COLLECTION DECISIONS AND COORDINATION IN A CLOSED-LOOP SUPPLY CHAIN UNDER RECOVERY PRICE AND SERVICE COMPETITION

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(Communicated by Gerhard-Wilhelm Weber)

ABSTRACT. With the increasing growth of consumers’ request for recovery channels, in addition to collecting price, the collecting service has gradually become a competitive point for collectors to collect used products. Focusing on a closed-loop supply chain (CLSC) with recovery competition (on collecting price and collecting service) and distinguishing collecting quality, we propose two models (decentralized and centralized models) to study the collection strategies and profits of the CLSC. Moreover, we analyze the impact of the collecting competition and quality on the CLSC. Finally, a revenue-cost sharing contract (RCSC) is introduced to coordinate the supply chain. And a numerical example is illustrated to verify the contract’s efficiency. It is found that the collected quantities and profits of the CLSC members are positively correlated with the remanufacturable ratio. The collecting competition dampens consumers’ enthusiasm for recycling, which is not conducive to collectors to carry out collecting activity, resulting in the reduction of the CLSC’s profit. The collectors appropriately improving collecting prices and service levels can increase the collected quantities, but to cope with the increasing competition, increasing collecting price is the main means for collectors to attract consumers to recycle. In addition, the designed RCSC can effectively improve the CLSC’s efficiency and increase the profits of each party.

1. Introduction. With the techniques’ improvement and consumers’ requirement, the products are updated rapidly, which leads to an increase in the generation of end-of-life (EOL) waste (Yenipazarli, 2016) [44]. If the EOL waste is discarded directly, it will not only waste resources, but also pollute the environment. In order to make the waste treated properly, the government has issued strict regulations (Govindan et al., 2015) [8], requiring companies to recover these wasted products. For the collected waste products, remanufacturing is an effective way of environmental protection, which is gradually accepted by enterprises. Collecting and remanufacturing of waste products can bring benefits to both environment and manufacturing economics,
especially for the Waste Electrical and Electronic Equipment (WEEE) (Nnorom & Osibanjo, 2010) [29]. According to the 2019 progress report (covering fiscal year 2018), Apple Inc. refurbished more than 7.8 million devices and recycled more than 48,000 metric tons of e-waste.

For different quality of collected waste products, there are different treatment methods (Liu et al., 2016) [21]. The common methods are remanufacturing and recycling, which are considered as different recovery techniques (Mangun & Thurston, 2002) [26]. Remanufacturing is the process of manufacturing ‘New’ product from old (recovered from disassembly of old devices) and new components. Recycling is the least efficient technique, which extracts the raw materials from used products and parts by vigorous separation processes (without conserving any product structure) (Nnorom & Osibanjo, 2010) [29]. Due to the technical barriers and licensing issues, the manufacturer (or OEM supplier) always controls the remanufacturing.

Unlike remanufacturing, the collection business can also be performed by other closed-loop supply chain members in addition to the manufacturer. The retailer (Xiong et al., 2016) [42], the third-party collector (Nie et al., 2013) [28] and the third-party remanufacturer (Zhang et al., 2016) [45] are becoming increasingly interested in collecting the waste. With the development of Internet, many online third-party collecting platforms (such as Aihuishou.com) are showing up recently, which have an impact on traditional collecting channels. The biggest advantage of online collecting is low cost, because it has no intermediate links such as recycle bin and trading market. And the third-party collecting platform has a set of accurate evaluation system of residual value of waste products, which can provide consumers with the maximum price. Compared with the Internet collecting channel, the collecting channel of retailer is closer to consumers, which is convenient for consumers to release and collect waste products. And it has certain channel advantages to carry out recovery activity, and can provide better collecting service. Previous studies believe that economic factors are effective incentives to promote consumers collecting. But Nowadays, the non-economic factors on consumers are playing a gradually important role, such as the convenience of the collection channel (Wagner, 2011) [33].

Good recovery service often attracts consumers to collect the used products. Recently, the third-party collecting platforms have built a series of collecting services, such as adding collection sites, door-to-door collecting, etc. The ecoATM (www.ecoatm.com), a third-party collecting platform aiming at WEEEs, collected over 14 million devices in 2017 by the collecting machines released on the street in the US, which can help consumers to simply the collecting progress (Q. He et al., 2019) [11]. Nowadays, when collecting the used products, consumers will pay attention to both the collecting price and service provided by the collectors, and will thus choose the recovery channel that is convenient and profitable.

