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A Dual-Channel Cooperative Strategy between Recyclers and E-Tailers for the Offline and Online Recycling of Waste Electronics

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Abstract: A Stackelberg game model was formulated for dual recycling channels for a supply chain with a recycler and an e-tailer, who recycle and resell waste electronics. A reverse solution was adopted to find the optimal recycling prices, the optimal selling prices, and the supply chain's overall profits for cooperative and non-cooperative models. The profits gained in the cooperative model were greater. We proposed a revenue-sharing contract to investigate the profit distribution. Finally, we validated the effectiveness of the cooperative recycling model through numerical simulations, calculated the revenue-sharing factors, and analyzed the effects of these factors on the decisions of the recycler and the e-tailer. By comparing the dual-channel non-cooperative recycling model based on online and offline recycling by the recycler to the dual-channel cooperative recycling model based on offline recycling by the recycler and online recycling by the e-tailer, as well as examining the results in relation to the contracts, we found that the recycler and the e-tailer should cooperate in recycling electronics to maximize the supply chain's overall profits. However, the e-tailer will see reduced profits and may be less willing to cooperate, so it is necessary to formulate a revenue-sharing contract. The revenue-sharing factors in the contract must be set within a reasonable range; otherwise, either party could see reduced profits and renounce cooperation, even if the supply chain's overall profit is maximized. The recycler is the more critical party for achieving cooperation. In this paper, we research the cooperative strategy between recyclers and e-tailers that is conducive for expanding the market scale of waste electronics recycling and improving the profits of both parties, while promoting the sustainable development of the supply chain.

Keywords: dual recycling channels; cooperative strategy; Stackelberg game; revenue-sharing contract



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1. Introduction

With the continuous innovation and iteration of science and technology, and the new pursuit of consumers for the diversification of electronic products, electronic products are being updated and iterated at an accelerated pace, and the number of waste electronic products is rising. According to the United Nations' Global E-Waste Monitor, it is estimated that 5.3 billion pieces of waste will be generated from just electronic communication products globally in 2022, and it is expected that the total amount of e-waste generated globally will reach a record 74 million tons in 2030 [1]. If waste electronic products are not scientifically recycled and treated, the large amount of metal elements contained within them will seriously pollute the environment and even harm human health. Therefore, governments and enterprises in various countries have formulated policies and taken actions to recycle WEEE. For example, the "People's Republic of China National Economic and Social Development Fourteenth Five-Year Plan and Vision 2035 Outline" proposed a "14th Five-Year Plan" period to comprehensively improve the efficiency of resource utilization, and to promote the recycling of waste and the centralized disposal of pollutants. This would strengthen the comprehensive utilization of bulk solid waste and the planning

and construction of recycling facilities for used and scrap materials [1]. Many electronic and electrical equipment companies (e.g., Kodak, Hewlett-Packard) have also commissioned third-party recyclers to recycle discarded products in order to build a green and sustainable reverse supply chain [2,3]. As a result, the market size of the waste electronics recycling industry has been expanding [4]. The recycling channel level of waste electronic products has also seen a new change. Unlike the traditional recyclers who usually carry out offline channel recycling by opening stores, for the past few years, online recycling channels based on new network recycling platforms have become a trend [5]. Compared to offline recycling channels, online recycling channels have improved information transmission, process simplification, and recycling efficiency [6]. Therefore, the emergence of a new network of recycling platforms responsible for online recycling has extended recycling channels to form a dual-channel recycling model that includes traditional offline stores. The development of a dual-channel recycling combination of waste electronic and electrical products has also become a trend. In May 2023, China's Ministry of Commerce and other four departments issued the Notice on Doing a Good Job in Promoting the Consumption of Green and Intelligent Household Appliances in 2023, proposing to accelerate the organic combination of online and offline recycling through the mode of "Internet + Recycling" and other modes, and to improve the recycling capacity and standardization level of used home appliances [7]. Many recyclers have also established both online and offline recycling channels. For instance, Aihuishou (aihuishou.com), a C2B trading platform for secondhand electronic devices, combines their network platforms with offline stores for the dual-channel recycling of electronics [8]. Through the dual-channel recycling of WEEE, the recycling rate of electronic and electrical products has been effectively increased, and the green and sustainable development of the reverse supply chain has been promoted.

The competing strategies among recycling entities have also changed with the changes in the recycling channels. In the past, when the online channel for recycling was not popularized, it was mainly dominated by offline competition among the supply chain members, such as the competition and cooperation between manufacturers and third-party recyclers in the process of electronics recycling [9], and the competition and cooperation between retailers and third-party recyclers in the process of electronics recycling [10]. As online channels become a prevailing trend, not only have many third-party recyclers established offline stores and online platforms for electronic product recycling at the recycling entity level, but also numerous professional e-commerce companies have ventured into the electronic product recycling industry [6]. For example, the e-commerce giant, JD.com, is cooperating with Aihuishou [11], which transfers their recycled electronics to the former to sell on Paipai.com. However, recyclers and e-tailers may encounter a series of problems from a dual-channel recycling cooperative strategy. In some cases, e-tailers have leveraged their position as the dominant party to establish irrational cooperation contracts and squeeze the profits of the recyclers, thereby weakening their motivation to cooperate. A lack of cooperation is inconducive for maximizing the total profits of the supply chain members in the recycling industry. Therefore, the cooperation between recyclers and e-tailers in the recycling process is an important issue. On the one hand, a good cooperation strategy could avoid a recycling price competition between the two and improve the profits of both parties. On the other hand, a cooperation strategy between the two could expand the market scale of electronic product recycling, which would be conducive for promoting the construction and development of a sustainable supply chain of electronic products [12,13]. The study of cooperative strategies between recyclers and e-tailers in a dual-channel recycling supply chain is of great significance.

This paper aims to solve the following problems. First, the competition between online and offline recycling channels is considered to determine the optimal recycling price, so that the recycler and the e-tailer can maximize their profits. Second, we compare the profits and recycling market size of the recycler and the e-tailer in the non-cooperative and cooperative scenarios, and verify whether cooperative recycling would have a significant impact on increasing the recycling market size and expanding the total profits of the recycler and

the e-tailer. Third, we design a contract with which to achieve supply chain coordination based on the success of the second validation, and analyze the conditions under which cooperation could be reached by exploring the revenue sharing factors for both parties.

The remainder of the paper is structured as follows: Section 2 discusses the relevant literature. Section 3 models the two-channel recovery and explains the meaning of the relevant parameters. Section 4 solves for the profits of each member of the supply chain in the non-cooperative and cooperative scenarios. Section 5 carries out a comparison of the models and designs the contract. Section 6 carries out a simulation analysis and derives some managerial insights from a comparative and sensitivity analysis. Section 7 gives our conclusions and the outlook for future research.

2. Literature Review

This paper draws on two streams of the existing literature: the dual-channel electronics reverse recycling supply chain problem and the supply chain coordination problem in the presence of recyclers.

