CHANNEL LEADERSHIP AND RECYCLING CHANNEL IN CLOSED-LOOP SUPPLY CHAIN: THE CASE OF RECYCLING PRICE BY THE RECYCLING PARTY

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ABSTRACT. Due to the fast growing of the waste electrical and electronic equipment (WEEE), the business values of closed-loop supply chains (CLSCs) have been well recognized. In this paper, we investigate the performance of the CLSCs under different combinations of the recycling channel and the channel leadership when the recycling price is determined by the recycling party. Specially, we consider a CLSC consisting of two channel members, i.e., a manufacturer and a retailer. Each member acting as the channel leader has three different channels to collect the used products, and they are (i) the manufacturer (M-channel), (ii) the retailer (R-channel) and (iii) the third-party (T-channel). Given the recycling party determines the recycling price, mathematical models are developed to investigate the performance of the CLSC under different combinations of the channel leadership and the recycling channel. Through a comparison analysis, we find that M-channel is the most effective recycling channel. Moreover, once the M-channel be adopted, the retailer-led structure is as good as manufacture-led structure. We find that the recycling channel structure could be more important than the channel leadership in the CLSC. Finally, we illustrate that the CLSC can be coordinated by a two-part tariff contract.

1. Introduction. With the rapid development of information technology and social economy, the utilization of electrical and electronic equipment (EEE) has tremendously increased over the last two decades (Wang et al., 2011 [40]; Feng et al., 2016 [12]). Consequently, the waste electrical and electronic equipment (WEEE) is currently witnessed to be one of the fast growing pollution streams in the world. Recycling WEEE for remanufacturing can bring environmental and economic benefits, since the demand for finite primary resources would be reduced (Wang et al., 2015 [41]). Therefore, closed-loop supply chains (CLSCs) which focus on collecting used products from customers and recovering the remaining value by reusing them have gained considerable attentions in industry and academia in recent years (Daniel and Guide, 2009 [10]; Atasu et al., 2010 [2]; Huang et al., 2013 [16]).

Recycling channel (Savaskan et al., 2004 [31]; Huang et al., 2013 [16]) and channel leadership (Choi et al., 2013 [7]; Almehdawe and Matin., 2010 [1]) are two important aspects of CLSCs, which have been investigated extensively. On one hand, the choice of recycling channels can have great influence on the profits of channel members (Chuang et al., 2014 [8]). Based on real observations from the market, Savaskan et al. (2004) [31] summarize three main types of recycling channels, i.e., the manufacturer collects the used products from the customers directly (M-channel), the manufacturer outsources the collection of used-products to the retailer or to a third-party (R-channel and T-channel). For instance, Xerox Corporation collects the used copiers from the customers directly. Eastman Kodak Company recycles single-use cameras from large retailers (Savaskan et al., 2004 [31]). Also many original equipment manufacturers (OEMs), such as Ford, General Motors, and Daimler-Chrysler, outsource the collection of used products to independent third-parties. On the other hand, the channel leadership may have a significant effect on the performance of CLSC (Choi et al., 2013 [7]). In general, there are two types of channel leadership in CLSCs. First, one can often see that the manufacturer acts as the channel leader to offer the retailers the contract (M-led) in traditional OEMs like GM and Toyota. Second, leading retailer, such as Tesco, Wal-Mart, Suning and Gome, acts as the channel leader and the manufacturer becomes the follower, namely R-led.

Notice that, previous studies on CLSCs usually assume that the recycling price is a fixed constant (Savaskan et al., 2004 [31]; Atasu et al., 2013 [3]; Chuang et al.,
In fact, the recycling price of the used products is not always a fixed constant in the recycling industry. For example, EcoATM, an American electronics recycling corporation, has developed a self-service recovery machine to automatically evaluate the value of used phones in real time. In general, the recycling price of the used products with high salvage values, such as WEEE, is not a fixed constant, but should be decided by the recycling party. To the best of our knowledge, when the recycling price is determined by the recycling party, the choice of recycling channels is not explicitly investigated. Furthermore, it is more challenging to investigate the performance of the CLSC by integrating the channel leadership under the scenario that the recycling price is determined by the recycling party.

Thus, motivated by the importance of recycling channel and the channel leadership, we aim to address the following research questions:

1. Which recycling channel (M-channel, R-channel, T-channel) is the most effective one under different channel leadership (M-led, R-led), when the recycling price is determined by the recycling party?

2. Which type of leadership (M-led, R-led) is the better one under each recycling channel, namely, M-channel, R-channel and T-channel, under the scenario that the recycling price is decided by the recycling party?

3. Between the channel leadership and the right of recycling, which one is more important for the manufacturer and the retailer? How to coordinate the CLSCs under the best combination of the channel leadership and recycling channel?

These questions form the main objective of this paper. The main contributions of this work are summarized as follows. First, we investigate the performance of the CLSC under different combinations of the channel leadership and the recycling channel under the scenario that the recycling price is decided by the recycling party. Second, we accidentally find that the M-channel is the most effective recycling channel, and R-led model is as good as M-led model. We further clarify the tradeoff between the channel leadership and the recycling channel for the manufacturer and the retailer when they face the suboptimal choice. Third, we propose a two-part tariff contract to coordinate the CLSC under the best combination of the channel leadership and recycling channel.

The remainder of this paper is organized as follows. Section 2 discusses the related literature. Section 3 introduces the problem description, assumptions and the centralized decision model. We provide M-led models and R-led models in Sections 4 and 5, respectively. In Section 6, we present the analytical results to find the optimal closed-loop supply chain structure. Section 7 examines the coordination mechanism in the best combination of the recycling channel and the channel leadership. Section 8 concludes our work with some future research directions.

2. Literature review. This paper investigates the performance of the CLSC under the different combinations of the recycling channel and the channel leadership when the recycling price is determined by the recycling party. Related literature considers three issues: channel leadership, recycling channel management and pricing strategies. A review of the relevant studies is provided as follows.

There are a growing number of works on channel leadership. Previous studies on CLSC management basically assume that the manufacturer acts as the channel leader and the retailer acts as the follower (c.f., McGuire and Staelin 1983 [22]; Jeuland and Shugan, 1983 [17]; Savaskan et al., 2004 [31]). In reality, channel
leadership will have a great effect on the efficiency and performance of the supply chain (Majumder and Srinivasan, 2008 [21]; Choi et al, 2013 [7]). Almehdawe and Matin (2010) [1] compare the efficiency of supply chain between the retailer-led and the manufacturer-led cases and find that the wholesale price is decreased in retailer-led case. Karakayali et al. (2007) [18] analyze two decentralized channel settings, namely the remanufacturer-driven channel and the collector-driven channel for an OEM of durable goods. They identify when and why the OEM prefers a collector-driven or a remanufacturer-driven channel. Wang et al. (2015) [41] study reward-penalty mechanism (RPM) for CLSCs with the third-party recycling channel, and find that collector-led structure is better than manufacturer-led structure. Choi et al. (2013) [7] investigate the influence of different channel leaderships (M-led, R-led, T-led) on the decisions and performance of CLSCs with the third-party recycling channel (T-channel) and find that the retailer-led model is better than the manufacturer-led model. The above literatures investigate the performance of CLSC under different channel leadership, but, they are limited to a certain kind of recycling channel structure. In fact, there are three kinds of recycling channel structures for CLSC, i.e., manufacturer recycling channel (M-channel), retailer recycling channel (R-channel) and the third-party recycling channel (T-channel). Unlike the above studies, our paper examines the influence of channel leadership on the performance of CLSCs with three recycling channel structures (i.e., M-channel, R-channel and T-channel), respectively.