The main purpose of this paper is to study the recovery competition between the retailer and third-party collector (based on Internet platform) on collecting price and service. And for the different quality of used products, the manufacturer has different treatment methods. Accordingly, we first propose a two-echelon closed-loop supply chain and separately investigate the collection decisions and profit levels of the supply chain in decentralized and centralized models. Furthermore, we analyze the influence of remanufacturable ratio and competitive factors on the recovery decisions and profits of the CLSC. Then, a contract coordination mechanism is proposed to study the profit level of the supply chain under decentralized decision-making and
In this paper, we address the following problems: what kind of collection decisions do the retailer and third-party collector have? What is the impact of remanufacturable ratio of collected used products on collecting decision and profit of the CLSC? And how do the competition factors of collecting price and collecting service affect the recovery decision and profit of the CLSC members? Additionally, we verify the coordination efficiency of revenue-cost sharing contract through numerical study.

To the best of our knowledge, this is the first research that collecting price and collecting service are both considered in the recovery competition of different collecting channels. From the study, we find out that the third-party collector always joins competitive collection and provides the same collecting price and service as the retailer. Appropriate collecting price and service can increase the collecting volume of used products, but the vicious collecting competition decreases the collecting volume of collectors, which can reduce the profits of the CLSC members. Revenue-cost sharing contract can effectively coordinate the supply chain under decentralized decision-making. Different from the unilateral consideration of collecting price competition (Xu et al., 2014) [43] or collecting service competition (Wang et al., 2020) [15] in the recovery market, the competitive collection model developed in this paper can better reflect the real business problem. Therefore, the management insights proposed in this paper can help the supply chain members to make the optimal recovery decisions and effective investments.

The remainder of the paper is organized as follows. Section 2 provides a thorough literature review of this research. Assumptions and notations are described and listed in Section 3. Two mathematical models and a coordination mechanism are developed in Section 4. Related analysis is raised in Section 5. Numerical examples and other managerial results are posted in Section 6. Finally, some conclusions and future research are concluded in Section 7.

2. Literature review. Literature closely related to this research can be classified into three broad categories: CLSC decision-making problem, service input and supply chain coordination.

First, the literature on CLSC decision-making problem related to our work includes two streams. One is to study the pricing decisions of CLSC. Ferrer and Swaminathan (2010) investigates a manufacturer’s pricing and remanufacturing strategy in two-period, multi-period and infinite planning horizons setting [4]. Wei et al. (2015) establishes four different game models with symmetric and asymmetric information to study the optimal pricing of the manufacturer and retailer [37]. Gao et al. (2016) investigates the optimal decisions of collection effort, sales effort, and pricing under different channel power structures [6]. Considering that new and remanufactured products have independent sales channels, Gan et al. (2017) develops a pricing decision CLSC model for short life-cycle products [5]. And P. He et al. (2019) explores channel structure and pricing decisions for the manufacturer and government’s subsidy policy with competing new and remanufactured products [10]. Modak et al. (2019) investigates the structure and pricing decisions of a two-echelon CLSC using social work donation as a CSR practice [27]. Wen et al. (2020) discusses the differential pricing and equal-pricing strategy of the retailer for new products and remanufactured products by game models, which consider heterogeneous consumers with environmental responsibility [38]. Previous literature studies the pricing decision-making of new and remanufactured products in forward
sales, and always considers the collecting price of used products as a constant or exogenous variable. This paper focuses on the pricing decision-making problem of reverse collecting, which takes the collecting price as an endogenous variable.

The other is to study the problem of reverse channel choice. Savaskan et al. (2004) investigates the collecting efficiency of three different recovery channels (manufacturer-, retailer-, and third-party-collecting channels) without competition. It is found that the collection activity carried by the retailer is most efficient [31]. Hong and Yeh (2012) points out that the return rate and profits of the retailer collection model are not always superior to those of the non-retailer collection model [12]. Atasu et al. (2013) [1] further extends Savaskan et al. (2004) [31] by studying the manufacturer’s choice of reverse channel structures under two alternative collection cost structures that exhibit economies and diseconomies of scale. Shi et al. (2015) constructs three remanufacturing models with different collecting channels to study the reverse channel selection problem under the collection responsibility sharing [32]. Liu and Xiao (2020) discusses the reverse channel structure strategy by manufacturer in a CLSC, within which the manufacturer and green consumers show environmental responsibility behaviors [23].

