost-sharing contract, which is of applicability and efficiency for both economic and environmental development. Furthermore, it can also increase the profit of CLSC up to cooperation case and improve each member's profit, eliminating double marginal effect and achieving supply chain coordination.

1. Introduction

With the shortage of raw material resources and the increase of environmental concerns, such as carbon emissions and global warming, resources conservation and environmental protection have become the most concerned topics all over the world [1, 2]. Manufacturing has the positive influences on the economic development but negative effects on environmental protection [3, 4]. The integration of the reverse supply chain system with multiforward channels has drawn public attention. Manufacturing activities, although can be beneficial to economic development, will prevent the environment and resource conservation [5]. Hence, it is necessary and important to create a closed-loop supply chain system for improving the efficiency of collecting and remanufacturing [6]. Moreover, unlike the traditional supply chain, in which competition only exists in its forward supply channel, the suppliers start to focus on the recycling activities in CLSC, which can create a huge profit margin. Meanwhile, firm's optimal decisions in the reverse channel can affect the performance in the forward channel, forcing

manufacturers to take pricing strategy and emission reducing strategy into consideration simultaneously. Nowadays, consumers have growing low-carbon awareness and are willing to purchase ecofriendly products even though have to pay a higher price, which facilitates manufacturers to reduce carbon emissions in producing process, then decreases negative impact on environment, improves social welfare, and stimulates low-carbon demand. For instance, Fuji Xerox, a Japanese firm which produces printers and duplicators, started its recycling business (such as collects printer consumables and remanufactures printers) from 2008, and had obtained over 200 million dollars cost saving in five years. At the same time, its carbon emissions incurred by producing had been effectively reduced. As to Hewlett-Packard, it began recycling business in 1990s and its collection efficiency was relatively higher than other enterprises. Early in 2012, HP collected over 160,000 tons of consumables and more than 80% were reused, which dramatically increased HP's competition in PC market. Likewise, in China, many electric vehicle manufacturers and power battery producers, such as FAW Group and CATL,

have realized the importance of recycling and emission reduction. They began to develop circular economy and build a conservation-oriented manufacturing system by collecting used batteries and remanufacturing new electric vehicles [7]. Therefore, this paper investigates the CLSC with competitive suppliers and (re-)manufacturer and then analyzes the optimal strategy of each member, which can increase the utilization of used products and decrease the carbon emissions in the entire society [8, 9].

According to a survey conducted by Chinese National Bureau of Statistics, “2018 Statistical Bulletin of National Economic and Social Development,” the GDP of the automobile manufacturing industry increased by 15.5% while the recycling and remanufacturing development was stagnant due to the inefficiency in combining pricing and collecting strategies at the same time. In 2017, the number of private electric vehicles in China reached more than 1.7 million, the year-on-year growth was 61.7% and kept growing. In general, a power battery’s lifetime is around five years, which will definitely cause a sharp increase of scrap rate in the near future. Nevertheless, the recycling number of used vehicles only accounts for 1.5% of the total private cars in 2016. Apparently, if the collecting and remanufacturing activities cannot be implemented efficiently, there will be huge waste of resources and environmental pollution. Therefore, the Chinese government offers subsidy to electric vehicle enterprises to support them in manufacturing as well as recycling, which is beneficial not only to social carbon emission reduction but also to resource conservation. Current studies should pay emphasis on several aspects: collecting used products, remanufacturing with emission reduction concern, and selling products to low-carbon consumers. Furthermore, it will be of great significance for researchers to focus on designing an effective recycling supply chain system and its coordination mechanism.

Up to now, there were a great number of research studies which investigated CLSC, but most of them focused on downstream firms and consumers’ strategy, analyzing the competition or cooperation between manufacturers, retailers, and collectors. Few research studies discussed the performance of competitive suppliers in forward channels when taking reverse flow and coordination contracts into consideration. Xie et al. [10] built a dual-channel model and discussed pricing competition between two retailers, neither concerning suppliers’ competition nor carbon emission reduction. Although Giri et al. [11] considered the competitive forward channel in CLSC, they did not investigate the impacts of emission reduction on supply chain performance. In CLSC research area, most studies focus on the optimal decision analysis [12, 13], coordination contract design [14, 15], recycling and remanufacturing strategy [16], differential pricing strategies of new and remanufactured products [17], and so on. Furthermore, concentrating on multireverse channels, many research studies discussed two types of collection ways: recycling by oneself [18, 19] or by third-party collector [20, 21]. However, these reviewed papers did not take emission reduction into consideration.

On the other hand, as to recyclable products, such as automobiles and electronic appliances, only the core components are worth to be collected and remanufactured. When the traditional suppliers started to collect used products, a dual-source supply system would immediately form and competition occurred between the new component suppliers and recycled component suppliers. Thus, the stronger supplier can gain more benefit by increasing the wholesale price, while the weaker one would inevitably lose profits [22]. Generally, when the recycling suppliers enter the market, they not only compete with the original suppliers but also count on them for new components. When this supply chain mode generates, it brings more conflicts and incoordination. Therefore, it is very urgent to study the optimal decision-making process and coordination mechanism of CLSC which is composed of new and recycled component suppliers as well as a (re-)manufacturer [23]. In existing research studies, many works designed coordination mechanism in the forward channel. Zheng et al. [24] analyzed a coordination model for CLSC with cooperative and noncooperative games. Xie et al. [25] further built a coordination model with two competitive sale channels and one reverse channel. However, these articles all neglected the impact of carbon emission reduction on supply chain and consumer’s strategies.

With the increasing emphasis paid by the government on resource and environment issues, the recycling of used products has received more attention, and then a series of policies and regulations were implemented. Recycling suppliers gained more power to compete with traditional suppliers [26]. As to dual-source supply, Li et al. [27] studied the procurement and pricing strategies in the dual-suppliers case and designed a coordination mechanism to effectively increase the total profit of CLSC. Moreover, Zhang and Chen [28] discussed the impact of different contract coordination mechanisms under dual-source supply and found that the impact of wholesale price contract and revenue-sharing contract in the dual-source supply chain is very different from the single-supply system. Xiong et al. [29] indicated that manufacturers are more willing to collect and remanufacture the used products. Furthermore, Cui et al. [30] focused on the utility of RFID technology in the dual-source supply chain and identified the optimal order quantity and profit. Nevertheless, these papers all ignored the low-carbon consumers’ influence on manufacturing and recycling.

As discussed above, the environmental concerns and consumers’ environmental awareness stimulates enterprises to make more ecofriendly efforts. In addition, emission reduction is an effective method to enhance the environmental features of products and attract more low-carbon consumers [31]. Recently, studies began to focus on this factor in supply chain management. Xu et al. [32] further investigated the optimal reduction degree in a CLSC, and Du et al. [33] found that proper supply chain contracts could positively affect the decision-making process of supply chain members. However, few studies consider emission reduction under competitive situation. Some studies have not proposed coordination contracts, and others have not taken

emission reduction into CLSC. Hence, this paper for the first time proposes a new method to simultaneously coordinate emission reduction and competitive dual-source supply decisions in a CLSC.