In the first stream, Ma et al. [14] constructed a closed-loop supply chain model of dual-channel recycling, which consisted of a manufacturer and a third-party recycler. They solved it using game-theoretic methods, simulated it numerically using entropy theory, and introduced adjustment parameters to control the chaotic state. Huang et al. [15] constructed a closed-loop supply chain with dual recycling channels for online recycling and offline recycling, and studied the cost perturbation problem for new and remanufactured products using the Stackelberg game. Jian et al. [16] explored collaborative recycling strategies between third-party recyclers and electronics retailers. They developed four recycling models, compared the recycling pricing and profits in each model, and designed a recycling effort cost-sharing mechanism for the profit distribution. Expanding on the dual-channel recycling, Huang et al. [17] investigated the optimal strategy for a retailer-led closed-loop supply chain (CLSC) with triple recycling channels. They established a mathematical model of the waste construction machinery recycling and remanufacturing system based on reasonable assumptions to solve the pricing and recycling effort allocation strategies. Huang et al. [18] constructed a dual-channel closed-loop supply chain model with retailers and third-party recyclers competing for recycling, and analyzed the recycling strategies from the perspectives of manufacturers and consumers, proving that dual-channel recycling is better than single-channel recycling. Wang et al. [19] established a closed-loop supply chain under the scenario of the dual-channel competition between a manufacturer and retailer, and compared it with single-channel recycling models of the manufacturer and retailer. The results indicate that the dual-channel competitive recycling model is optimal when the recycling price sensitivity factor is large. Despite the considerable research on dual-channel recycling, the focus has mainly been on scenarios where multiple members of the supply chain engage in recycling, with little attention given to the online and offline dual-channel recycling of electronic products. Moreover, there is limited research in the literature like the case in this paper that analyzes and compares the two modes of third-party recyclers carrying out online and offline dual-channel recycling alone, as well as the third-party recyclers responsible for offline recycling and the e-tailers responsible for online recycling, and designing a cooperation contract for both parties.

The second research stream on the supply chain coordination problem in the presence of recyclers has been extensively studied in the literature. In order to study the closed-loop supply chain model with third-party recyclers, Su et al. [20] developed a two-stage closed-loop supply chain game model and took environmental protection inputs into consideration, compared and analyzed the impacts of centralized and decentralized decision-making on the revenue and pricing strategies of each participant, and designed a cost profit-sharing contract. Wei et al. [21] introduced a three-level closed-loop supply chain containing two recyclers, then explored the effects of manufacturers' retail and recycling channel integration strategies on the optimal decision-making and the maximum profits of closed-loop supply chain members. They also investigated the interactions between

recycling competition and manufacturers' integration strategies. Wu et al. [22] examined the recycling channels based on self-built networks and cooperation with third-party recyclers, then introduced a revenue-sharing contract to distribute the profits earned from cooperation. Focusing on third-party recyclers, Liu et al. [23] found that the profits from closed-loop supply chains of waste electronics under centralized decision-making were higher than under decentralized decision-making. They formulated cost and revenue distribution factors for profit distribution. Zhu et al. [24] considered the influence of consumer behavior on recycling and constructed a closed-loop supply chain model consisting of manufacturers, retailers, and online recycling platforms, and the results of the study show that remanufacturing companies tend to increase the transfer payment price in order to concede part of their profits. Therefore, the expense-sharing contract is established and utilized to achieve supply chain coordination. Saha et al. [25] modeled a closed-loop supply chain containing a manufacturer, a retailer, and a third-party recycler. They considered an incentive-driven policy and discussed the pros and cons of decentralized versus cooperative recycling scenarios, and finally proposed a three-party discount mechanism for the manufacturer. Xie et al. [26] built a closed-loop supply chain consisting of a manufacturer and a retailer. They introduced both offline and online dual-channel sales and a single-channel recycling process by an offline retailer. They aimed to increase the profit of the dual-channel through a revenue-sharing contract and a cost-sharing contract. Zheng et al. [27] analyzed a three-level closed-loop supply chain consisting of a manufacturer, a distributor, and a retailer. They considered the fairness concerns of the retailer and explored both cooperative and non-cooperative scenarios. They designed the Shapley value, the nucleolus solution, and the equal satisfaction methods to coordinate the growing profits in cooperative and non-cooperative scenarios, respectively. It can be found that most of the supply chain coordination problems in the presence of recyclers are cooperation among closed-loop supply chain members. In fact, waste electronic products are not only transferred to manufacturers by recyclers, but also transferred to retailers for the sale of used electronic products after refurbishment by recyclers [28]. The coordination of the reverse supply chain for the sale of used electronics starting from the recycler through the e-tailer has rarely been considered in the previous literature.

The above studies on dual-channel recycling have focused on the coordinative and cooperative strategies between recyclers and other closed-loop supply chain members, as well as the comparison and selection of recycling channels but have rarely touched upon reverse supply chains where recycled electronics are resold as secondhand products or have examined dual-channel cooperation between recyclers and e-tailers, which affects the online and offline pricing and profits of electronics in supply chains. By formulating a Stackelberg game model for recyclers and e-tailers in cooperative and non-cooperative scenarios, this study obtained an equilibrium solution for a cooperative decision-making model, performed a comparative analysis to validate the effectiveness of the model through simulations, and examined the factor ranges of a revenue-sharing contract.

3. Problem Description and Modeling

Unlike the traditional forward sales supply chain, the reverse recycling supply chain starts with a recycler as the starting point of the supply chain, with raw materials reused by manufacturers or used products sold by retailers. In the field of electronic products, the reverse recycling supply chain can maximize the value of used electronic products and promote the sustainable development of the supply chain [29]. In this study of a recycling supply chain, a third-party recycler processes and tests waste electronics to sell to an e-tailer at higher transfer prices. After simple refurbishments of the electronics, the e-tailer resells them as secondhand products to consumers. By combining ideas from previous studies [30,31] with actual scenarios, we formulated a dual-channel recycling model consisting of offline store recycling and online network recycling. In the non-cooperative version of the model, the recycler is responsible for both online and offline

recycling. In the cooperative version, the recycler is responsible for offline recycling while the e-tailer is responsible for online recycling.

In waste electronics recycling, P_s , P_e denote the online and offline recycling prices, respectively, P_r denotes the transfer price of electronics from the recycler to the e-tailer, and P_2 denotes the e-tailer's reselling price of the secondhand product. Superscripts are used to represent the mode of cooperation between the recycler and the e-tailer. D represents the decentralized mode and C represents the centralized mode. Regardless of the presence of cooperation, it is always necessary to ensure profitability for both the recycler and the e-tailer: $P_2^D > P_r^D > P_e^D(P_s^D)$, $P_2^C > P_r^C > P_e^C(P_s^C)$.

