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A Closed-Loop Supply Chain with Competitive Dual Collection Channel under Asymmetric Information and Reward–Penalty Mechanism

Wenbin Wang [1], Shuya Zhou [1,2], Meng Zhang [1], Hao Sun [3,*] and Lingyun He [1,2]

1 School of Management, China University of Mining and Technology, Xuzhou 221116, China; wangwenbin818@126.com (W.W.); zhoushuya93@foxmail.com (S.Z.); 17851149002@163.com (M.Z.); helingyun-love@163.com (L.H.)
2 Jangsu Province's Energy Economics and Management Base, Xuzhou 221116, China
3 School of Business, Qingdao University, Qingdao 266071, China
* Correspondence: rivaldoking@126.com; Tel.: +86-0532-85952399

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Abstract: We investigate a closed-loop supply chain (CLSC) where the retailer and the third-party recycler compete against each other to collect waste electrical and electronic equipment (WEEE) given that collection effort is their private information. Using the principle-agent theory, we develop a CLSC model with dual collection channel without the government's reward–penalty mechanism (RPM). An information screening contract is designed for the manufacturer to attain real information on collection effort levels; meanwhile, the optimal decision-making results of other decision variables are derived. Next, we take RPM into account to further examine the efficacy of the government's guidance mechanism in improving collection rate and profits of CLSC members. Our results indicate that (i) the collection competition reduces the total collection quantity and the expected profits of all the CLSC members without RPM; (ii) all CLSC members' expected profits are improved if both two collection agents select a high collection effort level without and with RPM; (iii) RPM increases buyback price, collection price, collection quantity, and franchise fee but decreases wholesale price and retail price; with the reward–penalty intensity increasing, the manufacturer's expected profit first decreases and then increases, while the expected profits of H-type retailer and H-type third-party recycler continue to increase. We find that RPM may ultimately stimulate the collection agents to collect more WEEEs, while the intense collection competition reduces the profits of CLSC members.

Keywords: closed-loop supply chain; information screening contract; dual collection channel; collection competition; reward–penalty mechanism; asymmetric information

1. Introduction

Due to the development of the economy and technology, there are more and more demands for various electronic products that bring people a more convenient life but also create a huge amount of electronic waste. According to a report by the United Nations University, electronic products such as mobile phones and computers have produced 12.3 million tons of e-waste during 2010 to 2015 in Asia. In this period, the quantity of e-waste produced by China has more than doubled to 6.7 million tons. Wu et al. [1] showed that the value of recycling has reached about $286 billion, which accounts for 8.89% of total sales in the United States, compared to only $100 billion in 2006. These data indicate that such a huge amount of e-waste can be a tremendous resource if recycled and reused properly. If it is adequately utilized, resource waste and environment pollution will be reduced a lot.

Previous studies have proposed various CLSC models to find out how to increase the amount of returned products, and then improve the environmental performance and profits of CLSC members in different scenarios. Savaskan et al. [2] indicated the importance of remanufacturing used products and developed a model in which the manufacturer as the Stackelberg leader has three options for collecting WEEE. They also designed some simple coordination mechanisms so that the retailer's collection effort and the CLSC profit are achieved at the same level as in a centrally coordinated system. Giovanni et al. [3] developed a dynamic CLSC model consisting of one manufacturer and one retailer, with both players participating in a product recovery program to increase the collection rate of used products. Hammond and Beullens [4] developed a CLSC network model in which the manufacturers and consumer markets engage in a Cournot game with complete information. They suggested that legislation on the minimum collection quantity of new products can stimulate reverse chain activities in CLSC. Savaskan and Wassenhove [5] investigated the interaction between decisions in the forward channel and the reverse channel, and the influence of retail competition on CLSC profits. They indicated that channel profits are affected by the scale of return on collection efforts in a direct collection system, but in an indirect reverse channel, CLSC profits are affected by the competition intensity between the retailers. Hong and Yeh [6] showed that the third-party collection channel is strictly inferior to the retailer collection channel when it forms a non-profit organization for collection. He et al. [7] compared the centralized (integrated) collection channel CLSC with the decentralized collection channel CLSC. The conclusion indicates that the optimal collection price, the collection quantity, and the quantity of remanufactured products under a decentralized collection channel are always lower than those under a centralized collection channel due to the double marginalization effect. Atasu and Çetinkaya [8] indicated that the collection rate, return timing, and reusability rate should correspond to the active market supply and demand in order to obtain the highest profits from remanufactured products. Also, they found that the fastest reverse supply chain may not be the most efficient one. Gaur et al. [9] developed an integrated optimization model for addressing the CLSC configuration. Esenduran et al. [10] investigated a stylized model in which an original equipment manufacturer (OEM) competes with an independent remanufacturer in order to find appropriate collection and reuse targets for maximizing OEM profit.

All of the above papers are based on symmetrical information. However, in many scenarios, some information is only available to one supply chain member, and the other members have to make decisions based on limited information. Voigt and Inderfurth [11] indicated that the efficiency losses caused by the strategic use of private information cannot be overcome if all agents refuse to share their information. An appropriate contract is vital because supply chain members prefer to pursuit their own profits without considering the total supply chain profit under asymmetric information. In a forward supply chain, some contracts have been designed to reduce negative effects as follows. Biswas et al. [12] investigated how the asymmetry information, market-share, and supply chain structures affect the contract choice of the supplier. They found that the cost information of any buyers is beneficial for the supplier to increase her own profit. Liu et al. [13] examined how to design contracts for two competitive heterogeneous suppliers dealing with one common retailer under asymmetric information of external demand volumes for the retailer. Cao et al. [14] designed an optimal wholesale contract in a dual-channel supply chain under asymmetric information. Çakanyýldýrým et al. [15] indicated that asymmetric information alone does not necessarily result in channel inefficiency. Moreover, they designed an optimal contract to coordinate the supply chain. Similar to the forward supply chain, asymmetric information has a negative effect on CLSC. Zhang et al. [16] investigated the pricing and collection decision problem of a CLSC when the real information on collection efforts is only available to the retailer. They indicated that the asymmetric information may mislead the manufacturer into increasing the wholesale price, which can result in a higher sale price and a lower collection rate. Then they designed optimal contracts for the manufacturer. Giovanni [17] designed two incentive games by a profit-sharing contract to find out how the sharing information should be determined to benefit all the players. Wei et al. [18] investigated optimal strategies in different game scenarios under symmetric and asymmetric information structures. They found that the manufacturer's asymmetric information on manufacturing and remanufacturing costs may increase the retail price, while the private information of the retailer on the collection quantity and the size of the recycling market may increase the wholesale price. Zhang et al. [19] indicated that information sharing can be efficiently implemented through a bargaining mechanism when the collection efficiency of the manufacturer is moderate, but there must be no information sharing when the efficiency is low. Wang et al. [20] is the first to investigate the effect of RPM on the equilibrium decisions and profitability of the CLSC members with information asymmetry. They found that the RPM can reduce the negative effect of asymmetric information and improve the collection rate and profits of the manufacturers and retailers.

In the prior studies mentioned above, collection was usually done by only the retailer, the recycler, or the manufacturer. Differing from prior studies, one of the key points of this research is the dual collection channel. Some research on dual collection channels has been done before. Huang et al. [21] studied optimal decisions of a dual collection channel CLSC with a retailer and a third-party recycler competing to collect WEEEs. Hong et al. [22] showed that, ceteris paribus, the most effective reverse channel structure for the manufacturer is a dual collection channel consisting of one manufacturer and one retailer. Feng et al. [23] investigated a two-echelon reverse supply chain with a dual collection channel where the retailer acts as a Stackelberg game leader and the recycler as a follower with consideration of consumer behavior. The results showed that the dual collection channel is always superior to its single channel counterparts. Huang and Wang [24] indicated that in a CLSC with cost disruptions, the manufacturer prefers the dual collection channel rather than the single collection channel only if the negative disruption of remanufacturing cost comes to a large size. Zhao et al. [25] compared three dual collection channels with three single collection channels for a CLSC. They found that the manufacturer's optimal choice is to ensure that the retailer engages in collection irrespective of adopting single or dual collection channels.

Additionally, the government has been playing an important role in CLSC operations (Xie and Ma. [26]). For example, the Japanese government releases various data to encourage CLSC activities [27]. Ma et al. [28] studied how a consumption-subsidy program affects dual channel CLSC. Heydari et al. [29] demonstrated that government-sponsored incentive mechanisms for manufacturers are superior to those for retailers. Rahman and Subramanian [30] found that government legislation is one of the main driving forces to stimulate computer recycling operations. He et al. [31] indicated that the government's environmental policies increase the recycling proportion, but strengthen the reverse supply chain bullwhip effect. Wang et al. [32] found that the government's RPM can effectively improve the collection rate and reduce the price of a new product in a single collection channel CLSC.

The existing CLSC literature lays a solid foundation for this paper. However, no previous papers examined RPM in a CLSC except for those by Wang et al. [20] and Wang et al. [32]. Wang et al. [32] did not consider asymmetric information in collection. Moreover, both of them were confined to cases where only the third-party collector engages in collection; in actual operations, dual collection channels with competition are very common. For instance, ReCellular Inc., the largest mobile phone remanufacturer in the United States, collects used phones both from retailers and third-party recyclers [33,34]. Yi et al. [34] investigated a dual reverse channel in which both the retailer and the third-party collector collect the used products and assumed that the two collection agents take part in collection in different districts, so there is no competition between them. However, in this paper, we assume that the two agents engage in collection in the same district, so competition should not be overlooked. Such situations are not rare in reality. BYD Auto, China's leading electric carmaker (backed by Warren Buffett), entrusts his authorized distributor and GEM Co., Ltd., a third-party recycling company in China, to collect electrical vehicle batteries together. The two agents often engage in battery collection in the same district, so inevitably collection competition occurs between them. Wang et al. [35] studied three alternative scenarios selected by the manufacturer in hybrid CLSCs with competitive collector agents but they did not consider asymmetric information and government policy.

The contribution of this paper lies in that we investigate the efficacy of information screening contract and the RPM on a CLSC with competitive dual collection channel and asymmetric information. Specifically, it is assumed that the retailer and the third-party recycler are commissioned by the manufacturer to participate in the CLSC and compete with each other when they collect WEEEs. In addition, we consider that information on collection effort levels is available to the collection agents themselves but unknown to the manufacturer. In this context, we aim to answer the following questions:

(1) How does collection competition between the retailer and the third-party recycler affect the decisions and profits of CLSC members under information asymmetry?
(2) Can the manufacturer design a valid information screening contract to obtain the real collection effort levels of the two competitive collection agents with and without RPM?
(3) Can the RPM improve the collection rates and the profits of CLSC members with collection competition and asymmetric information?

Based on the above analysis, we design an information screening contract to reduce the negative impact of the asymmetric information. With a principal–agent theory, we propose two CLSC models with and without RPM. Numerical examples are provided to verify the efficiency of RPM and acquire more managerial insights.

The rest of the paper is organized as follows. Section 2 presents the notations and assumptions. The CLSC model without the RPM is proposed and analyzed in Section 3. Section 4 builds the CLSC model with the RPM and gives the analysis results. Finally, Section 5 presents conclusions and future directions.

2. Notations and Assumptions

In this paper, the collection effort levels of both the retailer and the third-party recycler can be divided into two types: high level and low level. The parameters with subscripts H and L represent high and low collection effort levels, respectively. Superscript * indicates the optimal solutions. Moreover, we will refer to the manufacturer as "he" and to the retailer/third-party recycler as "she" hereinafter.

The following notations in Table 1 are used throughout the paper:

Table 1. Notations.

Symbol	Description
Model parameters	
c_n	The cost of manufacturing one product with new materials.
c_r	The cost of remanufacturing one product with recycling components.
Δ	Unit cost savings from remanufacturing, $\Delta = c_n - c_r$.
ε	Competition intensity. It represents the degree of competition between the retailer and the third-party recycler when they collect WEEEs. $\varepsilon \in (0, 1)$.
e_{ri}	Collection effort level of the retailer. $i \in \{H, L\}$, $e_{rH} > e_{rL}$.
e_{ti}	Collection effort level of the third-party recycler. $i \in \{H, L\}$, $e_{tH} > e_{tL}$.
T_{rj}	The franchise fee that the manufacturer charges the retailer when she chooses contract G_{rj}, $j \in \{H, L\}$.
T_{tj}	The franchise fee that the manufacturer charges the third-party recycler when she chooses contract G_{tj}, $j \in \{H, L\}$.
Q_{ritj}	Collection quantity of the retailer when she chooses contract G_{ri} under her real collection effort level i, while the third-party recycler chooses contract G_{tj} under her real collection effort level j.
Q_{tirj}	Collection quantity of the third-party recycler when she chooses contract G_{ti} under her real collection effort level i, while the retailer chooses contract G_{rj} under her real collection effort level j.

Table 1. *Cont.*

Symbol	Description
k	Reward–penalty intensity decided by government.
Q_0	Target collection quantity set by government.
v	Probability of the retailer or the third-party recycler adopting H collection effort level, which is available to both collection agents.
Decision variables	
w_j	Wholesale price of the manufacturer when the retailer chooses contract G_{rj}, $j \in \{H, L\}$.
p_{ij}	Retail price of the retailer with the choice of contract G_{rj} when her real collection effort level is i, $i \in \{H, L\}, j \in \{H, L\}$.
r_{rij}	Unit collection price of the retailer with the choice of contract G_{rj} when her real collection effort level is $i, i \in \{H, L\}, j \in \{H, L\}$.
r_{tij}	Unit collection price of the third-party recycler with the choice of contract G_{tj} when her real collection effort level is $i, i \in \{H, L\}, j \in \{H, L\}$.
b_{rj}	Buyback price paid by the manufacturer to the retailer for each collected WEEE with her choice of contract G_{rj}, $j \in \{H, L\}$.
b_{tj}	Buyback price paid by the manufacturer to the third-party recycler for each collected WEEE with her choice of contract G_{tj}, $j \in \{H, L\}$.
Other notations	
G_{rj}	Information screening contract designed for the manufacturer, which means the retailer opts for buy-back price b_{rj}, wholesale price w_j and gives franchise fee T_{rj}, $j \in \{H, L\}$.
G_{tj}	Information screening contract designed for the manufacturer, which means the third-party recycler opts for buy-back price b_{tj}, wholesale price w_j and gives franchise fee T_{tj}, $j \in \{H, L\}$.
$E\left(\pi_{mij}\right)$	Expected profit of the manufacturer with the third-party recycler's choice of contract G_{ti} and the retailer's choice of contract G_{rj}, $i \in \{H, L\}, j \in \{H, L\}$.
$E\left(\pi_{rij}\right)$	Expected profit of the retailer with her choice of contract G_{rj} under her real collection effort level i, $i \in \{H, L\}, j \in \{H, L\}$.
$E\left(\pi_{tij}\right)$	Expected profit of the third-party recycler with her choice of contract G_{tj} under her real collection effort level $i, i \in \{H, L\}, j \in \{H, L\}$.
π_r^0	Reserved profit of the retailer without contract.
π_t^0	Reserved profit of the third-party recycler without contract.

