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A Green Closed-Loop Supply Chain Coordination Mechanism Based on Third-Party Recycling

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Abstract: Taking an environment-friendly green closed-loop supply chain as the research object, this work established a two-stage closed-loop supply chain game model. Considering the influence of the environmental protection input on the whole supply chain, there are different decisions among the participants in the supply chain, and the different choices will have impacts on the benefits of the whole supply chain when manufacturers select a closed-loop supply chain model of third-party recycling. Hence, this work compared and analyzed the impact of centralized decision-making and decentralized decision-making on the returns and pricing strategies of each participant. Finally, an optimized cooperative mechanism decision model considering a cost profit sharing contract was further designed. The model is conducive to obtaining the maximum profit value in centralized decision-making and avoids the negative impact of a "double marginal effect" on supply chain income in decentralized decision-making, and finally, improves the overall coordination and profit of a green closed-loop supply chain. The numerical examples are conducted to verify the effectiveness and practicality of the proposed models. This work provides a helpful decision support and guidance for enterprises and the government on the used products recycling decisions to better manage the green closed-loop supply chain.

Keywords: green closed-loop supply chain; green and environment-friendly; used product; game model; third-party recycling; coordination mechanism

1. Introduction

Because of the progress of science and technology driving the rapid development of the economy, the renewal of consumer products, especially consumer electronics, is getting faster and faster, and more waste products are eliminated and abandoned, which has produced a great burden on the environment [1,2]. Furthermore, with the continuous deepening of the green supply chain management concept, more and more enterprises are beginning to adopt reverse logistics and reverse supply chains to recycle used products to new ones [3]. This is well-known as a green closed-loop supply chain, in which the manufacturers not only sell products to customers through the forward channel, but also collect used products through the reverse channel and recycle them [4]. The survey data show that there are nearly 100 billion dollars of remanufactured products being vended per year in the United States, and it is also of large volumes in other countries [5]. On an enterprise level, successful cases of waste products recycling include the following: Recellular, the largest mobile phone recycling enterprise in the United States, uses certain incentives to recycle used phones from third-party logistics companies.

Recellular's revenue in 2005 was $40 million and grew at double-digit rates. Xerox reutilizes and refurbishes the toner warehouse on its photocopying products for free, making the recovery rate reach 60%, which has indirectly expanded the market share and increased the enterprise profit.

The green closed-loop supply chain achieves great work results in reducing energy usage, materials consumption, air and water pollution, and so on [6]. Because of its increasing importance, the green closed-loop supply chain has garnered substantial attention from businesses and academia. Studies on green closed-looped supply chains can be mainly classified into the following perspectives: supply chain network design [7,8], production planning and inventory management [9–11], coordination mechanism [12,13], channel management [14,15], and so on. Among them, the green closed-looped supply chain coordination mechanism is one of the most important issues, which has received great attention in both the forward and reverse flows of supply chains. For example, Swami and Shah [16] investigated the channel coordination mechanism between a single manufacturer and retailer in a green closed-loop supply chain. Qiang et al. [17] investigated the competition and coordination of a closed-loop supply chain with two suppliers, two manufacturers, and two retailers, where both new and remanufactured products are launched at the same time. Huang et al. [18] developed a coordination mechanism considering a creative quantity discount contract to cut down customer's false failure returns in a closed-loop supply chain. Although plenty of existing literature has studied the coordination mechanism of various closed-loop supply chains, the issue that the factors of environmental protection investment (such as advertising and other environmental promotion, etc.) can significantly affect the recycling ratio of the used products, and further influence the overall coordination and profit of the supply chain, should get enough attention. The main contribution of this work seeks to investigate a more practical coordination mechanism considering the environmental protection factors in order to better coordinate the green closed-loop supply chain for used products. Consequently, this paper aims at designing an optimized coordination decision model taking environmental protection factors into account, in order to improve the used products recycling ratio, so as to enhance the overall level of coordination and the profits of a green closed-loop supply chain.

The remainder of this paper is structured as follows: Section 2 reviews the literature related to the reverse logistic and closed-looped supply chain. The problem description and basic notations are specified in Section 3. Section 4 proposes two coordination decision models of green closed-loop supply chains. Section 5 presents the example analysis and discussion. Section 6 concludes the paper and provides directions for future research.

2. Literature Review

As the importance of a green closed-looped supply chain has increased, large amounts of related research have been from different perspectives of closed-looped supply chains, such as the work of Turki et al. [19,20], Govindan et al. [3], Dekker et al. [21], and Oláh et al. [22]. As this work focuses on the coordination mechanism of a green closed-looped supply chain, this research is mainly related to two streams of literature. The first stream concentrates on the reverse logistics in various green closed-looped supply chain scenarios. Savaskan et al. [23] proposed three reverse logistic models for closed-looped supply chains, namely: the manufacturer's collection channel, the retailer's collection channel, and a third-party collection channel. By comparing the three models, they found that the retailer's collection process might be the optimal reverse logistic channel. De Giovanni and Zaccour [24] investigated the collection outsourcing choice of the manufacturer in a closed-looped supply chain, in which the retailer or the third-party firm can undertake the reverse logistic task. A survey of 209 manufacturers in China conducted by Ye et al. [25] revealed that in China there is a significant positive correlation between institutional pressures and top managers' implementation intended toward reverse logistics. Huang et al. [26] investigated a dual recycle channel closed-looped supply chain where the manufacturer sells products in the forward channel, while the retailer and the third party simultaneously collect the used products in the reverse channel, and they found that the dual recycle channel performed better than the single channel when the competition of the reverse logistic channel was not very strong. The above research mainly discussed the reverse logistic issues with a single member in a green closed-looped supply chain for undertaking the collection and recycling tasks.