1.1. Research Gaps and Contributions. From the literature review, the following research gaps are identified:

(1) Most previous research studies have not paid enough attention to the competition between new and recycled component suppliers when the latter one also acts as a collector, not even researched on the coordination of this dual-source supply system. (2) Few research studies have considered supply competition under coordination contracts when reverse logistics is provided by one of the suppliers. (3) Although some studies have discussed the competition in the supply channel, few of them introduce the ecofriendly factor, such as emission reduction, into the supply chain, which will dramatically influence the consumer's willingness to pay and manufacturer's profit.

This paper investigates a two-echelon CLSC comprising of one manufacturer, two competitive suppliers in forward logistics, and one of suppliers also acts as a monopolistic collector in reverse logistics. This model fits in many practical cases, such as home appliance, electronic equipment, production facility, and electric vehicle, while the (re-) manufacturer faces three challenges. (1) How to increase the recycling rate of recycled products? (2) How to enhance the consumers' willingness to pay? (3) How to satisfy the stricter carbon emission requirements? The model has been investigated under various decision-making modes: centralized, decentralized, and coordinated, which can be regarded as the competition, cooperation, and coordination structures in business operation. First, firms make pricing, recycling, and emission reducing strategies under the aim of maximizing their respective profits in the competition model. Second, the cooperation model is an optimal, benchmark case, in which firms make joint decisions for maximizing the total profit of CLSC. Ultimately, due to the double marginal effect caused by decentralized decision in the competition model, we design and implement a cost-sharing contract to coordinate CLSC. Under the proposed contract, firms in CLSC are simultaneously coordinated in which all members' profit are improved and total profit reach up to the level of the cooperation model.

2. Model Description and Assumption

In this paper, a dual-channel CLSC with competitive forward supplying and monopolistic reverse recycling is taken into account. The article builds a CLSC model consisting of one (re-)manufacturer and two competing suppliers in which one of suppliers also play the role of recycling recycled products. In the forward channel, (re-)manufacturers produce or remanufacture products from both new and recycled component suppliers. In this case, the new supplier competes on selling components to the (re-)manufacturer with the recycling supplier. The suppliers who take charge of the

core technology can dominate the whole supply chain firstly decide their wholesale price and collection rate individually. Then, the (re-)manufacturer decides the pricing and emission reducing strategies. On the other hand, in the reverse channel, the recycled component supplier is responsible for collecting recycled products from the consumers to the (re-) manufacturer. Therefore, the collection rate is a key factor, which significantly affects profit, which needs to be optimized. For instance, in the case of HP printers, Hewlett-Packard commissioned the recycled plastics supplier, Lavergne Group, to collect the used ink cartridges and then further reprocess them. At the same time, HP also purchases new ink cartridges from other cartridge suppliers, manufactures all cartridges from different supply channels, and then sells to consumers. Recently, HP has recognized the importance of environmental products and considered emission reduction in producing process, not only to attract low-carbon consumers but also to satisfy government emission regulation.

The proposed model is analyzed under three decision-making structures: competition, cooperation, and coordination models. In the two-echelon decentralized model, firms make their own strategies only considering their own profit, forming a Stackelberg game model in which the equilibriums can be obtained by the Nash backward induction method [34]. The dominant suppliers make decisions first, and then the (re-)manufacturer acts according to the optimal strategies of suppliers. However, the double marginal effect occurs in this decision model, decreasing the supply chain efficiency. Therefore, a coordination model needs to be introduced. In order to design a proper contract, we investigate a cooperation model as a benchmark, in which all supply chain members make joint decisions under the aim of optimizing the entire CLSC profit. Finally, a coordination model is proposed to facilitate the cooperation between firms and achieve channel coordination. The structure of CLSC is shown in Figure 1.

2.1. Notations. The notations used in this study are summarized in Table 1.

2.2. Assumptions. In order to simplify the calculation, we make necessary assumptions without loss of generality:

- (1) In the low-carbon market, demand is affected by the consumers' preference of environmental protection. In addition to the price, consumers also take the emission reduction level of products into consideration. Therefore, the higher the environmental performance of products (in terms of carbon emission reduction degree), the higher the demand. In this paper, linear demand function is used as follows, which is also used in studies of Chen [35], and Kouvelis and Zhao [36]. Market demand function is $D(p, L) = d - \alpha p + \beta L$, where d denotes the market size, α denotes the price elasticity of demand, β denotes the consumer's preference intensity for low-carbon products, and $\alpha > \beta > 0$.

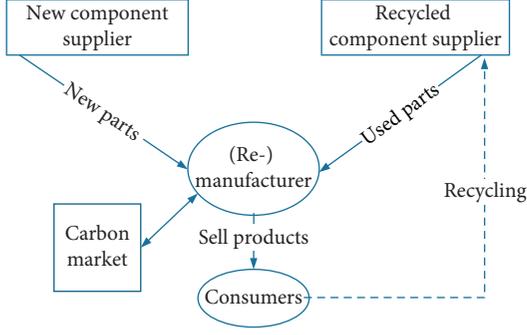


FIGURE 1: Framework of the competitive supply chain.

- (2) The collection rate is depended on the investment in collecting recycled products. According to the research of Huang et al. [37], the collection rate increases with the growth of investment, $\theta = \sqrt{2I_\theta/b}$. In order to increase the collection rate, the recycling supplier should invest more, such as promoting and advertising events. In general, the investment increases faster in the higher range of the collection rate. b is a scalar parameter which should be large enough to ensure the range of the collection rate in $[0, 1]$.
- (3) The downstream (re-)manufacturer can produce from new components with cost c_n and recycled components with cost c_o , $c_o < c_n$. Manufactured and remanufactured products have the same quality level and can be sold as the same price. Same assumption was considered in the paper of Xie et al. [10].
- (4) In reality, the environmental enterprises will make effort to reduce carbon emissions during producing process, through improving technology or equipment. According to Giri et al. [38], emission reduction degree is positively correlated with reduction efforts. The cost will increase more rapidly with the growth of emission reduction. In other words, the cost of emission reduction increases concavely with respect to reduction degree. Therefore, (re-)manufacturer's investment function can be assumed as a quadratic function, $c(L) = kL^2/2$. The higher the k , the higher the technical resistance and the investment in reduction. In order to ensure the existence of solutions, k should be assumed as large as possible.

3. Model Formulation

3.1. Competition Structure. In the decentralized CLSC, that is, the competition structure, (re-)manufacturer, and new and recycling suppliers decide their strategies individually in order to maximize their own profit. In this two-echelon Stackelberg game model, the dominant suppliers first decide the wholesale price and collection rate simultaneously, and then the following (re-)manufacturer decides its sales price and emission reduction degree. Two competitive suppliers ignore the effect of their strategies on others. According to

Nash equilibrium, the optimal decision of each member in CLSC can be solved. The following sections analyze the problems in detail.