Except for the above issue, recycling channel management is an important and popular field, and many researchers devote to the recycling channel choice strategy. Savaskan et al. (2004) [31] conclude three types of recycling channel structure and find that for the retailer recycling channel is most effective. Atasu et al. (2013) [3] extend the above model by adding a recycling cost structure component which exhibits either economies or diseconomies of scale. They conclude that retailer collection is optimal when there are economies of scale, while manufacturer collection is optimal when there are diseconomies of scale. Chuang et al. (2014) [8] examine the impact of collection cost structures and take-back law on the choice of reverse channel structures aiming at high-tech product, where the collection cost structures exhibit either economies or diseconomies of scale. They find that the legislator can set a relatively high collection rate target in the take-back law when there are economies of scale in collection cost. Giovanni, et al. (2014) find that the choice of recycling channel is more sensitive to environmental effectiveness (environmental performance) than to collection efficiency (operational performance), and the cost differences among players are just less important in the selection of the CLSC structures. Except for the above literature of single recycling channel, we refer readers to Huang et al. (2013) [16], Hong et al. (2013) [15], Giovanni et al. (2014) [9] and Taleizadeh et al. (2018) [35] for more studies on dual recycling channel. In addition, some researchers investigate the impacts of factors that affect the choice of recycling channel, such as channel leadership (Choi et al., 2013 [7]) and government subsides (Hong et al., 2013 [15]; Wang et al., 2015 [41]). The above studies provide theories and approaches to study the recycling channel choice of CLSC, however, to the best of our knowledge, they are all built on the assumption that the recycling price is a fixed constant. Different from the above studies, we focus on the recycling of the used products with high salvage, and explore the most effective recycling channel for the channel leader (the manufacturer or the retailer) under the scenario that the recycling price is decided by the recycling party.
Last, many researchers are interested in pricing strategies of remanufacturing. Taleizadeh et al. (2018) [35] and Nielsen et al. (2019) [26] use game theoretic approach to optimize the pricing strategies of supply chain. Guide et al. (2003) [14] construct a pricing model to investigate the relationship between recycling price and recycling amount. Vorasayan and Ryan (2006) [39] and Liang et al. (2009) [19] investigate how the prices of refurbished products affect the demand of the new products. Garg, et al. (2015) [13] consider fuzzy pricing models. Shi et al. (2011) [33] discuss the uncertainty in pricing, and built a stochastic pricing model for the remanufacturer. Sumil et al. (2018) [34], Sana et al. (2018) [28] and Bhattacharyya et al. (2019) [4] consider the stochastic situation in supply chain. In addition, some researchers consider the inhomogeneity of the used products in recycling and provide differential pricing strategies. Saha et al. (2018) [28] consider the effects of delivery time on the pricing strategies and Saha et al. (2019) [29] integrate sales effort in the pricing. Örşdemir et al. (2014) [27] illustrate that ignoring the quality choice of a OEM leads to overestimating benefits of remanufacturing for social welfare and consumer. Teunter (2006) [36] consider the factors of quality distribution for determining the recovery choices (disposal, material recycling, energy recycling, remanufacturing). Mitra (2007) [24] focuses on two quality levels, namely remanufactured and refurbished products, and develops a pricing model to maximize the expected profits. Liu et al. (2015) [20] point out that quality is a crucial factor in the pricing of the recycling industry. They develop a quality-based price competition model for the WEEE recycling with government subsidy, and find that the acquisition prices in the two channels may crossover as quality increased, which cannot be get in a uniform pricing model. Likewise, our study is conducted under the scenario that the recycling price is determined by the recycling party, and we expect to obtain different conclusions from the uniform pricing case.

3. Problem formulation.

3.1. Problem description. To investigate the performance of the CLSC under the different combination of channel leadership and recycling channel when the recycling price is determined by the recycling party, we consider a CLSC which consists of a manufacturer and a retailer who acts as the Stackelberg leader, respectively. Firstly, we present the notations in Table 1, which are used throughout the paper.

In the forward supply chain, the manufacturer commissions sales to the retailer at a wholesale price $w$, and the retailer sells products to customers at a retail price $p$. While in the reverse supply chain, the manufacturer has three choices for collecting used products from the customers in practice (Savaskan, 2004).

When the manufacturer is the channel leader (M-led), there are three choices for the manufacturer to collect the used products from the customers: (i) the manufacturer collects the used products directly from the customers at a recycling price $b_m$ (Model MM) (ii) the manufacturer contracts the collection of the used products to the retailer at a transfer price $b_{mr}$, and the retailer collects used products from the customers at a recycling price $b_r$ (Model MR) (iii) the manufacturer contracts the collection of the used products to a third-party at a transfer price $b_{mt}$, and the third-party collects the used products from the customers at a recycling price $b_t$ (Model MT).

Likewise, when the retailer acts as the channel leader (R-led), there are also three choices for the manufacturer to collect used products from the customers: (i) the manufacturer collects the used products directly from the customers at a
recycling price \( b_m \) (Model RM) (ii) the manufacturer contracts the collection of the used products to the retailer at a transfer price \( b_{mr} \), and the retailer collects used products from the customers at a recycling price \( b_r \) (Model RR) (iii) the manufacturer contracts the collection of the used products to a third-party at a transfer price \( b_{mt} \) and the third-party collects the used products from the customers at a recycling price \( b_t \) (Model RT).

### Table 1. Notations

| Symbol | Description |
|--------|-------------|
| \( c_m \) | Unit producing cost from original materials |
| \( c_0 \) | Unit producing cost from returns |
| \( \delta \) | Unit saving cost by recovery, \( \delta = c_m - c_0 \) |
| \( A \) | The size of the market |
| \( \alpha \) | Sensitivity of the consumers for the retail price, \( \alpha > 0 \) |
| \( k \) | The basic recovery quantity, which represents the level of environmental awareness of consumers |
| \( h \) | Sensitivity of the customers for the recycling price, \( h > 0 \) |
| \( p \) | The unit retail price |
| \( w \) | The unit wholesale price |
| \( b \) | The unit recycling price in centralized decision system |
| \( b_j \) | The unit recycling price of the recycling party \( j \), subscript \( j = t, r, m \) denotes the recycling by the third-party, the retailer and the manufacturer, respectively |
| \( b_{mj} \) | The unit transfer price, \( j = r, t \), denotes R-channel and T-channel, respectively |

### 3.2. Basic assumptions.

To achieve the primary goal of this study, we make the following assumptions in our study.

1. There are no difference between the new products and the remanufactured products (Savaskan et al., 2004 [31]; Savaskan et al., 2006 [32]).
2. The unit cost of producing products from new materials is higher than that from returns, i.e., \( c_m > c_0 \) (Savaskan et al., 2004 [31]; Chen and Chang, 2012 [6]). The unit saving cost by recycling is denoted by \( \delta \) (i.e., \( \delta = c_m - c_0 \)).
3. All agents are interested in cooperating as a whole. More specifically, \( p > w > 0; b_j < b_{mj} < \delta (j = r, t) \).
4. The demand is a linear function of the retail price, i.e., \( D(p) = A - \alpha p \), where \( A(\alpha > 0) \) presents the market size and \( \alpha(\alpha > 0) \) presents consumers’ sensitivity to the retail price.
5. The amount of recycling products is a linear function of the recycling price, i.e., \( G(b_j) = k + hb_j \), where \( k \) presents the basic recycling quantity and the level of
environmental awareness of consumers, and \( h(h > 0) \) represents consumers’ sensitivity to the recycling price (Karakayali et al., 2007 [18]; Tsay and Agrawal, 2000 [38]; Yao and Liu, 2005 [42], Mukhopadhyay et al., 2006 [25]).

(6) The information is symmetric.

3.3. Model C-Centralized model. First, the centralized decision model (Model C) is considered as a benchmark to highlight the inefficiencies generating from decentralized decision making, and is later used to derive the coordinating pricing scheme. In Model C, there is only one decision maker, the internal transfer parameters (the wholesale price \( w \) and the transfer price \( b_{m_j} \)) are irrelevant to the objective function. Therefore, the central decision maker optimizes the following problem:

\[
\max_{p,b} \Pi_C = (p - c_m)(A - \alpha p) + (\delta - b)(k + hb)
\]  

With the above model, we can have Lemma 1.