The second stream of research related to our study is the coordination mechanism of green closed-looped supply chains. De Giovanni [27] introduced an exogenous incentive mechanism, that is, the income sharing of recycled waste products, and found that a transaction incentive would affect the balance of the whole supply chain. Hong et al. [28] investigated whether it was necessary to entrust retailers to recycle waste products when manufacturers entrusted third parties to do the recycling business. They concluded that when a third party was a non-profit organization, entrusting the business to retailers at the same time was beneficial to the revenue of the entire supply chain. Sun and Da [29] established a decision model of the differential pricing between remanufactured products and new products, compared and analyzed the optimal decision results of centralized decision-making and decentralized decision-making, and finally proposed a cost-benefit sharing mechanism to make the supply chain more coordinated as a whole. Based on the cost and benefit sharing of manufacturers, retailers and third parties, Guo et al. [30] studied the profit distribution model of the whole supply chain system when the manufacturer outsourced the recovery business to the third party, and proposed a coordination mechanism. Maiti and Giri [31] studied a closed-loop supply chain where the manufacturer sold products to consumers in the context of a third party collecting the used products, and they found that the centralized mechanism was always optimal, and among the decentralized cases, the retailer-led one was much more profitable. Recently, there has been more and more research about the coordination mechanism of a closed-loop supply chain based on third-party recycling. Chen et al. [32] realized the coordination of a three-party closed-loop supply chain through the application of a cost-income sharing contract. Zhou [33] established a game model between manufacturers and retailers for manufacturer's order, and he got the results that the optimal sales price of retailers under decentralized decision, the optimal initial production quantity and optimal wholesale price of suppliers under decentralized decision, as well as the optimal initial production quantity and optimal sales price of supply chain under centralized decision are obtained, respectively. Xu and Tang [12] investigated the coordination mechanism of a dual-channel closed-loop supply chain based on third-party recycling. Through constructing a two-channel closed-loop supply chain decision model in which manufacturers sell online, retailers carry out traditional sales and the third party is responsible for recycling waste products, they analyzed and compared the income situation of a closed-loop supply chain under centralized decision-making and decentralized decision-making, and they further put forward an income and cost sharing mechanism to ensure that the supply can finally achieve the overall coordination.

The above literature mainly focuses on the decision-making mechanism of a closed-loop supply chain for the recovery of waste products by the third party by simply assuming that the products sold in the first stage can be directly recycled and reused in the second stage, without considering the inefficient recycling and even inability of recycling waste products. However, in real life, the used and waste products can hardly be recycled completely, only a certain proportion of them can be recycled, while other products may be completely damaged and cannot be reused, which may reduce the performance of the green closed-loop supply chain and produce an adverse effect on the environment [34,35]. Therefore, taking the environmental protection into account, the recycling ratio of waste products is an important issue in the green closed-loop supply chain management. Savaskan and Wassenhove [23] stated that recyclers can improve the recycling ratio of waste products through some incentives. Furthermore, Giovanni and Zaccour [24] found that the incentive factors of environmental protection investment (such as environmental or advertising promotion, etc.) can significantly affect the recovery ratio of waste products. Based on the above consideration, this work will consider the environmental protection factors into the decision-making model of green closed-loop supply chain based on third-party recycling, and then analyzed the coordination mechanism of the whole green closed-loop supply chain. Thus, this paper aims to shed some light on the coordination of a green closed-loop supply chain from the perspective of environmental protection, which will be helpful to improve the decision-making level of the green closed-loop supply chain.

3. Problem Description

To develop the model, the key parameters and variables are presented by the following notations throughout the paper (Appendix A).

This work considers a green closed-loop supply chain, which is composed of a manufacturer, a retailer and a third-party contractor ("third party" for short) for the recovery of waste products. Manufacturers sell their products to retailers at wholesale prices, w, via the traditional way, retailers sell their products to consumers at retail price p, and third parties are only responsible for recycling used products from consumers to manufacturers for remanufacturing. When recycling waste products, the third party will invest in advertising or other environmental protection promotion measures, in order to facilitate the recovery of waste products and increase the recovery rate of waste products.

In this paper, we assume that there is a linear relationship between demand, q, and price, p, which can be denoted as $q = \alpha - \beta p$, where, α and β are both positive values and respectively represent the market potential of the product and the sensitivity of consumers to price. For the above formulas, the further discussions are presented as follows. Firstly, the demand varies linearly with price, which can be proved by the maximizing consumer utility. For simplicity, we assume that demand is a static variable related to retail prices only. Meanwhile, we regarded α and β as constant parameters which are independent of time. r_E indicates the recovery ratio of the recovered products in the second phase to the sold products in the first phase. Moreover, we state that the supply chain will introduce some positive measures to increase this ratio, which has been confirmed by Savaskan's related research [36]. For instance, the recyclers can advertise some green activities to attract attention and recognition of people to increase the recovery ratio. Combining the related work of De Giovanni [27] and Talbot et al. [37], we further propose that the recovery ratio of actually recycled waste products to sold products is $r_E = hA$, where, A indicates the environmental investment composite index of the cost for advertising or other environmental promotion, and h is a positive coefficient which is used to reflect the sensitivity of consumers to advertising or other publicity measures. Then, we can also get the cost $C(A) = \frac{\varphi A^2}{2}$ for advertising or other environmental promotions, where, φ is a positive balance coefficient of the cost for advertising or other environmental promotion.