3.1.1. (Re-)manufacturer's Problem. The (re-)manufacturer profit consists of four terms: sales revenue, cost of products by new components, cost of products by recycled components, and cost of emission reduction. The profit function is as follows:

$$\max_{p,L} \pi_M = pD - (w + c_n)(1 - \theta)D - (w + c_o)\theta D - \frac{kL^2}{2}. \quad (1)$$

Proposition 1. *In this CLSC, the (re-)manufacturer makes pricing and emission reduction policies after suppliers. The optimal decisions exist due to the concavity of profit function w.r.t p and L . The optimal profit is dramatically influenced by the suppliers' wholesale price and collection rate.*

Proof. Take the second order derivative of the (re-)manufacturer's profit function with respect to carbon emission reduction effort and sales price separately, obtaining $\partial^2 \pi_M / \partial p^2 = -2\alpha < 0$, $\partial^2 \pi_M / \partial L^2 = -k < 0$, and Hessian matrix $\begin{vmatrix} \partial^2 \pi_M / \partial p^2 & \partial \pi_M / \partial L \partial p \\ \partial \pi_M / \partial p \partial L & \partial^2 \pi_M / \partial L^2 \end{vmatrix} = 2k\alpha - \beta^2 > 0$. The profit function of the (re-)manufacturer under the competition structure is concave with respect to p and L . Then, according to the backward induction method, the optimal decisions are solved by FOC; substituting in $\partial \pi_M / \partial L = 0$ and $\partial \pi_M / \partial p = 0$ gives

$$L = \frac{d\beta - \alpha\beta[w + (1 - \theta)c_n + \theta c_o]}{2k\alpha - \beta^2}, \quad (2)$$

$$p = \frac{kd + (k\alpha - \beta^2)[w + (1 - \theta)c_n + \theta c_o]}{2k\alpha - \beta^2},$$

which when substituted into the objective function yields

$$\pi_M = \frac{k[d - w\alpha - \alpha c_n(1 - \theta) - \alpha\theta c_o]^2}{4k\alpha - 2\beta^2}. \quad (3)$$

□

3.1.2. Suppliers' Problem. The new component supplier's profit consists of the sales revenue minus supply cost, and its supply quantity is equal to the market demand minus the quantity of recycled products. The profit function is as follows:

$$\max_{w_n} \pi_N = (w - sc_n)(1 - \theta)D. \quad (4)$$

Likewise, the profit function of the recycling supplier can be expressed as follows:

$$\max_{\theta} \pi_O = (w - a_o)\theta D - I_\theta. \quad (5)$$

In the first stage of decision-making process, two competitive suppliers simultaneously and individually make

TABLE 1: Decision variables and parameters.

Parameters	
c_n	Unit manufacture cost from a new component
c_o	Unit manufacture cost from a recycled component, $c_o < c_n$
sc_n	Unit supply cost of new component supplier
a_o	Unit acquisition price of recycled products paid to consumers, $a_o < sc_n$
k	Cost coefficient of emission reduction effort
b	Cost coefficient of investment in collecting used products
I_θ	Investment of recycling supplier in collecting used products from consumers
L_0	Initial unit carbon emission of (re-)manufacturer before reducing emissions
L_G	Unit carbon quota set by government, $0 < L_G < L_0$
P_c	Unit carbon emission right trading price in carbon market
D	Market demand function
π_N	New component supplier's profit
π_M	(Re-)manufacturer's profit
π_O	Recycled component supplier's profit
π_S	Supply chain total profit
Decision variables	
L	Unit emission reduction degree decided by (re-)manufacturer
p	Unit sales price decided by (re-)manufacturer
θ	Collection rate of used products decided by recycling supplier, $0 < \theta < 1$
w	Wholesale price decided by new component supplier

their optimal decisions, wholesale price and collection rate. The equilibrium can be calculated by the backward induction method.

Proposition 2. *In this CLSC, two competitive suppliers make pricing and collection investment policies firstly. The optimal decisions exist due to the concavity of profit functions w.r.t w and θ .*

Proof. Substitute equation (2) into profit functions (4)–(5). Take the second order derivative of the suppliers' profit functions with respect to the wholesale price and collection rate separately, obtaining $\partial^2 \pi_N / \partial w^2 = -(2k\alpha^2(1-\theta)^2 / 2k\alpha - \beta^2) < 0$ and $\partial^2 \pi_O / \partial \theta^2 = -b - (2k\alpha^2(w - a_o)(c_o - c_n) / 2k\alpha - \beta^2) < 0$. The profit functions of suppliers under the competition structure are both concave with respect to their own decision variables. Then, the optimal decisions are solved by FOC; substituting in $\partial \pi_N / \partial w = 0$ and $\partial \pi_O / \partial \theta = 0$ gives

$$w^{*d} = \frac{d - \alpha[(1 - \theta^*)c_n + \theta^*c_o - sc_n]}{2\alpha}, \quad (6)$$

$$\theta^{*d} = \frac{k\alpha[d - \alpha(c_n + w^*)](w^* - a_o)}{b(2k\alpha - \beta^2) - 2k\alpha^2(w^* - a_o)(c_n - c_o)}.$$

Substituting (6) into (2) yields

$$L^{*d}(\theta^*) = \frac{\beta[d - \alpha(1 - \theta^*)c_n - \alpha(\theta^*c_o + sc_n)]}{4k\alpha - 2\beta^2},$$

$$p^{*d}(\theta^*) = \frac{2\alpha dk + (k\alpha - \beta^2)[d + \alpha((1 - \theta^*)c_n + \theta^*c_o + sc_n)]}{2\alpha(2k\alpha - \beta^2)}. \quad (7)$$

Finally, the optimal profits of enterprises in CLSC obtain

$$\pi_M^{*d} = \frac{k[d - \alpha(1 - \theta)c_n - \alpha(\theta c_o + sc_n)]^2}{16k\alpha - 8\beta^2},$$

$$\pi_N^{*d} = \frac{k(1 - \theta)[d - \alpha(1 - \theta)c_n - \alpha(\theta c_o + sc_n)]^2}{8k\alpha - 4\beta^2}, \quad (8)$$

$$\pi_O^{*d} = \frac{k\theta[d - \alpha(2a_o + (1 - \theta)c_n + \theta c_o - sc_n)][d - \alpha(1 - \theta)c_n - \alpha(\theta c_o + sc_n)]}{8k\alpha - 4\beta^2} - \frac{b\theta^2}{2}.$$

□

Lemma 1. *In this CLSC under the competition structure, when the collection investment of the recycled component supplier gradually increases, that is, the collection rate grows, the wholesale price paid by the (re-)manufacturer will increase.*

Lemma 2. *In this CLSC, the sales price decreases with the growth of the collection rate, but the emission reduction degree increases. Recycling is beneficial to both consumers and social welfare.*

Proof. Take the first derivative order of the optimal wholesale price w.r.t. collection investment, $\partial w^{*d}/\partial\theta = c_n - c_o/2$. Because the cost of producing from recycled components is less than the new components, $c_n > c_o$; therefore, $\partial w^{*d}/\partial\theta > 0$. As to the (re-)manufacturer's sales price and emission reduction policies, obtain $\partial p^{*d}/\partial\theta = -((k\alpha - \beta^2)(c_n - c_o)/4k\alpha - 2\beta^2) < 0$ and $\partial L^{*d}/\partial\theta = (\alpha\beta(c_n - c_o)/4k\alpha - 2\beta^2) > 0$.

According to Lemma 1 and 2, in the CLSC, when the competitive suppliers dominate the whole supply chain and the (re-)manufacturer makes decisions accordingly, the collection investment of the recycled component supplier has a positive effect on the wholesale price paid by the (re-)manufacturer. This is because the order quantity of new components reduces when the quantity of recycled components rises. In order to maintain profit, the new component supplier can increase the wholesale price due to the leadership power. On the other hand, when the collection rate increases, the (re-)manufacturer's producing cost decreases, leading the dominant suppliers gain more advantages from the (re-)manufacturer.