**Lemma 1.** In Model C, the optimal retail price and the optimal recycling price are given by 
\( p^C_* = \frac{A + \alpha c_m}{2\alpha} \), \( b^C_* = \frac{h\delta - k}{2h} \). The equilibrium channel profits are given as follows: \( \Pi^C_* = P_f + P_r \) (where \( P_f = \frac{(A - \alpha c_m)^2}{4\alpha} \), \( P_r = \frac{(h\delta + k)^2}{4h} \)).

**Proof.** See Appendix A1.

4. Manufacturer-led CLSCs with different recycling channels. Traditionally, the manufacturer has the dominant power to affect the decisions of a supply chain and acts as the channel leaders. In this section, we consider M-led CLSCs in which the manufacturer has the dominant power to determine the production decisions and managerial delegation. To examine which recycling channel (M-channel, R-channel or T-channel) is the best in M-led CLSCs when the recycling price is decided by the recycling party, we present the optimal decisions and performance of M-led CLSCs with three recycling channel structures (M-channel, R-channel and T-channel), respectively.

4.1. Model MM-Manufacturer-led CLSC with manufacturer recycling channel. In this model, the manufacturer as the channel leader collects the used products directly from consumers, and decides the wholesale price and the recycling price. Therefore, the problem of the manufacturer is given by

\[
\max_{w,b} \pi^M_m = (w - c_m)(A - \alpha p) + (\delta - b_m)(k + hb_m)
\]  

The profit function of the retailer is given by

\[
\max_p \pi^R_r = (p - w)(A - \alpha p)
\]

Under Model MM, the sequence of decisions is as follows. First, the manufacturer determines the transfer price \( w^{MM} \) and the recycling price \( b^{MM}_m \) from equation (2). Second, the retailer decides the retail price \( p^{MM} \) from equation (3).

Through backward induction, we can obtain Lemma 2.

**Lemma 2.** In Model MM, the optimal wholesale price, the optimal recycling price, and the optimal retail price are given by 
\( w^{MM*} = \frac{A + \alpha c_m}{2\alpha} \), \( b^{MM*}_m = \frac{h\delta - k}{2h} \), \( p^{MM*} = \frac{3A + \alpha c_m}{4\alpha} \), respectively. The equilibrium channel profits are given as follows: \( \pi^M_m = \frac{P_f}{4} + P_r \), \( \pi^R_r = \frac{P_f}{4} \), \( \Pi^{MM*} = \frac{3P_f}{4} + P_r \).

**Proof.** See Appendix A2.
4.2. Model MR-Manufacturer-led CLSC with retailer recycling channel.

In this model, the manufacturer acts as the channel leader and the retailer is engaged in collecting used products. Therefore, the profit function of the manufacturer is

$$\max_{w, b_{mr}} \pi_m^R = (w - c_m)(A - \alpha p) + (\delta - b_{mr})(k + h b_r) \quad (4)$$

The profit function of the retailer is

$$\max_{p, b_r} \pi_r^R = (p - w)(A - \alpha p) + (b_{mr} - b_r)(k + h b_r) \quad (5)$$

Under Model MR, the sequence of decisions is as follows. First, the manufacturer decides the transfer price \(w_{MR}^*\) and the recycling transfer price \(b_{mr}^*\) from equation (4). Second, the retailer decides the retail price \(p_{MR}^*\) and the recycling price \(b_{r}^*\) from equation (5).

Through backward induction, we have Lemma 3.

**Lemma 3.** In Model MR, the optimal wholesale price, the optimal transfer price, the optimal retail price, and the optimal recycling price are given by

- \(w_{MR}^* = A + \frac{\alpha c_m}{2}\)
- \(b_{mr}^* = \frac{h \delta - k}{2h}\)
- \(p_{MR}^* = \frac{3A + \alpha c_m}{4}\)
- \(b_{r}^* = \frac{h \delta - 3k}{4h}\), respectively. The equilibrium channel profits are given as follows:

- \(\pi_m^R = \frac{P_f + P_r}{2}\)
- \(\pi_r^R = \frac{P_f + P_r}{4}\)
- \(\Pi_{MR}^* = \frac{3(P_f + P_r)}{4}\)

**Proof.** See Appendix A3. \(\square\)

4.3. Model MT-Manufacturer-led CLSC with third-party recycling channel.

In this model, the manufacturer acts as the channel leader and the third-party is engaged in collecting used products. Therefore, the profit function of the manufacturer is

$$\max_{w, b_{mt}} \pi_m^T = (w - c_m)(A - \alpha p) + (\delta - b_{mt})(k + h b_t) \quad (6)$$

The profit function of the retailer is

$$\max_p \pi_r^T = (p - w)(A - \alpha p) \quad (7)$$

The profit function of the third-party is

$$\max_{b_t} \pi_t^T = (b_{mt} - b_t)(k + h b_t) \quad (8)$$

Under Model MT, the sequence of decisions is as follows. First, the manufacturer decides the transfer price \(w_{MT}^*\) and the recycling price \(b_{mt}^*\) from equation (6). Second, the retailer decides the retail price \(p_{MT}^*\) from equation (7). And then, the third-party decides the recycling price \(b_{t}^*\) from equation (8).

Through backward induction, we have Lemma 4.

**Lemma 4.** In Model MT, the optimal wholesale price, the optimal recycling price, and the optimal retail price, and the optimal recycling price are given by

- \(w_{MT}^* = \frac{A + 3\alpha c_m}{4}\)
- \(b_{mt}^* = \frac{h \delta - k}{2h}\)
- \(p_{MT}^* = \frac{3A + \alpha c_m}{4}\)
- \(b_{t}^* = \frac{h \delta - 3k}{4h}\), respectively. The equilibrium channel profits are given as follows:

- \(\pi_m^T = \frac{P_f + P_r}{2}\)
- \(\pi_r^T = \frac{P_f}{4}\)
- \(\pi_t^T = \frac{P_r}{4}\)
- \(\Pi_{MT}^* = \frac{3(P_f + P_r)}{4}\)

**Proof.** See Appendix A4. \(\square\)
5. Retailer-led CLSCs with different recycling channels. With the shift of downstream power in the supply chain, the retailer-led supply chain is widely observed and becomes a popular and important topic (Messinger and Narasimhan 1995 [23]; Ertek and Griffin, 2002 [11]). To investigate which recycling channel (M-channel, R-channel or T-channel) is the best in R-led leadership when the recycling price is decided by the recycling party, we present the optimal decisions and performance of R-led CLSCs with three recycling channel structures (M-channel, R-channel and T-channel), respectively, in this section.

5.1. Model RM-Retailer-led CLSC with manufacturer recycling channel. In this model, the retailer acts as the channel leader and the manufacturer are engaged in collecting used products. The manufacturer’s profit function and the retailer’s profit function are given by equation (2) and equation (3). Under Model RM, the sequence of decisions is as follows. First, the retailer decides the retail price from equation (3). Second, the manufacturer decides the transfer price and the recycling price from equation (2). Through backward induction, we can obtain Lemma 5.

Lemma 5. In Model RM, the optimal wholesale price, the optimal recycling price, and the optimal retail price are given by $w^{RM*} = \frac{A + 3\alpha c_m}{4\alpha}$, $b^{RM*} = \frac{h\delta - k}{2h}$, $p^{RM*} = \frac{3A + \alpha c_m}{4\alpha}$, respectively. The equilibrium channel profits are given as follows: $\pi^{RM*}_m = \frac{P_f}{4} + P_r$, $\pi^{RM*}_r = \frac{P_l}{2}$, $\Pi^{RM*} = \frac{3P_f}{4} + P_r$.

Proof. See Appendix B1.