D_s^D , D_e^D , D_s^C , D_e^C denote the recycled volumes of electronics through offline and online channels in both the non-cooperative and cooperative scenarios, respectively. As per the model of dual-channel linear demand functions [23,32], the recycled volume is expressed as a linear demand function:

$$D_s^D = \lambda\theta + bP_s^D - cP_e^D + (l - k)Q \quad (1)$$

$$D_e^D = (1 - \lambda)\theta + bP_e^D - cP_s^D + kQ \quad (2)$$

For the non-cooperative scenario:

$$D_s^C = \lambda\theta' + bP_s^C - cP_e^C + k'W \quad (3)$$

$$D_e^C = (1 - \lambda)\theta' + bP_e^C - cP_s^C + (l' - k')W \quad (4)$$

The parameters and descriptions in the demand function are as follows:

θ and θ' denote the potential market capacities of waste electronics recycling in both scenarios, respectively, or the recycled volumes when the recycling prices of both channels are 0, which are related to the customers' environmental awareness. Generally speaking, the traffic of online recycling by the e-tailer in the cooperative recycling scenario is greater than that of online recycling by the recycler in the non-cooperative scenario. Therefore, the potential market capacity in the cooperative scenario is greater, i.e., $\theta' > \theta$. Assuming that λ is the market share of the offline recycling channel, then the market share of the online recycling channel can be expressed as $1 - \lambda$. b denotes the elasticity coefficient of the recycling price. c denotes the substitution coefficient of the recycling price between different recycling channels and characterizes customers' switching from one recycling channel to the other because of the differences in recycling prices. Referring to the existing literature study [33], the relationship between b and c is generally satisfied by $b > c > 0$.

l , l' are the elasticity coefficients of the advertising levels; for facilitating calculations, the elasticity coefficients of the publicity and promotion levels are assumed to be equal in the two scenarios. This assumption implies that the increase in recovery size resulting from publicity and promotion is fully positively correlated with the publicity and promotion levels. k , k' are the degrees of customers' free-riding behaviors, which measures the proportion of customers who learn about the recycler through the offline channel but shift to the online recycling of waste electronics in the non-cooperative scenario and the proportion of customers who learn about the recycler through the online channel but shift to the offline recycling of waste electronics in the cooperative scenario, respectively, where $0 \leq k \leq l$, $0 \leq k' \leq l'$. $k = 0$ means that all customers who have learned about the recycler through the offline channel choose offline recycling. $k = l$ means that all customers who have learned about the recycler offline shift to online recycling. The same equations apply to k' . Based on the relevant literature [23,32], the e-tailer's sales volume of secondhand electronics is expressed as $D_2 = g - hp_2$, where g denotes the basic market demand for secondhand electronics and h denotes the sensitivity of consumers to the selling price.

The assumptions of this model are as follows:

This problem considers only a single decision cycle. When the recycler and the e-tailer are not cooperating, the recycler's dual recycling channels make joint decisions to maximize the recycler's profit. At the same time, the recycler and the e-tailer each aim at their own

maximum profit, and there is a Stackelberg game relationship where the recycler assumes the role of leader and the e-tailer acts as the follower. When the recycler and the e-tailer cooperate, their objective is to maximize the overall supply chain benefit.

The model only considers the situation where the net value of the recycled electronic products is high, i.e., the recycler recycles the used electronic products and then transfers them to the e-tailer for the second-hand electronic products sale, and does not consider the situation where the recycler transfers them to the manufacturer for remanufacturing.

When the recycler recovers electronic products that can be sold as used products, it will first estimate the value of the electronic products according to their condition, and then refurbishes these products and transfers them to the e-tailer at a price P_r . The recycling price of an electronic product is considered as the optimal recycling price. To ensure that the recycler is profitable, there is $P_r > P_s$, $P_r > P_e$. The recycling price in this paper refers to the sum of the recycling valuation and the refurbishment fee, and it is based on the optimal recycling price minus the refurbishment fee of the electronic products that the recycler arrives at the valuation of the electronic product.

Assuming that consumers have equal price sensitivity towards online and offline channels of recycling and in the channel selection of the two channels is a perfect substitution relationship, that is, the elasticity coefficient of the recycling price and the substitution coefficient of the recycling price of the two channels is the same. That is, $b^C = b^D$, $c^C = c^D$.

In reference to the relevant literature [34], the recycler and the e-tailer can increase recycling volume by advertising WEEE recycling behaviors while also paying advertising costs $C_Q = a_1 Q^2/2$ and $C_W = a_2 W^2/2$, respectively, which represent the advertising costs of the offline stores borne by the recycler in the non-cooperative recycling model and the advertising costs borne by the e-tailer for advertising the recycler's brand by using online traffic in the cooperative recycling model, where $a_1 > 0$, $a_2 > 0$ are the advertising degree coefficients,

π_t denotes the profit of the third-party recycler; π_r denotes the profit of the e-tailer. According to the parameter settings, the profits of the recycler and the e-tailer in the non-cooperative and cooperative scenarios are:

$$\pi_t^D = (P_r^D - P_s^D)D_s^D + (P_r^D - P_e^D)D_e^D - a_1 Q^2/2 \quad (5)$$

$$\pi_r^D = (P_2^D - P_r^D)D_2^D \quad (6)$$

$$\pi_t^C = (P_r^C - P_s^C)D_s^C + (P_r^C - P_e^C)D_e^C \quad (7)$$

$$\pi_r^C = (P_2^C - P_r^C)D_2^C - a_2 W^2/2 \quad (8)$$

The revenues of the recycler and the e-tailer in the two scenarios come from the transfers of electronics and the sales of secondhand electronics, respectively. The difference lies in that advertising costs are paid by the recycler in the non-cooperative scenario and by the e-tailer in the cooperative scenario.

4. Model Solving

4.1. Dual-Channel Non-Cooperative Recycling Model

Figure 1 shows the decentralized decision-making on the part of the recycler and the e-tailer, and they each make decisions with the goal of maximizing their respective interests. P_r is regarded as a fixed value. The e-tailer, as the dominant party, first determines sales price P_2 , whereas the recycler determines recycling prices P_s and P_e afterwards.

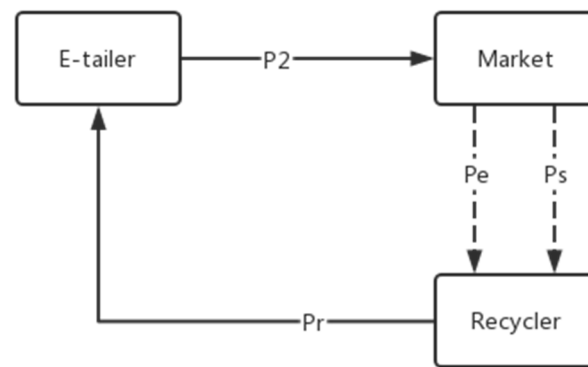


Figure 1. Flowchart of the non-cooperative recycling model.

According to Equations (5) and (6) for the profits of the recycler and the e-tailer, respectively, the total profit of the supply chain under non-cooperative decision-making is:

$$\pi^D = \pi_r^D + \pi_t^D \quad (9)$$

Theorem 1. In the dual-channel non-cooperative recycling model between the recycler and the e-tailer, the optimal offline recycling price P_s of the recycler, the optimal online recycling price P_e , and the optimal selling price P_2 of the e-tailer for the used electronic products can be expressed as follows:

$$\begin{cases} P_s^D = \frac{b[-\lambda\theta - (l-k)Q + (b-c)P_r] + c[-(1-\lambda)\theta - kQ + (b-c)P_r]}{2(b^2 - c^2)} \\ P_e^D = \frac{c[-\lambda\theta - (l-k)Q + (b-c)P_r] + b[-(1-\lambda)\theta - kQ + (b-c)P_r]}{2(b^2 - c^2)} \\ P_2^D = \frac{g + hP_r}{2h} \end{cases} \quad (10)$$

Proof. According to the inverse solution method, we first solve for the selling price of the e-tailer based on the e-tailer profit expression. Since $\partial^2 \pi_r^D / \partial (P_2^D)^2 = -2h < 0$, π_r^D has an optimal solution with respect to P_2^D . We make $\partial \pi_r^D / \partial P_2^D = 0$ and according to Equation (6) can be obtained:

$$P_2^D = \frac{g + hP_r}{2h} \quad (11)$$

The second-order partial derivatives and mixed partial derivatives of π_t^D for P_s^D and P_e^D , respectively, in Equation (5) give the Hessian matrix of π_t^D as: $H_\pi = \begin{pmatrix} -2b & 2c \\ 2c & -2b \end{pmatrix}$.