As to the products' sales price and emission reduction degree, their changing trends are different with the growth of the collection rate: sales price decreases and emission reduction degree increases. This is because recycling from used products can reduce the producing cost of the (re-)manufacturer and further push him to make more effort on attracting low-carbon consumers, which is beneficial to both himself and his upstream firms-suppliers. \square

Lemma 3. *In this CLSC, as the collection investment of the recycling supplier increases, the profit of the new supplier decreases, but the (re-)manufacturer's profit rises. Furthermore, as to the cost-saving efficiency of recycling, $\Delta = c_n - c_o$, it can facilitate the influence of the collection rate on profits.*

Proof. According to the assumptions, $\partial\pi_M^{*d}/\partial\theta = (k\alpha(c_n - c_o)[d - \alpha(1 - \theta)c_n - \alpha(\theta c_o + sc_n)]/8k\alpha - 4\beta^2) > 0$ and $\partial\pi_N^{*d}/\partial\theta = -(k(d - 3\alpha(1 - \theta)c_n + \alpha(2 - 3\theta)c_o - \alpha sc_n)[d - \alpha(1 - \theta)c_n - \alpha(\theta c_o + sc_n)]/8k\alpha - 4\beta^2) < 0$. The increasing slope of $\partial\pi_M^{*d}/\partial\theta$ and decreasing slope of $\partial\pi_N^{*d}/\partial\theta$ will become sharper when Δ increases.

From the perspective of Lemma 3, when the recycling supplier invests more in collecting used products, such as advertising and door-to-door service, the downstream enterprise in CLSC-(re-)manufacturer can gain more profit

from the recycling supplier's action. However, the new component supplier's profit decreases when the competitor craves up more market. This result is consistent with the reality. This is because the producing cost of the remanufactured component is less than the new component so that when the wholesale prices are equal and the recycling capacity increases, the cost of the (re-)manufacturer decreases while the market demand does not, leading to a growth in the manufacturer's profit. At the same time, the dominant, the competitive supplier gets less profit instead because of losing demand.

Generally, with the continuous development of recycling and remanufacturing technology, the recycling cost will gradually decrease. Therefore, the products' sales price and reduction degree will change more dramatically with the collection rate. Likewise, the profits of supply chain members also change sharply. This shows that the advancement of producing technology and recycling methods and management can be beneficial to not only the low-carbon consumers but also the social welfare. Eventually, recycling of used products hurts the new component suppliers, forcing them to prevent the entry and development of the recycling supplier at the initial stage. Thus, it is necessary and important to eliminate the double marginal effect caused by decentralized decision-making and keep the high profit margins of CLSC, which are the main objectives of the following sections. \square

3.2. Cooperation Structure. In the centralized decision-making structure, that is, the cooperation structure, all CLSC members collectively make policy from the whole supply chain view, maximizing the entire CLSC profit. Therefore, the total profit function is a sum of the profits of the (re-)manufacturer and suppliers as follows:

$$\max_{p, L, \theta} \pi_S = pD - D(1 - \theta)(c_n + sc_n) - \theta D(a_o + c_o) - \frac{kL^2}{2} - \frac{b\theta^2}{2}. \quad (9)$$

Proposition 3. *In the cooperation model, the optimal decisions exist due to the concavity of profit function w.r.t p , L , and θ .*

Proof. As discussed above, the concavity of the CLSC can be verified by $\partial^2\pi_S/\partial p^2 = -2\alpha < 0$, $\partial^2\pi_S/\partial L^2 = -k < 0$, and $\partial^2\pi_S/\partial\theta^2 = -b < 0$. Hessian matrix $\begin{vmatrix} \partial^2\pi_M/\partial p^2 & \partial\pi_M/\partial L \partial p \\ \partial\pi_M/\partial p \partial L & \partial^2\pi_M/\partial L^2 \end{vmatrix} = 2k\alpha - \beta^2 > 0$ and $\begin{vmatrix} \partial^2\pi_S/\partial p^2 & \partial\pi_M/\partial p \partial L & \partial\pi_M/\partial p \partial\theta \\ \partial\pi_M/\partial L \partial p & \partial^2\pi_S/\partial L^2 & \partial\pi_M/\partial L \partial\theta \\ \partial\pi_M/\partial\theta \partial p & \partial\pi_M/\partial\theta \partial L & \partial^2\pi_S/\partial\theta^2 \end{vmatrix} = -2kab + b\beta^2 + k\alpha^2(c_n - c_o + sc_n - a_o)^2 < 0$. According to the FOC and backward induction method, the optimal sales price, emission reduction degree, and collection rate are solved by $\partial\pi_S/\partial p = 0$, $\partial\pi_S/\partial L = 0$, and $\partial\pi_S/\partial\theta = 0$ as follows:

$$\begin{aligned}
p^{*c} &= \frac{b(c_n + sc_n)(k\alpha - \beta^2) + dkb - dk\alpha(c_n - c_o + sc_n - a_o)^2}{b(2k\alpha - \beta^2) - k\alpha^2(c_n - c_o + sc_n - a_o)^2}, \\
L^{*c} &= \frac{b\beta[d - \alpha(c_n + sc_n)]}{b(2k\alpha - \beta^2) - k\alpha^2(c_n - c_o + sc_n - a_o)^2}, \\
\theta^{*c} &= \frac{k\alpha(c_n - c_o + sc_n - a_o)[d - \alpha(c_n + sc_n)]}{b(2k\alpha - \beta^2) - k\alpha^2(c_n - c_o + sc_n - a_o)^2},
\end{aligned} \tag{10}$$

which when substituted into the objective function yields

$$\pi_S^{*c} = \frac{bk[d - \alpha(c_n + sc_n)]^2}{b(4k\alpha - 2\beta^2) - 2k\alpha^2(c_n - c_o + sc_n - a_o)^2}. \tag{11}$$

□

Lemma 4. *The double marginal effect can be eliminated under the cooperation structure. Meanwhile, the sales price is relatively lower but the emission reduction degree is higher than the competition case. Similarly, the changing trends of the sales price and emission reduction are the same with the competition case.*

Proof. Substituting the optimal collection rate function into sales price, emission reduction and profit function obtains $\pi_S^{*c} - \pi_S^{*d} = (k[d - \alpha(c_n + sc_n)] + \alpha\theta(2sc_n - 2a_o + c_n - c_o)]^2 / 16k\alpha - 8\beta^2 > 0$, $p^{*c} - p^{*d} = -((k\alpha - \beta^2)[d - \alpha(c_n - \theta(2sc_n - 2a_o + c_n - c_o) + sc_n)] / 2\alpha(2k\alpha - \beta^2)) < 0$, and $\pi_S^{*c} - \pi_S^{*d} = (k[d - \alpha(c_n + sc_n)] + \alpha\theta(2sc_n - 2a_o + c_n - c_o)]^2 / 16k\alpha - 8\beta^2 > 0$. Then, investigate the changing trend with respect to the collection rate: $\partial L^{*c} / \partial \theta = \alpha\beta(c_n - c_o + sc_n - a_o) / 2k\alpha - \beta^2 > 0$,

$$\frac{\partial p^{*c}}{\partial \theta} = -\frac{(k\alpha - \beta^2)(c_n - c_o + sc_n - a_o)}{2k\alpha - \beta^2} < 0. \tag{12}$$

It can be learnt from Lemma 4 that, since all CLSC members can be treated as one and have the same pursuit in centralized decision-making process, double marginal effect disappears and the total profit is distributed according to their bargaining power. A higher profit will motivate the (re-)manufacturer to pursue more market demand by increasing investment in emission reduction and reduce sales price. In fact, the dominant suppliers will also force the (re-)manufacturer to do so for more ordering quantity of components. This shows that the cooperation structure is more efficient for both consumers and enterprises in CLSC. The cooperation structure as a benchmark achieves the optimal performance. However, in reality, although the upstream and downstream enterprises cooperate in one supply chain, they hardly completely reach an agreement and share their information without distinction. Therefore, a proper coordination mechanism, which can be accepted by all firms, needs to be proposed.