5.2. Model RR-Retailer-led CLSC with retailer recycling channel. In this model, the retailer acts as channel leader and is engaged in collecting used products. The manufacturer’s profit function and the retailer’s profit function are given by equation (4) and equation (5). In Model RR, the sequence of decisions is as follows. First, the retailer decides the retail price $p^{RR}$ and the recycling price $b^{RR}_r$ from equation (5). Second, the manufacturer decides the transfer price $w^{RR}$ and the recycling transfer price $b^{RR}_{mr}$ from equation (4). Through backward induction, we can have Lemma 6.

Lemma 6. In Model RR, the optimal wholesale price, the optimal transfer price, the optimal retail price, and the optimal recycling price are given by $w^{RR*} = \frac{A + 3\alpha c_m}{4\alpha}$, $b^{RR*}_{mr} = \frac{3h\delta - k}{4h}$, $p^{RR*} = \frac{3A + \alpha c_m}{4\alpha}$, $b^{RR*}_r = \frac{h\delta - 3k}{4h}$, respectively. The equilibrium channel profits are given as follows: $\pi^{RR*}_m = \frac{P_l + P_c}{4}$, $\pi^{RR*}_r = \frac{P_l + P_c}{2}$, $\Pi^{RR*} = \frac{3(P_l + P_c)}{4}$.

Proof. See Appendix B2.

5.3. Model RT-Retailer-led CLSC with third-party recycling channel. In this model, the retailer acts as the channel leader and the third-party takes charge of collecting used products. The manufacturer’s profit function, the retailer’s profit function and the third-party’s profit function are given by equation (6), equation (7), and equation (8), respectively. In Model RR, the sequence of decisions is as follows. First, the retailer decides the retail price $p^{RT}$ from equation (7). Second, the manufacturer decides the transfer price $w^{RT}$ from equation (6), and the recycling transfer price $b^{RT}_{mt}$ from equation (6), and then, the third-party decides the recycling price $b^{RT}_t$ from equation (8). Through backward induction, we can have Lemma 7.
Lemma 7. In Model RT, the optimal wholesale price, the optimal recycling price, and the optimal retail price, and the optimal recycling price are given by

\[ w_{RT}^* = \frac{A}{4\alpha} + \frac{3}{2}, \quad b_{RT}^* = \frac{k}{h} - \frac{\delta}{2}, \quad p_{RT}^* = \frac{3A}{4\alpha} + \frac{3}{2}, \]

\[ b_{RT}^* = \frac{h\delta}{k} - \frac{3}{2}. \]

The equilibrium channel profits are given as follows:

\[ \pi_{mRT}^* = \frac{P_f + P_r}{4}, \quad \pi_{rRT}^* = \frac{P_f}{2}, \quad \pi_{tRT}^* = \frac{P_r}{2}. \]

\[ \Pi_{RT}^* = \frac{3(P_f + P_r)}{4}. \]

Proof. See Appendix B3.

6. Analysis of comparative statistics. Targeting on answering the questions addressed in Introduction, we provide some comparative statistics in this section.

6.1. Comparisons of the CLSC models with the same recycling channel.

To reveal which type of leadership (M-led, R-led) is more effective under the same recycling channel, we compare the performance of CLSCs with the same recycling channel structure. First, we have Proposition 1.

Proposition 1. With the same recycling channel, (a) the manufacturer’s profits under different leadership are related as follows: \( \pi_{MM}^* > \pi_{RM}^* > \pi_{MR}^* = \pi_{RR}^* \), \( \pi_{MT}^* > \pi_{RT}^* \); (b) the retailer’s profits under different leadership are related as follows: \( \pi_{RM}^* > \pi_{MM}^* > \pi_{RR}^* > \pi_{MR}^* > \pi_{RT}^* = \pi_{MT}^* \).

It is apparent that the manufacturer’s profits in M-led model are more than in R-led model irrespective of the recycling channel. In the same way, the retailer’s profits in M-led model are more than in M-led model irrespective of the recycling channel. Proposition 1 indicates that the channel leader gets a lion share of the channel profits regardless of the recycling channel. This conclusion provides a scientific evidence that the fight to gain the channel leadership in CLSC is fierce.

Proposition 2. With the same recycling channel, the system’s profits are related as follows:

\[ \Pi_{MM}^* = \Pi_{RM}^*, \quad \Pi_{MR}^* = \Pi_{RR}^*, \quad \Pi_{MT}^* = \Pi_{RT}^*. \]

It is apparent that M-led CLSC is as good as R-led CLSC. Despite the manufacturer’s influential role in the CLSC, it is not the only best case for the manufacturer to act as the channel leader. Retailer-led case may lead to the best result. This finding provides another evidence to support the viewpoint of shifting the channel leadership from upstream manufacturer to downstream retailer in a CLSC (Choi et al., 2013 [7]).

6.2. Comparisons of the three Manufacturer-led CLSC models. To examine which recycling channel is the most effective when the manufacturer acts as the channel leader under the scenario that the recycling price is decided by the recycling party, we summarizes the major results of M-led models with different recycling channel in Table 2 (see Appendix D1). Some interesting observations on the performance of M-led CLSCs can be made as follows.

Proposition 3. The optimal retail prices and wholesale prices in the three M-led models with different recycling channel satisfy the following relationships: \( p^{MM*} = p^{MR*} = p^{MT*} \), and \( w^{MM*} = w^{MR*} = w^{MT*} \).

It is obvious that the optimal retail prices and wholesale prices are the same in the three recycling channels when the manufacturer acts the channel leader. Proposition 3 indicates that the choice of the recycling channel has no effect on the pricing decisions in the forward supply chain.
Proposition 4. The optimal recycling prices and transfer prices in three M-led models with different recycling channel satisfy the relations as follows: $b^*_{MT} > b^*_{MR}$, and $b^*_{mt} = b^*_{mr}$. Consequently, we have $G^*_{MM} > G^*_{MR}$.

It is apparent that the recycling price in M-channel is the highest when the manufacturer is the channel leader. Both the recycling price and the transfer price in R-channel are the same as in T-channel. Proposition 4 indicates that M-channel is more beneficial to the resource saving and environment protection when the manufacturer acts as the channel leader.

Theorem 1. The manufacturer’s profits, the retailer’s profits and the system’s profits in three M-led models with different recycling channel are related as: $\pi^*_{MM} > \pi^*_{MR}$, $\pi^*_{MT}$, $\pi^*_{RR} > \pi^*_{RM}$, and $\Pi^*_{MM} > \Pi^*_{MR}$, $\Pi^*_{MT}$. Theorem 1 shows that the ranking of profits of CLSCs with different recycling channels when the manufacturer is the channel leader. From Proposition 4, it is apparent that the higher recycling price is, the more profits will be. Therefore, except for the centralized model, the profits of the system and the manufacturer are greater in the CLSC with M-channel when the manufacturer is the channel leader. That is to say, M-channel is the most effective recycling channel from the system’s and the manufacturer’s perspective when the manufacturer acts as the channel leader. This is an important finding of our work. We come to the interesting conclusion which is different from Savaskan et al. (2004) [31], i.e., retailer recycling channel is most effective for the manufacturer. The reason behind the different findings lies in the fact that the two studies are conducted under different scenarios. Savaskan et al. (2004) [31] focus on the used products with low salvage and conduct the study under the scenario that the recycling price is a fixed constant. While, our study focuses on the used products with high salvage and is conducted under the scenario that the recycling price is determined by the recycling party. This finding is very important as it can be used as a reference for the recycling channel management of used products with high salvage value.

6.3. Comparisons of the three retailer-led CLSC models. To examine which recycling channel is the most effective when the retailer acts as the channel leader under the scenario that the recycling price is decided by the recycling party, we summarize the major results of R-led models with different recycling channel in Table 3 (see Appendix D2). Some interesting conclusions on the performance of R-led CLSCs can be made as follows. Firstly, we have Proposition 5.