Most of the previous studies on recovery channel are more about the channel selection without the collection competition, and rarely involve recovery incentives for consumers. In recent years, there are studies on collection competition showing up. To expand the study of Savaskan et al. (2004) [31], Huang et al. (2013) investigates the competitive recovery competition conducted by the retailer and the third party [14]. L. Liu et al. (2017) [22] extends the work of Huang et al. (2013) [14] by considering two other hybrid dual-channel competition models. Liu et al. (2016) develops a quality-based competition model with dual channel recycling, in which formal sector and informal sector compete in price [21]. Wang et al. (2018) constructs a dual-channel competitive competition model by using the principle-agent theory to investigate the government’s reward–penalty mechanism (RPM) [36]. Wang et al. (2019) discusses the hybrid competition between the manufacturer and remanufacturer from both the selling and collecting market [34].

However, the literature on recovery competition mainly considers the competition between collecting prices, and does not consider the competition caused by collecting service factors such as channel convenience, advertising investment, etc.

The second stream of related research to our work involves service input. Wu (2012) introduces the service factor into a CLSC and investigates the competition of new and remanufactured products [39]. Considering the effect of advertising on demand, Hong et al. (2015) builds Stackelberg game models to study the optimal decisions of local advertising, used-product collection and pricing [13]. Zhang et al. (2015) models a dual-channel CLSC to examine the impacts of the retail services and the degree of customer loyalty to the retail channel on the pricing of players in CLSC [46]. Jena and Sarmah (2016) investigates the competition of price and service between the two remanufacturers under uncertain demand and condition of the acquired items [16]. Kong et al. (2017) establishes a benchmark model of dual-channel price and service competition, and analyzes the optimal pricing and service decision under centralization and decentralization [18]. Zhao et al. (2019) investigates the pricing and service in different remanufacturing modes by CLSC decision models based on third party recycling [47]. Li et al. (2019) explores the problems of remanufacturing channel design and after-sales service pricing, and discusses how remanufacturing and after-sales service jointly affect channel selection...
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decision-making [19]. Q. He et al. (2019) studies the investment level of recovery
channels of the manufacturer and retailer through a CLSC with competitive collection
[11]. Huang et al. (2020) develops three CLSC models to discuss the government
subsidy, which includes service advertisement and monetary subsidy [15].

The previous researches of service (like advertising, after-sales service) are focused
on the forward sales of new and remanufactured products, of which the purpose
is to indirectly promote reverse recovery through the forward sales. There are few
studies on the direct impact of service investment in recovery channels (such as the
recovery sites addition and door-to-door collecting) on the recovery rate or volume.

Third, the issue of supply chain coordination has been attracting more attention
in the literature. De Giovanni (2014) builds up the goodwill dynamic based on
green advertising and evaluates the convenience of collaborative remanufacturing
by implementing a Reverse Revenue Sharing Contract (RRSC) [2]. Panda et al.
(2017) explores channel coordination in a socially responsible manufacturer-retailer
CLSC. It is found that revenue sharing contract resolves channel conflict [30]. Liang
et al. (2017) designs product plus after-market service contract by using revenue
sharing contract model, and discusses channel coordination of forward and backward
cross-revenue sharing contract between wind farm and manufacturer [20]. Xie et
al. (2017) develops a revenue-sharing mechanism to study the contract coordination
of online/offline dual-channel CLSC [40]. Furthermore, Xie et al. (2018) [41]
investigates coordination mechanism by combining the forward revenue sharing with
the reverse investment cost sharing. Zheng et al. (2019) proposes three coordination
mechanisms to allocate surplus profit and examines the effects of retailer’s fairness
concerns on profit allocation [48]. Wang et al. (2020) uses revenue sharing contracts
and two-part tariff contracts to coordinate the reverse channels in two CLSC models
[35]. As mentioned before, the revenue sharing contract is always used to coordinate
the supply chain in the study by most scholars, which ignores the recovery costs and
reverse channel investments.

The reviewed researches are summarized in Table 1.

The innovation of this paper is that collecting price and collecting service are
considered simultaneously in the collecting competition between the third-party
collecting platform and retailer. In addition, different quality levels of collected
products are considered in this research. Considering these factors, we establish two
models (decentralized decision model and centralized decision model) to study the
collecting decisions and profits of the CLSC. Due to the double marginal effect of
decentralized decision-making, this paper designs a revenue-cost sharing contract
to coordinate the supply chain. It is worth mentioning that in this contract, both
benefit and cost are considered, which is rare in previous literature.