The cost of each unit of product produced by the manufacturer is represented by c, and the cost of each unit product recovered by the third party is denoted by g_E. For manufacturers, the residual value of each waste product is Δ, which means when recycling each unit of the product for remanufacture, the manufacturer can save Δ costs. Obviously, there are $0 \leq \Delta \leq c$, and $\Delta \geq g_E$, which means that manufacturers are profitable when recycling waste products. In fact, under the normal circumstances, the used products will not be more valuable than the original new products. When the manufacturer outsourced the recycling business to a third party, d_E is used to indicate the fee paid by the manufacturer to the third party. Here, it can be regarded as a way of cost plus pricing, that is, $d_E = (1 + \mu)g_E$, and $g_E \leq d_E \leq \Delta$, where, μ can be seen as a producer's incentive to a third party. The cost-plus pricing approach allows recyclers to quickly feel the benefits of participating in the business to increase its initiative, without being affected by other participants.

We assumed that the incentives do not depend on the quality of the product, but on the recovery price of the used product [37]. For manufacturers, the profit of each recycled product is $\Delta - (1 + \mu)g_E$, and each recycled part makes up the total profit of the product. Π_j is defined as the profit of each participant, j can be regarded as M, R or E, which represents manufacturer, retailers and third-party recyclers, respectively. The overall profits, Π, of the whole supply chain are the following:

$$\Pi = \Pi_M + \Pi_R + \Pi_E \tag{1}$$

Based on the above discussion and conditions, the profit optimization equations of the manufacturers, retailers and third parties can be obtained as follows:

$$\Pi_M = (w-c)q + (\Delta - d_E)rq = (w-c)(\alpha - \beta p) + hA(\Delta - d_E)(\alpha - \beta p) \tag{2}$$

$$\Pi_R = (p-w)q = (p-w)(\alpha - \beta p) \tag{3}$$

$$\Pi_E = hA(d_E - g_E)(\alpha - \beta p) - \frac{\varphi A^2}{2} \tag{4}$$

Thus, the overall profit of the whole supply chain can be obtained as follows:

$$\begin{aligned} \Pi &= \Pi_M + \Pi_R + \Pi_E \\ &= (w-c)(\alpha - \beta p) + hA(\Delta - d_E)(\alpha - \beta p) + (p-w)(\alpha - \beta p) + hA(d_E - g_E)(\alpha - \beta p) - \tfrac{\varphi A^2}{2} \end{aligned} \tag{5}$$

4. Decision Model of a Green Closed-Loop Supply Chain

4.1. Centralized Decision Model

Each enterprise in the supply chain is an independent legal individual, without an administrative affiliation with each other. However, there is a core enterprise in the supply chain generally. The supply chain is established around this core enterprise, which plays a leading role in the whole supply chain. Centralized decision-making regards manufacturers as the core enterprises of the supply chain, which controls and owns the sales and recovery channels of the whole supply chain. By determining the optimal retail price, p, the optimal environmental protection input compound index,A, and the optimal recovery price, g_E, the manufacturers connect each node enterprise in order to maximize the profit of the whole supply chain. The profit function of the whole green closed-loop supply chain can be obtained as follows:

$$\Pi^c = \Pi^c{}_M + \Pi^c{}_R + \Pi^c{}_E = hA(\Delta - g_E)(\alpha - \beta p) + (p-c)(\alpha - \beta p) - \frac{\varphi A^2}{2} \tag{6}$$

The optimal solutions of the retail price, p, and the composite index, A, are obtained respectively, by the above equation. Calculating the first order partial derivatives of the above equation with respect to p and A, as well as making them equal zero respectively, we can obtain the following:

$$\frac{\partial \Pi^c}{\partial p} = (\alpha + \beta c) - 2\beta p - hA\beta(\Delta - g_E) = 0 \tag{7}$$

$$\frac{\partial \Pi^c}{\partial A} = h(\Delta - g_E)(\alpha - \beta p) - A\varphi = 0 \tag{8}$$

Then, it can be further obtained, as follows:

$$p^c = \frac{\alpha\beta h^2(\Delta - g_E)^2 - (\alpha + \beta c)\varphi}{\beta^2 h^2 (\Delta - g_E)^2 - 2\varphi\beta},\ A^c = \frac{\alpha\beta h\left(1 - h^3\right)(\Delta - g_E)^3 - h\varphi(\alpha - \beta c)(\Delta - g_E)}{\varphi\beta^2(\Delta - g_E)^2 - 2\varphi^2}$$

$$q^c = (\alpha - \beta p) = \frac{(\alpha - \beta c)\varphi}{2\varphi - \beta h^2 (\Delta - g_E)^2}$$