Since $|H_\pi|_1 = -2b < 0$, $|H_\pi|_2 = 4(b^2 - c^2) > 0$, π_t^D has an optimal solution with respect to P_s^D and P_e^D , substituting into Equation (11) and making $\partial \pi_t^D / \partial P_s^D = 0$, $\partial \pi_t^D / \partial P_e^D = 0$, we obtain:

$$\begin{cases} P_s = \frac{b[-\lambda\theta - (l-k)Q + (b-c)P_r] + c[-(1-\lambda)\theta - kQ + (b-c)P_r]}{2(b^2 - c^2)} \\ P_e = \frac{c[-\lambda\theta - (l-k)Q + (b-c)P_r] + b[-(1-\lambda)\theta - kQ + (b-c)P_r]}{2(b^2 - c^2)} \end{cases} \quad (12)$$

□

By substituting Equation (10) into Equations (5) and (6), we obtain the equation for the total profit of the supply chain members in the non-cooperative scenario:

$$\begin{aligned} \pi^D = & \left(\frac{P_r}{2} + \frac{[b\lambda + c(1-\lambda)]\theta + [b(l-k) + ck]Q}{2(b^2 - c^2)} \right) \left(\frac{(b-c)P_r + \lambda\theta + (l-k)Q}{2} \right) \\ & + \left(\frac{P_r}{2} + \frac{[c\lambda + b(1-\lambda)]\theta + [c(l-k) + bk]Q}{2(b^2 - c^2)} \right) \left(\frac{(b-c)P_r + (1-\lambda)\theta + kQ}{2} \right) - a_1 Q^2 / 2 \end{aligned} \quad (13)$$

4.2. Dual-Channel Cooperative Recycling Model

As shown in Figure 2, the centralized decision-making by the recycler and the e-tailer determines selling price P_2 , as well as recycling prices P_s and P_e , and they make decisions as a whole with the goal of maximizing the profitability of the system. According to Equations (7) and (8) for the profits of the recycler and the e-tailer, respectively, the total profit of the supply chain under cooperative decision-making is:

$$\pi^C = \pi_r^C + \pi_t^C \quad (14)$$

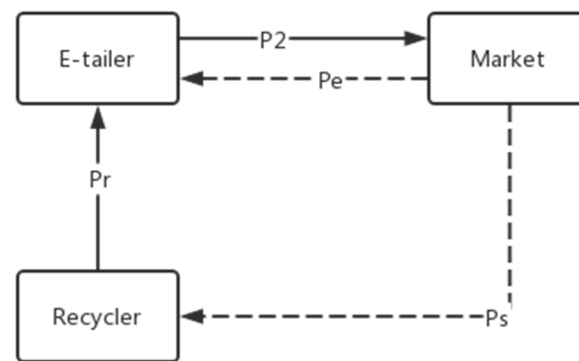


Figure 2. Flow chart of the cooperative recycling model.

Theorem 2. In the dual-channel cooperative recycling model between the recycler and the e-tailer, the optimal offline recycling price P_s of the recycler, the optimal online recycling price P_e , and the optimal used electronics sales price P_2 of the e-tailer can be expressed as follows:

$$\begin{cases} P_2^C = \frac{g+hP_r}{2h} \\ P_s^C = \frac{(b^2-c^2)P_r - [c(1-\lambda)+b\lambda]\theta' - [c(l'-k')+bk']W}{2(b^2-c^2)} \\ P_e^C = \frac{(b^2-c^2)P_r - [c\lambda+b(1-\lambda)]\theta' - [ck'+b(l'-k')]W}{2(b^2-c^2)} \end{cases} \quad (15)$$

Proof. Find the second order derivatives of π^C with respect to P_s^C , P_e^C and P_2^C in Equation (14), since $\partial^2 \pi^C / \partial (P_2^C)^2 = -2h < 0$, $\partial^2 \pi^C / \partial (P_s^C)^2 = -2b < 0$, $\partial^2 \pi^C / \partial (P_e^C)^2 = -2b < 0$. π^C have optimal solutions with respect to P_s^C , P_e^C and P_2^C , make $\partial \pi^C / \partial P_s^C = 0$, $\partial \pi^C / \partial P_e^C = 0$, $\partial \pi^C / \partial P_2^C = 0$, and solve the equation to arrive at Equation (15). $\square$

By substituting Equation (15) into Equations (7) and (8), we obtain the equation for the total profit of the supply chain members in the cooperative scenario:

$$\begin{aligned} \pi^C = & \left(\frac{P_r}{2} + \frac{[b\lambda+c(1-\lambda)]\theta' + [c(l'-k')+bk']W}{2(b^2-c^2)} \right) \left(\frac{(b-c)P_r + \lambda\theta' + k'W}{2} \right) \\ & + \left(\frac{P_r}{2} + \frac{[c\lambda+b(1-\lambda)]\theta' + [ck'+b(l'-k')]W}{2(b^2-c^2)} \right) \left(\frac{(b-c)P_r + (1-\lambda)\theta' + (l'-k')W}{2} \right) \\ & - a_2 W^2 / 2 \end{aligned} \quad (16)$$

5. Model Comparison and Revenue-Sharing Contract

The non-cooperative model and the cooperative model are compared for total recycled volume, their profits of the recycler, profits of the e-tailer, and total profits of the supply chain so that we can select a suitable recycling model for both the recycler and the e-tailer.

Theorem 3. The dual-channel cooperative recycling model is compared to the dual-channel non-cooperative recycling model with $D^C > D^D$, $\pi_t^C > \pi_t^D$, $\pi_r^C > \pi_r^D$, $\pi^C > \pi^D$.