Due to the complexity of calculation, the comparison and sensitivity analysis are shown by numerical examples in the next section. □

4. Numerical and Sensitivity Analysis

This section analyzes the performance of various models through the numerical examples, investigates variations of the optimal decisions and profits, and discusses the impacts of firms' decisions on consumers utility and social welfare. Furthermore, to investigate the performance of the proposed models, sensitivity analyses on the critical parameters are provided.

According to our model, a real case of a Chinese power battery (EV Cell) manufacturing enterprise, CATL, can be used. In practice, CATL can produce electric vehicle batteries from both new and recycled cells because cells' material can be extracted and purified repeatedly without reducing the battery's efficiency. Generally, CATL has two types of suppliers: one provides new cells and the other collects used batteries and provides recycled cells. Furthermore, in order to promote environmental sustainability in electric vehicles and increase low-carbon consumers' willingness to pay, it is important for CATL to consider carbon emission reduction and invest in manufacturing technology. Due to the complexity of valuing parameters, we set some number based on the assumptions and CATL case.

In the forward channel, two suppliers compete in providing different types of components. The cost of providing a new component is $sc_n = 6$, which is higher than that of the recycled component, $a_o = 4$. The producing cost with the new component, $c_n = 2$, is also higher than the recycled one, $c_o = 1$, because producing by the new component cause the extra cost of fittings. Furthermore, in order to satisfy consumers' low-carbon preference, the (re-)manufacturer invests in emission reduction. The reduction cost coefficient $k = 10^4$ and its impact on demand with coefficient β . The potential market demand is $d = 10^4$ and the price coefficient is $\alpha = 100$. The collection cost is associated with the recycling supplier's investment which has cost coefficient $b = 4 \times 10^5$, which should be extremely high to ensure the rational range of the collection rate.

Results of the numerical studies with various decision-making structures are indicated in the following figures. Firstly, in the presence of competition structure, the decision variables and profits of supply chain members are all significantly influenced by consumers' low-carbon preference, as shown in Figure 2. Z is a constant which can make figures more intuitive without affecting the conclusions.

As can be seen from Figure 2, the wholesale price decided by the new component supplier, the collection rate set by the recycling supplier as well as the emission reduction degree and sales price determined by the (re-)manufacturer all increase with the growth of the consumers' low-carbon preference, and the stronger the preference, the steeper the slope scale. When the CLSC faces the low-carbon market, the consumers' willingness to pay is greatly influenced by the products reduction degree. The higher the reduction level, the more the demand. Therefore, the manufacturer will firstly increase the investment in reduction, which causes a growth in producing cost and eventually raises the sales price. Because suppliers dominate the whole supply chain, they can immediately increase the wholesale price in order to

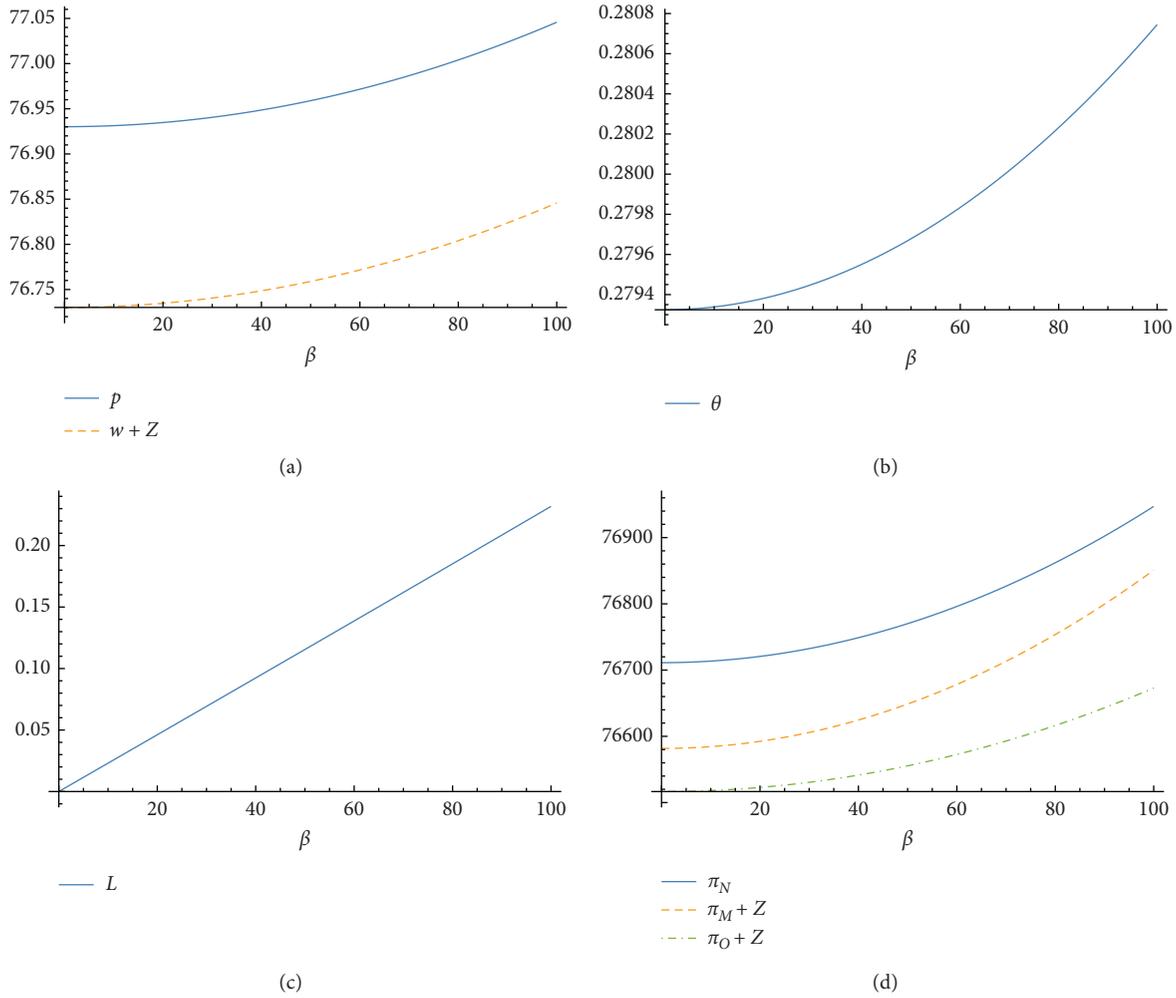


FIGURE 2: Optimal decisions and profits over low-carbon preference.

carve up more revenue from the following manufacturer. Although sales price slightly negatively affects consumer's utility, the low-carbon factor will catch more attention of ecofriendly consumers which eventually can bring in sales. On the other hand, the low-carbon preference also can boost recycling. That is, because the growth in demand is beneficial to the whole supply chain, leading the dominant recycling supplier gain more profit thus promoting it to invest more in collecting used products. In order to develop society sustainably and harmoniously, government should pay more emphasis on improving customers' environmental awareness because it is not only the most effective way to promote waste recycling and emission reduction simultaneously but also beneficial to all the supply chain members' profits. Similarly, the coefficient of collection investment cost also can affect firms' profits, as shown in Figure 3.