The overall profits of the supply chain can be obtained as follows:

$$\Pi^c = \frac{\left[(3\alpha + \beta c)h\mu g_E\right]^2 \left[\beta c(\alpha - \beta c) + \alpha(3\beta + \varphi)\right] h^2 \mu g_E (\Delta - g_E) - (\alpha + 2\beta c)\varphi\right]}{4[2\varphi + \beta h^2 \mu g_E(\Delta - d_E)]^2}$$

Proposition 1. *The overall profit of the supply chain is increased first and then decreased with the environmental investment composite index and retail price, which means that the overall profit of the supply chain will increase with the increase of the two factors and will reach the maximum at a certain critical value. After passing this critical value, the profit function will decrease with their increase.*

When calculating the derivation of Π^c with respect to p, it can be obtained that the first derivative is greater than zero before its critical value, and less than zero after its critical value. This proposition shows that the profit of the whole supply chain can be affected by controlling the retail price and environmental protection investment. When they take their critical value separately, the profit of the whole supply chain can be maximized.

In addition, from the expression of p^c, we can conclude that when the market that can be developed is larger, retailers will be more daring to price and sell products to consumers at a higher retail price. The more sensitive consumers are to prices, the lower retail the prices of retailers are, so that they can get enough sales. It can be seen from the expression of A^c that A^c increases with the increase of $(\Delta - g_E)$. This shows that the greater the profit $(\Delta - g_E)$ of recycling for each waste product, the more funds the third party will invest in environmental protection publicity, so as to increase the recycling amount of waste products.

4.2. Decentralized Decision Model

In the centralized decision-making, the manufacturer plays the leading role in the supply chain, controlling the retail price and recovery price of the product, in order to maximize the profit of the whole supply chain. However, in reality, as every node enterprise in the supply chain is "economic man" not "social man", when making decisions, they tend to firstly consider maximizing their own profits, rather than maximizing the overall profits of the supply chain. Therefore, we assumed that the game between manufacturers, retailers, and third parties belongs to the Stackelberg model, and the decision-making process can be regarded as a two-stage dynamic game. In the game, the manufacturer acts as the leader of the whole supply chain, and the retailers and the third-party act as the followers. The manufacturer firstly determines the wholesale price, w, and the recovery price, d_E, paid to the third party, then, the retailers set the corresponding retail price according to the wholesale price, and in the end, the third-party formulates the environmental protection promotion input when recycling the waste products according to the recovery price paid by the manufacturer. By the same token, we can get the profit equation of the manufacturers, retailers and third parties using the following:

$$\Pi_M{}^d = (w-c)q + (\Delta - d_E)rq = (w-c)(\alpha - \beta p) + hA(\Delta - d_E)(\alpha - \beta p) \tag{9}$$

$$\Pi_R{}^d = (p-w)q = (p-w)(\alpha - \beta p) \tag{10}$$

$$\Pi_E{}^d = hA(d_E - g_E)(\alpha - \beta p) - \frac{\varphi A^2}{2} \tag{11}$$

According to the reverse solution method, we first determine the retail sales price p and the environmental protection investment composite index, A, of the third party for environmental protection promotion, and then determine the wholesale price, w, of the manufacturer and the price, d_E, paid to the third party according to the existing optimization equation.

Firstly, we will determine the retail price, p, of retailers and the composite index, A, of environmental protection investment used by third parties for recycling.

Because $\frac{\partial \Pi_R{}^{d2}}{\partial p^{d2}} = -2 < 0$, so $\Pi_R{}^{d2}$ is a strict concave function for p, and $\Pi_R{}^{d2}$ has an optimal solution on p, make $\frac{\partial \Pi_R{}^d}{\partial p} = -2\beta p + (\alpha + \beta w) = 0$, then we can get $p^d = \frac{\alpha + \beta w}{2\beta}$.

Similarly, $\frac{\partial \Pi_E{}^{d2}}{\partial A^d} = -\varphi < 0$, so $\Pi_E{}''$ is a strict concave function for A, and $\Pi_E{}^d$ has an optimal solution on A. Thus, make $\frac{\partial \Pi_E{}^d}{\partial A} = -\varphi A + \frac{h\mu g_E(\alpha - \beta w)}{2} = 0$, then we can get $A^d = \frac{h\mu g_E(\alpha - \beta w)}{2\varphi}$.

For the manufacturer's decision, because $\frac{\partial^2 \Pi_M{}^d}{\partial w^2} < 0$, it is a strict concave function for w, and $\Pi_M{}^d$ has an optimal solution on w, make $\frac{\partial 2\Pi_M{}^d}{\partial w} = 2\beta\varphi w + (\alpha+\beta c) + \beta^2 h^2 \mu g_E(\Delta - d_E)w - \alpha\beta h^2 \mu g_E(\Delta - d_E) = 0$, then we can get $w^d = \frac{(\alpha+\beta c)\varphi - (\Delta - d_E)\alpha\beta h^2 \mu g_E}{2\beta\varphi + \beta^2 h^2 \mu g_E(\Delta - d_E)}$.