3. Model assumptions and notation. This paper proposes a two-echelon closed-
loop supply chain model consisting of one manufacturer, one retailer and one
third-party collector (based on Internet platform). The manufacturer produces and
wholesales the products, which is made from new raw materials and collected items,
and the retailer sells the products to consumers. In this CLSC, the manufacturer
entrusts the collection business to the retailer and the third-party collector, instead of
collecting directly from the market. The retailer and the third-party collector compete
in the recovery market via providing different collecting prices and services. For the
collected products, the manufacturer has different disposal methods according to
their different quality levels. Based on the above, the centralized and decentralized
Table 1. Comparison between our research and related literatures.

| References                  | Collecting channel | Pricing on | Service on | Collecting competition on | Collecting quality | Coordination mechanism |
|-----------------------------|--------------------|------------|------------|---------------------------|--------------------|------------------------|
|                            |                    | Single channel | dual-channel | Sales | Collection | Sales | Collection | Price | Service |                     |                     |                        |
| Ferrer and Swaminathan (2010) | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     | LPSS                |                        |
| Wei et al. (2015)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     | TPTC                |                        |
| Gao et al. (2016)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     | WPC                 |                        |
| Gan et al. (2017)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| P. He et al. (2019)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Modak et al. (2019)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Wen et al. (2020)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Savaskan et al. (2004)      | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Hong and Yeh (2012)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Atanu et al. (2013)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Shi et al. (2015)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Liu et al. (2015)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Huang et al. (2013)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| L. Lin et al. (2017)        | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Liu et al. (2016)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Wang et al. (2018)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Q. He et al. (2019)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Wang et al. (2019)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Wu (2012)                   | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Hong et al. (2015)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Zhang et al. (2015)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Jena and Sarma (2016)       | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Kong et al. (2017)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Zhao et al. (2019)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Li et al. (2019)            | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Huang et al. (2020)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| De Giovanni (2014)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Panda et al. (2017)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Liang et al. (2017)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Xie et al. (2017)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Xie et al. (2018)           | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Zheng et al. (2019)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Zheng et al. (2019)         | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| Wang et al. (2020)          | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |
| This research               | ✓                  | ✓          | ✓          | ✓              | ✓                  | ✓              | ✓                  | ✓               |                     |                     |                        |

LPPS: Low Price Promotion Strategy, TPTC: Two Part Tariff Contract, WPC: Wholesale Price Contract, RPM: Reward-Penalty Mechanism, CA: Cooperative advertising, QDC: Quantity Discount Contract, RSC: Revenue Sharing Contract, RRSC: Reverse Revenue Sharing Contract, RCSC: Revenue and Cost Sharing Contract, AM: Authorization Mechanism, SVM: Shapley Value Mechanism, NSM: Nucleolus Solution Mechanism, ESM: Equal Satisfaction Mechanism.
Table 2. Notations.

| Symbol  | Description                                          |
|---------|------------------------------------------------------|
| **Parameters**                                |
| $c_m$   | Production costs via new raw materials               |
| $c_r$   | Production costs via collected products              |
| $\Delta$ | The cost-savings provided by remanufacturing. Note that $\Delta = c_m - c_r$ |
| $\rho$  | Remanufacturable ratio of the collected products     |
| $r$     | The revenue by disassembling collected products      |
| $q_R$   | Quantity of used product collected by the retailer   |
| $q_T$   | Quantity of used product collected by the third-party collector |
| $m_b$   | Collecting price sensitivity coefficient             |
| $n_b$   | Collecting price competition coefficient             |
| $m_S$   | Collecting service sensitivity coefficient           |
| $n_S$   | Collecting service competition coefficient           |
| $A$     | Cost index of reverse channel investment             |
| $d$     | Product demand. Note that $d = \alpha - \beta p$    |
| **Decision variables**                        |
| $p$     | Selling price of products                            |
| $w$     | Wholesale price                                      |
| $B$     | The transfer price that the manufacturer pays to the retailer or the third-party collector |
| $S_R$   | The retailer’s collecting service level              |
| $S_T$   | The third-party collector’s collecting service level |
| $b_R$   | Collecting price to market given by the retailer     |
| $b_T$   | Collecting price to market given by the third-party collector |
| **Other notations**                           |
| $M$     | The manufacturer                                     |
| $R$     | The retailer                                         |
| $T$     | The third-party collector                            |
| $\pi_C$ | The total profit of the supply chain                 |
| $\pi_M$ | The profit of the manufacturer                        |
| $\pi_R$ | The profit of the retailer                            |
| $\pi_T$ | The profit of the third-party collector               |
| CM      | The centralized model                                |
| DM      | The decentralized model                              |

Note that $p > w > c_m > c_r > 0, \Delta > B > b_i > 0, S_i > 0, i = \{R, T\}$.