As can be seen from Figure 3, the coefficient of the collection cost has a positive correlation with the profit of the new component supplier, but affects the recycling supplier in an exact opposite way. When the recycling supplier costs more in increasing the collection rate, the profit of itself will definitely decrease. However, the profit of its competitor,

new component supplier, will increase. That is, because these two suppliers dominate the whole supply chain and monopolize the market, when one of them face higher cost, the other one will obtain the price advantage and attract more order quantity from the (re-)manufacturer. Therefore, it is extremely necessary and urgent for the recycling supplier to develop the collection technology, service, and advertising campaign, in order to not be squeezed out of the market by the original supplier. Furthermore, when the collection rate increases, that is, when the manufacturer uses more recycled components to produce, the advantage of low-cost manufacturing appears. Both the (re-)manufacturer and recycling supplier can gain more profit. In general, recycling of used products has benefits to the overall supply chain. It can not only bring economic benefits to enterprises but also improve social welfare, especially meeting low-carbon consumers' environmental protection requirements. Thus, the government should also pay emphasis on promoting enterprises to collect used products and further remanufacture them.

In order to compare the efficiency of different decision structures: cooperation and competition structures, the

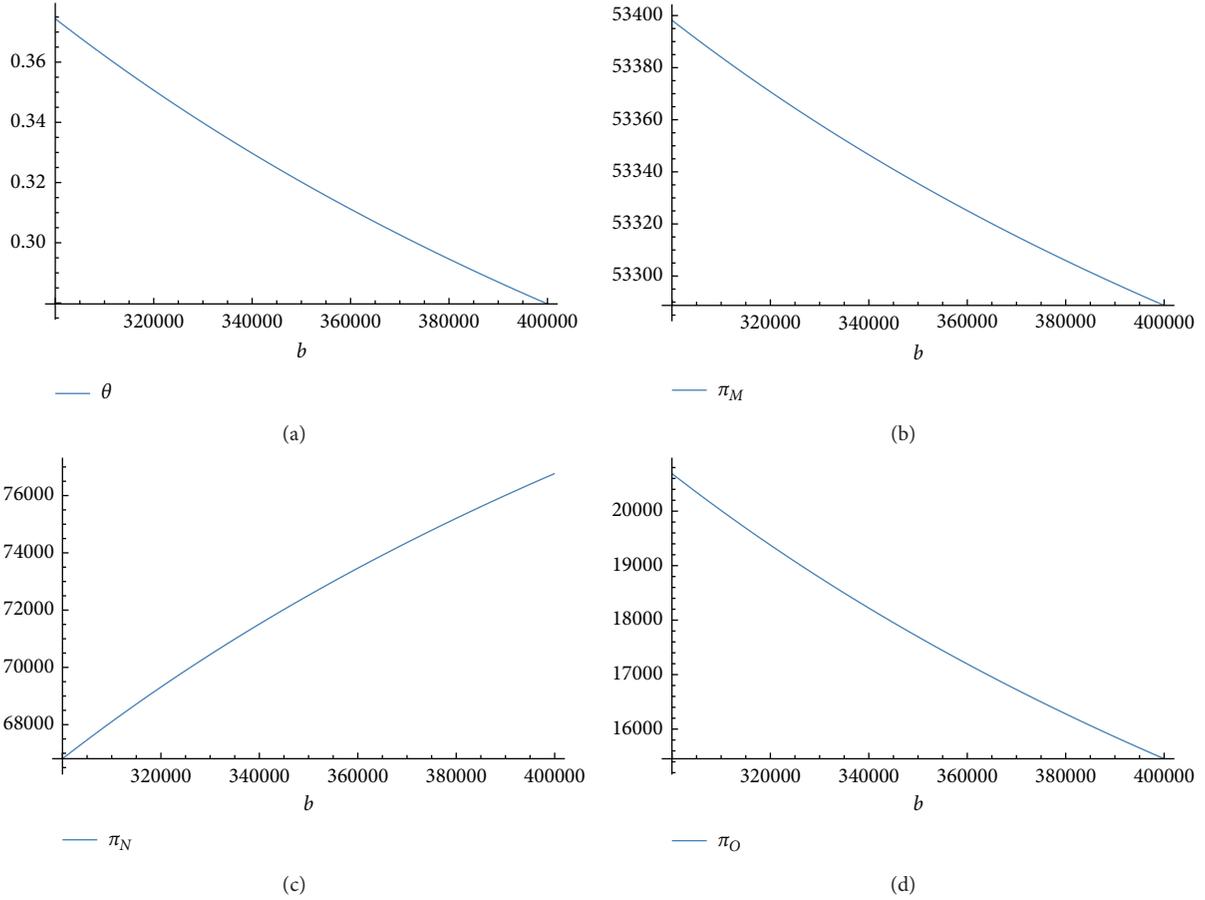


FIGURE 3: Optimal suppliers' profits over collection cost coefficient.

optimal decision variables and profits of each supply chain member in different decision models can be obtained, as shown in Figure 4.

According to Figure 4, the sales price and the collection rate in cooperation model are both lower than that of the competition model. Meanwhile, the emission reduction degree is higher in the cooperation structure. Apparently, the total profit of the supply chain is much higher in the cooperation model. This is consistent with the reality; centralized decision-making is the most efficient way for firms to cooperate, for consumers to get high utility, and for the government to achieve social emission reduction. However, as to the collection rate, it is, surprisingly, lower in the cooperation mode than the competition mode. Although they both decrease with the collection cost coefficient, the decreasing slope scale in the competition model is larger than the cooperation model. This is because the recycling supplier needs to invest more in collecting for improving its competitiveness, grabbing more order quantity from the (re-)manufacturer. When all enterprises cooperate as one decision-maker, the recycling supplier loses motivation to invest more because there is no competition in CLSC. Nevertheless, the carbon emission reduction degree is significantly improved in the cooperation model, bringing benefits to low-carbon consumers and environmental government.

Overall, the cooperation model is much more profitable and efficient for both firms and society, but in practice, it is extremely hard to achieve a full-cooperation among supply chain members due to the information barriers and conflicts of interest. Therefore, a coordination structure is introduced in the following section.