Proof. Comparing the volume of WEEE recycled in the two models, there is:

$$D^C - D^D = (\theta' - \theta) + (b - c)(P_s^C - P_s^D + P_e^C - P_e^D) + l'W - lQ = ((\theta' - \theta) + l'W - lQ)/2 \quad (17)$$

Comparing the profits of recycler under both models, there is:

$$\begin{aligned} \pi_t^C - \pi_t^D &= a_1 Q^2/2 + ((\theta' - \theta) - (l - k)Q + (l' - k')\omega - kQ + k'\omega)P_r/4 \\ &+ \left(\begin{aligned} &(2(b - c)\lambda^2 + 2(c - b)\lambda + b)(\theta'^2 - \theta^2) + (b^2 - c^2)(P_r\theta' - P_r\theta) \\ &+ (4(b - c)k'\lambda + 2(c - b)l'\lambda + 2(c - b)k' + 2bl')\theta'\omega \\ &- (4(c - b)k\lambda + 2(b - c)l\lambda + 2(b - c)k + 2cl)\theta Q \\ &+ (bl' + cl')(b - c)P_r\omega - (bl + cl)(b - c)P_rQ \\ &+ (2(b - c)k'^2 + 2(c - b)k'l' + bl'^2)\omega^2 + (2(b - c)k^2 + 2(c - b)kl + bl^2)Q^2 \end{aligned} \right) / 4(b^2 - c^2) \quad (18) \\ &> 0 \end{aligned}$$

Similarly, comparing the profits of the e-tailer under the two models, there is:

$$\pi_r^C - \pi_r^D = -a_2 W^2/2 < 0 \quad (19)$$

Finally, comparing the total profit of the supply chain under the two models, there is:

$$\begin{aligned} \pi^C - \pi^D &= -1/2(a_2 W^2 - a_1 Q^2) + ((\theta' - \theta) - (l - k)Q + (l' - k')\omega - kQ + k'\omega)P_r/4 \\ &+ \left(\begin{aligned} &(2(b - c)\lambda^2 + 2(c - b)\lambda + b)(\theta'^2 - \theta^2) + (b^2 - c^2)(P_r\theta' - P_r\theta) \\ &+ (4(b - c)k'\lambda + 2(c - b)l'\lambda + 2(c - b)k' + 2bl')\theta'\omega \\ &- (4(c - b)k\lambda + 2(b - c)l\lambda + 2(b - c)k + 2cl)\theta Q \\ &+ (bl' + cl')(b - c)P_r\omega - (bl + cl)(b - c)P_rQ \\ &+ (2(b - c)k'^2 + 2(c - b)k'l' + bl'^2)\omega^2 + (2(b - c)k^2 + 2(c - b)kl + bl^2)Q^2 \end{aligned} \right) / 4(b^2 - c^2) \quad (20) \\ &> 0 \end{aligned}$$

□

By analyzing the changes in the total recycling volume of waste electronic products under the two modes, it can be seen that compared with the dual-channel recycling carried out by the recycler alone, the mode of cooperative recycling between the recycler and the e-tailer can effectively improve the recycling rate of waste electronic products, which is conducive to the sustainable development of the reverse supply chain of waste electronic product recycling. By analyzing the changes in the total profits of the supply chain and the respective profits of the supply chain members under the two modes, the cooperative recycling model is superior to the non-cooperative recycling model in terms of higher profit for the recycler and the total profit of the supply chain, thus yielding the potential for cooperative recycling between the recycler and the e-tailer. However, the e-tailer, seeing a drop in profit, is not motivated to cooperate. To achieve Pareto improvement in the supply chain and ensure cooperation between the two parties, we referred to previous studies on this scenario to propose a contract and calculate the parameters [23,35] for guarantees and reasonable allocations of profits to each supply chain member.

Relying on their traffic advantages, the e-tailer invests in advertising to establish their online recycling channel and to help the recycler increase the recycled volume of electronics. As compensation, a portion of the recycler's revenue is allocated to the e-tailer. The recycler provides a stable supply channel and qualified secondhand electronics to the e-tailer, who also allocates a portion of their sales revenue to the recycler. Compared with the decentralized scenario, the scenario of revenue-sharing contract-based coordination between the two parties can achieve rational profit distribution and increase the profit of the recycler, the profit of the e-tailer, and the total profit of the supply chain.

According to the revenue-sharing contract, a portion based on the revenue-sharing factor α_1 of the recycler's transfer payment income P_r is given to the e-tailer. α_1 is deter-

mined by the recycler. Similarly, a portion based on α_2 of the e-tailer's sales income P_2 is allocated to the recycler. α_2 is determined by the e-tailer.

As shown in Figure 3, the incomes of the recycler and the e-tailer come from two sources, which are the transfer payment income of the recycler and the sales income of the e-tailer. Before the revenue-sharing contract, these two parts correspond to the incomes of the recycler and the e-tailer, respectively. After the revenue-sharing contract has been made, the transfer payment income of the recycler is divided into two parts, of which one is for the recycler and the other is for the e-tailer, whose share is determined by the revenue-sharing factor α_1 . Similarly, the sales income of the e-tailer is divided into two parts, of which one is for the e-tailer and the other is for the recycler, whose share is determined by α_2 . Hence, the incomes of the recycler and the e-tailer are changed by the contract while their costs, as expressed in Equations (7) and (8), respectively, remain the same as before the contract.

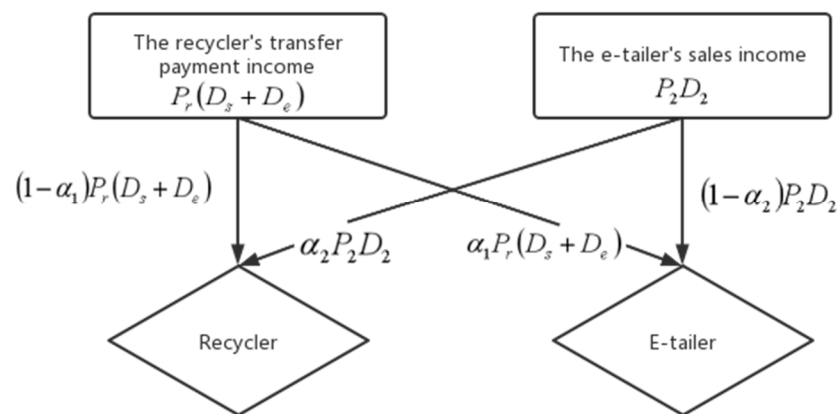


Figure 3. Schematic diagram of the revenue-sharing contract.

π_t^R and π_r^R denote the profits of the recycler and the e-tailer, respectively, under the revenue-sharing contract:

$$\begin{cases} \pi_t^R = (1 - \alpha_1)P_r(D_s + D_e) - P_sD_s - P_eD_e + \alpha_2P_2D_2 \\ \pi_r^R = (1 - \alpha_2)P_2D_2 - P_rD_2 + \alpha_1P_r(D_s + D_e) - a_2W^2/2 \end{cases} \quad (21)$$

To achieve the expected effects of the revenue-sharing contract, the following conditions must be met:

$$\begin{cases} \pi^R = \pi^C \\ \pi_t^R > \pi_t^D \\ \pi_r^R > \pi_r^D \end{cases} \quad (22)$$

Substituting Equations (5), (6) and (21) into Equation (22) yields revenue-sharing factors α_1 , α_2 , which must satisfy:

$$\begin{cases} \alpha_1 > \frac{P_2D_2}{P_r(D_s^R + D_e^R)}\alpha_2 + \frac{a_2W^2}{2P_r(D_s^R + D_e^R)} \\ \alpha_1 < \frac{P_2D_2}{P_r(D_s^R + D_e^R)}\alpha_2 + 1 - \frac{P_s^R D_s^R + P_e^R D_e^R + (P_r - P_s^D)D_s^D + (P_r - P_e^D)D_e^D - a_1Q^2/2}{P_r(D_s^R + D_e^R)} \end{cases} \quad (23)$$

Because of the high complexity of the α_1 , α_2 relationship, a specific case study was used to analyze the profits of the supply chain members under the contract.