Assumptions

(1) There is no difference between newly manufactured products and remanufactured products [2,3,5,20].

(2) $c_r < c_n$ represents that unit production cost c_n is more than unit remanufacturing cost c_r [2,20,21]. We also assume that the unit cost of remanufacturing used products is fixed regardless of their different quality levels, which can avoid complex calculations without changing the major conclusions of the CLSC model.

(3) It is assumed that collected WEEE materials and components take precedence over the new components in production [6,18,25].

(4) In this model, we assume that all CLSC members are risk-neutral, without regard to risk preference or risk aversion. Their targets are to earn the maximum profits.

(5) The market demand function is $D = \phi - p_{ij} + \theta$ [25,36,37], where ϕ is the size of potential market, p_{ij} is the retail price, and θ is a random variable that follows the uniform distribution $U(0, a)$. We denote the probability density function as $f(\cdot)$ and probability distribution function of θ as $F(\cdot)$. So,

$$f(x) = \begin{cases} 1/a, x \in (0, a) \\ 0, else \end{cases}.$$

(6) We assume the retailer's collection quantity Q_{ritj} and the third-party recycler's collection quantity Q_{tirj} are both collection-effort-sensitive and collection-price-sensitive. Specifically, in this paper the linear functions of Q_{ritj} and Q_{tirj} are employed by $Q_{ritj} = e_{ri} + r_{rij} - \varepsilon r_{tij}$ and $Q_{tirj} = e_{ti} + r_{tij} - \varepsilon r_{rij}$ respectively [23,38]. That is, for either party, collection quantity increases as the own collection effort level or collection price increases, but decreases as the competitor's collection price increases.

In the following, we examine CLSC models without and with RPM, and compare the differences between the two models.

3. CLSC Model without the RPM (Case 1)

Figure 1 gives the general structure of CLSC without RPM, which is comprised of a manufacturer, a retailer, a third-party recycler, and consumers. The solid line and the dotted line represent the forward flow direction and the reverse flow direction, respectively. As the Stackelberg leader of CLSC, the manufacturer entrusts the retailer and the third-party recycler to collect WEEEs. According to assumptions, the two collection agents choose high or low collection effort levels separately, denoted as H-type or L-type retailers and H-type or L-type third-party recyclers. The third-party recycler collects WEEEs at the collection price r_{tij} from consumers, and then transfers them at buyback price b_{tj} back to the manufacturer. The retailer acquires WEEEs at the collection price r_{rij} from consumers, and then resells them at buyback price b_{rj} back to the manufacturer. The manufacturer uses recycled materials and components in preference to new materials in production owing to the lower cost. The retailer purchases new products at wholesale price w_j from the manufacturer, and then sells them at the retail price p_{ij} to final consumers. However, the real collection effort levels are only known to the retailer and the third-party recycler themselves. To enhance the efficiency of CLSC, we investigate how to design an information screening contract for the manufacturer to acquire their real private information. The decision process of the screening information is as follows: (1) the manufacturer designs information screening contracts based on the probability of being an H-type retailer or an H-type third-party recycler; (2) either the retailer or the third-party recycler chooses one contract; (3) the manufacturer identifies real collection effort levels of the two collection agents through their contract choices.

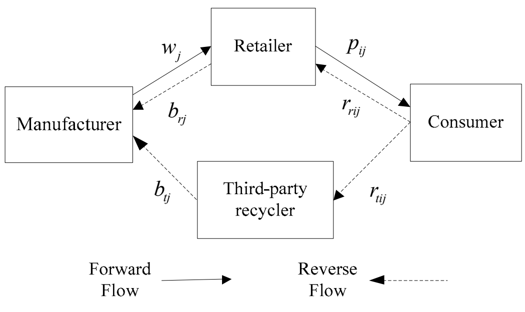

Figure 1. CLSC structure with competitive retailer and third-party recycler without RPM.

3.1. Model Description

In this section, we examine the information screening contract for the manufacturer to obtain private information from the retailer and the third-party recycler. Figure 1 shows that both the transactions of WEEEs and finished products combine the manufacturer with the retailer; only the transactions of WEEEs combine the manufacturer with the third-party recycler. So, the screening contracts designed by manufacturer for the retailer and the third-party recycler can be expressed as $\{G_{rH}(b_{rH}, w_H, T_{rH}), G_{rL}(b_{rL}, w_L, T_{rL})\}$ and $\{G_{tH}(b_{tH}, T_{tH}), G_{tL}(b_{tL}, T_{tL})\}$, respectively.

Based on Assumptions (5) and (6), the expected profit of the manufacturer with the retailer's choice of contract G_{rH} and the third-party recycler's choice of contract G_{tH} under their real collection level H can be expressed as:

$$\begin{array}{l} E(\pi_{mHH}) = \int_0^{z_{HH}} (\phi - p_{HH} + x)(w_H - c_r)f(x)dx + \int_{z_{HH}}^{a} (\phi - p_{HH} + x)(w_H - c_n)f(x)dx + \\ \Delta\int_{z_{HH}}^{a} [e_{rH} + e_{tH} + (1-\varepsilon)(r_{tHH} + r_{rHH})]f(x)dx - b_{tH}(e_{tH} + r_{tHH} - \varepsilon r_{rHH}) - \\ b_{rH}(e_{rH} + r_{rHH} - \varepsilon r_{tHH}) + T_{tH} + T_{rH} \end{array}, \quad (1)$$

where $z_{HH} = e_{rH} + e_{tH} + (1-\varepsilon)(r_{tHH} + r_{rHH}) - \phi + p_{HH}$. If $0 < x \leq z_{HH}$, products made of recycled components can meet market demand; however, if $z_{HH} < x < a$, market demand is higher than the collection quantity of WEEEs, so it is met by products made of recycled materials and new materials together.

Similarly, when the retailer chooses contract G_{rL} under real collection level L and the third-party recycler chooses contract G_{tH} under real collection level H, the expected profit of the manufacturer can be formulated as:

$$\begin{array}{l} E(\pi_{mHL}) = \int_0^{z_{HL}} (\phi - p_{LL} + x)(w_L - c_r)f(x)dx + \int_{z_{HL}}^{a} (\phi - p_{LL} + x)(w_L - c_n)f(x)dx \\ +\Delta\int_{z_{HL}}^{a} [e_{tH} + e_{rL} + (1-\varepsilon)(r_{tHH} + r_{rLL})]f(x)dx - b_{tH}(e_{tH} + r_{tHH} - \varepsilon r_{rLL}) - \\ b_{rL}(e_{rL} + r_{rLL} - \varepsilon r_{tHH}) + T_{tH} + T_{rL} \end{array}, \quad (2)$$

where $z_{HL} = e_{tH} + e_{rL} + (1-\varepsilon)(r_{tHH} + r_{rLL}) - \phi + p_{LL}$. If $0 < x \leq z_{HL}$, the products made of recycled components can meet market demand; however, if $z_{HL} < x < a$, market demand is higher than the collection quantity of WEEEs, so it is met by products made of recycled materials and new materials together.

When the retailer chooses contract G_{rH} under real collection level H and the third-party recycler chooses contract G_{tL} under real collection level L, the expected profit of the manufacturer can be expressed as:

$$\begin{array}{l} E(\pi_{mLH}) = \int_0^{z_{LH}} (\phi - p_{HH} + x)(w_H - c_r)f(x)dx + \int_{z_{LH}}^{a} (\phi - p_{HH} + x)(w_H - c_n)f(x)dx + \\ \Delta\int_{z_{LH}}^{a} [e_{tL} + e_{rH} + (1-\varepsilon)(r_{tLL} + r_{rHH})]f(x)dx - b_{tL}(e_{tL} + r_{tLL} - \varepsilon r_{rHH}) - \\ b_{rH}(e_{rH} + r_{rHH} - \varepsilon r_{tLL}) + T_{tL} + T_{rH} \end{array}, \quad (3)$$

where $z_{LH} = e_{tL} + e_{rH} + (1-\varepsilon)(r_{tLL} + r_{rHH}) - \phi + p_{HH}$. If $0 < x \leq z_{LH}$, products made of recycled components can meet market demand; however, if $z_{LH} < x < a$, market demand is higher than the collection quantity of WEEEs, so it is met by newly manufactured products and remanufactured products together.

When the retailer chooses contract G_{rL} under real collection level L and the third-party recycler chooses contract G_{tL} under real collection level L, the expected profit of the manufacturer can be formulated as:

$$\begin{array}{l} E(\pi_{mLL}) = \int_0^{z_{LL}} (\phi - p_{LL} + x)(w_L - c_r)f(x)dx + \int_{z_{LL}}^{a} (\phi - p_{LL} + x)(w_L - c_n)f(x)dx + \\ \Delta\int_{z_{LL}}^{a} [e_{tL} + e_{rL} + (1-\varepsilon)(r_{tLL} + r_{rLL})]f(x)dx - b_{tL}(e_{tL} + r_{tLL} - \varepsilon r_{rLL}) - \\ b_{rL}(e_{rL} + r_{rLL} - \varepsilon r_{tLL}) + T_{tL} + T_{rL} \end{array}, \quad (4)$$

where $z_{LL} = e_{tL} + e_{rL} + (1-\varepsilon)(r_{tLL} + r_{rLL}) - \phi + p_{LL}$. If $0 < x \le z_{LL}$, the product made of recycled components can meet market demand; however, if $z_{LL} < x < a$, market demand is higher than the collection quantity of WEEEs, hence newly manufactured products and remanufactured products together meet the market demand.

In a case where the third-party recycler adopts H collection effort level with the choice of contract G_{tH}, her expressed profit is:

$$E(\pi_{tHH}) = (b_{tH} - r_{tHH})\{e_{tH} + r_{tHH} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - {e_{tH}}^2/4 - T_{tH}. \tag{5}$$

When the H-type third-party recycler chooses contract G_{tL}, her expected profit is:

$$E(\pi_{tHL}) = (b_{tL} - r_{tHL})\{e_{tH} + r_{tHL} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - {e_{tH}}^2/4 - T_{tH}. \tag{6}$$

In a case where the third-party recycler adopts L collection effort level with the choice of contract G_{tL}, her expected profit is:

$$E(\pi_{tLL}) = (b_{tL} - r_{tLL})\{e_{tL} + r_{tLL} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - {e_{tL}}^2/4 - T_{tL}. \tag{7}$$

When the L-type third-party recycler chooses contract G_{tH}, her expected profit is:

$$E(\pi_{tLH}) = (b_{tH} - r_{tLH})\{e_{tL} + r_{tLH} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - {e_{tL}}^2/4 - T_{tH}. \tag{8}$$

In the case that the retailer makes H level collection effort with the choice of contract G_{rH}, her expected profit is:

$$\begin{array}{l} E(\pi_{rHH}) = (b_{rH} - r_{rHH})\{e_{rH} + r_{rHH} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - {e_{rH}}^2/4 + \\ (p_{HH} - w_H)\int_0^a (\phi - p_{HH} + x) f(x)dx - T_{rH} \end{array}. \tag{9}$$

If the H-type retailer chooses contract G_{rL}, her expected profit is:

$$\begin{array}{l} E(\pi_{rHL}) = (b_{rL} - r_{rHL})\{e_{rH} + r_{rHL} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - {e_{rH}}^2/4 + \\ (p_{HL} - w_L)\int_0^a (\phi - p_{HL} + x) f(x)dx - T_{rL} \end{array}. \tag{10}$$

When the retailer makes L level collection effort with the choice of contract G_{rL}, her expected profit is:

$$\begin{array}{l} E(\pi_{rLL}) = (b_{rL} - r_{rLL})\{e_{rL} + r_{rLL} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - {e_{rL}}^2/4 + \\ (p_{LL} - w_L)\int_0^a (\phi - p_{LL} + x) f(x)dx - T_{rL} \end{array}. \tag{11}$$

If the L-type retailer chooses contract G_{rH}, her expected profit is:

$$\begin{array}{l} E(\pi_{rLH}) = (b_{rH} - r_{rLH})\{e_{rL} + r_{rLH} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - {e_{rL}}^2/4 + \\ (p_{LH} - w_H)\int_0^a (\phi - p_{LH} + x) f(x)dx - T_{rH} \end{array}, \tag{12}$$

where ${e_{tj}}^2/4$ and ${e_{rj}}^2/4$ denotes the cost of collection effort of the third-party recycler and the retailer, respectively.

In the CLSC without government intervention under random demand and information asymmetry, the expected profit maximization problem of the manufacturer can be expressed as:

$$\max E(\pi_m) = v^2 E(\pi_{mHH}) + v(1-v)E(\pi_{mHL}) + v(1-v)E(\pi_{mLH}) + (1-v)^2 E(\pi_{mLL}) \tag{13}$$

$$s.t.$$

$$r_{tHH}^* = \operatorname{argmax} E(\pi_{tHH}) \tag{14}$$

$$r_{tLL}^* = \operatorname{argmax} E(\pi_{tLL}) \tag{15}$$

$$r^*_{rHH} = \text{argmax}E(\pi_{rHH}) \tag{16}$$

$$r^*_{rLL} = \text{argmax}E(\pi_{rLL}) \tag{17}$$

$$p^*_{HH} = \text{argmax}E(\pi_{rHH}) \tag{18}$$

$$p^*_{LL} = \text{argmax}E(\pi_{rLL}) \tag{19}$$

$$E(\pi_{tHH}) \geq \pi_t^0 \tag{20}$$

$$E(\pi_{tLL}) \geq \pi_t^0 \tag{21}$$

$$E(\pi_{rHH}) \geq \pi_r^0 \tag{22}$$

$$E(\pi_{rLL}) \geq \pi_r^0 \tag{23}$$

$$E(\pi_{tHH}) \geq E(\pi_{tHL}) \tag{24}$$

$$E(\pi_{tLL}) \geq E(\pi_{tLH}) \tag{25}$$

$$E(\pi_{rHH}) \geq E(\pi_{rHL}) \tag{26}$$

$$E(\pi_{rLL}) \geq E(\pi_{rLH}). \tag{27}$$

The optimal profits of the retailer and the third-party recycler without contract are π_r^0 and π_t^0 respectively, which can be called conserved profits. Equations (20)–(23) can guarantee that the expected profits of both two collection agents are no less than their conserved profits when they accept the contract. We call these equations participation constraints.