5. Coordination Structure

According to the above analysis, it can be concluded that the cooperation structure, as a benchmark, is more efficient than competition one. However, in most practical cases of CLSC operation, enterprises usually prefer not to fully cooperate, which allows them to reserve own right to make independent choices. In this section, we design a coordination mechanism to improve the total profit of CLSC and ensure each firm can increase their profits. First of all, in order to make sure all the supply chain members are willing to participate in coordination contract, the necessary conditions include: (1) overall profit of the coordinated supply chain is greater than the competition model and (2) all members' profits in the coordination structure are greater than the competition structure.

Since this CLSC is dominated by upstream suppliers, so they can take priority to set a higher wholesale price and take advantages from the downstream (re-)manufacturer.

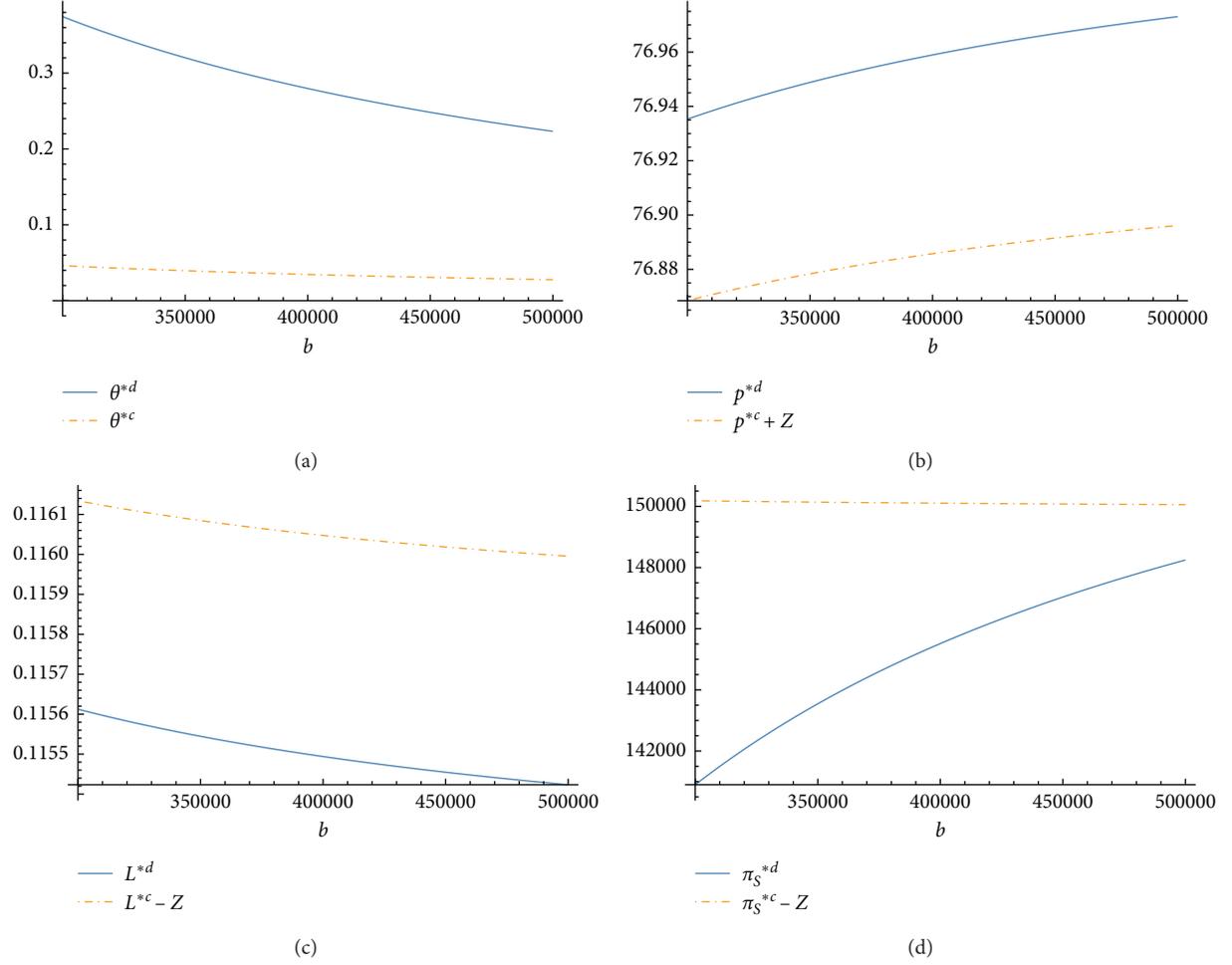


FIGURE 4: Optimal decisions and profits compared in different structures.

Therefore, the following enterprise has motivation to share the component producing cost in order to get a lower wholesale price in return. The lower wholesale price can further stimulate the (re-)manufacturer to make more effort for emission reduction and then boost the market demand. Thus, a cost-sharing contract is introduced in this coordination structure, in which the (re-)manufacturer shares the producing cost of the new component supplier and obtains a new wholesale price, which can be divided into two parts: a sharing part Tsc_n and a wholesale price w^{co} . The profit functions in the coordination structure are derived as follows:

$$\begin{aligned}
 U_M &= pD - (w^{co} + c_n + Tsc_n)(1 - \theta)D - (w + c_o)\theta D - \frac{kL^2}{2}, \\
 U_N &= [w^{co} - (1 - T)sc_n](1 - \theta)D, \\
 U_O &= (w^{co} - a_o)\theta D - I_\theta, \\
 \text{s.t. } U_M &\geq \pi_M, U_N \geq \pi_N, U_O \geq \pi_O.
 \end{aligned} \tag{13}$$

Proposition 4. *In the cost-sharing coordination mechanism, if the pricing strategy (w^{co}, T) satisfies the conditions: $w^{co} = d - \alpha(1 - \theta)c_n - \alpha\theta c_o + \alpha sc_n[1 - T(2 - \theta)]/2\alpha$ and $T = d -$*

$\alpha[c_n - \theta(c_n - c_o + 2sc_n - 2a_o) + sc_n]/\alpha\theta sc_n$, the coordination mechanism can achieve the Pareto improvement.

Proof. As discussed above, the concavity can be verified by the second order derivative conditions. According to the FOC and backward induction method, the optimal sales price, emission reduction degree, and collection rate are solved as p^{*co} , L^{*co} , and θ^{*co} . In order to achieve the coordination, the equations $p^{*co} = p^{*c}$, $L^{*co} = L^{*c}$, and $\theta^{*co} = \theta^{*c}$ must be satisfied.

According to the results, this contract can achieve supply chain coordination through a cost-sharing contract, motivating the (re-)manufacturer to sell products and reduce carbon emissions at the level of the centralized decision-making case. Therefore, the double marginal effect in the competition structure can be eliminated and the total profit reaches the level of cooperation case. Ultimately, supply chain members share the total profit according to their bargaining power. Without loss of generality, participants are assumed to have bargaining powers as follows: $bp_N = 0.5$, $bp_M = 0.35$, and $bp_O = 0.15$. When the supply chain is coordinated, it meets $U_M = bp_M\pi^{*c} \geq \pi_M^{*d}$, $U_N = bp_N\pi^{*c} \geq \pi_N^{*d}$, and $U_O = bp_O\pi^{*c} \geq \pi_O^{*d}$.