6. Case Study

Aihuishou is a famous O2O electronics recycler in China, which on the one hand recycles used electronics through establishing offline stores and transfers them to JD.com's second-hand electronics retailer "Paipai", and on the other hand cooperates with JD.com to promote its electronics recycling website in JD.com's e-mall [11]. The cooperation between

Aihuishou and JD.com can be regarded as a typical case in this study. A case study was performed to compare the changes before and after the cooperation between Aihuishou and JD.com more intuitively and obtain more specific management implications. The case relates to the cooperation between Aihuishou and JD.com for the recycling of a Huawei Mate40 mobile phone over a one-month period in Shanghai. We found that Aihuishou engaged in both offline recycling through its offline stores and online recycling through cooperation with JD.com. After recycling this mobile phone, Aihuishou transferred it to Paipai.com, which is a secondhand goods trading platform owned by JD.com, for reselling. Our market data estimates and assumptions are as follows. The transfer price is set as $P_r = 1800$. The potential market capacities of product recycling before and after cooperation within one month are $\theta = 10,000$ and $\theta' = 12,000$, respectively. The market share of the offline recycling channel for this product is $\lambda = 0.6$. Other parameters are set as follows: $a_1 = 10$, $a_2 = 100$, $Q = 150$, $W = 180$, $l = l' = 10$, $k = k' = 5b = 8$, $c = 1$, $g = 16,500$, $h = 7.5$.

6.1. Sustainability Analysis of Cooperation between Recycler and E-Tailers

In order to illustrate the significance of this study in promoting the recycling flow of used and second-hand electronic products, facilitating the sustainable development of the reverse supply chain, and raising consumers' awareness of recycling of used and second-hand electronic products, we explore the scenarios of no-recycler recycling, recycler recycling alone, and recycler recycling in cooperation with e-tailers, and validate the benefits of cooperative recycling on sustainable development of reverse supply chain by comparing the simulation data of used and second-hand electronic products recycling scale. The benefits of cooperative recycling for the sustainable development of the reverse supply chain are verified by comparing the simulation data with the recycling scale of used electronic products. Substituting the example values into Equations (1)–(4), and (9), the results are shown in Figure 4.

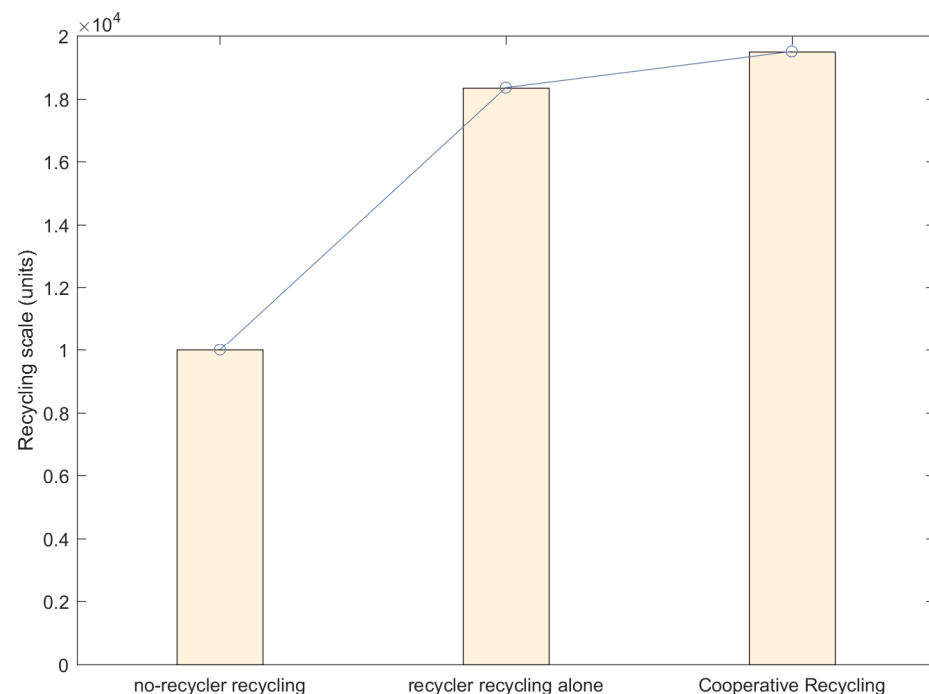


Figure 4. Comparison of the scale of recovery under different scenarios.

As can be seen in Figure 4, when there is no recycler to carry out recycling of used electronic products, the potential market recycling scale depends entirely on consumer awareness of recycling, i.e., the number of used electronic products that consumers voluntarily recycle for free in order to promote the sustainable development of the reverse supply chain of electronic products. When a third-party recycler carries out recycling

alone, on the other hand, the scale of used electronics recycling rises by 83.5%, driven by the recycling price, indicating that the emergence of the role of recyclers can effectively increase the scale of recycling of used electronics and accelerate the reverse flow of the electronics supply chain. When e-tailers cooperate with recyclers for recycling, more people will understand and join the recycling process of used electronic products due to the traffic advantage of e-tailers. Therefore, compared to recyclers recycling used electronic products alone, the cooperation between e-tailers and recyclers recycling electronic products can more effectively increase the scale of recycling used electronic products, and is more able to promote the reverse supply chain of product flow and sustainable development.

The conclusion of Figure 4 effectively confirms the conclusion of Theorem 3. The previous related literature [36] also studies the cooperation between the recycler and the e-tailer, and consistently concludes that such cooperation is conducive to the expansion of the total amount of recycling. However, it is important to note that this literature differs from the literature that discusses the “trade-in” cooperation in which the recycler recycle electronic products while the e-tailer simultaneously sell new electronic products. In contrast, this paper discusses the dual-channel recycling process cooperation between the e-tailer recycling through the online channel and the recycler recycling through offline channels. It can be seen that for the sustainable development of the recycling industry, more dual-channel resources should be integrated. This integration would enable offline recycling companies to partner with e-tailers in related product categories to expand online and offline dual-channel recycling cooperation. Importantly, this approach aligns with the Chinese government’s proposal of combining the form of “Internet + Recycling” to carry out online and offline dual-channel recycling, and improve the recycling of waste products capacity and standardization of waste electronic products [7].

6.2. Effectiveness of the Revenue-Sharing Contract

The following numerical analysis was conducted to better compare the optimal solutions of the cooperative and non-cooperative models, as well as prove the rationality of the contract. In accordance with the coordination mechanism proposed in this paper and Equation (20), $\alpha \in (0.05, 0.10)$ was calculated, and 0.08 was substituted for validation. The results are shown in Table 1.

Table 1. Optimal solutions in the non-cooperative recycling model, the cooperative recycling model, and the revenue-sharing contract model.