Equations (24)–(27) indicate that both two collection agents can make the maximum profit when they choose the right contracts corresponding to their own real collection effort levels. If not, they cannot get their maximum profit. In other words, these constraint conditions avoid the third-party recycler and the retailer telling lies, so we call these constraint equations incentive compatible constraints. Specifically, Equation (24) indicates the profit of the H-type third-party recycler when the choice of contract G_{tH} is more than that with the choice of contract G_{tL}. Meanwhile, Equation (25) shows that the profit of the L-type third-party recycler with contract G_{tL} is higher than that with contract G_{tH}. Equations (26) and (27) do the same for the retailer.

It is difficult to calculate and analyze the model because it has too many constraints and its arithmetic formulas are very complicated. We will give the relevant parameters specific values, and then compute the optimal solutions with the help of a software tool of MATLAB. Finally, we will analyze the results.

3.2. Numerical Examples

To verify the efficiency of the information screening contract and analyze the competition between the two collection agents on CLSC operations without RPM, we set the parameters as follows: $c_n = 60$, $c_r = 45$, $a = 4$, $\phi = 120$, $e_{tH} = e_{rH} = 10$, $e_{tL} = e_{rL} = 7$, $\pi_r^o = 300$, $\pi_t^o = 60$; in addition, we specify $v \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$, $\varepsilon \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$. The optimal decision-making of CLSC with different v and ε is shown in Appendix A.

(1) We find that when $\varepsilon < 0.5$, the buyback price $b^*_{tH}(b^*_{rH})$ increases as the probability v increases. When $\varepsilon = 0.5$, both the buyback prices $b^*_{tH}(b^*_{rH})$ and $b^*_{tL}(b^*_{rL})$ decrease as the probability v increases. Both $b^*_{tH}(b^*_{rH})$ and $b^*_{tL}(b^*_{rL})$ decrease as the competition intensity ε increases. As shown in Figure 2, with the probability v of H level of collection effort increasing, the buyback price is not always increasing. This indicates that when the degree of collection competition between the retailer and recycler reaches a certain level, the manufacturer will still take the measure of reducing the buyback price, even if the probability v increases. This shows that competition is not advantageous to both collection agents. Buyback price under high collection effort level is always higher than that under

low collection effort level when ε and v are fixed. This will make both two agents choose H level of collection effort for a higher buyback price.

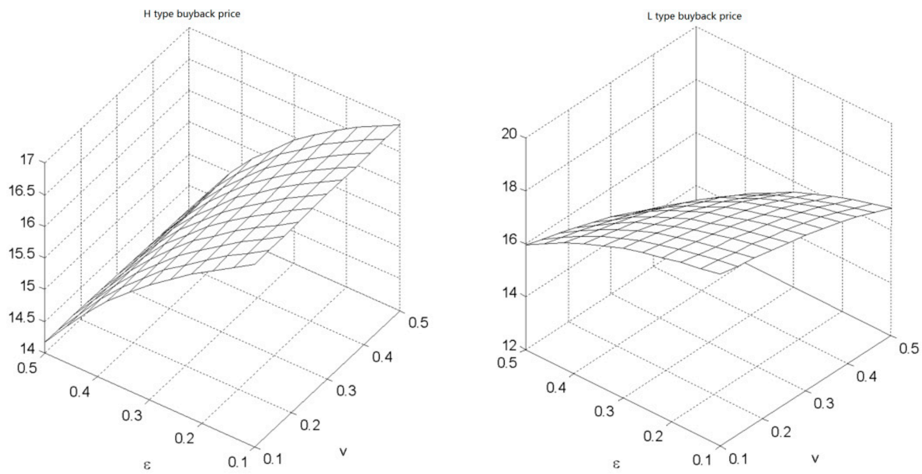

Figure 2. The buyback price $b^*_{tH}\left(b^*_{rH}\right)$ and $b^*_{tL}\left(b^*_{rL}\right)$ vs. v and ε.

(2) As shown in Figures 3 and 4, the wholesale prices w^*_H, w^*_L and the retail prices p^*_{HH}, p^*_{LL} increase with the probability v and competition intensity ε. The manufacturer can get more profit by raising the wholesale prices while reducing buyback prices. Accordingly, the retailer will raise the sale price to get more profit. Wholesale price w^*_L is higher than w^*_H when ε and v are fixed. This shows that the retailer should choose H level of collection effort for a lower wholesale price and a higher buyback price.

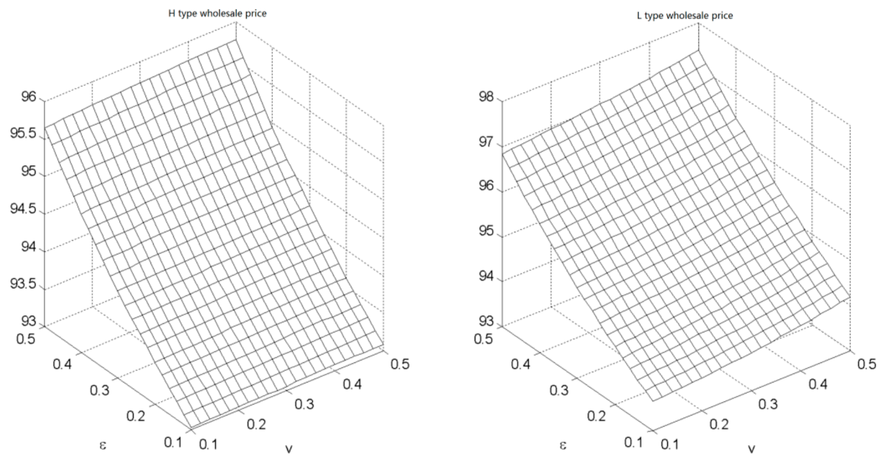

Figure 3. The wholesale price w^*_H and w^*_L vs. v and ε.

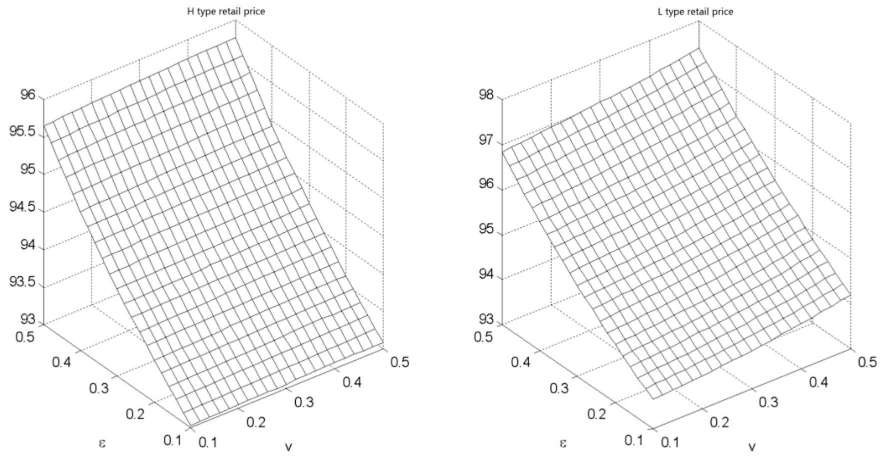

Figure 4. The retail price p^*_{HH} and p^*_{LL} vs. v and ε.

(3) From the computing results, it can be found that the collection price of the third-party recycler is equivalent to the retailer's, $r^*_{tHH} = r^*_{rHH}$, $r^*_{tLL} = r^*_{rLL}$. As shown in Figure 5, the collection price decreases with the increase in probability v, and first increases then decreases in competition intensity ε. To sum up, the collection price under L level of collection effort is higher than the H level of collection effort. By analyzing r^*_{tHH}, we find that when $v = 0.1$, if $\varepsilon \leq 0.3$, r^*_{tHH} increases in ε; if $\varepsilon > 0.3$, r^*_{tHH} decreases in ε. When $v > 0.1$, if $\varepsilon \leq 0.2$, r^*_{tHH} increases in ε; if $\varepsilon > 0.2$, r^*_{tHH} decreases in ε. Now let's analyze r^*_{tLL}. When $v \leq 0.2$, if $\varepsilon \leq 0.3$, r^*_{tLL} increases in ε; if $\varepsilon > 0.3$, r^*_{tLL} decrease in ε. When $0.2 < v < 0.5$, if $\varepsilon \leq 0.2$, r^*_{tLL} increases in ε; if $\varepsilon > 0.2$, r^*_{tLL} decreases in ε. When $v = 0.5$, if $0.1 \leq \varepsilon \leq 0.5$, r^*_{tLL} decreases in ε. Through an analysis of the collection price, we know that when the collection competition intensifies, the collection price will decrease. Under the situation above, when the probability of a high collection effort level is relatively small, the third-party recycler and the retailer are still able to increase the quantity of WEEEs by raising the collection price despite the buyback price falling. However, in order to deal with the buyback price reduction caused by the level of collection competition intensifying, both two collection agents will reduce the collection prices gradually.

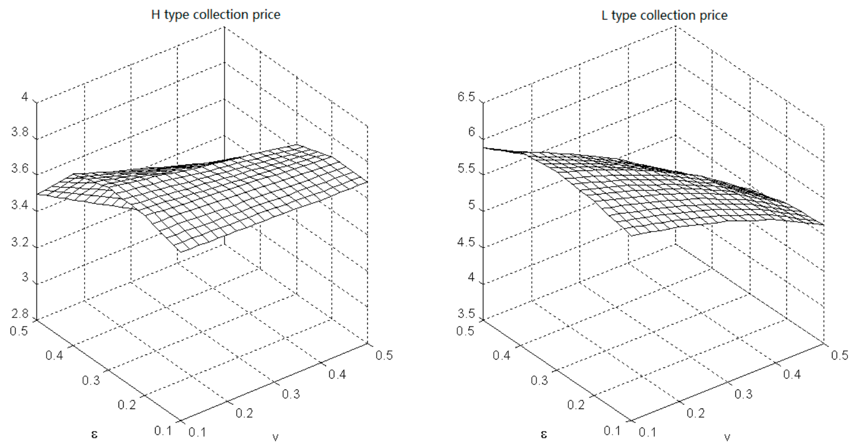

Figure 5. The collection price r^*_{tHH} and r^*_{tLL} vs. v and ε.

(4) As shown in Figures 6 and 7, the franchise fee T^*_{tL} and T^*_{rL} will decrease in the process of v and ε increasing; T^*_{tH} and T^*_{rH} increase in v, but decrease in ε. Therefore, in cases of competitive collection, the franchise fee charged by the manufacturer turns out to be lower when the competition

becomes more intense. In addition, the franchise fee paid by the retailer is higher than that paid by the third-party recycler.

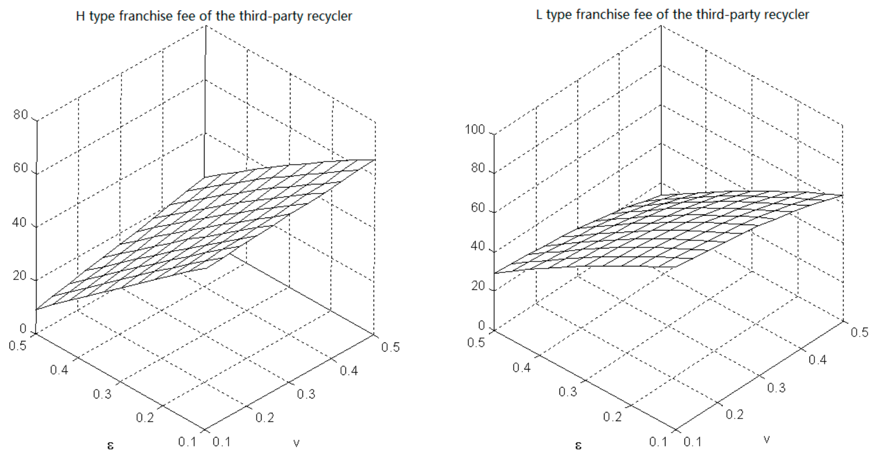

Figure 6. The franchise fee of the third-party recycler T^*_{tH} and T^*_{tL} vs. v and ε.

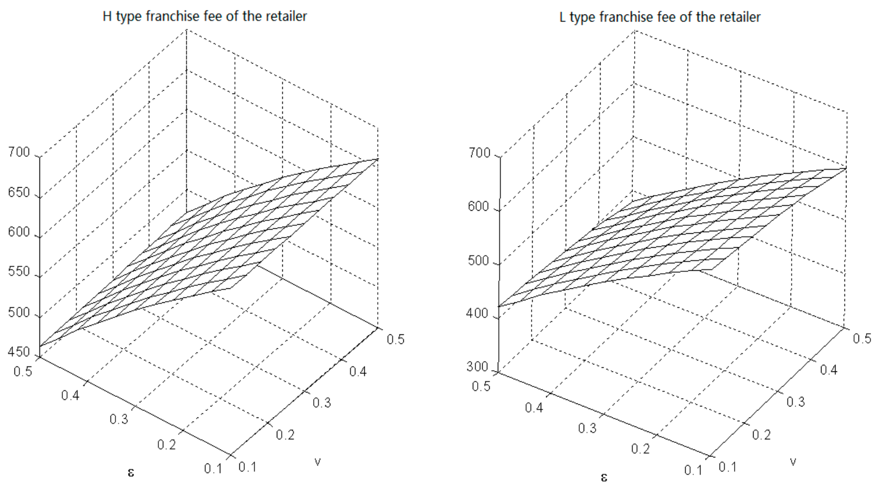

Figure 7. The franchise fee of the retailer T^*_{rH} and T^*_{rL} vs. v and ε.