Proposition 5. The optimal retail prices and wholesale prices in three R-led models satisfy the relations as follows: $p^*_{RM} = p^*_{RR} = p^*_{RT}$, and $w^*_{RM} = w^*_{RR} = w^*_{RT}$. It is obvious that the optimal retail prices and wholesale prices in three R-led models with different recycling channels are the same. This result indicates that the choice of recycling channel has no effect on the pricing decisions in the forward supply chain.

Proposition 6. The optimal recycling prices and transfer prices in three R-led Models are related as follows: $b^*_{RM} > b^*_{RR}$, $b^*_{RT}$, and $b^*_{mr} > b^*_{mt}$. Accordingly, $G^*_{RM} > G^*_{RR} = G^*_{RT}$. It is apparent that the recycling price in M-channel is the highest when the retailer acts as the channel leader. Proposition 6 indicates that M-channel is more
beneficial to the resource saving and environment protection when the retailer acts as the channel leader.

**Theorem 2.** We have (a) The manufacturer’s profits and the retailer’s profits in three R-led models with different recycling channel are related as follows: \( \pi_{RM} > \pi_{RT} > \pi_{RR} \), and \( \pi_{rM} > \pi_{rT} = \pi_{rR} \). (b) The system’s profits satisfy: \( \Pi_{C} > \Pi_{RM} > \Pi_{RR} = \Pi_{RT} \).

Theorem 2 shows that the ranking of profits of CLSCs with different recycling channels when the retailer is the channel leader. It is apparent that M-channel is the most effective recycling channel from the system’s and the manufacturer’s perspective when the retailer is the channel leader. Together with Theorem 1, we find that M-channel is the most effective recycling channel no matter who dominates the channel. That is to say, the shift of leadership will not influence the most effective recycling channel under the scenario that the recycling price is decided by the recycling party.

### 6.4. Analysis of combinations of channel leadership and recycling channel

From the above analysis, we find that R-led model is better than, at least as good as M-led model under the same recycling channel structure. Together with the conclusion that M-channel is the most effective recycling channel no matter who dominates the channel. Thereupon, we obtain the optimal combination of channel leadership and recycling channel from the total CLSC’s perspective, as shown in Proposition 7.

**Proposition 7.** In the different combination of the channel leadership and the recycling channel, the system’s profits are related as follows: \( \Pi_{C} > \Pi_{MM} = \Pi_{RM} > \Pi_{MR} = \Pi_{MT} = \Pi_{RT} = \Pi_{RR} \).

Proposition 7 reveals that the ranking of profits of decentralized CLSC under different combination of the channel leadership and the recycling channel. Except for Model C, Model MM and Model RM are optimal from the system’s perspective. Together with Propositions 4 and 6, it is obvious that the more the recycling products are recycled, the more profits the system can gain. Proposition 7 suggests that recycling channel (M-channel) is the most important for the CLSC, and it doesn’t matter who is the channel leader. This interesting and important finding provides a reference for the government that makes the incentive policy to encourage the development of the CLSC with M-channel.

Furthermore, channel leadership or recycling channel, which one is more important for the manufacturer and the retailer? In order to clarify these two problems, we define \( v = \frac{P_f}{P_r} \) which represents the ratio of profits from the forward channel and the reverse channel.

**Proposition 8.** The manufacturer’s profits in the different combination of the channel leadership and the recycling channel satisfy the following relationships: when \( v < 2 \), \( \pi_{MM} > \pi_{RM} > \pi_{MR} = \pi_{MT} = \pi_{RT} > \pi_{RR} \); when \( v > 2 \), \( \pi_{MM} > \pi_{MR} > \pi_{RM} > \pi_{MT} = \pi_{RT} > \pi_{RR} \).

**Proof.** See Appendix B4. \(\square\)

It is apparent that the Model MM is optimum for the manufacturer all the way. Moreover, when \( v < 2 \), Model RM is suboptimum for the manufacturer. And, when \( v > 2 \), Model MR are suboptimum for the manufacturer. Proposition 8
analytically reveals the critical value (i.e., $v = 2$) for the manufacturer to weigh the importance of the channel leadership and the recycling channel, if the manufacturer faces the suboptimal choice. This finding clarifies the importance between the channel leadership and the recycling channel for the manufacturer. When the profits from the reverse channel are twice as much as the forward channel, the right of recycling is more important than the channel leadership for the manufacturer. When the profits from the forward channel are more than twice the profits from the reverse channel, the channel leadership is more important than the recycling channel for the manufacturer (See Fig.1).

![Figure 1](image-url)

**Figure 1.** The manufacturer’s tradeoff between the channel leadership and the recycling channel

**Proposition 9.** In the different combination of the channel leadership and the recycling channel, the retailer’s profits satisfy the following relationships: when $v < 1$, $\pi_{RR^*} > \pi_{RM^*} > \pi_{RT^*} = \pi_{MT^*} = \pi_{MM^*}$; when $v > 1$, $\pi_{RR^*} > \pi_{RM^*} = \pi_{RT^*} > \pi_{MT^*} > \pi_{MM^*}$.

**Proof.** See Appendix B5.

It is apparent that the Model RR is optimal for the retailer. When $v < 1$, Model MR is suboptimum for the retailer. When $v > 1$, Model RM and Model RT are suboptimum for the retailer. Proposition 9 analytically reveals critical value (i.e., $v = 1$) for the retailer to weigh the channel leadership and the recycling channel, if the retailer faces the suboptimal choice. This finding clarifies the importance between the channel leadership and the recycling channel for the retailer. When the profits from the reverse channel are more than the profits from the forward channel, the recycling channel is more important than the channel leader for the retailer. When the profits from the forward channel are more than the profits from the reverse channel, channel leadership is more important than the right of recycling for the retailer (See Fig.2).

From the above analysis, we clarify the tradeoff between the channel leadership and the recycling channel for the manufacturer and the retailer when they face the suboptimal choice. We come to the interesting conclusion that the right of recycling could be more important than the channel leadership for the manufacturer and the retailer in a certain case.
Figure 2. The retailer’s tradeoff between the channel leadership and the recycling channel

7. Coordination of CLSCs in MM Model and RM Model. Notice that the performance of CLSCs under the optimum combinations of the channel leadership and the recycling channel (i.e., Model MM and Model RM) are inferior to Model C. In this section, we explore the coordination of CLSCs in Model MM and Model RM. We consider two-part tariff contract which is generally found in practice and very helpful in coordinating supply chains (Cachon and Kok, 2010 [5]).

7.1. Coordination in MM Model. In Model MM, the manufacturer as the Stackelberg leader offers a suitable contract \((w^{MM*}; F^{MM})\) to the retailer who is the Stackelberg follower. Where, \(w^{MM*}\) represents wholesale price and \(F^{MM}\) stands for the fixed fees paid by the retailer to the manufacturer. To achieve the CLSC’s coordination, the retail price and the recycling price should be equal to that in Model C. Thus, the coordination problem is formulated as follows:

\[
\begin{align*}
\max_{w,F} \pi^{MM*}_m &= (w - c_m)(A - \alpha p) + (\delta - b_m)(k + h b_m) + F \\
\text{s.t.} \quad \pi^{MM*}_r &= (p - w)(A - \alpha p) - F \\
p^{MM*} &= p^C \\
b_m^{MM*} &= b^C \\
\pi^{MM*}_m &> \pi^*_m \\
\pi^{MM*}_r &> \pi^*_r \\
\end{align*}
\]

With above model, we have Proposition 10.

**Proposition 10.** In Model MM, the manufacturer can offer the contract \((w^{MM*}; F^{MM}) = (c_m; 3P_t/4)\) to the retailer to coordinate the CLSC. The manufacturer’s and the retailer’s profits are given as follows: \(\pi^{MM*}_m = \frac{3P_t}{4} + P_r\), \(\pi^{MM*}_r = P_r\). Accordingly, the system’s profits are attained at the same level as in Model C.