TABLE 2: Comparison of different decision-making structures in Test 1 ($\theta = 0.45$).

	Competition structure	Cooperation structure	Coordination structure, $T = 34.91$
p	76.916	53.383	53.383
L	0.116	0.234	0.234
w	52.225	—	$w^{co} + Tsc_n = 99.35$
π_M	53485.62	—	62169.88
π_O	9719.79	—	26644.23
π_N	58834.18	—	88814.11
π_S	122039.60	177628.22	177628.22

TABLE 3: Comparison of different decision-making structures in Test 2 ($\theta = 0.25$).

	Competition structure	Cooperation structure	Coordination structure, $T = 62.17$
p	76.967	53.683	53.683
L	0.115	0.232	0.232
w	52.125	—	$w^{co} + Tsc_n = 98.75$
π_M	53254.46	—	70991.63
π_O	15281.80	—	30424.98
π_N	79881.69	—	101416.62
π_S	148417.94	202833.23	202833.23

TABLE 4: Comparison of different decision-making structures in Test 3 ($\theta = 0.05$).

	Competition structure	Cooperation structure	Coordination structure, $T = 307.5$
p	77.02	53.983	53.983
L	0.115	0.231	0.231
w	52.025	—	$w^{co} + Tsc_n = 98.15$
π_M	53023.79	—	74219.69
π_O	5032.79	—	31808.44
π_N	100745.21	—	106028.13
π_S	158801.80	212056.26	212056.26

According to Proposition 4, when the enterprises in CLSC make decentralized decision-making in the competition model, the profit decline caused by the double marginal effect can be solved by designing a coordination mechanism, and the (re-)manufacturer can further cooperate with the new and recycled component suppliers. Due to the complexity of calculation, we further discuss the effectiveness of the coordination contract in the next section. \square

5.1. Numerical Analysis of Coordination Effectiveness. The effectiveness of coordination mechanism is verified through numerical analysis. Similarly, each parameter is valued as in the previous section. The results of the case study under competition, cooperation, and coordination structures are indicated in Tables 2–4. As can be seen from Tables 2–4, the cooperation structure is optimal and the coordination structure can improve all members' profits compared with the competition structure. Furthermore, in order to indicate the robustness of the proposed models under various cases, test problems 1–3 are designed. In Test 1, the collection rate is relatively higher than Test 2 and 3, and collection rate in Test 3 is the lowest.

From Table 2, the proposed cost-sharing contract improves the profit of overall CLSC and its members compared to the competition model. Moreover, under the

contract, the emission reduction degree increases in comparison with the competition structure. In addition, under the cooperation model, the sales price decreases which is consistent with the result of previous research studies. Accordingly, the proposed cost-sharing contract as a coordination scheme is able to improve both the economic and environmental aspects.

Results of comparison of competition, cooperation, and coordination structures in Test 2 are shown in Table 3. The proposed cost-sharing contract also can improve the profit of overall CLSC and its members compared to the competition structure, when the collection rate decreases. Moreover, under the coordination contract, the sales price decreases which is consistent with the previous results of other scholars, and the emission reduction degree improved compared to those of the competition model. When the collection rate of used products goes further lower, similar results are shown in Table 4.

As can be seen from Tables 2–4, the cost-sharing contract coordination mechanism can achieve the optimal supply chain performance and improve each firm's profit. Meanwhile, through Test 1–3, the robustness and effectiveness of coordination structures are proved.

Conclusion 1. The cost-sharing contract can achieve the Pareto improvement of the CLSC system and ensure all

enterprises in CLSC are willing to participate in the contract, by keeping their own profit increasing. In addition, the coordination mechanism is beneficial to both economic and environmental aspects.

Under these three types of decision-making structures, the sales price decreases and emission reduction effort increases with the growth of the collection rate. This indicates that recycling is beneficial to both consumers' utility and social welfare. However, the total profits cannot increase with the collection rate. This is because collecting used products is not only the cost of the supplier but also the source of its income. Thus, the recycling supplier needs to investigate a proper collection rate, in order to preserve a higher profit. Furthermore, cost of investment in collecting is too high for CLSC to reach an increasing in total profit over the collection rate. It is necessary for each firm in CLSC to pay emphasis on technical innovation and improvement.

6. Conclusion

Most previous research studies have not paid enough attention to the competition between new and recycled component suppliers when the latter one also acts as a collector, not even researched on the coordination of this dual-source supply system. Although some studies have discussed the competition in the supply channel, few of them introduce the ecofriendly factor, such as emission reduction, into the supply chain, which will dramatically influence the consumer's willingness to pay and manufacturer's profit. Therefore, this article focuses on a closed-loop supply chain system consisting of a (re-)manufacturer, a new component supplier, and a recycled component supplier, in which the (re-)manufacturer considers carbon emission reduction and the recycling supplier considers used product collection. Decisions on the sales price, emission reduction degree, wholesale price, and collection rate are analyzed and further compared under three decision-making models: competition, cooperation, and coordination structures on the basis of Stackelberg game and Nash equilibrium. In order to eliminate the negative effects of the competition structure, this paper designs a cost-sharing contract to coordinate the whole supply chain. The results indicate that

- (1) In the CLSC system in which the upstream suppliers dominate and the (re-)manufacturer focuses on emission reduction, the wholesale price increases with the growth of collection investment, but the sales price of products decreases. Meanwhile, the emission reduction degree rises with the collection investment decided by the recycling supplier. Moreover, recycling is beneficial to both consumers' utility and social welfare.
- (2) Under competition structure, the collection investment in used component recycling has positive effect on the profit of the (re-)manufacturer, but has negative impact on the new component supplier.

Moreover, cost-saving efficiency of recycling can facilitate these influences.

- (3) The double marginal effect can be eliminated under the cooperation structure compared to the competition structure. Meanwhile, the sales price is relatively lower but emission reduction degree is higher in the cooperation case, which is beneficial to both consumers and enterprises.
- (4) Due to the difficulty of collection and high cost of investment, recycling negatively affects the profit and efficiency of CLSC. Although recycling is beneficial to social benefits and environmental protection requirements, it hurts enterprises' profits to a certain extent.
- (5) Although centralized decision-making can optimize the CLSC system, it is extremely hard to achieve in reality and practice. Therefore, a coordination mechanism is introduced, cost-sharing contract. It can fully coordinate CLSC and achieve Pareto improvement, making the total profit reach the level of the cooperation structure as well as bringing benefits to environmental protection.

For future research, this study can be extended in several directions. First, the paper investigates a symmetric game model of two competitive suppliers and one recycling channel; it can be extended by several collecting channels, such as the third-part collector and second-hand market, and then it considers information barriers and market demand uncertainty. Second, this model can be extended by taking other coordination mechanisms into consideration, including two-part tariff, quantity discount, and buy back contract. Moreover, this paper assumes that the costs of collecting, manufacturing, and producing components are constant. In fact, due to the uncertain quality of used products and stochastic producing output, these costs should be assumed as uncertainty. Finally, this model only studies on a single-period game model and there is no competition between manufacturers. Thus, in future research, this model can be extended into multiperiod and multicompensation among collectors and manufacturers, in addition to suppliers.

Data Availability

No data were used to support this study.

Conflicts of Interest

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

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