(5) When $e_{ti} = e_{ri}$, $Q^*_{tHrH} = Q^*_{rHtH}$, $Q^*_{tLrL} = Q^*_{rLtL}$; when e_{ti} is relatively high (or low) and e_{ri} is relatively low (or high), $Q^*_{tHrL} = Q^*_{rHtL}$, $Q^*_{tLrH} = Q^*_{rLtH}$. According to the expression of the collection price and $r^*_{tHH} = r^*_{rHH}$, $r^*_{tLL} = r^*_{rLL}$, we can obtain the equivalence relationship between the collection quantities of the retailer and third-party recycler. Let us analyze the third-party recycler's collection quantity. When both collection agents choose a high collection effort level, the collection quantity Q^*_{tHrH} arrives at its maximum. When both of them choose a low collection effort level, the collection quantity Q^*_{tLrL} reaches its minimum. What will happen when they choose different collection effort levels? Now we analyze the case where the third-party recycler chooses a high collection effort level and the retailer chooses a low collection effort level. When $v = 0.1$, if $\varepsilon < 0.2$, then $Q^*_{tHrL} > Q^*_{rLtH}$; if $\varepsilon > 0.2$, then $Q^*_{tHrL} < Q^*_{rLtH}$. When $v = 0.2$, if $\varepsilon \leq 0.3$, then $Q^*_{tHrL} > Q^*_{rLtH}$; if $\varepsilon > 0.3$, then $Q^*_{tHrL} < Q^*_{rLtH}$; when $v > 0.2$, $Q^*_{tHrL} > Q^*_{rLtH}$ regardless of ε.

From the analysis above, we can infer that even though the third-party recycler makes a high collection effort, his collection quantity is not always higher than the retailer's. The relationship depends on the probability of a high collection effort level. For instance, in the case that the probability of high collection effort level is relatively low, e.g., $v \leq 0.2$, when the collection competition is not intense, although the third-party recycler's collection price r^*_{tHH} is lower than that of the retailer r^*_{rLL}, the third-party recycler can still collect more WEEEs than the retailer due to her high collection effort level. However, as the collection competition intensifies the collection difficulties for both parties increase, resulting in the collection price playing a more important role than the collection effort level. So, with a more intense collection competition, a higher collection price will make the retailer collect more WEEEs than the third-party recycler despite the lower collection effort.

In the case that the probability of H collection effort level is relatively high, e.g., $v > 0.2$, the effect of collection effort level outweighs that of collection price. Although the collection competition intensifies and the retailer provides a higher collection price, the third-party recycler can still acquire more WEEEs than the retailer due to her higher collection effort level. As depicted in Figure 8, the total quantity of WEEEs decreases as the collection competition intensity ε increases. When both two collection agents choose H collection effort level, the total collection quantity reaches its maximum in the case where the two parties choose different collection effort levels; the minimum will be the case where both of them choose L collection effort level.

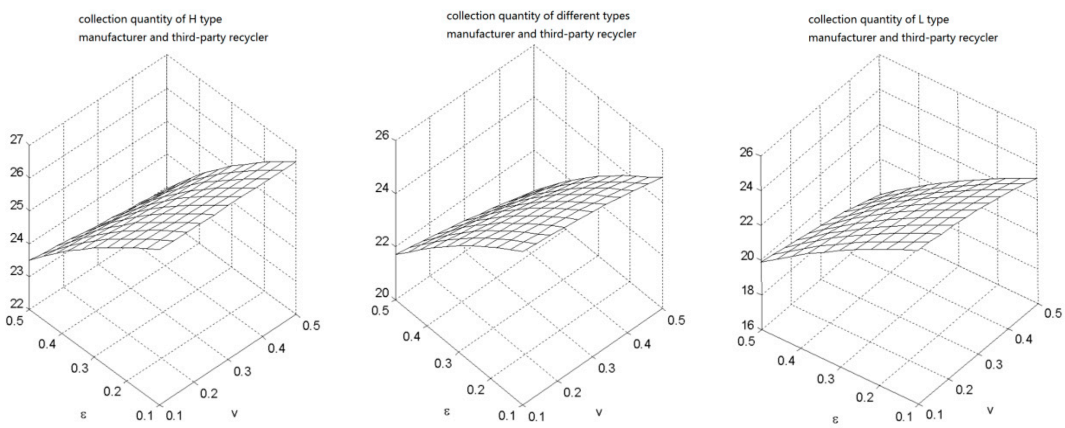

Figure 8. The total collection quantity of WEEEs vs. v and ε.

(6) As shown in Figure 9, when the third-party recycler and retailer choose different collection effort levels, the profits of manufacturer $E(\pi^*_{mHH})$, $E(\pi^*_{mHL})$, $E(\pi^*_{mLH})$ and $E(\pi^*_{mLL})$ decrease in ε. $E(\pi^*_{mHH})$, $E(\pi^*_{mHL})$ and $E(\pi^*_{mLH})$ increase in v. When $v \leq 0.2$, $E(\pi^*_{mLL})$ increases in v; in contrast, when $v > 0.2$, $E(\pi^*_{mLL})$ decreases in v. That is, as the collection competition intensifies, although the manufacturer raises the wholesale price and cuts the buyback price, his expected profit will shrink owing to the collection quantity decreasing. Moreover, both the expected profits of the third-party recycler and the retailer $E(\pi^*_{tHH})$, $E(\pi^*_{rHH})$ reduce in the competition intensity ε and the probability of H collection effort level v. $E(\pi^*_{tLL})$ and $E(\pi^*_{rLL})$ always remain at the level of their reservation profits. The above results indicate that intense competition has a detrimental effect on both the retailer and the third-party recycler. Whether the two collection agents should cooperate to mitigate the negative impact of competition deserves further investigation.

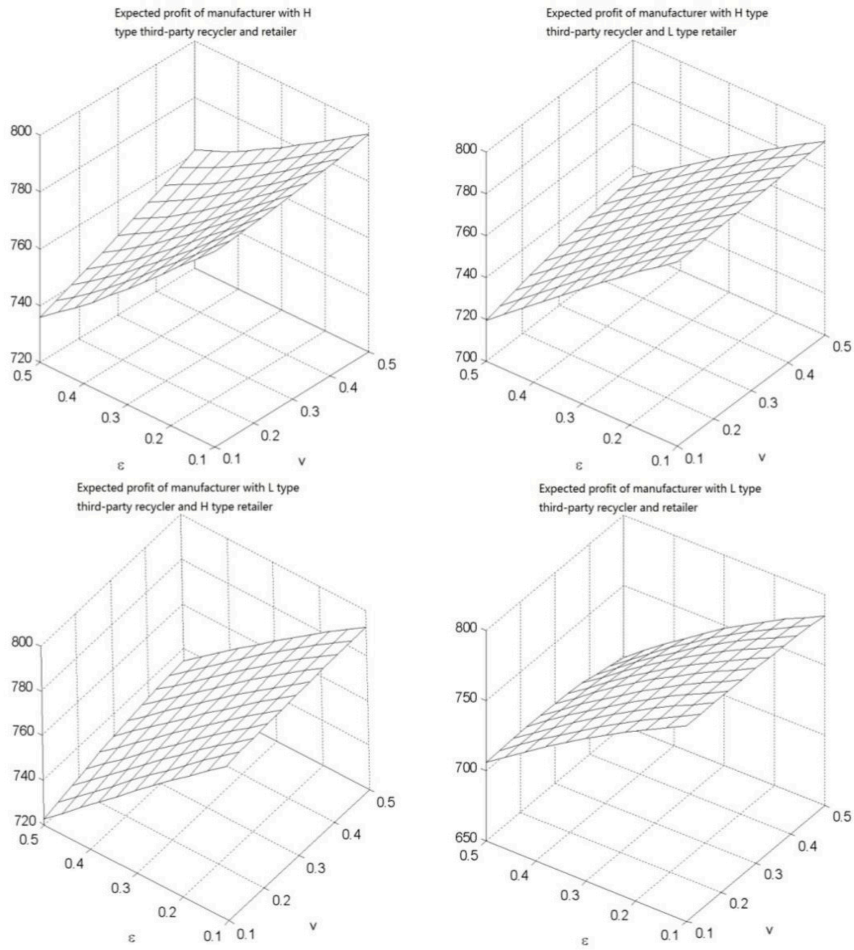

Figure 9. The expected profits of manufacturer $E(\pi^*_{mHH})$, $E(\pi^*_{mHL})$, $E(\pi^*_{mLH})$ and $E(\pi^*_{mLL})$ vs. v and ε.

4. CLSC Model with the RPM (Case 2)

With RPM, although the manufacturer still plays a leading role in CLSC, the government will take some measures to stimulate WEEEs collection. Thus, we add government intervention to the basic model. As shown in Figure 10, the government sets a target collection quantity Q_0 and the reward–penalty intensity k for the manufacturer. That is, when the total quantity of WEEEs collected by the third-party recycler and the retailer exceeds the target collection quantity, the government will reward the manufacturer for the exceeding part; otherwise, the government will penalize him for the unmet part. The intensity of reward and penalty is assumed to be the same, k, for avoiding complicated computation. The details of the information screening contract in this case are similar to those of the basic model.

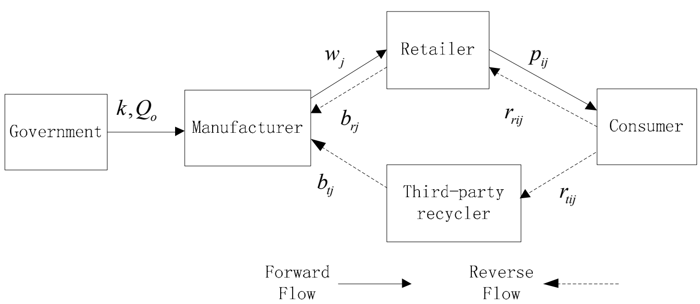

Figure 10. The CLSC structure with competitive retailer and third-party recycler with RPM.

4.1. Model Description

The manufacturer designs the information screening contracts similar to the basic model. The screening contracts designed for the retailer and the third-party recycler can be expressed as $\{G_{rH}(b_{rH}, w_H, T_{rH}), G_{rL}(b_{rL}, w_L, T_{rL})\}$ and $\{G_{tH}(b_{tH}, T_{tH}), G_{tL}(b_{tL}, T_{tL})\}$, respectively. Based on their choices of the screening contracts, we can develop the model as follows:

When the third-party recycler chooses contract G_{tH} and the retailer opts for contract G_{rH} corresponding to their real collection level H, the expected profit of the manufacturer can be expressed as:

$$\begin{array}{l} E(\pi_{mHH}) = \int_0^{z_{HH}} (\phi - p_{HH} + x)(w_H - c_r) f(x) dx + \int_{z_{HH}}^a (\phi - p_{HH} + x)(w_H - c_n) f(x) dx + \\ \Delta \int_{z_{HH}}^a [e_{tH} + e_{rH} + (1-\varepsilon)(r_{tHH} + r_{rHH})] f(x) dx - b_{tH}(e_{tH} + r_{tHH} - \varepsilon r_{rHH}) - \\ b_{rH}(e_{rH} + r_{rHH} - \varepsilon r_{tHH}) + T_{tH} + T_{rH} + k[e_{tH} + e_{rH} + (1-\varepsilon)(r_{tHH} + r_{rHH}) - Q_0] \end{array}, \quad (28)$$

where $z_{HH} = e_{tH} + e_{rH} + (1-\varepsilon)(r_{tHH} + r_{rHH}) - \phi + p_{HH}$. If $0 < x \le z_{HH}$, the remanufactured products made of recycled components can meet market demand; however, if $z_{HH} < x < a$, market demand exceeds the collection quantity of WEEEs, it is met by products made of recycled materials and new materials together.

Similarly, when the third-party recycler opts for contract G_{tH} with her real collection level H and the retailer chooses contract G_{rL} under her real collection level L, the expected profit of the manufacturer can be formulated as:

$$\begin{array}{l} E(\pi_{mHL}) = \int_0^{z_{HL}} (\phi - p_{LL} + x)(w_L - c_r) f(x) dx + \int_{z_{HL}}^a (\phi - p_{LL} + x)(w_L - c_n) f(x) dx + \\ \Delta \int_{z_{HL}}^a [e_{tH} + e_{rL} + (1-\varepsilon)(r_{tHH} + r_{rLL})] f(x) dx - b_{tH}(e_{tH} + r_{tHH} - \varepsilon r_{rLL}) - \\ b_{rL}(e_{rL} + r_{rLL} - \varepsilon r_{tHH}) + T_{tH} + T_{rL} + k[e_{tH} + e_{rL} + (1-\varepsilon)(r_{tHH} + r_{rLL}) - Q_0] \end{array}, \quad (29)$$

where $z_{HL} = e_{tH} + e_{rL} + (1-\varepsilon)(r_{tHH} + r_{rLL}) - \phi + p_{LL}$. If $0 < x < z_{HL}$, the remanufactured products are enough to meet market demand; however, if $z_{HL} < x < a$, market demand exceeds the collection quantity of WEEEs, so it is met by the newly manufactured products and remanufactured products together.

When the third-party recycler chooses contract G_{tL} with her real collection level L and the retailer opts for contract G_{rH} with her real collection level H, the expected profit of manufacturer can be formulated as:

$$\begin{array}{l} E(\pi_{mLH}) = \int_0^{z_{LH}} (\phi - p_{HH} + x)(w_H - c_r) f(x) dx + \int_{z_{LH}}^a (\phi - p_{HH} + x)(w_H - c_n) f(x) dx + \\ \Delta \int_{z_{LH}}^a [e_{tL} + e_{rH} + (1-\varepsilon)(r_{tLL} + r_{rHH})] f(x) dx - b_{tL}(e_{tL} + r_{tLL} - \varepsilon r_{rHH}) - \\ b_{rH}(e_{rH} + r_{rHH} - \varepsilon r_{tLL}) + T_{tL} + T_{rH} + k[e_{tL} + e_{rH} + (1-\varepsilon)(r_{tLL} + r_{rHH}) - Q_0] \end{array}, \quad (30)$$

where $z_{LH} = e_{tL} + e_{rH} + (1-\varepsilon)(r_{tLL} + r_{rHH}) - \phi + p_{HH}$. If $0 < x \le z_{LH}$, the remanufactured products can meet the market demand; however, if $z_{LH} < x < a$, the market demand exceeds the collection quantity of WEEEs, so it is met by the new-manufactured products and remanufactured products together.