Therefore, we can get the retail price of the retailers, product sales and third-party environmental investment composite index as follows, respectively:

$$p^d = \frac{(\alpha+\beta w)}{2\beta} = \frac{2(\Delta - d_E)\alpha\beta h^2 \mu g_E + (\alpha - \beta c)\varphi}{4\beta\varphi + 2\beta^2 h^2 \mu g_E(\Delta - d_E)},\ q^d = \frac{4\alpha\varphi - (\alpha-\beta c)\varphi}{4\varphi + 2\beta h^2 \mu g_E(\Delta - d_E)}$$

$$A^d = \frac{h\mu g_E(\alpha - \beta w)}{2\varphi} = \frac{(3\alpha+\beta c)h\mu g_E}{4\varphi + 2\beta h^2 \mu g_E(\Delta - d_E)}$$

The profits of producers, retailers and third parties under decentralized decision-making are obtained as follows:

$$\Pi_M{}^d = (w-c)(\alpha - \beta p) + hA(\Delta - d_E)(\alpha - \beta p)$$

$$= \frac{[\beta c(c-1) + \alpha(3\beta+1)]h^2 \mu g_E(\Delta - d_E) - (\alpha + 3\beta c)\varphi]}{4\beta\varphi + 2\beta^2 h^2 \mu g_E(\Delta - d_E)} \cdot \frac{(3\alpha+\beta c)\varphi}{4\varphi + 2\beta h^2 \mu g_E(\Delta - d_E)}$$

$$\Pi_R{}^d = (p-w)q = (p-w)(\alpha - \beta p) = \frac{(3\alpha+\beta c)^2 \varphi^2}{4\beta[2\varphi + \beta h^2 \mu g_E(\Delta - d_E)]^2}$$

$$\Pi_E{}^d = hA(d_E - g_E)(\alpha - \beta p) - \frac{\varphi A^2}{2}$$

$$= \frac{(3\alpha+\beta c)h^2 \mu g_E(d_E - g_E)}{4\varphi + 2\beta h^2 \mu g_E(\Delta - d_E)} \cdot \frac{(3\alpha+\beta c)\varphi}{4\varphi + 2\beta h^2 \mu g_E(\Delta - d_E)} - \frac{\varphi[(3\alpha+\beta c)h\mu g_E]^2}{8[2\varphi + \beta h^2 \mu g_E(\Delta - d_E)]^2}$$

The overall profit of the whole supply chain is as follows:

$$\Pi^d = \Pi_M{}^d + \Pi_R{}^d + \Pi_E{}^d = \frac{\varphi\left[(3\alpha+\beta c)h\mu g_E\right]^2\left[\beta c(\alpha - \beta c) + \alpha(3\beta+1)\right]h^2 \mu g_E(\Delta - d_E) - (\alpha + 3\beta c)\varphi\right]}{8[2\varphi + \beta h^2 \mu g_E(\Delta - d_E)]^2}$$

Proposition 2. *The wholesale price, retail price and environmental investment composite index are a quadratic function of the recycling price, g_E, for the waste products. p^d, A^d, Π^d are the increasing functions of g_E in certain ranges, and when they go beyond this range, p^d, A^d, Π^d are the subtraction functions of g_E. The increase and decrease interval of q^d to g_E is just the opposite.*

By calculating the first derivative of g_E for p^d, A^d and Π^d, the critical value which makes the first derivative zero can be obtained, which is the dividing line of the monotonic increase and decrease intervals of each function.

This proposition shows that the recovery price is not a linear influence on one variable. However, when the recovery price changes, the other variables will change dynamically and interact with each other at the same time. In the end, there will always be a critical value, so that each variable reaches the optimal value.

Proposition 3. *$p^c < p^d$, $A^c < A^d$, $\Pi_E{}^c > \Pi_E{}^d$.*

From proposition 3, we can get the following: First, the retail price under the decentralized decision is larger than the retail price under the centralized decision, because of the existence of the "double marginal effect". Second, the cost of the green environmental protection promotion fee for recycling waste products under decentralized decision-making is greater than that under centralized decision-making. Third, the overall profit of supply chain under the decentralized decision is smaller than that under the centralized decision, which indicates that the profit of each node enterprise in the supply chain has not reached the optimal value and needs to be further improved.

4.3. Cooperative Mechanism Decision Model

In order to achieve the overall profit under centralized decision-making and avoid the decrease of the overall profit of supply chain caused by the "double marginal effect" of decentralized decision-making, a cooperative mechanism decision model based on the profit and expense sharing contract is proposed in this work. The model is mainly used to achieve the following goals: first, it makes the profit of the whole supply chain reach the profit under the centralized decision, while eliminating the influence of the "double boundary effect" under the distribution decision. Second, it makes all of the node enterprises get more profits than the decentralized decision-making, in order to encourage the node enterprises to participate better in the supply chain. The specific implementation method is as follows: the manufacturer sells the products to the retailers at a wholesale price, w. Meanwhile, the manufacturer uses d_E as an incentive to third parties for recycling waste products. The manufacturer and retailer share the total revenue of sales, specifically the manufacturer gets the percentage of ϕ_1 and the retailers get percentage of $1-\phi_1$. The manufacturer and the third party share the cost of the environmental promotion investment, with the manufacturer sharing the percentage of ϕ_2 and the third party sharing the percentage of $1-\phi_2$. ϕ_1 and ϕ_2 are both proportional coefficients, thus $\phi_1,\ \phi_2 \in (0,1)$.

Under the decentralized decision, when the wholesale price is determined, the retail price is $p(w) = \frac{\alpha+\beta w}{2\beta}$.