Models are proposed to study the impact of recovery products’ quality and recovery competition on the CLSC.

3.1. **Model notations.** All notations related to this paper are listed in Table 2.

3.2. **Model assumptions.** In order to better describe the research objects and problems, this paper puts forward the following assumptions for the proposed model without loss of generality:

1. There is no difference of quality between new products and remanufactured products, and consumers do not distinguish between new products and remanufactured products (Savaskan et al., 2004) [31].
2. The volume of sales is linear with the selling price given by the retailer: \[ d = \alpha - \beta p \] (Q. He et al., 2019; Huang et al., 2013; Savaskan et al., 2004) \[ 11, 14, 31\].

3. This is a single-period problem without considering inventory, transportation, or lead-time problems (Savaskan et al., 2004) \[ 31\].

4. The collected quantity of the retailer (or the third-party collector) is linearly associated with the collecting price and service level set by the retailer (or the third-party collector).

According to Klausner et al. (2000) \[ 17\] and Qiaolun et al. (2008) \[ 9\], we know that the recovery quantity has a linear relationship with the recovery price. Referring to the impact of advertising service on demand from Hong et al. (2015) \[ 13\], we consider that there is also a linear relationship between recovery quantity and recovery service level. Therefore, similar to the definition of demand function from Wu (2012) \[ 39\], the recovery quantity function is defined as follows:

\[ q_i = g + m_b b_i - n_b b_j + m_S S_i - n_S S_j \] (1)

where \( g, m_b, n_b, m_S, n_S > 0 \), \( i = \{R, T\} \) and \( j = \{R, T\} \setminus i \); \( R \) denotes the retailer, and \( T \) denotes the third-party recyclers.

\( g \) is a constant, indicating the quantity of used products voluntarily returned by consumers in the market when the collector does not provide recovery compensation and collecting service. In order to reduce the complexity of mathematical processing, we set \( g \) to 0. It should be pointed out that even if \( g \) is not 0, it will not change the conclusion of this paper. Therefore, we have

\[ q_i = m_b b_i - n_b b_j + m_S S_i - n_S S_j \] (2)

Here we assume that \( m_b > n_b, m_S > n_S, b_i (i = R \text{ or } T) \) denotes the collecting price of the retailer or the third-party collector. \( S_i (i = R \text{ or } T) \) denotes the collecting service level of the retailer or the third-party collector. Referring to Q. He et al. (2019) \[ 11\], the cost of the retailer (or the third-party collector) to invest the recovery channel services for collection is \( \frac{3}{2} S_i^2 \) \( (i = R \text{ or } T) \).

5. All used products can be collected, and their residual value is not 0.

Combined with the research of Z. Liu et al. (2017) \[ 24\], we assume that all products sold to consumers can be collected after use, and the residual value is not 0. However, due to the different wear degree of the products after use, the quality of the collected used products is different. The collected products with high quality are used for remanufacturing by the manufacturer, while those with low quality is disassembled by the manufacturer to obtain raw materials. Here, we use \( \rho \) to denote the remanufacturable ratio of the collected products, and then \( 1 - \rho \) denotes the ratio of the collected products for disassembly. The unit profit of raw materials obtained from disassembly is \( r \), which is less than the unit cost-savings \( \Delta \) from remanufacturing, that is \( \Delta > r \).

6. In the decentralized model, a symmetric-information Stackelberg game led by the manufacturer is applied in describing the relationship among the manufacturer, the retailer and the third-party collector.

Similar to the study of Savaskan et al. (2004) \[ 31\], compared with the retailer and the third-party collector, the manufacturer has sufficient channel power to act as a game leader in the CLSC. In this game, the manufacturer makes a decision by the retailer’s and the third-party collector’s reaction functions first. Then, the retailer and the third-party collector make decisions based on the manufacturer’ decision. For a perfectly competitive market, information is always symmetrical, so all supply chain members can obtain the same information.
4. Models and Coordination. Two models are proposed in this section to study the collection decisions and profit levels of the CLSC. And a revenue-cost sharing contract is introduced to coordinate the CLSC members’ profits under decentralized decision-making.