Model	P_s	P_e	P_2	π_t	π_r	π
Dual-channel non-cooperative recycling model	434	545	2000	23,994,663	300,000	24,294,663
Dual-channel cooperative recycling model	340	474	2000	27,240,714	−1,320,000	25,920,714
Revenue-sharing contract model	340	474	2000	24,672,714	1,248,000	25,920,714

Table 1 shows that the cooperative recycling model between the recycler and the e-tailer is superior to the non-cooperative recycling model in terms of the total profit of the supply chain. However, only the third-party recycler sees an increase in profit. Hence, even if the cooperative recycling model can increase the total profit of the supply chain, it cannot guarantee the establishment of cooperation, which now becomes the responsibility of the revenue-sharing contract. A reasonable revenue-sharing factor and the huge platform traffic of the e-tailer for online recycling increase the profit of each supply chain member and the total profit of the supply chain.

6.3. Revenue-Sharing Factor

(1) Effects of revenue-sharing factor on the profits of the recycler and the e-tailer

The revenue-sharing factor is divided into two parts, which are the recycler’s revenue-sharing factor α_1 and the e-tailer’s revenue-sharing factor α_2 . As the values of the two factors differ, the profits of the recycler and the e-tailer differ as well. The values of the other

parameters are those given at the beginning of this chapter. Random values are assigned to α_1 and α_2 within the range of $[0, 1]$ to simulate the profits of the recycler and the e-tailer under different contracts, which are then compared to the profits in the non-cooperative scenario in order to explore the critical points of cooperation between the two parties. The results are shown in Figure 5.

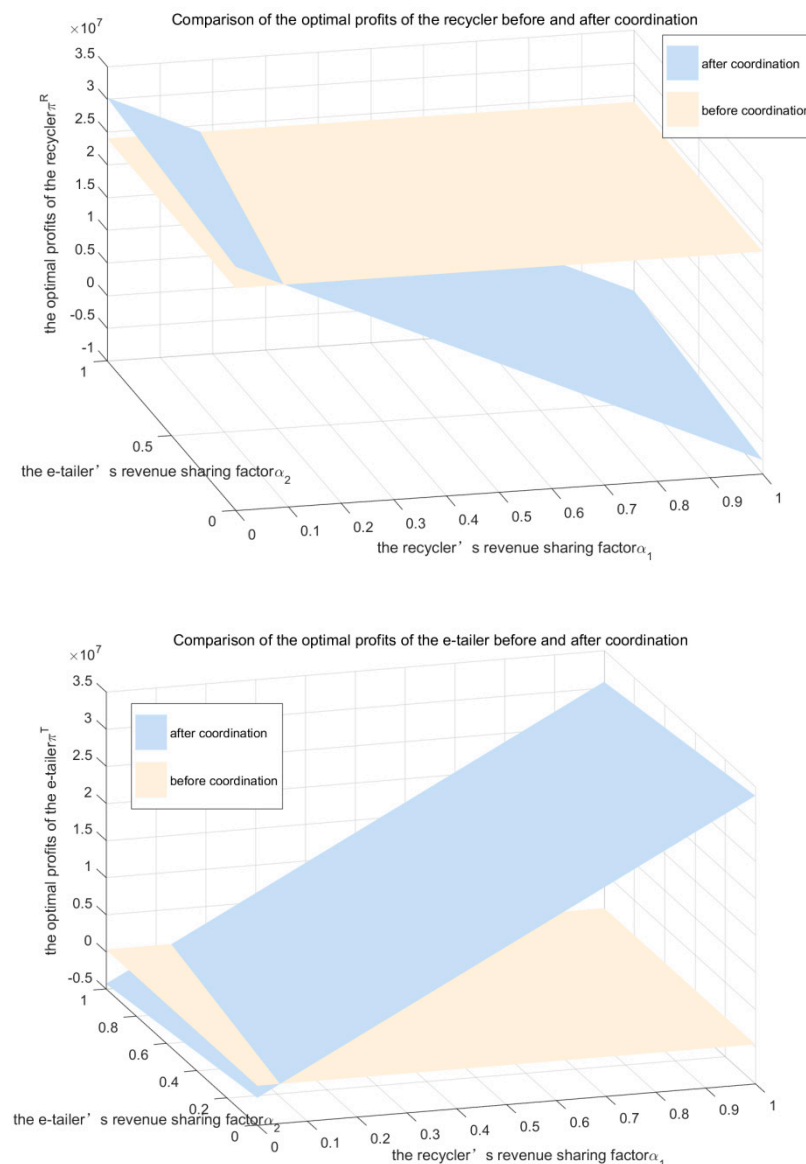


Figure 5. Comparison of the optimal profits of the recycler and the e-tailer before and after coordination.

Referring to the contract design ideas in the related literature [23], the condition for achieving cooperation is to find suitable revenue sharing factors that increase the total profit of the supply chain and the individual profits of its members when compared to the non-cooperative scenario. This analysis in the current section further extends the literature by dividing the revenue sharing factors into the recycler's revenue sharing factors and the retail e-commerce's revenue sharing factors. It explores the changes in the respective profits of the recycler and the e-tailer as well as the choice of cooperation strategies under the joint effect of both factors. According to the above profit analysis in Figure 5, the recycler and the e-tailer will choose to cooperate only when the blue area of the contract scenario is higher than the orange part of the decentralized decision-making scenario. Otherwise, they will give up cooperation to maximize their respective profits. The intersection of the two areas identifies their respective critical points of cooperation. For the recycler,

achieving cooperation requires the satisfaction of $\alpha_1 < 0.086\alpha_2 + 0.092$, i.e., the recycler allocates up to 17.8% of its revenue to the e-tailer and this upper limit will decrease as the e-tailer's revenue-sharing factor decreases to 9.2%, which is the lowest limit. For the e-tailer, achieving cooperation requires the satisfaction of $\alpha_1 > 0.086\alpha_2 + 0.046$, i.e., the recycler allocates at least 4.6% of its revenue to the e-tailer and this lower limit will increase as the e-tailer's revenue-sharing factor increases to 13.2%, which is the highest limit.

(2) Effects of revenue-sharing factors on the strategy selections of the recycler and the e-tailer

The effects of the revenue-sharing factors on the strategy selection of the two parties can be identified by summarizing their revenue-sharing factors in the previous section. The strategy selection of each party is shown in Figure 6.

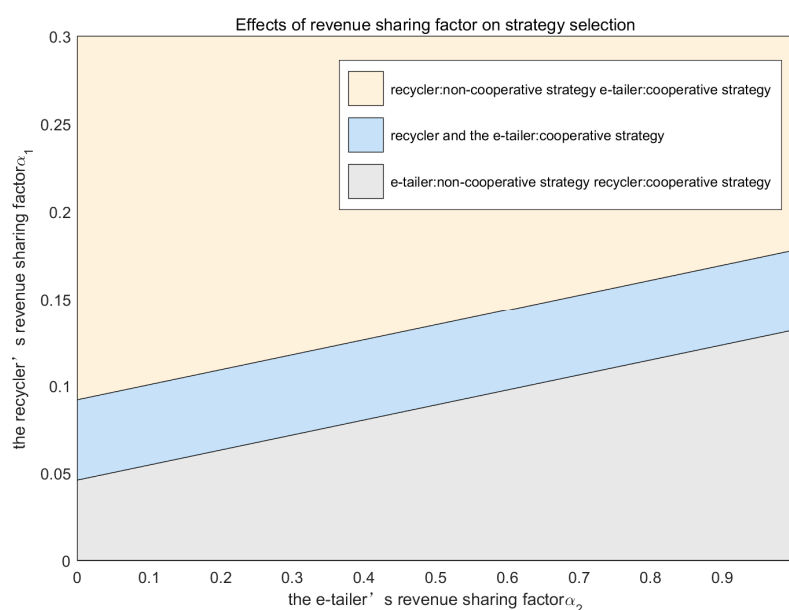


Figure 6. Effects of revenue-sharing factor on strategy selection.