Then, we make the retail price under the mechanism equal to the retail price under the centralized decision, as well as making the environmental protection promotion fee equal to the environmental protection promotion fee under the centralized decision. In this way, the pricing strategy under this mechanism is the same as that under centralized decision making, which can maximize the profit of the whole supply chain. Under the centralized decision-making, the comprehensive index of the retail price, environmental protection input and retail volume are as follows:

$$p^c = \frac{\alpha\beta h^2(\Delta - g_E)^2 - (\alpha + \beta c)\varphi}{\beta^2 h^2(\Delta - g_E)^2 - 2\varphi\beta},\ A^c = \frac{\alpha\beta h\left(1 - h^3\right)(\Delta - g_E)^3 - h\varphi(\alpha - \beta c)(\Delta - g_E)}{\varphi\beta^2(\Delta - g_E)^2 - 2\varphi^2}$$

$$q^c = (\alpha - \beta p) = \frac{(\alpha - \beta c)\varphi}{2\varphi - \beta h^2(\Delta - g_E)^2}$$

At this point, the profit functions of manufacturers, retailers and third parties are as follows:

$$\Pi_M{}^{co} = \phi_1(p-c)q + (\Delta - d_E)rq - \phi_2\frac{\varphi A^2}{2} \tag{12}$$

$$\Pi_R{}^{co} = (1-\phi_1)(p-c)q \tag{13}$$

$$\Pi_E{}^{co} = hA(d_E - g_E)(\alpha - \beta p) - (1-\phi_2)\frac{\varphi A^2}{2} \tag{14}$$

Therefore, the overall profit of the supply chain is as follows:

$$\Pi^{co} = \Pi_M{}^{co} + \Pi_R{}^{co} + \Pi_E{}^{co}$$

$$= \phi_1(p-c)q + (\Delta - d_E)rq - \phi_2\frac{\varphi A^2}{2} + (1-\phi_1)(p-c)q + hA(d_E - g_E)(\alpha - \beta p) - (1-\phi_2)\frac{\varphi A^2}{2} = \Pi^c$$

In this way, under the profit and expense sharing contract, the overall profit of the supply chain is equal to the profit under the centralized decision, and also achieves the maximization of the overall profit of the supply chain. The value of coefficients $\varphi_1,\ \varphi_2$ will affect the profit of each node enterprise. Only when their value satisfies certain conditions, can the profit of each node enterprise be guaranteed to be greater than that obtained under the decentralized decision model. Only in this way can we encourage the node enterprises to participate more actively in the implementation of the model and promote the smooth implementation of the model.

Proposition 4. *Only when $\varphi_1,\ \varphi_2$ are satisfied: $\frac{(\alpha-\beta\ c)\varphi}{\beta^2h^2(\Delta-g_E)^2-2\varphi\beta} \leq \phi_1 \leq \frac{(\alpha-\beta\ c)\varphi}{2\beta^2h^2(\Delta-g_E)^2-4\varphi\beta}$, $\frac{1}{2} \leq \phi_2 \leq \frac{3}{4}$, and the cost-profit sharing model can be implemented smoothly in the supply chain.*

In order for the manufacturer to accept the contract, the following needs to be satisfied: $\Pi_M{}^{co} \geq \Pi_M{}^d$, that is:

$$\phi_1(p-c)q + (\Delta - d_E)rq - \phi_2\frac{\varphi A^2}{2} \geq \frac{\left[\beta c(c-1)+\alpha(3\beta+1)\right]h^2\mu g_E(\Delta-d_E)-(\alpha+3\beta c)\varphi}{4\beta\varphi+2\beta^2h^2\mu g_E(\Delta-d_E)}\cdot\frac{(3\alpha+\beta c)\varphi}{4\varphi+2\beta h^2\mu g_E(\Delta-d_E)}$$

So we can get that $\phi_1,\ \phi_2$ should meet: $\phi_1 \geq \frac{(\alpha-\beta\ c)(\Delta-g_E)}{\beta^2(\Delta-g_E)^2-2\varphi\beta}$ and $\phi_2 \geq \frac{1}{2}$.

In order for retailers to accept the contract, the following needs to be satisfied: $\Pi_R{}^{co} \geq \Pi_R{}^d$, which is:

$$(1-\phi_1)(p-c)q \geq \frac{(3\alpha+\beta c)^2\varphi^2}{4\beta\left[2\varphi+\beta h^2\mu g_E(\Delta-d_E)\right]^2}$$

So, we can get that ϕ_1 should meet: $\phi_1 \leq \frac{(\alpha-\beta\ c)\varphi}{2\beta^2h^2(\Delta-g_E)^2-4\varphi\beta}$.

In order for a third party to accept the contract, the following needs to be satisfied: $\Pi_E{}^{co} \geq \Pi_E{}^d$, that is:

$$hA(d_E-g_E)(\alpha-\beta p) - (1-\phi_2)\frac{\varphi A^2}{2} \geq \frac{(3\alpha+\beta c)h^2\mu g_E(d_E-g_E)}{4\varphi+2\beta h^2\mu g_E(\Delta-d_E)}\cdot\frac{(3\alpha+\beta c)\varphi}{4\varphi+2\beta h^2\mu g_E(\Delta-d_E)} - \frac{\varphi\left[(3\alpha+\beta c)h\mu g_E\right]^2}{8\left[2\varphi+\beta h^2\mu g_E(\Delta-d_E)\right]^2}$$

So, we can get that ϕ_2 should meet: $\phi_2 \leq \frac{3}{4}$.