When the third-party recycler chooses contract G_{tL} with her real collection level L and the retailer chooses contract G_{rL} under her real collection level L, the expected profit of the manufacturer can be expressed as:

$$\begin{array}{l} E(\pi_{mLL}) = \int_0^{z_{LL}} (\phi - p_{LL} + x)(w_L - c_r) f(x) dx + \int_{z_{LL}}^a (\phi - p_{LL} + x)(w_L - c_n) f(x) dx + \\ \Delta \int_{z_{LL}}^a [e_{tL} + e_{rL} + (1-\varepsilon)(r_{tLL} + r_{rLL})] f(x) dx - b_{tL}(e_{tL} + r_{tLL} - \varepsilon r_{rLL}) - \\ b_{rL}(e_{rL} + r_{rLL} - \varepsilon r_{tLL}) + T_{tL} + T_{rL} + k[e_{tL} + e_{rL} + (1-\varepsilon)(r_{tLL} + r_{rLL}) - Q_0] \end{array}, \quad (31)$$

where $z_{LL} = e_{tL} + e_{rL} + (1-\varepsilon)(r_{tLL} + r_{rLL}) - \phi + p_{LL}$. If $0 < x \le z_{LL}$, the remanufactured products can meet market demand; however, if $z_{LL} < x < a$, market demand exceeds the collection quantity of WEEEs, so newly manufactured products and remanufactured products together satisfy the market demand.

In a case where the third-party recycler with collection effort level H chooses contract G_{tH}, her expected profit is given as follows:

$$E(\pi_{tHH}) = (b_{tH} - r_{tHH})\{e_{tH} + r_{tHH} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - \frac{e_{tH}^2}{4} - T_{tH}. \quad (32)$$

When the H-type third-party recycler chooses contract G_{tL}, her expected profit can be formulated as:

$$E(\pi_{tHL}) = (b_{tL} - r_{tHL})\{e_{tH} + r_{tHL} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - \frac{e_{tH}^2}{4} - T_{tL}. \quad (33)$$

In a case where the third-party recycler with collection effort level L opts for contract G_{tL}, her expected profit is given as follows:

$$E(\pi_{tLL}) = (b_{tL} - r_{tLL})\{e_{tL} + r_{tLL} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - \frac{e_{tL}^2}{4} - T_{tL}. \quad (34)$$

When the L-type third-party recycler chooses contract G_{tH}, her expected profit can be formulated as:

$$E(\pi_{tLH}) = (b_{tH} - r_{tLH})\{e_{tL} + r_{tLH} - \varepsilon[vr_{rHH} + (1-v)r_{rLL}]\} - \frac{e_{tL}^2}{4} - T_{tH}. \quad (35)$$

When the retailer makes H level collection effort with the choice of contract G_{rH}, her expected profit is given as follows:

$$\begin{array}{l} E(\pi_{rHH}) = (b_{rH} - r_{rHH})\{e_{rH} + r_{rHH} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - \frac{e_{rH}^2}{4} + \\ (p_{HH} - w_H)\int_0^a (\phi - p_{HH} + x)f(x)dx - T_{rH} \end{array}. \quad (36)$$

If the H-type retailer opts for contract G_{rH}, her expected profit can be expressed as:

$$\begin{array}{l} E(\pi_{rHL}) = (b_{rL} - r_{rHL})\{e_{rH} + r_{rHL} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - \frac{e_{rH}^2}{4} + \\ (p_{HL} - w_L)\int_0^a (\phi - p_{HL} + x)f(x)dx - T_{rL} \end{array}. \quad (37)$$

When the retailer makes L level collection effort with the choice of contract G_{rL}, her expected profit is given as follows:

$$\begin{array}{l} E(\pi_{rLL}) = (b_{rL} - r_{rLL})\{e_{rL} + r_{rLL} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - \frac{e_{rL}^2}{4} + \\ (p_{LL} - w_L)\int_0^a (\phi - p_{LL} + x)f(x)dx - T_{rL} \end{array}. \quad (38)$$

If the L-type retailer opts for contract G_{rH}, her expected profit can be expressed as:

$$\begin{array}{l} E(\pi_{rLH}) = (b_{rH} - r_{rLH})\{e_{rL} + r_{rLH} - \varepsilon[vr_{tHH} + (1-v)r_{tLL}]\} - \frac{e_{rL}^2}{4} + \\ (p_{LH} - w_H)\int_0^a (\phi - p_{LH} + x)f(x)dx - T_{rH} \end{array}. \quad (39)$$

In the CLSC with RPM imposed on the manufacturer by government under random demand and information asymmetry, the expected profit maximization problem of the manufacturer can be formulated as follows:

$$\max E(\pi_m) = v^2 E(\pi_{mHH}) + v(1-v)E(\pi_{mHL}) + v(1-v)E(\pi_{mLH}) + (1-v)^2 E(\pi_{mLL}) \quad (40)$$

$$s.t.$$

$$r_{tHH}^{**} = \text{argmax} E(\pi_{tHH}) \quad (41)$$

$$r_{tLL}^{**} = \text{argmax} E(\pi_{tLL}) \quad (42)$$

$$r_{rHH}^{**} = \text{argmax} E(\pi_{rHH}) \quad (43)$$

$$r_{rLL}^{**} = \text{argmax} E(\pi_{rLL}) \tag{44}$$

$$p_{HH}^{**} = \text{argmax} E(\pi_{rHH}) \tag{45}$$

$$p_{LL}^{**} = \text{argmax} E(\pi_{rLL}) \tag{46}$$

$$E(\pi_{tHH}) \geq \pi_t^0 \tag{47}$$

$$E(\pi_{tLL}) \geq \pi_t^0 \tag{48}$$

$$E(\pi_{rHH}) \geq \pi_r^0 \tag{49}$$

$$E(\pi_{rLL}) \geq \pi_r^0 \tag{50}$$

$$E(\pi_{tHH}) \geq E(\pi_{tHL}) \tag{51}$$

$$E(\pi_{tLL}) \geq E(\pi_{tLH}) \tag{52}$$

$$E(\pi_{rHH}) \geq E(\pi_{rHL}) \tag{53}$$

$$E(\pi_{rLL}) \geq E(\pi_{rLH}). \tag{54}$$

Equations (47)–(50) are participation constraints. These equations ensure that the expected profits of both two collection agents are no less than their conserved profits if they accept the contract. Equations (51)–(54) are incentive compatibility constraints, which ensure that both two collection agents will get higher profits when they select the same type contracts as their real collection effort levels.

We will give the relevant parameters specific values and compute these optimal solutions with the aid of a software tool of MATLAB.

4.2. Numerical Example

We assumed that $c_n = 60$, $c_r = 45$, $a = 4$, $\phi = 120$, $e_{tH} = e_{rH} = 10$, $e_{tL} = e_{rL} = 7$, $\pi_r^o = 300$, $\pi_t^o = 60$, $\Delta = c_n - c_r$, $v = 0.5$; moreover, we specify $\varepsilon \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$, $k \in \{10, 20, 30, 40\}$ and $Q_0 = 32$. The optimal decisions of this model (given in Appendix B) vary when the competition intensity ε and the reward–penalty intensity k have different values.

(1) As shown in Figures 11–13, we know that both the buyback prices b_H^{**} and b_L^{**}, all the collection prices r_{tHH}^{**}, r_{rHH}^{**}, r_{tLL}^{**} and r_{rLL}^{**}, and all the collection quantities Q_{tHrH}^{**}, Q_{rHtH}^{**}, Q_{tHrL}^{**}, Q_{rHtL}^{**}, Q_{tLrH}^{**}, Q_{rLtH}^{**}, Q_{tLrL}^{**} and Q_{rLtL}^{**} increase in the reward–penalty intensity k, while $r_{tHH}^{**} = r_{rHH}^{**}$, $r_{tLL}^{**} = r_{rLL}^{**}$ and $Q_{tHrH}^{**} = Q_{rHtH}^{**}$, $Q_{tHrL}^{**} = Q_{rHtL}^{**}$, $Q_{tLrH}^{**} = Q_{rLtH}^{**}$, $Q_{tLrL}^{**} = Q_{rLtL}^{**}$. So, in a case where collection competition exists, the total collection quantity of the two collection agents will increase in the reward–penalty intensity with RPM. From these figures, we also see the relationship between these parameters: buyback price, collection price, collection quantity, the reward–penalty intensity, and competition intensity. When both the third-party recycler and the retailer choose collection effort level H, their own collection quantities Q_{tHrH}^{**} and Q_{rHtH}^{**} will be the highest. In contrast, when both choose collection effort level L, their collection quantities Q_{tLrL}^{**} and Q_{rLtL}^{**} will be the least. When one of them chooses collection effort level H while the other chooses collection effort level L, the one choosing H can collect more WEEEs than the other choosing L. By comparison with the results in Appendix A, the buyback prices with RPM are higher than without RPM, i.e., $b_H^{**} > b_H^*$, $b_L^{**} > b_L^*$. It is the same with the collection prices and collection quantities, namely $r_{tHH}^{**} > r_{tHH}^*$, $r_{tLL}^{**} > r_{tLL}^*$, $r_{rHH}^{**} > r_{rHH}^*$, $r_{rLL}^{**} > r_{rLL}^*$ and $Q_{tHrH}^{**} > Q_{tHrH}^*$, $Q_{tHrL}^{**} > Q_{tHrL}^*$, $Q_{tLrH}^{**} > Q_{tLrH}^*$, $Q_{tLrL}^{**} > Q_{tLrL}^*$, $Q_{rHtH}^{**} > Q_{rHtH}^*$, $Q_{rHtL}^{**} > Q_{rHtL}^*$, $Q_{rLtH}^{**} > Q_{rLtH}^*$, $Q_{rLtL}^{**} > Q_{rLtL}^*$. The RPM makes the manufacturer raise the buyback prices, and then both the collection agents increase the collection prices accordingly. So, the collection quantities are boosted.

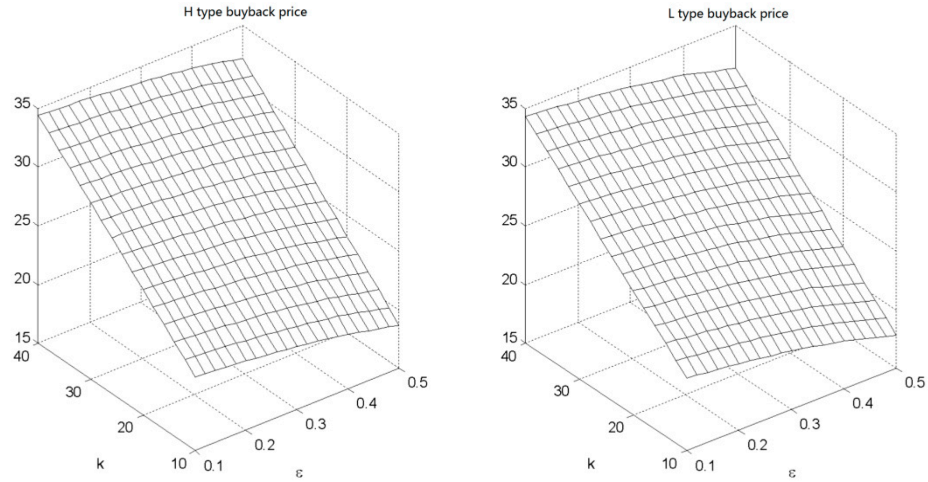

Figure 11. The buyback price b_H^{**} and b_L^{**} vs. k and ε.

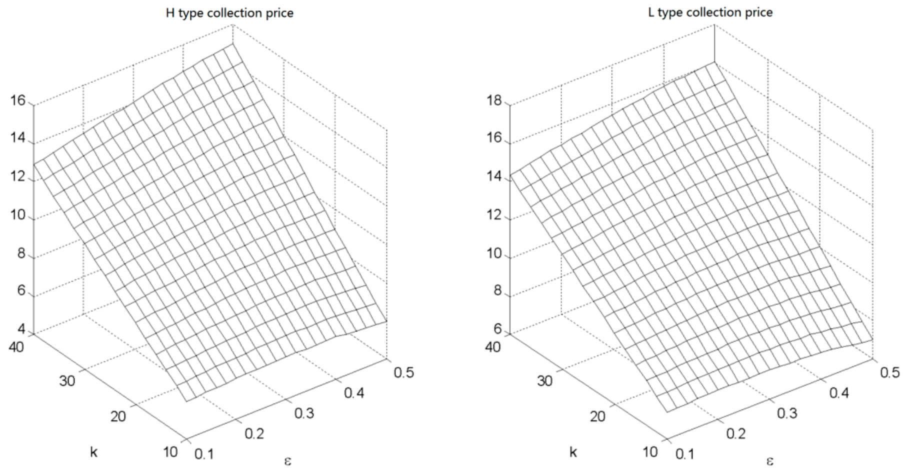

Figure 12. The collection price r_{tHH}^{**} and r_{tLL}^{**} vs. k and ε.

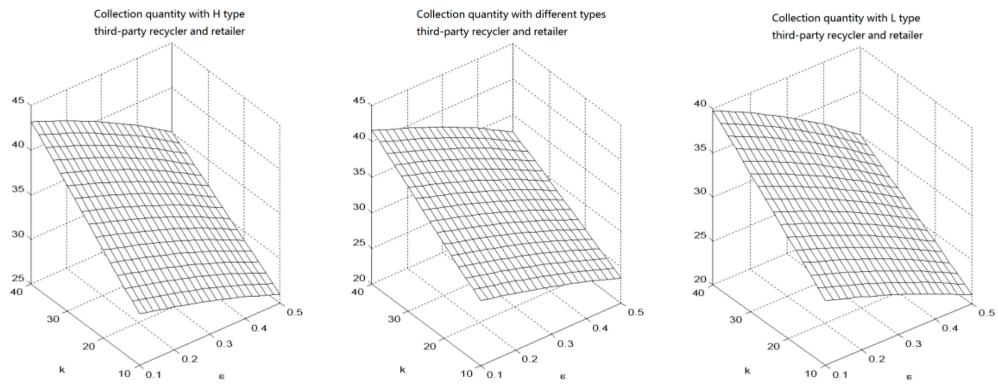

Figure 13. The total collection quantity of WEEEs vs. k and ε.