4.1. Decentralized model (DM). In practical, the decentralized decision-making model is more common for the enterprises. Therefore, we propose a two-echelon CLSC model consisting of one manufacturer, one retailer and one third-party collector (Figure 1) to study the collection competition between the retailer and third-party collector. In this decentralized model, the manufacturer produces products and disposes of collected products, the retailer sells products and collects used products, while the third-party collector competes with the retailer to collect used products. The participation of different collectors makes the recovery market more complex, which may affect the collecting volume and profit level of the supply chain.

Figure 1. Decentralized model (DM)

Under decentralized decision-making, the manufacturer, the retailer and the third-party collector pursue their own profit maximization.

According to Assumption 6, we describe the decision sequence relationship among the members of the CLSC by a Stackelberg game, in which the manufacturer is the market leader, the retailer and the third-party collector are the followers. The decision sequence of the game is: the manufacturer first determines the wholesale price $w$ and the collecting transfer price $B$; secondly, the retailer determines the sales price $p$, the collecting price $b_R$, and the collecting service level $S_R$, while the third-party collector determines the collecting price $b_T$ and the collecting service level $S_T$.

For the manufacturer, the source of profit includes two parts: one is to produce and wholesale the products for profit; the other is to remanufacture and disassemble
the used products which collected from the retailer and the third-party collector for profit. Therefore, the manufacturer’s profit function is

$$\pi_M|_{w, B} = (w - c_m) d + \rho(c_m - c_r)(q_R + q_T) + r(1 - \rho)(q_R + q_T) - B(q_R + q_T)$$  \hspace{0.5cm} (3)$$

For the retailer, the source of profit includes two parts: one is to sell products to consumers for profit, and the other is to accept the manufacturer’s commission to collect used products from consumers for profit. Therefore, the retailer’s profit function is

$$\pi_R|_{p, b_R, S_R} = (p - w) d + (B - b_R) q_R - \frac{A}{2} S_R^2$$  \hspace{0.5cm} (4)$$

For the third-party collector, the only way to obtain profits is to accept the manufacturer’s commission to collect used products from consumers. Therefore, the profit function of the third-party collector is

$$\pi_T|_{b_T, S_T} = (B - b_T) q_T - \frac{A}{2} S_T^2$$  \hspace{0.5cm} (5)$$

Then, we have

$$\max_{w, B} \pi_M = (w - c_m)(\alpha - \beta p) + [\rho \Delta + r(1 - \rho) - B]$$

$$m_b(b_R + b_T) - n_b(b_R + b_T) + m_S(S_R + S_T) - n_S(S_T + S_R)$$

$$\max_{p, b_R, S_R} \pi_R = (p - w)(\alpha - \beta p) + (B - b_R)(m_b b_R - n_b b_T + m_S S_R - n_S S_T)$$

$$- \frac{A}{2} S_R^2$$

$$\max_{b_T, S_T} \pi_T = (B - b_T)(m_b b_T - n_b b_R + m_S S_T - n_S S_R) - \frac{A}{2} S_T^2$$  \hspace{0.5cm} (8)$$

We solve the model via the reverse solving method proposed by Ferrer and Swaminathan (2006) [3], which need to calculate out the results of followers first, and then the results of leaders. The specific solution process is given below.

(i) To solve the optimization problems of the retailer and the third-party collector. When $2A m_b > m_S^2$ is satisfied, $\pi_R$ is a strictly concave function of $p, b_R$ and $S_R$, and $\pi_T$ is a strictly concave function of $b_T$ and $S_T$ (see Appendix A). Then, according to the FOC, we have:

$$p_1^* = \frac{\alpha + \beta w}{2\beta},$$

$$b_{R1}^* = \frac{(m_S^2 - m_S n_S - A m_b)B}{m_S^2 - m_S n_S - A(2m_b - n_b)},$$

$$S_{R1}^* = \frac{-m_S(m_b - n_b)B}{m_S^2 - m_S n_S - A(2m_b - n_b)},$$

$$b_{T1}^* = \frac{(m_S^2 - m_S n_S - A m_b)B}{m_S^2 - m_S n_S - A(2m_b - n_b)};$$