To sum up, when $\phi_1,\ \phi_2$ are satisfied: $\frac{(\alpha-\beta\ c)\varphi}{\beta^2h^2(\Delta-g_E)^2-2\varphi\beta} \leq \phi_1 \leq \frac{(\alpha-\beta\ c)\varphi}{2\beta^2h^2(\Delta-g_E)^2-4\varphi\beta}$ and $\frac{1}{2} \leq \phi_2 \leq \frac{3}{4}$, the manufacturers, retailers and third parties can accept the contract at the same time, which makes the cooperative mechanism better adjusted to balancing the supply chain.

Proposition 5. *Under the cooperative mechanism, we can also draw the following conclusions.*

Firstly, $\Pi_M{}^{co} \geq \Pi_M{}^d$, $\Pi_R{}^{co} \geq \Pi_R{}^d$, $\Pi_E{}^{co} \geq \Pi_E{}^d, \Pi^{co} = \Pi^c$. It suggests that the profits of the manufacturers, retailers and third parties under the cooperative mechanism have increased relative to those under decentralized decision-making mechanisms. At the same time, because the retail price and the environmental protection promotion fee under the cooperative mechanism are the same as that under the centralized decision mechanism, the overall profit of the supply chain under the cooperative decision mechanism is equal to that under the centralized decision mechanism, thus optimizing the profit of the supply chain.

Secondly, $A^{co} = A^c > A^d$. It shows that the environmental protection promotion fee under the cooperative decision-making mechanism is the same as that under the centralized decision-making mechanism, but higher than that under the decentralized decision-making mechanism. The environmental protection investment is beneficial to improve the recovery of waste products, and then increase the profits of the whole supply chain. In this sense, each node enterprise on the supply chain should give full play to the advantages of all kinds of resources, regard the environmental protection investment as the opportunity to improve the enterprise image and increase the enterprise profit. Therefore, enterprises should be encouraged to increase the environmental protection investment in the operation of the closed-loop supply chain, which can not only improve the social image of the enterprise, but also increase its operating profit.

Thirdly, $p^{co} < p^{d}$. It shows that the retail price of retailers under the cooperative mechanism is lower than that of the decentralized decision-making mechanism, which will increase the sales of products and increase the overall profit of the supply chain to a certain extent. In the future, this will be conducive to further exploiting the market, tapping the market potential and improving product popularity.

5. Numerical Examples

In this section, we will introduce some numerical data and apply the above-described model to compute the decision variables. We will also use the numerical examples to verify the conclusion obtained in this work. In this work, the example is mainly referred to in the work of Xu and Tang [12], and on its basis, some improvements are carried out. We assume that the total demand for the product is $\alpha = 800$, the cost of each unit of a new product is $c = 80$, the unit cost of remanufactured products is 50, and we set $h = 0.01$, $\mu = 0.4$, $\varphi = 2$, $\Delta = 40$, $g_E = 20$, $0.40 \leq \phi_1 \leq 0.80$, $0.50 \leq \phi_2 \leq 0.75$.

Based on the above parameter values, the optimal values of each variable under the centralized decision and the decentralized decision can be obtained in Table 1.

Table 1. The optimal value of each decision variable.

Decision Variable	Centralized Decision Optimal Value	Decentralized Decision Optimal Value
w	-	116.68
p	117.90	138.34
A	16.00	14.33
Π_M	-	4158.68
Π_R	-	2345.78
Π_E	-	1036.21
Π	8395.56	7540.67

It can be obtained from Table 1 that the retail price in the centralized decision is lower than that in the decentralized decision, which verifies Proposition 3. The environmental protection investment is greater than that in decentralized decision-making, and it also confirms Proposition 3. The above numerical results show that the centralized decision-making model is more beneficial to consumers, and it can also increase the ratio of recycled waste products, which is more conducive to improving the competitiveness of remanufactured products, enhancing the consumer perception of the remanufactured product, and finally promoting environmental protection and the development of the circular green closed-loop supply chain. On the other hand, the overall profit of supply chain under centralized decision-making is larger than that under decentralized decision-making, which shows that centralized decision-making can improve the efficiency of the supply chain and contribute to the coordination and sustainable development of the supply chain.

The following examples are used to analyze and illustrate the influence of the decision model of the coordination mechanism on the whole supply chain and each node enterprise. Within the range of its prescribed values, we take different values of ϕ_1, ϕ_2 to analyze the change of decision variables (Table 2).

Table 2. The impact of different values of ϕ_1, ϕ_2 on the supply chain.