(2) As shown in Figures 14 and 15, the wholesale prices w_H^{**} and w_L^{**}, and the retail prices p_{HH}^{**} and p_{LL}^{**} decrease in the reward–penalty intensity k. By comparison with the results in Appendix A, the wholesale prices with RPM are lower than without RPM, i.e., $w_H^{**} < w_H^*$, $w_L^{**} < w_L^*$. It is the same with the retail prices, namely $p_{HH}^{**} < p_{HH}^*$ and $p_{LL}^{**} < p_{LL}^*$.

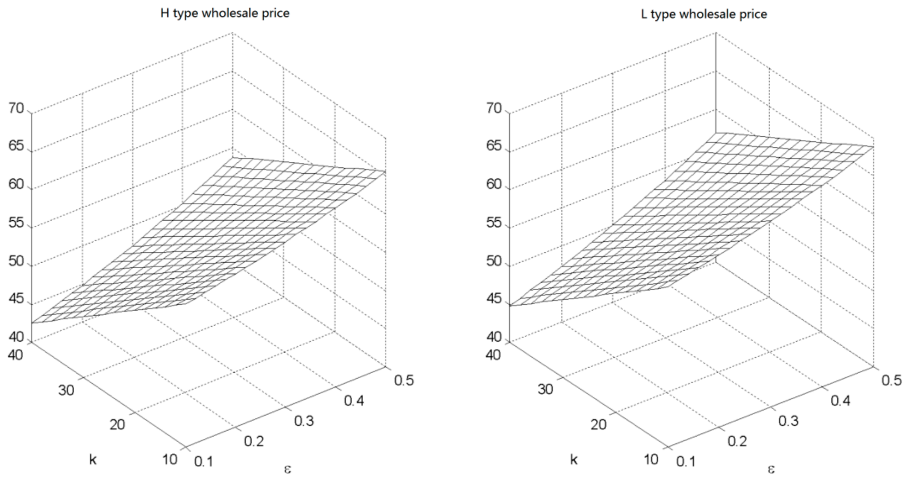

Figure 14. The wholesale price w_H^{**} and w_L^{**} vs. k and ε.

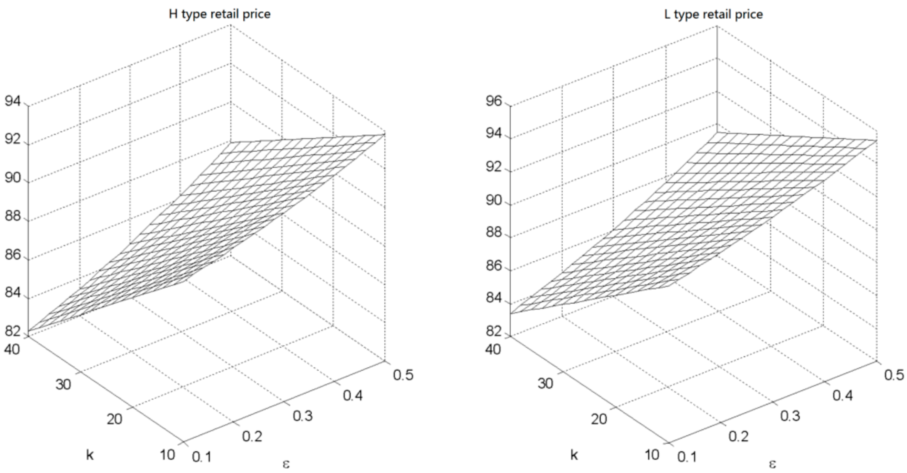

Figure 15. The retail price p_{HH}^{**} and p_{LL}^{**} vs. k and ε.

(3) As shown in Figures 16 and 17, the franchise fees T_{tH}^{**} and T_{tL}^{**} of the third-party recycler and T_{rH}^{**} and T_{rL}^{**} of the retailer charged by the manufacturer increase in the reward–penalty intensity k. By comparison with the results of Appendix A, we see that the franchise fees charged by the manufacturer on the two collection agents with RPM are more than without RPM, i.e., $T_{tH}^{**} > T_{tH}^{*}$, $T_{tL}^{**} > T_{tL}^{*}$, $T_{rH}^{**} > T_{rH}^{*}$, $T_{rL}^{**} > T_{rL}^{*}$. In addition, the manufacturer can get more profit by raising the franchise fee under RPM.

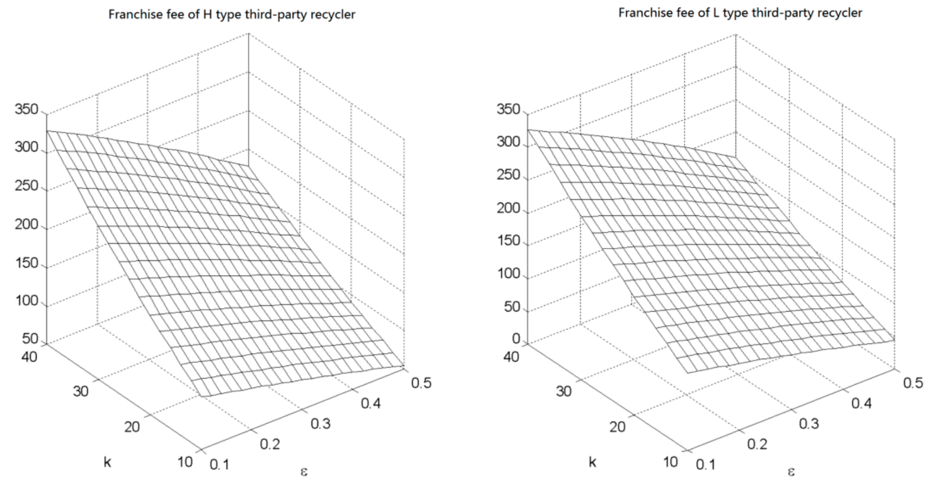

Figure 16. The franchise fee of the third-party recycler T_{tH}^{**} and T_{tL}^{**} vs. k and ε.

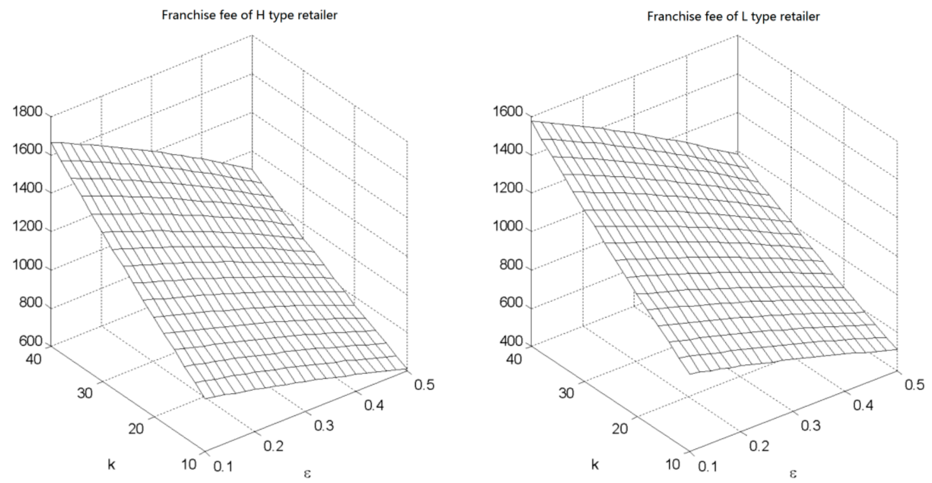

Figure 17. The franchise fee of the retailer T_{rH}^{**} and T_{rL}^{**} vs. k and ε.

(4) As shown in Figure 18, as the reward–penalty intensity k increases, the expected profits of the manufacturer $E(\pi_{mHH}^{**})$, $E(\pi_{mHL}^{**})$, $E(\pi_{mLH}^{**})$ and $E(\pi_{mLL}^{**})$ first decrease, then increase. Specifically, when $\varepsilon \leq 0.3$, if $k \leq 20$, the expected profit of the manufacturer decreases in the reward–penalty intensity k; but if $k > 20$, his expected profit increases in k. When $\varepsilon = 0.4$, if $k \leq 30$, his expected profit decreases with k rising; if $k > 30$, the changing trend of his expected profit is just the opposite. When $\varepsilon \geq 0.5$, his expected profit is always decreasing with k rising. We can deduce that under moderate collection competition intensity between the third-party recycler and the retailer, there is a large enough reward–penalty intensity to make the manufacturer better off. However, in the case without RPM, the manufacturer's expected profits always decrease as the competition intensity rises. Therefore, the RPM can motivate the manufacturer, which serves as the leader of the CLSC, to collect more WEEEs via the retailer and the third-party recycler.

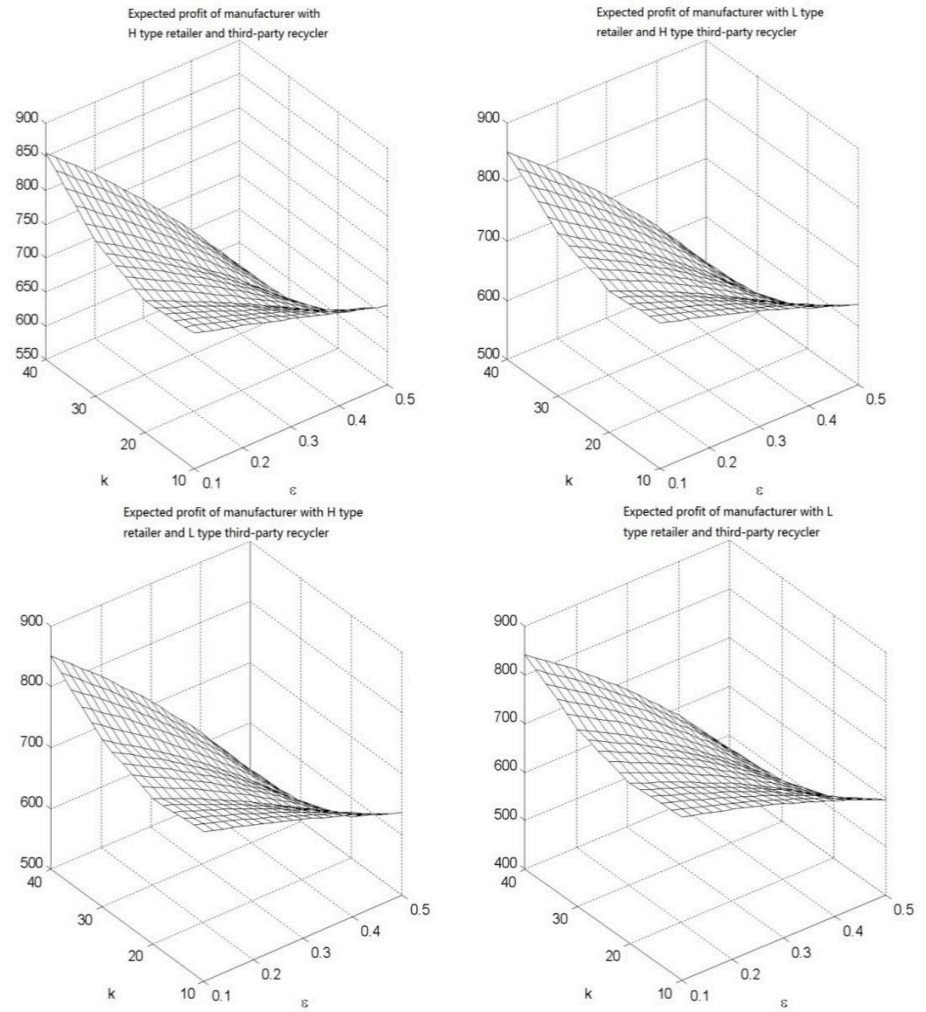

Figure 18. The expected profits of manufacturer $E(\pi^{**}_{mHH})$, $E(\pi^{**}_{mHL})$, $E(\pi^{**}_{mLH})$ and $E(\pi^{**}_{mLL})$ vs. k and ε.

By comparing the manufacturer's expected profits under RPM with those in the absence of RPM, we find that when $\varepsilon \leq 0.2$, if $k \leq 30$, $E(\pi^{**}_{mHH}) < E(\pi^{*}_{mHH})$, $E(\pi^{**}_{mHL}) < E(\pi^{*}_{mHL})$, $E(\pi^{**}_{mLL}) < E(\pi^{*}_{mLL})$; if $k > 30$, $E(\pi^{**}_{mHH}) > E(\pi^{*}_{mHH})$, $E(\pi^{**}_{mHL}) > E(\pi^{*}_{mHL})$, $E(\pi^{**}_{mLL}) > E(\pi^{*}_{mLL})$. When $\varepsilon > 0.2$, $E(\pi^{**}_{mHH}) < E(\pi^{*}_{mHH})$, $E(\pi^{**}_{mHL}) < E(\pi^{*}_{mHL})$, $E(\pi^{**}_{mLL}) < E(\pi^{*}_{mLL})$.

In the model with RPM, we find that in order to improve the expected profit of the manufacturer, a larger reward–penalty intensity is needed as the collection competition intensifies. This is because, with the increase of the reward–penalty intensity, the quantity of WEEEs collected by the third-party recycler and the retailer is lower than the target collection quantity to start with, and then turns out to be higher than the target collection quantity. When the collection quantity is lower than the target collection quantity, the manufacturer will be penalized, and thus the expected profit is lower than without RPM; on the contrary, when the collection quantity is higher than the target collection quantity, the manufacturer will be rewarded, and thus the expected profit is higher than without RPM.

(5) The expected profit of the third-party recycler $E(\pi^{**}_{tHH})$ and the expected profit of the retailer $E(\pi^{**}_{tHH})$ increase in reward–penalty intensity when both of them choose collection effort level H, while their expected profits are equal to the conserved profits when they choose collection effort level L. By comparison with the results in Appendix A, the expected profits of the two collection agents with RPM are higher than without RPM when they choose collection effort level H, i.e., $E(\pi^{**}_{tHH}) > E(\pi^{*}_{tHH})$, $E(\pi^{**}_{rHH}) > E(\pi^{*}_{rHH})$; when they choose collection effort level L, their expected profits with

RPM are equal to without RPM, which are their conserved profits, i.e., $E(\pi_{tLL}^{**}) = E(\pi_{tLL}^{*}) = \pi_t^0$, $E(\pi_{rLL}^{**}) = E(\pi_{rLL}^{*}) = \pi_r^0$.