**Proof.** See Appendix C1.

\[\blacksquare\]
7.2. Coordination in RM Model. In Model RM, the retailer as the Stackelberg leader offers a suitable contract \((p_{RMe}^*, F_{RM})\) to the manufacturer who is the Stackelberg follower. Where, \(p_{RMe}^*\) represents wholesale price and \(F_{RM}\) stands for the fixed fees paid by the retailer to the manufacturer. To achieve the CLSC’s coordination, the retail price and the recycling price should be equal to that in Model C. Thus, the coordination problem is formulated as follows:

\[
\begin{align*}
\max_{p, F} & \quad \pi_{RMe}^r = (p - w)(A - \alpha p) + F \\
\text{s.t.} & \quad \pi_{RMe}^m = (w - c_m)(A - \alpha p) + (\delta - b_m)(k + h b_m) - F \\
& \quad p_{RMe}^* = p_C^* \\
& \quad b_{RMe}^* = b_C^* \\
& \quad \pi_{RMe}^m > \pi_{RMe}^* \\
& \quad \pi_{RMe}^r > \pi_{RMe}^* \\
& \quad (w_{RMe}^*) = \arg\max \pi_{RMe}^m
\end{align*}
\]

With above model, we have Proposition 11.

**Proposition 11.** In Model RM, the retailer can offer the contract \((p_{RMe}^*, F_{RM}) = (\frac{A + \alpha c_m}{2 \alpha}; \frac{P_f + P_r}{2})\) to the manufacturer to coordinate the CLSC. The manufacturer’s and the retailer’s profits are given as follows: \(\pi_{RMe}^m = \frac{P_f + P_r}{2}\), \(\pi_{RMe}^r = \frac{P_f + P_r}{2}\). Accordingly, the system’s profits are attained at the same level as in Model C.

**Proof.** See Appendix C2.

8. Conclusions. In this paper, we investigate the performance of the CLSC under the different combinations of the channel leadership and the recycling channel, when the recycling party determines the recycling price. Several useful and meaningful managerial insights are summarized as follows. First, M-channel is the most effective recycling channel irrespective of the channel leadership (M-led, R-led) when the recycling price is determined by the recycling party. Second, our analysis illustrates that the right of recycling could be more important than channel leadership in a certain case for the manufacturer and the retailer when they face the suboptimal choice. Third, a two-part tariff contract can coordinate the CLSC under the best combination of the channel leadership and the recycling channel, i.e., Model MM and Model RM, and provide a win-win situation. This work provides some insights into the channel leadership and the recycling channel structure of the CLSC by integrating the decision of recycling price. It provides a reference for the government that makes the incentive policy to encourage the development of the CLSC with M-channel. It also offers an tradeoff between the channel leadership and the right of recycling for the manufacturer and the retailer. There are several interesting extensions of this work for future research. In this paper, we only investigate the case of a manufacturer or a retailer acts as the channel leader, a possible extension is to consider the cases that the third-party acts as the channel leader and other channel leadership. This paper is conducted under the scenario that the recycling price is determined by the recycling party; a promising extension is to consider the random factors in the process of pricing decisions. Also, future study can explore the recycling channel choice of closed-loop supply chain with dual-recycling channel. All of the above issues can be explored.
Appendix. Appendix A.

Appendix A1. Proof of Lemma 1

Proof. We first prove the concavity of $\Pi^C$. Taking the second-order derivation of $\Pi^C$ with respect to $p$, we get $\frac{d^2\Pi^C}{dp^2} = -2\alpha < 0$, which implies the concavity of $\Pi^C$. Then through first-order condition of equation (1), we have $p^C = \frac{A + \alpha c_m}{2\alpha}$, $h^C = \frac{\delta - k}{2h}$. Substituting $p^C$ and $b^C$ into equation (1), we get $\Pi^C = P_f + P_r$, where $P_f = \frac{(A - \alpha c_m)^2}{4\alpha}$, $P_r = \frac{(\delta^2 + k^2)^2}{4h}$. Lemma 1 is thus proved. \qed

Appendix A2. Proof of Lemma 2

Proof. First, we prove the concavity of $\pi^M_m$ and $\pi^M_r$.

The manufacturer’s problem: We let $p = w + n$ and carry out the following calculations: $\frac{\partial \pi^M_m}{\partial p} = A - 2\alpha w - \alpha n + \alpha c_m$, $\frac{\partial \pi^M_m}{\partial b_m} = -k - 2hb_m + h\delta$. The resulting Hessian matrix of $\pi^M_m$ is given by

\[
\begin{pmatrix}
-2\alpha & 0 \\
0 & -2h \\
\end{pmatrix}
\]

(11)

It is easy to see that the Hessian matrix of $\pi^M_m$ is negative, namely, $\pi^M_m$ is concave with respect to $(w, b_m)$.

The retailer’s problem: Taking the second-order derivation of $\pi^M_r$ with respect to $p$, yields $\frac{\partial^2 \pi^M_r}{\partial p^2} = -2\alpha < 0$, which implies the concavity of $\pi^M_r$.

Then by solving the first-order condition of $\pi^M_r$, we obtain $\hat{p}^{MM} = \frac{A + \alpha w}{2\alpha}$, which is the optimal response function of the retailer. Substituting $\hat{p}^{MM}$ into $\pi^M_m$, yields $\hat{\pi}^M_m = \frac{(w - c_m)(A - \alpha w)}{\alpha} + (\delta - b_m)(k + hb_m)$.

From the first-order condition, we get $w^{MM} = \frac{A + \alpha c_m}{2\alpha}$ and $b^{MM} = \frac{\delta + k}{2h}$.

Substituting $w^{MM}$ into $\hat{p}^{MM}$, we get $p^{MM} = \frac{A + \alpha w}{2\alpha c_m}$.

Substituting $w^{MM}$, $b^{MM}$ and $p^{MM}$ into $\pi^M_m$ and $\pi^M_r$, we get $\pi^M_m = P_f + P_r$, $\pi^M_r = P_f$ and $\Pi^{MM} = \frac{3P_f}{4} + P_r$. This completes the proof. \qed

Appendix A3. Proof of Lemma 3

Proof. We first prove the concavity of $\pi^R_m$ and $\pi^R_r$.

The manufacturer’s problem: We let $p = w + n$, $b_r = b_{mr} + m$ and carry out the following calculations: $\frac{\partial \pi^R_m}{\partial p} = A - 2\alpha w - \alpha n + \alpha c_m$, $\frac{\partial \pi^R_m}{\partial b_m} = -k - 2hb_{mr} + h\delta - hm$.

The resulting Hessian matrix of $\pi^R_m$ is given by

\[
\begin{pmatrix}
-2\alpha & 0 \\
0 & -2h \\
\end{pmatrix}
\]

(12)

It is easy to see that the Hessian matrix of $\pi^R_m$ is negative, namely, $\pi^R_m$ is concave with respect to $(w, b_{mr})$.

The retailer’s problem: We carry out the following calculations: $\frac{\partial \pi^R_r}{\partial p} = A - 2\alpha p + \alpha w$, $\frac{\partial \pi^R_r}{\partial b_r} = -k - 2hb_r + hb_{mr}$. The resulting Hessian matrix of $\pi^R_r$ is given by

\[
\begin{pmatrix}
-2\alpha & 0 \\
0 & -2h \\
\end{pmatrix}
\]

(13)

It is easy to see that the Hessian matrix of $\pi^R_r$ is negative, namely, $\pi^R_r$ is concave with respect to $(p, b_r)$. 
Then by solving the first-order condition of \( \pi_r^R \), we obtain \( p_{MR}^* = \frac{A+\alpha w}{2\alpha} \) and \( b_{MR}^* = \frac{h\delta-k}{2\alpha} \) which is the optimal response function of the retailer.

Substituting \( p_{MR}^* \) into \( \pi_m^R \), yields \( \hat{\pi}_m^R = \frac{(w-c_m)(A-\alpha w)}{2} + (\delta - b_m)(k + h\delta - k) \).