Decision Parameters		Coordination Mechanism Model			
ϕ_1	ϕ_2	$\Pi_M{}^{co}$	$\Pi_R{}^{co}$	$\Pi_E{}^{co}$	$\Pi^{co} = \Pi^{c}$
0.50	0.55	3850.1	3989.02	154.24	7993.36
	0.60	3837.3		167.04	
	0.65	3824.5		179.84	
0.60	0.55	4647.92	3191.20	154.24	7993.36
	0.60	4635.12		167.04	
	0.65	4622.32		179.84	
0.70	0.55	5445.72	2393.40	154.24	7993.36
	0.60	5432.92		167.04	
	0.65	5420.12		179.84	

Table 2 shows that the overall profit of the supply chain under the coordination decision mechanism is equal to that under the centralized decision mechanism, which makes the optimal coordination of the whole supply chain to promote its sustainable development. Further, through setting different values of ϕ_1, ϕ_2, it can be obtained that the profit of manufacturer, retailer and third party varies with the two parameters as follows: When ϕ_1 is determined, the profit of the manufacturer will decrease with the increase of ϕ_2, the profit of the third party will increase with the increase of ϕ_2 and the profit of retailers will only be related to the value of ϕ_1 and not affected by the value of ϕ_2. When ϕ_2 is determined, the profit of the manufacturer will increase with the increase of ϕ_1, the profit of retailers will decrease with the increase of ϕ_1 and the profit of the third party will only be related to the value of ϕ_2 and not affected by the value of ϕ_1. Specifically, proposition 5 and the numerical results all show that the profit of the whole supply chain does not change with the change of the two parameters.

6. Conclusions

Considering the influence of environmental protection investment on the coordination of the whole green closed-loop supply chain, this work constructed a green closed-loop supply chain to recycle waste products by the third party. Aiming at the decision-making of each node enterprise in the closed-loop supply chain, we developed the centralized decision-making model and the decentralized decision-making model, respectively. By comparing the advantages and disadvantages between the two models, we further proposed the optimized cooperative mechanism decision-making model to integrate the advantages of the previous two. The cooperative mechanism decision-making model can not only maximize the benefit of centralized decision-making, but also avoid the negative influence of the "double marginal effect" on profit under decentralized decision-making, thus making each node enterprise in the supply chain get more profit than decentralized decision-making. Meanwhile, the environmental protection utility and consumer utility of the green closed-loop supply chain have also been greatly improved, which can realize the overall coordination and sustainable development of green closed-loop supply chain.

The main theoretical contribution of this work is to introduce the factor of environmental protection investment into the coordination decision model, which is an important factor affecting the overall profit of the green closed-loop supply chain. On its basis, an optimized cooperative mechanism decision-making model is further developed to improve the overall coordination of the supply chain. This evidence introduces some interesting ideas to researchers of the closed-loop supply chain to further deepen the study of the coordination mechanism of the supply chain. On the other hand, we also obtained some interesting managerial findings. First, the environmental protection investment can improve the recycling effect of waste products, and further increase the overall profit of the green closed-loop supply chain. Hence, the decision-makers in the supply chain should attach great importance to investing on environmental protection advertising or other promotion measures in order to improve the recycling ration of waste products and the overall profit of the supply chain. Second, the cooperative mechanism decision-making model is a better coordination mechanism to optimize the coordination and overall profit of the supply chain, which can help the enterprises to improve its profit, expand the market and realize its sustainable green development.

However, this work is not free of limitations, which can be seen as opportunities to extend the findings in future research. Firstly, when considering the effect of environmental protection investment on the recovery ratio of waste products, the premise is to assume that the recovery price is a certain value. If the above two factors can be considered simultaneously, the research will be more practical and interesting. Secondly, in the closed-loop supply chain, there are often many retailers and third parties, in which there are also game problems among them. The more complex game scenarios integrating multiple supply chain participants, and the competitive environment should get further investigation in the future research. Thirdly, the market for different types of products may be different. Therefore, the division of the market under different green closed loop supply chains is also worth investigating, which would increase the practice value of green closed loop supply chains.

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Appendix A

Notations	**Definitions**
α	Market potential of the product
β	Sensitivity of consumers to price
r_E	Recovery ratio of the recovered products to the sold products
h	Sensitivity of consumers to environmental promotion measures
φ	Balance coefficient of the cost for environmental promotion measures
μ	Sensitivity of consumers to environmental promotion measures
ϕ_1	When manufacturer and retailers share the total proceeds of sales, the proportion of the profit the manufacturer can obtain from the total profit
ϕ_2	When the manufacturer and the third party share the cost of the environmental promotion, the proportion of the profit the manufacturer can obtain from the total profit
w	Wholesale prices of the product
p	Retail price of the product
p^c	Retail price of the product under the centralized decision model
p^d	Retail price of the product under the decentralized decision model
p^{co}	Retail price of the product under the cooperative mechanism decision model
q	Demand volume of the product
q^c	Demand volume of the product under the centralized decision model
q^d	Demand volume of the product under the decentralized decision model
q^{co}	Demand volume of the product under the cooperative mechanism decision model
$C(A)$	Cost for advertising or other environmental promotion
A	Environmental investment composite index of the cost for environmental promotion measures
A^c	Environmental investment composite index of the cost for environmental promotion measures under the centralized decision model
A^d	Environmental investment composite index of the cost for environmental promotion measures under the decentralized decision model

A^{co}	Environmental investment composite index of the cost for environmental promotion measures under the cooperative mechanism decision model
c	The cost of the product
g_E	Cost of each unit product recovered by the third party
Δ	Residual value of each waste product
d_E	Fee paid by the manufacturer to the third party
M	Manufacturer
R	Retailers
E	Third-party
Π_j	Profit of each participant (j can be M, R or E)
Π	Total profit of the whole supply chain
Π^c	Total profit of the whole supply chain under the centralized decision model
Π^d	Total profit of the whole supply chain under the decentralized decision model
Π^{co}	Total profit of the whole supply chain under the cooperative mechanism decision model

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