5. Conclusions and Future Research

In this paper, we study a CLSC with dual collection channel, in which the manufacturer entrusts one retailer and one third-party recycler with collecting WEEEs in competition. The collection effort levels of both collection agents are only known to themselves. The manufacturer provides information screening contracts for the two collection agents in order to attain real information about their collection effort levels. In this context, we focus on verifying the efficiency of the information screening contracts and exploring the influence of the RPM on the CLSC with competitive dual collection channel and information asymmetry. The contract parameters and optimal decision-making results are obtained by numerical simulation and the main findings are as follows:

(1) The information screening contract can help the manufacturer acquire the real collection effort levels effectively because the two collection agents are induced to choose the same type of contract as their collection effort type for profit maximization. That is, the screening contract can prevent them from lying and improve the efficiency of the CLSC system.
(2) The retailer and the third-party recycler will earn more profit by choosing a high level collection effort when competing against each other. The collection competition reduces the total collection quantity and the expected profit of the manufacturer, while the expected profits of both two collection agents first increase and then decrease as the competition intensity increases. In addition, the more intense the collection competition is, the more losses they will suffer. Therefore, the CLSC channel members should make efforts to come to a cooperation agreement for mitigating the negative effect of the competition.
(3) The RPM has a positive effect on CLSC with collection competition. First, RPM increases the collection price, buyback price, franchise fee, and total collection quantity; secondly, it can encourage initiatives of the collectors in collecting WEEEs, and then the environmental benefits to society will improve. What is more, the RPM can ensure that the profits of all the CLSC members are superior to without RPM.

This paper is among the first efforts to investigate the impact of RPM on a CLSC with competitive dual collection channel and information asymmetry. Several possible extensions deserve future research. First, all the conclusions we have obtained are based on a case where the manufacturer delegates the collection task to the mutual competitive retailer and third-party recycler. However, as Savaskan et al. [5] have noted, the manufacturer may choose to collect the WEEEs itself. So, other competition forms, such as mutual competitive manufacturer and retailer (or mutual competitive manufacturer and the third-party recycler) can also be examined. Secondly, we assume that there is no difference between the new product and the remanufactured product. In reality, however, there are many differences between the two types of products. For instance, the price of a remanufactured product may be lower than that of a new product, so the product differentiation needs to be considered in the future. Finally, this paper assumes that all the CLSC members are risk-neutral and profit maximizers. We may need to incorporate the risk attitudes of the decision-makers into the CLSC model.

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Conflicts of Interest: The authors declare no conflict of interests.

Appendix A

Table A1. The optimal CLSC decision results vs. v and ε without RPM.

ε	v				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
b^*_{rH}, b^*_{tH}					
0.1	16.870	16.890	16.910	16.920	16.940
0.2	16.390	16.420	16.450	16.480	16.510
0.3	15.820	15.860	15.890	15.930	15.960
0.4	15.120	15.140	15.170	15.190	15.210
0.5	14.170	14.160	14.150	14.130	14.120
b^*_{rL}, b^*_{tL}					
0.1	18.510	18.250	17.920	17.470	16.830
0.2	18.150	17.860	17.490	17.000	16.300
0.3	17.660	17.330	16.910	16.360	15.590
0.4	16.960	16.580	16.100	15.470	14.620
0.5	15.940	15.480	14.910	14.190	13.230
w^*_H					
0.1	64.070	64.090	64.120	64.150	64.180
0.2	65.120	65.160	65.190	65.230	65.260
0.3	66.320	66.370	66.410	66.450	66.480
0.4	67.700	67.760	67.810	67.850	67.890
0.5	69.300	69.380	69.440	69.500	69.540
w^*_L					
0.1	65.260	65.450	65.680	65.990	66.400
0.2	66.550	66.760	67.000	67.300	67.720
0.3	68.030	68.240	68.490	68.790	69.190
0.4	69.710	69.930	70.180	70.480	70.860
0.5	71.660	71.880	72.130	72.410	72.770
r^*_{tHH}					
0.1	3.726	3.718	3.711	3.698	3.691
0.2	3.788	3.764	3.740	3.717	3.694
0.3	3.808	3.763	3.713	3.670	3.622
0.4	3.744	3.656	3.575	3.490	3.407
0.5	3.496	3.349	3.205	3.059	2.922
r^*_{tLL}					
0.1	6.046	5.898	5.716	5.473	5.136
0.2	6.168	5.984	5.760	5.477	5.089
0.3	6.228	5.998	5.723	5.385	4.937
0.4	6.164	5.876	5.540	5.130	4.612
0.5	5.880	5.509	5.085	4.589	3.978
r^*_{rHH}					
0.1	3.726	3.718	3.711	3.698	3.691
0.2	3.788	3.764	3.740	3.717	3.694
0.3	3.808	3.763	3.713	3.670	3.622
0.4	3.744	3.656	3.575	3.490	3.407
0.5	3.496	3.349	3.205	3.059	2.922
r^*_{rLL}					
0.1	6.046	5.898	5.716	5.473	5.136
0.2	6.168	5.984	5.760	5.477	5.089
0.3	6.228	5.998	5.723	5.385	4.937
0.4	6.164	5.876	5.540	5.130	4.612
0.5	5.880	5.509	5.085	4.589	3.978

Table A1. *Cont.*

ε	v				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
p^*_{HH}					
0.1	93.035	93.045	93.060	93.080	93.090
0.2	93.560	93.580	93.600	93.620	93.630
0.3	94.160	94.180	94.200	94.220	94.240
0.4	94.850	94.880	94.900	94.920	94.940
0.5	95.650	95.690	95.720	95.750	95.770
p^*_{LL}					
0.1	93.630	93.720	93.840	94.000	94.200
0.2	94.280	94.380	94.500	94.650	94.860
0.3	95.020	95.120	95.240	95.400	95.600
0.4	95.860	95.960	96.090	96.240	96.430
0.5	96.830	96.940	97.060	97.200	97.380
T^*_{tH}					
0.1	60.880	61.943	63.108	64.326	65.961
0.2	48.364	50.046	51.846	53.819	56.113
0.3	35.494	37.849	40.218	42.886	45.769
0.4	22.517	25.262	28.262	31.374	34.789
0.5	9.269	12.460	15.814	19.259	23.127
T^*_{tL}					
0.1	83.109	80.319	76.694	71.674	64.507
0.2	71.318	68.789	65.334	60.523	53.433
0.3	58.443	56.172	52.899	48.204	41.238
0.4	44.295	42.317	39.261	34.670	27.912
0.5	28.946	27.166	24.276	19.924	13.359
T^*_{rH}					
0.1	659.860	660.340	660.630	660.980	661.750
0.2	617.190	617.740	618.690	619.530	620.970
0.3	570.560	571.530	572.780	574.340	576.380
0.4	519.640	520.760	522.400	524.430	526.760
0.5	463.590	464.680	466.450	468.330	471.140
T^*_{rL}					
0.1	647.970	639.800	629.680	615.950	597.350
0.2	599.990	591.650	581.580	568.550	550.010
0.3	546.630	538.710	528.730	516.030	498.460
0.4	487.860	480.140	470.590	458.250	441.740
0.5	422.470	415.170	406.030	394.720	379.260
Q^*_{tHrH}, Q^*_{rHtH}					
0.1	13.353	13.346	13.340	13.330	13.320
0.2	13.030	13.011	12.992	12.974	12.955
0.3	12.666	12.634	12.599	12.569	12.535
0.4	12.246	12.194	12.145	12.094	12.044
0.5	11.748	11.674	11.602	11.530	11.461
Q^*_{tHrL}, Q^*_{rHtL}					
0.1	13.120	13.130	13.140	13.150	13.180
0.2	12.550	12.570	12.590	12.620	12.680
0.3	11.940	11.960	12.000	12.050	12.140
0.4	11.280	11.310	11.360	11.440	11.560
0.5	10.560	10.590	10.660	10.760	10.930

Table A1. *Cont.*

ε	v				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
Q^*_{tLrH},Q^*_{rLtH}					
0.1	12.670	12.530	12.340	12.100	11.770
0.2	12.410	12.230	12.010	11.730	11.350
0.3	12.090	11.870	11.610	11.280	10.850
0.4	11.670	11.410	11.110	10.730	10.250
0.5	11.130	10.830	10.480	10.060	9.517
Q^*_{tLrL},Q^*_{rLtL}					
0.1	12.440	12.310	12.140	11.930	11.620
0.2	11.930	11.790	11.610	11.380	11.070
0.3	11.360	11.200	11.010	10.770	10.460
0.4	10.700	10.530	10.320	10.080	9.767
0.5	9.940	9.754	9.542	9.294	8.989
$Q^*_{tHrH}+Q^*_{rHtH}$					
0.1	26.710	26.690	26.680	26.660	26.640
0.2	26.060	26.020	25.980	25.950	25.910
0.3	25.330	25.270	25.200	25.140	25.070
0.4	24.490	24.390	24.290	24.190	24.090
0.5	23.500	23.350	23.200	23.060	22.920
$Q^*_{tHrL}+Q^*_{rHtL}$, $Q^*_{tLrH}+Q^*_{rLtH}$					
0.1	25.790	25.650	25.480	25.250	24.940
0.2	24.960	24.800	24.600	24.360	24.030
0.3	24.030	23.830	23.610	23.340	22.990
0.4	22.940	22.720	22.470	22.170	21.810
0.5	21.690	21.430	21.140	20.820	20.450
$Q^*_{tLrL}+Q^*_{rLtL}$					
0.1	24.880	24.620	24.290	23.850	23.240
0.2	23.870	23.570	23.220	22.760	22.140
0.3	22.720	22.400	22.010	21.540	20.910
0.4	21.400	21.050	20.650	20.160	19.530
0.5	19.880	19.510	19.080	18.590	17.980
$E(\pi^*_{mHH})$					
0.1	788.550	790.150	791.890	794.010	796.730
0.2	774.670	777.180	779.930	783.020	786.790
0.3	760.750	764.290	768.090	772.260	777.080
0.4	747.460	752.050	756.950	762.290	768.220
0.5	736.050	741.810	747.900	754.370	761.460
$E(\pi^*_{mHL})$					
0.1	788.440	789.610	790.740	791.810	792.760
0.2	772.310	774.310	776.240	778.020	779.420
0.3	755.130	758.050	760.790	763.190	765.070
0.4	737.300	741.090	744.570	747.640	749.890
0.5	719.400	724.050	728.330	731.940	734.420
$E(\pi^*_{mLH})$					
0.1	789.270	790.390	791.440	792.320	792.760
0.2	773.500	775.420	777.180	778.650	779.430
0.3	756.840	759.570	761.990	763.990	765.070
0.4	739.650	743.100	746.180	748.600	749.850
0.5	722.600	726.770	730.390	733.130	734.410

Table A1. *Cont.*

ε	v				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
$E(\pi^*_{mLL})$					
0.1	788.820	789.050	788.830	787.780	785.000
0.2	771.260	771.880	771.820	770.650	767.330
0.3	751.710	752.630	752.620	751.190	747.160
0.4	729.930	731.020	730.950	729.060	724.230
0.5	705.920	707.040	706.680	704.220	698.430
$E(\pi^*_{tHH})$					
0.1	86.893	86.556	86.113	85.491	84.584
0.2	85.446	85.128	84.688	84.068	83.133
0.3	83.797	83.497	83.061	82.425	81.459
0.4	81.887	81.611	81.180	80.521	79.524
0.5	79.678	79.412	78.974	78.303	77.257
$E(\pi^*_{tLL})$					
0.1	60.000	60.000	60.000	60.000	60.000
0.2	60.000	60.000	60.000	60.000	60.000
0.3	60.000	60.000	60.000	60.000	60.000
0.4	60.000	60.000	60.000	60.000	60.000
0.5	60.000	60.000	60.000	60.000	60.000
$E(\pi^*_{rHH})$					
0.1	326.880	326.550	326.110	325.490	324.580
0.2	325.450	325.130	324.690	324.060	323.130
0.3	323.800	323.490	323.060	322.420	321.470
0.4	321.890	321.610	321.180	320.520	319.530
0.5	319.680	319.410	318.980	318.290	317.260
$E(\pi^*_{rLL})$					
0.1	300.000	300.000	300.000	300.000	300.000
0.2	300.000	300.000	300.000	300.000	300.000
0.3	300.000	300.000	300.000	300.000	300.000
0.4	300.000	300.000	300.000	300.000	300.000
0.5	300.000	300.000	300.000	300.000	300.000

Appendix B

Table A2. The optimal CLSC decision results vs. k and ε with RPM.

k	″				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
b^{**}_{tH}, b^{**}_{rH}					
10	21.310	20.920	20.400	19.700	18.660
20	25.680	25.320	24.850	24.180	23.190
30	30.050	29.730	29.290	28.670	27.730
40	34.420	34.130	33.730	33.160	32.270
b^{**}_{tL}, b^{**}_{rL}					
10	21.200	20.700	20.030	19.100	17.770
20	25.570	25.110	24.480	23.590	22.310
30	29.940	29.510	28.920	28.080	26.850
40	34.310	33.920	33.360	32.570	31.390

Table A2. *Cont.*

k	″				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
w_H^{**}					
10	58.780	60.150	61.710	63.500	65.590
20	53.380	55.040	56.940	59.110	61.650
30	47.980	49.940	52.160	54.720	57.700
40	42.580	44.830	47.390	50.330	53.750
w_L^{**}					
10	61.000	62.610	64.420	66.470	68.820
20	55.600	57.500	59.650	62.080	64.870
30	50.200	52.400	54.880	57.690	60.920
40	44.800	47.290	50.100	53.300	56.980
r_{tHH}^{**}					
10	5.991	6.144	6.234	6.212	5.949
20	8.291	8.589	8.851	9.013	8.970
30	10.590	11.040	11.460	11.820	12.000
40	12.890	13.480	14.070	14.630	15.020
r_{tLL}^{**}					
10	7.436	7.534	7.549	7.412	7.004
20	9.736	9.984	10.170	10.220	10.030
30	12.040	12.430	12.780	13.020	13.060
40	14.340	14.880	15.390	15.830	16.080
r_{rHH}^{**}					
10	5.991	6.144	6.234	6.212	5.949
20	8.291	8.589	8.851	9.013	8.970
30	10.590	11.040	11.460	11.820	12.000
40	12.890	13.480	14.070	14.630	15.020
r_{rLL}^{**}					
10	7.436	7.534	7.549	7.412	7.004
20	9.736	9.984	10.170	10.220	10.030
30	12.040	12.430	12.780	13.020	13.060
40	14.340	14.880	15.390	15.830	16.080
p_{HH}^{**}					
10	90.390	91.080	91.860	92.750	93.800
20	87.690	88.520	89.470	90.560	91.820
30	84.990	85.970	87.080	88.360	89.850
40	82.290	83.420	84.700	86.160	87.880
p_{LL}^{**}					
10	91.500	92.300	93.210	94.240	95.410
20	88.800	89.750	90.820	92.040	93.440
30	86.100	87.200	88.440	89.840	91.460
40	83.400	84.640	86.050	87.650	89.490
T_{tH}^{**}					
10	118.890	104.340	88.739	72.353	54.769
20	180.390	160.060	138.510	115.410	90.868
30	250.450	223.630	194.870	164.290	131.630
40	329.090	294.670	257.930	218.790	177.050
T_{tL}^{**}					
10	117.210	101.100	83.532	64.350	43.654
20	178.480	156.560	132.620	106.550	78.548
30	248.310	219.530	188.310	154.430	117.980
40	326.720	290.350	250.690	207.940	162.070