As shown in Figure 6, at least one party will choose the cooperative strategy, regardless of how the revenue-sharing factors of the recycler and the e-tailer are determined, because, unlike the non-cooperative scenario, the cooperative strategy increases the total profit of the supply chain members. Regardless of the strategy of profit distribution between the recycler and the e-tailer, at least one party will see an increase in profit. Any party with increased profit will undoubtedly select the cooperative strategy. The revenue-sharing factors must be set within reasonable ranges, otherwise, either the recycler or the e-tailer will give up cooperation on account of reduced profits. Cooperation between the recycler and the e-tailer may increase the total profit of both parties, but it also changes the original profit distribution mode in the non-cooperative scenario. In the absence of a revenue-sharing contract, i.e., when α_1 , α_2 are both zero, to redistribute the total profit after cooperation, the e-tailer will ultimately withdraw from cooperation because it earns less after spending more on publicity to attract traffic for the recycler. Only reasonable revenue-sharing factors (α_1 , α_2 within the blue area of Figure 6 can create a win–win outcome by increasing the profits of both parties that choose to cooperate. Compared with the e-tailer, the recycler is the more critical party. Regardless of the e-tailer's choice of revenue-sharing factor, the establishment of cooperation ultimately depends on the recycler's revenue-sharing factor. Cooperation can be established only when the recycler sets its revenue-sharing factor within the range of [4.6%, 17.8%]. Notably, when the recycler's revenue-sharing factor is set within the range of [4.6%, 9.2%], cooperation can be established with ease, even without the allocation of the e-tailer's revenue.

The conclusions drawn in this section offer valuable management insights for both the recycler and the e-tailer. For recyclers, compared with the recycling model of establishing

dual-channel recycling with offline stores and online platforms through recyclers themselves, the cooperative recycling model of cooperating with the e-tailer to set up online recycling platforms while establishing offline recycling stores is better from the perspectives of expanding the scale of recycling as well as increasing the total profit of the supply chain. Significantly, this cooperative approach is relatively simple to implement from the perspective of contract design. By allocating a small portion of the recycling revenue to the e-tailer, a win–win cooperation can be achieved between the recycler and the e-tailer. As for the e-tailer, the platform should be fully utilized to help the offline recyclers to develop online recycling channels, and to obtain greater profits for themselves by expanding the recycling business.

The conclusions in this section also contribute to some extent to the development of research on the reverse supply chain for waste electronics. In terms of the dual-channel electronics reverse recycling supply chain problems, based on previous research on the effectiveness of the dual-channel offline recycling supply chain design consisting of manufacturers and third-party recyclers [14], as well as the comparison of the triple offline recycling channels dominated by retailers [16], and competitive strategies between manufacturers and retailers in offline dual-channel recycling [19], this paper investigates the online and offline dual-channel recycling cooperation between recyclers and e-tailers. The findings in Sections 6.1 and 6.2 also demonstrate the feasibility of online and offline dual-channel recycling cooperation between recyclers and e-tailers, both from the perspective of economic efficiency and environmental sustainability. In the supply chain coordination problem in the presence of recyclers, the three-level closed-loop supply chain coordination contract setup composed of manufacturers, retailers, and recyclers is the key research problem [20,24,27], while this paper focuses on the reverse supply chain of the recycling process, as the literature [36] states that studying the cooperation between recyclers and e-tailers as well as the problem of contract setting is a future research direction, this paper, by designing a revenue-sharing contract, clarifies the range of the value for the revenue-sharing factors in the contract through the research in Section 6.3, which is instructive for the cooperation between recyclers and e-tailers.

7. Conclusions

This paper proposes two dual-channel models for recycling waste electronics: a non-cooperative model based on online and offline recycling by a recycler, and a cooperative model based on offline recycling by a recycler but online recycling by an e-tailer. The two models were compared with regard to their maximizing of the supply chain's overall profit. After finding the cooperative recycling model to be superior, we proposed a revenue-sharing contract to redistribute the profits of the recycler and the e-tailer after both parties had chosen to cooperate, then investigated the two parameters affecting cooperative decision-making: the recycler's revenue-sharing factor and the e-tailer's revenue-sharing factor. Our findings are as follows.

- (1) Compared with the dual-channel non-cooperative recycling model, the dual-channel cooperative recycling model effectively utilizes the high traffic of the e-tailer and makes it possible to recycle more waste electronics, thereby increasing the total profit of the supply chain. This indicates that leveraging online publicity is an effective way to increase the recycling rate of WEEE and expand the scale of recycling. From the point of view of overall supply chain profitability and the recycling volume, the recycler should actively cooperate with the e-tailer, helping them to enter the recycling market and simultaneously increasing their own scale of recycling;
- (2) Even if the total profit of the supply chain is higher in the cooperative recycling model, the recycler and the e-tailer may not necessarily choose to cooperate. The key to cooperation lies in ensuring increases in the profits of both the recycler and the e-tailer as a result of the revenue-sharing contract. The profits of both parties can be increased as long as their revenue-sharing factors in the contract are set within reasonable ranges. This suggests that the original distribution of the revenue generated from the cooperation between the recycler and the e-tailer is unfair. Without coordination, the

e-tailer pays extra costs for publicity without receiving any compensation, making it unlikely for the e-tailer to cooperate;

- (3) The recycler is the more critical party and their revenue-sharing factor is the key to whether cooperation can be established. This suggests that for the reverse supply chain selling second-hand electronic products, recyclers must carefully consider a reasonable distribution of their earnings after cooperation. This will enable both parties to establish a cooperative relationship that both parties can realize increased profits through cooperation.

In conclusion, the main theoretical contribution of this paper is to design a cooperation model for recycling of used electronic products involving recyclers and e-tailers at the same time, and to explore the conditions for the two parties to reach cooperation by designing a revenue-sharing contract, which is instructive for the decision-making of recyclers and e-tailers in the recycling of used electronic products. At the same time, the cooperation strategy proposed in this paper can fully integrate the advantages of both parties, accelerate the product flow of the reverse supply chain of electronic products, expand the scale of the electronic product recycling market, help enterprises to improve their profits, and better realize the recycling of used electronic products and the sustainable green development of the supply chain.

However, there are some limitations of this paper, the limitations and future research directions are as follows:

- (1) While the existing model considers only one stage of the game, in real-world dual-channel competition, the game will continue for many stages until reaching an equilibrium. We plan to extend the model to multi-stage games in future research;
- (2) The reverse supply chain of waste electronics recycling is often accompanied by the sales of electronics in a forward supply chain. Future research should examine a combination of forward and reverse supply chains for trade-in subsidies of electronics between the recycler and the e-tailer.

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