From the first-order condition, we get \( w_{MR^*} = \frac{A+\alpha c_m}{2\alpha} \) and \( b_{MR^*} = \frac{h\delta-k}{2\alpha} \).

Substituting \( w_{MR^*} \) into \( \hat{p}_{MR}^* \), we get \( p_{MR^*} = \frac{3A+\alpha c_m}{4\alpha} \).

Substituting \( w_{MR^*}, b_{MR^*} \) into \( \hat{b}_{MR}^* \), we get \( \hat{\pi}_m^R = \frac{3(A+\alpha c_m)}{4\alpha} \) and \( \Pi_{MR^*} = \frac{3\alpha w}{4} \). This completes the proof.

\[ \square \]

Appendix A4. Proof of Lemma 4

Proof. We first prove the concavity of \( \pi_m^T \) and \( \pi_r^T \) and \( \pi_i^T \).

The manufacturer’s problem: We let \( p = w + n, b_t = b_{mt} + m \) and carry out the following calculations: \( \frac{\partial \pi_m^T}{\partial w} = A - 2\alpha w - \alpha n + \alpha c_m \), \( \frac{\partial \pi_m^T}{\partial b_t} = -k - 2h b_{mt} + h\delta - hm \).

The resulting Hessian matrix of \( \pi_m^T \) is given by

\[
\begin{pmatrix}
-2\alpha & 0 \\
0 & -2h \\
\end{pmatrix}
\] (14)

It is easy to see that the Hessian matrix of \( \pi_m^T \) is negative, namely, \( \pi_m^T \) is concave with respect to \( (w, b_{mt}) \).

The retailer’s problem: Taking the second-order derivation of \( \pi_r^T \) with respect to \( p \), yields \( \frac{d^2\pi_r^T}{dp^2} = -2\alpha < 0 \), which implies the concavity of \( \pi_r^T \).

The third-party’s problem: Taking the second-order derivation of \( \pi_i^T \) with respect to \( b_{mt} \), yields \( \frac{d^2\pi_i^T}{db_{mt}^2} = -2h < 0 \), which implies the concavity of \( \pi_i^T \).

Then by solving the first-order condition of \( \pi_r^R \) and \( \pi_i^R \), we obtain \( \hat{p}_{MT}^* = \frac{A+\alpha w}{2\alpha} \) and \( \hat{b}_{MT}^* = \frac{h\delta-k}{2\alpha} \) which are the optimal response functions of the retailer and the third-party.

Substituting \( \hat{p}_{MT}^* \) and \( \hat{b}_{MT}^* \) into \( \pi_m^T \), yields \( \hat{\pi}_m^T = \frac{(w-c_m)(A-\alpha w)}{2} + (\delta - b_m)(k + h\delta - k) \).

From the first-order condition, we get \( w_{MT^*} = \frac{A+\alpha c_m}{2\alpha} \) and \( b_{MT^*} = \frac{h\delta-k}{2\alpha} \).

Substituting \( w_{MT^*} \) into \( \hat{p}_{MT}^* \), we get \( p_{MT^*} = \frac{3A+\alpha c_m}{4\alpha} \).

Substituting \( b_{MT^*} \) into \( \hat{b}_{MT}^* \), we get \( \hat{\pi}_m^T = \frac{3(A+\alpha c_m)}{4\alpha} \) and \( \Pi_{MT^*} = \frac{3\alpha w}{4} \). This completes the proof.

\[ \square \]

Appendix B.

Appendix B1. Proof of Lemma 5

Proof. We have already proved the concavity of \( \pi_m^M \) and \( \pi_i^M \) in the proof of Lemma 2. In RM model, the retailer acts as channel leader and the manufacturer is the follower. According to backward induction, by solving the first-order condition of \( \pi_m^M \), we obtain \( \hat{w}_{RM}^* = \frac{A-\alpha \pi^R + \alpha c_m}{2} \) and \( \hat{b}_{mR}^* = \frac{h\delta-k}{2\alpha} \) which are the optimal response functions of the manufacturer that retailer makes the optimal decisions based on. Substituting \( \hat{w}_{RM}^* \) into \( \pi_r^M \), and from the first-order condition, we get \( p_{RM^*} = \frac{3A+\alpha c_m}{4\alpha} \).
Substituting \( p_{RM}^* \) into \( \hat{w}_{RM}^* \) and \( b_{m}^* \), we obtain \( w_{RM}^* = \frac{A + 3ac}{4\alpha} \) and \( b_{m}^* = h \frac{\delta - k}{2h} \).

Substituting \( w_{RM}^* \), \( b_{RM}^* \), \( p_{RM}^* \) into \( \pi_m^* \) and \( \pi_t^* \), we get \( \pi_{RM}^* = \frac{P_f}{4} + P_r \), \( \pi_{r}^* = \frac{P_f}{2} \) and \( \Pi_{RM}^* = \frac{3P_f}{4} + P_r \). This completes the proof.

**Appendix B2. Proof of Lemma 6**

**Proof.** We have already proved the concavity of \( \pi_m^R \) and \( \pi_r^R \) in the proof of Lemma 3. In RR model, the retailer acts as channel leader and the manufacturer is the follower. According to backward induction, by solving the first-order condition of \( \pi_m^R \), we obtain \( \hat{w}_{RR}^R = \frac{A - \alpha p + \alpha c}{\alpha} \) and \( \hat{b}_{mr}^R = h \frac{\delta - k - \delta h}{2h} \), which are the optimal response functions of the manufacturer that the retailer makes the optimal decisions based on. Substituting \( \hat{w}_{RR}^R \), \( \hat{b}_{mr}^R \), \( p_{RR}^* \) into \( \pi_r^R \), and then from the first-order condition, we get \( p_{RR}^* = \frac{A + 3ac}{4\alpha} \) and \( b_{mr}^R = h \frac{\delta - k}{4h} \).

Substituting \( w_{RR}^* \), \( b_{mr}^R \), \( p_{RR}^* \) into \( \pi_m^R \) and \( \pi_r^R \), we get \( \pi_m^R = \frac{P_f + P_r}{4} \), \( \pi_r^R = \frac{P_f}{4} \) and \( \Pi_{RR}^* = \frac{3(P_f + P_r)}{4} \). This completes the proof.

**Appendix B3. Proof of Lemma 7**

**Proof.** We have already proved the concavity of \( \pi_m^T \), \( \pi_r^T \) and \( \pi_t^T \) in the proof of Lemma 4. In RT model, the retailer acts as channel leader and the third-party takes charge of collecting used products. According to backward induction, by solving the first-order condition of \( \pi_t^T \), we obtain \( b_{MT}^T = \frac{h \delta - \alpha k}{2h} \). Substituting \( \hat{w}_{RT}^T \) into \( \pi_t^T \) and then from the first-order condition, we get \( \hat{w}_{RT}^T = \frac{A - \alpha p + \alpha c}{\alpha} \) and \( \hat{b}_{MT}^T = h \frac{\delta - k}{2h} \).

Substituting \( \hat{w}_{RT}^T \) into \( \pi_r^T \), then from the first-order condition of \( \pi_r^T \), we get \( p_{RT}^* = \frac{3A + \alpha c}{4\alpha} \).

Substituting \( b_{mt}^R \) into \( \hat{b}_{RT}^T \), we get \( \hat{b}_{RT}^T = h \frac{\delta - k}{4h} \).

Substituting \( p_{RT}^* \) into \( \hat{w}_{RT}^T \), we get \( w_{RT}^* = \frac{A + 3ac}{4\alpha} \).

Substituting \( w_{RT}^* \), \( b_{mt}^R \), \( p_{RT}^* \), \( b_{RT}^R \) into \( \pi_m^T \), \( \pi_r^T \) and \( \pi_t^T \), we get \( \pi_{RT}^* = \frac{P_f + 2P_r}{4} \), \( \pi_{MT}^* = \frac{P_f}{2} \), \( \pi_{MR}^* = \frac{P_f}{4} \) and \( \Pi_{RT}^* = \frac{3(P_f + P_r)}{4} \). This completes the proof.