Table A2. *Cont.*

k	″				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
T_{rH}^{**}					
10	878.080	820.690	757.460	687.920	610.290
20	1117.500	1041.000	956.710	864.200	761.400
30	1380.200	1281.800	1174.300	1055.900	925.250
40	1666.000	1543.400	1409.600	1263.000	1101.600
T_{rL}^{**}					
10	807.460	742.890	672.400	595.250	510.680
20	1040.700	956.620	864.500	764.150	654.510
30	1297.100	1190.600	1074.600	948.380	810.670
40	1576.700	1445.700	1303.100	1147.900	978.970
$Q_{tHrH}^{**}, Q_{rHtH}^{**}$					
10	15.392	14.915	14.364	13.727	12.974
20	17.462	16.871	16.196	15.408	14.485
30	19.531	18.832	18.022	17.092	16.000
40	21.601	20.784	19.849	18.778	17.510
$Q_{tHrL}^{**}, Q_{rHtL}^{**}$					
10	15.250	14.640	13.970	13.250	12.450
20	17.320	16.590	15.800	14.920	13.960
30	19.390	18.550	17.630	16.610	15.470
40	21.460	20.500	19.450	18.300	16.980
$Q_{tLrH}^{**}, Q_{rLtH}^{**}$					
10	13.840	13.310	12.680	11.930	11.030
20	15.910	15.270	14.510	13.610	12.540
30	17.980	17.220	16.340	15.290	14.060
40	20.050	19.180	18.170	16.980	15.570
$Q_{tLrL}^{**}, Q_{rLtL}^{**}$					
10	13.690	13.030	12.280	11.450	10.500
20	15.760	14.990	14.120	13.130	12.020
30	17.840	16.940	15.950	14.810	13.530
40	19.910	18.900	17.770	16.500	15.040
$Q_{tHrH}^{**}+Q_{rHtH}^{**}$					
10	30.780	29.830	28.730	27.450	25.950
20	34.920	33.740	32.390	30.820	28.970
30	39.060	37.660	36.040	34.180	32.000
40	43.200	41.570	39.700	37.560	35.020
$Q_{tHrL}^{**}+Q_{rHtL}^{**}, Q_{tLrH}^{**}+Q_{rLtH}^{**}$					
10	29.080	27.940	26.650	25.170	23.480
20	33.220	31.860	30.310	28.540	26.500
30	37.370	35.780	33.970	31.900	29.530
40	41.510	39.690	37.620	35.280	32.550
$Q_{tLrL}^{**}+Q_{rLtL}^{**}$					
10	27.380	26.050	24.570	22.890	21.000
20	31.520	29.970	28.240	26.260	24.030
30	35.670	33.890	31.890	29.620	27.060
40	39.810	37.810	35.550	33.000	30.080
$E(\pi_{mHH}^{**})$					
10	749.410	729.820	709.240	688.080	667.100
20	743.440	712.030	677.950	641.510	603.030
30	778.980	733.340	683.350	628.660	569.160
40	855.890	793.690	725.290	649.550	565.640

Table A2. *Cont.*

k	η				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
$E(\pi^{**}_{mHL})$					
10	745.050	721.570	695.630	667.150	636.310
20	738.730	702.800	662.750	618.080	568.460
30	773.810	723.230	666.450	602.690	530.920
40	850.340	782.720	706.790	620.940	523.600
$E(\pi^{**}_{mLH})$					
10	745.050	721.570	695.630	667.150	636.330
20	738.680	702.830	662.770	618.080	568.460
30	773.850	723.240	666.460	602.590	530.920
40	850.360	782.700	706.770	620.950	523.640
$E(\pi^{**}_{mLL})$					
10	736.900	708.460	676.040	638.890	596.610
20	730.180	688.860	641.610	587.300	525.080
30	764.920	708.360	643.700	569.220	483.780
40	841.070	766.960	682.320	585.010	472.700
$E(\pi^{**}_{tHH})$					
10	90.792	88.993	86.944	84.562	81.797
20	96.999	94.878	92.440	89.619	86.340
30	103.210	100.740	97.932	94.666	90.882
40	109.420	106.630	103.410	99.719	95.426
$E(\pi^{**}_{tLL})$					
10	60.000	60.000	60.000	60.000	60.000
20	60.000	60.000	60.000	60.000	60.000
30	60.000	60.000	60.000	60.000	60.000
40	60.000	60.000	60.000	60.000	60.000
$E(\pi^{**}_{rHH})$					
10	330.790	329.000	326.940	324.560	321.800
20	337.060	334.850	332.440	329.620	326.340
30	343.200	340.730	337.910	334.710	330.880
40	349.390	346.700	343.400	339.660	335.390
$E(\pi^{**}_{rLL})$					
10	300.000	300.000	300.000	300.000	300.000
20	300.000	300.000	300.000	300.000	300.000
30	300.000	300.000	300.000	300.000	300.000
40	300.000	300.000	300.000	300.000	300.000

References

1. Wu, H.; Han, X.; Yang, Q.; Pu, X. Production and coordination decisions in a closed-loop supply chain with remanufacturing cost disruptions when retailers compete. *J. Intell. Manuf.* **2018**, *29*, 227–235. [CrossRef]
2. Savaskan, R.C.; Bhattacharya, S.; Van Wassenhove, L.N. Closed-Loop Supply Chain Models with Product Remanufacturing. *Manag. Sci.* **2004**, *50*, 239–252. [CrossRef]
3. Giovanni, P.D.; Reddy, P.V.; Zaccour, G. Incentive strategies for an optimal recovery program in a closed-loop supply chain. *Eur. J. Oper. Res.* **2016**, *249*, 605–617. [CrossRef]
4. Hammond, D.; Beullens, P. Closed-loop supply chain network equilibrium under legislation. *Eur. J. Oper. Res.* **2007**, *183*, 895–908. [CrossRef]
5. Savaskan, R.C.; Van Wassenhove, L.N. Reverse Channel Design: The Case of Competing Retailers. *Manag. Sci.* **2006**, *52*, 1–14. [CrossRef]
6. Hong, I.H.; Yeh, J.S. Modeling closed-loop supply chains in the electronics industry: A retailer collection application. *Transp. Res. Part E* **2012**, *48*, 817–829. [CrossRef]

7. He, Y. Acquisition pricing and remanufacturing decisions in a closed-loop supply chain. *Int. J. Prod. Econ.* **2015**, *163*, 48–60. [CrossRef]
8. Atasu, A.; Çetinkaya, S. Lot Sizing for Optimal Collection and Use of Remanufacturable Returns over a Finite Life-Cycle. *Prod. Oper. Manag.* **2006**, *15*, 473–487. [CrossRef]
9. Gaur, J.; Amini, M.; Rao, A.K. Closed-loop supply chain configuration for new and reconditioned products: An integrated optimization model. *Omega* **2017**, *66*, 212–223. [CrossRef]
10. Esenduran, G.; Kemahlýoðlu-Ziya, E.; Swaminathan, J.M. Impact of Take-Back Regulation on the Remanufacturing Industry. *Prod. Oper. Manag.* **2017**, *26*, 924–944. [CrossRef]
11. Voigt, G.; Inderfurth, K. Supply chain coordination with information sharing in the presence of trust and trustworthiness. *IIE Trans.* **2012**, *44*, 637–654. [CrossRef]
12. Biswas, I.; Avittathur, B.; Chatterjee, A.K. Impact of structure, market share and information asymmetry on supply contracts for a single supplier multiple buyer network. *Eur. J. Oper. Res.* **2016**, *253*, 593–601. [CrossRef]
13. Liu, Z.; Zhao, R.; Liu, X.; Chen, L. Contract designing for a supply chain with uncertain information based on confidence level. *Appl. Soft Comput.* **2017**, *56*, 617–631. [CrossRef]
14. Cao, E.; Ma, Y.; Wan, C.; Lai, M. Contracting with asymmetric cost information in a dual-channel supply chain. *Oper. Res. Lett.* **2013**, *41*, 410–414. [CrossRef]
15. Çakanyýldýrým, M.; Feng, Q.; Gan, X.; Sethi, S.P. Contracting and Coordination under Asymmetric Production Cost Information. *Prod. Oper. Manag.* **2012**, *21*, 345–360. [CrossRef]
16. Zhang, P.; Xiong, Y.; Xiong, Z.; Yan, W. Designing contracts for a closed-loop supply chain under information asymmetry. *Oper. Res. Lett.* **2014**, *42*, 150–155. [CrossRef]
17. Giovanni, P.D. Closed-loop supply chain coordination through incentives with asymmetric information. *Ann. Oper. Res.* **2017**, *253*, 133–167. [CrossRef]
18. Wei, J.; Govindan, K.; Li, Y.; Zhao, J. Pricing and collecting decisions in a closed-loop supply chain with symmetric and asymmetric information. *Comput. Oper. Res.* **2015**, *54*, 257–265. [CrossRef]
19. Zhang, P.; Xiong, Z.; Mauro, A. Information Sharing in a Closed-Loop Supply Chain with Asymmetric Demand Forecasts. *Math. Probl. Eng.* **2017**, *2017*, 1–12. [CrossRef]
20. Wang, W.; Zhang, Y.; Li, Y.; Zhao, X.; Cheng, M. Closed-loop supply chains under reward-penalty mechanism: Retailer collection and asymmetric information. *J. Clean. Prod.* **2017**, *142*, 3938–3955. [CrossRef]
21. Huang, M.; Song, M.; Lee, L.; Ching, W. Analysis for strategy of closed-loop supply chain with dual recycling channel. *Int. J. Prod. Econ.* **2013**, *144*, 510–520. [CrossRef]
22. Hong, X.; Wang, Z.; Wang, D.; Zhang, H. Decision models of closed-loop supply chain with remanufacturing under hybrid dual-channel collection. *Int. J. Adv. Manuf. Technol.* **2013**, *68*, 1851–1865. [CrossRef]
23. Feng, L.; Govindan, K.; Li, C. Strategic planning: Design and coordination for dual-recycling channel reverse supply chain considering consumer behavior. *Eur. J. Oper. Res.* **2016**, *260*, 601–612. [CrossRef]
24. Huang, Y.; Wang, Z. Dual-Recycling Channel Decision in a Closed-Loop Supply Chain with Cost Disruptions. *Sustainability* **2017**, *9*, 2004. [CrossRef]
25. Zhao, J.; Wei, J.; Li, M. Collecting channel choice and optimal decisions on pricing and collecting in a remanufacturing supply chain. *J. Clean. Prod.* **2017**, *167*, 530–544. [CrossRef]
26. Xie, L.; Ma, J. Study the complexity and control of the recycling-supply chain of China's color TVs market based on the government subsidy. *Commun. Nonlinear Sci. Numer. Simul.* **2016**, *38*, 102–116. [CrossRef]
27. Shimada, T.; Van Wassenhove, L.N. Closed-Loop supply chain activities in Japanese home appliance/personal computer manufacturers: A case study. *Int. J. Prod. Econ.* **2016**, in press. [CrossRef]
28. Ma, W.; Zhao, Z.; Ke, H. Dual-channel closed-loop supply chain with government consumption-subsidy. *Eur. J. Oper. Res.* **2013**, *226*, 221–227. [CrossRef]
29. Heydari, J.; Govindan, K.; Jafari, A. Reverse and closed loop supply chain coordination by considering government role. *Transp. Res. Part D* **2017**, *52*, 379–398. [CrossRef]
30. Rahman, S.; Subramanian, N. Factors for implementing end-of-life computer recycling operations in reverse supply chains. *Int. J. Prod. Econ.* **2012**, *140*, 239–248. [CrossRef]
31. He, S.; Yuan, X.; Zhang, X. The Government's Environment Policy Index Impact on Recycler Behavior in Electronic Products Closed-Loop Supply Chain. *Discret. Dyn. Nat. Soc.* **2016**, *2016*, 1–8. [CrossRef]
32. Wang, W.; Zhang, Y.; Zhang, K.; Bai, T.; Shang, J. Reward-penalty mechanism for closed-loop supply chains under responsibility-sharing and different power structures. *Int. J. Prod. Econ.* **2015**, *170*, 178–190. [CrossRef]

33. Teunter, R.H.; Flapper, S.D.P. Optimal core acquisition and remanufacturing policies under uncertain core quality fractions. *Eur. J. Oper. Res.* **2011**, *210*, 241–248. [CrossRef]
34. Yi, P.; Huang, M.; Guo, L.; Shi, T. Dual recycling channel decision in retailer oriented closed-loop supply chain for construction machinery remanufacturing. *J. Clean. Prod.* **2016**, *137*, 1393–1405. [CrossRef]
35. Wang, N.; He, Q.; Jiang, B. Hybrid closed-loop supply chains with competition in recycling and product markets. *Int. J. Prod. Econ.* **2018**, in press. [CrossRef]
36. Ghosh, D.; Shah, J. A comparative analysis of greening policies across supply chain structures. *Int. J. Prod. Econ.* **2012**, *135*, 569–583. [CrossRef]
37. Ghosh, D.; Shah, J. Supply chain analysis under green sensitive consumer demand and cost sharing contract. *Int. J. Prod. Econ.* **2015**, *164*, 319–329. [CrossRef]
38. Giri, B.C.; Chakraborty, A.; Maiti, T. Pricing and return product collection decisions in a closed-loop supply chain with dual-channel in both forward and reverse logistics. *J. Manuf. Syst.* **2017**, *42*, 104–123. [CrossRef]