**Appendix B4. Proof of Proposition 8**

**Proof.** Obviously, \( \pi_{MM}^* \) is the largest one and \( \pi_{RR}^* \) is the smallest ones. From \( \pi_{RM}^* = \frac{P_f}{4} + P_r \) and \( \pi_{MR}^* = \frac{P_f + P_r}{2} \), we have \( \pi_{RM}^* - \pi_{m}^R = \frac{P_f}{2} - \frac{P_f}{4} \). When \( \frac{P_f}{4} < v < 2 \), we have \( \pi_{RM}^* > \pi_{m}^R \); when \( \frac{P_f}{4} = v > 2 \), we have \( \pi_{RM}^* = \pi_{m}^R \). This completes the proof.

**Appendix B5. Proof of Proposition 9**

**Proof.** Obviously, \( \pi_{RR}^* \) is the largest one and \( \pi_{MT}^* = \pi_{MM}^* \) are the smallest ones. From \( \pi_{MR}^* = \frac{P_f + P_r}{4} \) and \( \pi_{MR}^* = \pi_{RT}^* = \frac{P_f}{2} \), we have \( \pi_{MR}^* - \pi_{RM}^* = \frac{P_f}{2} - \frac{P_f}{4} \). When \( \frac{P_f}{4} = v < 1 \), we have \( \pi_{MR}^* > \pi_{RM}^* = \pi_{RT}^* \); when \( \frac{P_f}{4} = v > 1 \), we have \( \pi_{MR}^* < \pi_{RM}^* = \pi_{RT}^* \). This completes the proof.
Appendix C.

Appendix C1. Proof of Proposition 10

Proof. From the first-order condition of \( \pi_m^{MM*} \), we get \( \hat{p}^{MM*} = \frac{a w + A}{2 a} \), which is the optimal response function of the retailer. Letting \( \hat{p}^{MM*} = p^C \), i.e., \( p^{MM*} = \frac{A + \alpha c_m}{2 a} \), we can get \( w^{MM*} = c_m \). Letting \( b^{MM*} = b^C \), i.e., \( b^{MM*} = \frac{h \delta - k}{2 h} \), then substituting \( p^{MM*} \), \( w^{MM*} \), \( b^{MM*} \) into \( \pi_m^{MM*} \) and \( \pi_r^{MM*} \), we get \( \pi_m^{MM*} = P_r + F \) and \( \pi_r^{MM*} = P_f - F \). For ensuring that the parties have the initiative to implement the contract, the contract parameter \( F \) satisfies:

\[
\begin{align*}
\pi_m^{MM*} &\geq \pi_m^{MM*} \\
\pi_r^{MM*} &\geq \pi_r^{MM*} ,
\end{align*}
\]

i.e.,

\[
\begin{align*}
P_r + F &\geq \frac{P_f + P_r}{2} \\
P_f - F &\geq \frac{P_f + P_r}{2} 
\end{align*}
\]

Then we get the scope of \( F \), i.e.,

\[
\frac{P_f + P_r}{4} \leq F \leq \frac{P_f + P_r}{2}.
\]

The manufacturer maximizes her profits and chooses the largest fixed payment \( F = \frac{P_f + P_r}{2} \). Accordingly, \( \pi_m^{MM*} + \pi_r^{MM*} = P_f + P_r = \Pi^C \), the system’s profits are attained at the same level as in Model C. Proposition 10 is thus proved.

Appendix C2. Proof of Proposition 11

Proof. From the first-order condition of \( \pi_m^{RM*} \), we get \( \hat{w}^{RM*} = \frac{A - \alpha p^{RM*} + \alpha c_m}{\alpha} \) and \( b_m^{RM*} = \frac{h \delta - k}{2 h} \). Letting \( p^{RM*} = p^C \), we can get \( w^{RM*} = \frac{A + \alpha c_m}{2 a} \).

Substituting \( p^{RM*} \), \( w^{RM*} \), \( b_m^{RM*} \) into \( \pi_m^{RM*} \) and \( \pi_r^{RM*} \), we get \( \pi_m^{RM*} = F \) and \( \pi_r^{RM*} = P_f - F \). For ensuring that the parties have the initiative to implement the contract, the contract parameter \( F \) satisfies:

\[
\begin{align*}
\pi_m^{RM*} &\geq \pi_m^{RM*} \\
\pi_r^{RM*} &\geq \pi_r^{RM*} ,
\end{align*}
\]

i.e.,

\[
\begin{align*}
P_f + P_r - F &\geq \frac{P_f + P_r}{2} \\
P_f + P_r - F &\geq \frac{P_f + P_r}{2} 
\end{align*}
\]

Then we get the scope of \( F \), i.e.,

\[
\frac{P_f + P_r}{4} \leq F \leq \frac{P_f + P_r}{2}.
\]

The retailer maximizes his profits and chooses the largest fixed payment \( F = \frac{P_f + P_r}{2} \). Accordingly, \( \pi_m^{RM*} + \pi_r^{RM*} = P_f + P_r = \Pi^C \), the system’s profits are attained at the same level as in Model C. Proposition 11 is thus proved.

Appendix D.

Appendix D1.

| Model MM | Model MR | Model MT |
|----------|----------|----------|
| \( p^* \) | \( p^{MM*} = \frac{3 A + \alpha c_m}{2 a} \) | \( p^{MR*} = \frac{3 A + \alpha c_m}{4 a} \) | \( p^{MT*} = \frac{3 A + \alpha c_m}{3 a} \) |
| \( b_m^* \) | \( b_m^{MM*} = \frac{h \delta - k}{2 h} \) | \( b_m^{MR*} = \frac{5 h \delta - 3 k}{4 h} \) | \( b_m^{MT*} = \frac{h \delta - k}{2 h} \) |
| \( w^* \) | \( w^{MM*} = \frac{2 h}{A + \alpha c_m} \) | \( w^{MR*} = \frac{4 h}{A + \alpha c_m} \) | \( w^{MT*} = \frac{4 h}{A + \alpha c_m} \) |
| \( b_{mj}^* \) | \( N/A \) | \( b_{mjr}^{MR*} = \frac{h \delta - k}{2 h} \) | \( b_{mjr}^{MT*} = \frac{h \delta - k}{2 h} \) |
| \( \pi_m^* \) | \( \pi_m^{MM*} = \frac{P_f}{4} + P_f \) | \( \pi_m^{MR*} = \frac{P_f}{2} + P_f \) | \( \pi_m^{MT*} = \frac{P_f}{3} + P_f \) |
| \( \pi_r^* \) | \( \pi_r^{MM*} = \frac{P_f}{4} \) | \( \pi_r^{MR*} = \frac{P_f}{2} + P_r \) | \( \pi_r^{MT*} = \frac{P_f}{3} \) |
| \( \Pi^* \) | \( \Pi^{MM*} = \frac{3 P_f}{4} + P_f \) | \( \Pi^{MR*} = \frac{3 (P_f + P_r)}{4} \) | \( \Pi^{MT*} = \frac{3 (P_f + P_r)}{4} \) |
Appendix D2.

Table 3. Main results of the R-led models

| Model   | Model RM | Model RR | Model RT |
|---------|----------|----------|----------|
| \( \pi \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) |
| \( b^* \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) |
| \( u^* \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) | \( \frac{3A+2\alpha c_m}{4} \) |
| \( b_{mj} \) | N/A | N/A | N/A |
| \( \pi_m \) | \( \frac{P_f + P_r}{2} \) | \( \frac{P_f + P_r}{2} \) | \( \frac{P_f + P_r}{2} \) |
| \( \pi_r \) | N/A | N/A | N/A |
| \( \Pi^R \) | \( \frac{3P_f + P_r}{4} \) | \( \frac{3P_f + P_r}{4} \) | \( \frac{3P_f + P_r}{4} \) |

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