$$S_{T1}^* = \frac{-m_S(m_b - n_b)B}{m_S^2 - m_S n_S - A(2m_b - n_b)}. $$

(ii) To solve the optimization problem of the manufacturer. We substitute the $p_1^*, b_{R1}^*, S_{R1}^*, b_{T1}^*$ and $S_{T1}^*$ into the manufacturer’s profit function. When $A(2m_b - n_b) > m_S^2 - m_S n_S$, $\pi_M$ is a strictly concave function of $w$ and $B$ (see Appendix A). Then, we have the FOC results:

$$w^* = \frac{\alpha + \beta c_m}{2\beta},$$

(14)
ties of the retailer and the third-party collector in the decentralized model: functions in the decentralized decision-making model have the optimal solution.

Through the above optimal solutions, we can obtain the optimal collected quantities of the retailer and the third-party collector in the decentralized model:

\[ q_{R1}^* = \frac{-Am_b (m_b - n_b) (\Delta \rho + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2m_b - n_b)]}, \]  \hspace{1cm} (21)

\[ q_{T1}^* = \frac{-Am_b (m_b - n_b) (\Delta \rho + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2m_b - n_b)]}, \]  \hspace{1cm} (22)

Further, we have the total optimal collected quantity:

\[ q_{C1}^* = \frac{-Am_b (m_b - n_b) (\Delta \rho + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2m_b - n_b)]}, \]  \hspace{1cm} (23)

And the profits of supply chain members are:

\[ \pi_M^* = \frac{(\alpha - \beta c_m)^2}{8 \beta} - \frac{Am_b (m_b - n_b) (\Delta \rho + r - \rho r)^2}{2 [m_S^2 - m_S n_S - A (2m_b - n_b)]}, \]  \hspace{1cm} (24)

\[ \pi_R^* = \frac{(\alpha - \beta c_m)^2}{16 \beta} + \frac{A (2Am_b - m_S^2) (m_b - n_b)^2 (\Delta \rho + r - \rho r)^2}{8 [m_S^2 - m_S n_S - A (2m_b - n_b)]^2}, \]  \hspace{1cm} (25)

\[ \pi_T^* = \frac{A (2Am_b - m_S^2) (m_b - n_b)^2 (\Delta \rho + r - \rho r)^2}{8 [m_S^2 - m_S n_S - A (2m_b - n_b)]^2}. \]  \hspace{1cm} (26)

And the total profit of the supply chain is

\[ \pi_{C1}^* = \pi_M^* + \pi_R^* + \pi_T^*. \]  \hspace{1cm} (27)
4.2. **Centralized model (CM).** In the previous studies of forward supply chains, double marginalization effect weakens the performance of the supply chain, resulting in the loss of the total profit of the decentralized decision-making supply chain, and the vertically integrated supply chain structure can always achieve the optimal profits of the whole supply chain. Therefore, we introduce a centralized decision-making model (Figure 2) to further explore whether decentralized decision-making will reduce the collecting volume and profit level of the supply chain.

Under centralized decision-making, the manufacturer, the retailer and the third-party collector make unified decisions to maximize the profit of the whole supply chain. Therefore, the total profit of the CLSC is equal to the sum of the profits of the three supply chain members. That we have the profit function as follows:

\[
\pi_C|_{p,b_R,S_R,b_T,S_T} = (p - c_m) d \rho (c_m - c_r) (q_R + q_T) + r (1 - \rho) (q_R + q_T)
\]

\[
- b_Rq_R - b_Tq_T - \frac{A}{2} S_R^2 - \frac{A}{2} S_T^2 \tag{28}
\]

Further, we have

\[
\max_{p,b_R,S_R,b_T,S_T} \pi_C = (p - c_m) (\alpha - \beta p) + [(\Delta \rho + r - \rho r)] [ m_b (b_R + b_T) \\
- n_b (b_T + b_R) + m_S (S_R + S_T) - n_S (S_T + S_R)] \\
- b_R (m_b b_R - n_b b_T + m_S S_R - n_S S_T) \\
- b_T (m_b b_T - n_b b_R + m_S S_T - n_S S_R) \\
- \frac{A}{2} S_R^2 - \frac{A}{2} S_T^2 \tag{29}
\]

The profit function of the centralized model is jointly concave in \(p, b_R, S_R, b_T\) and \(S_T\) as long as \(2A (m_b - n_b) > (m_S - n_S)^2\) (see Appendix B). Then, according
implement the coordination contract. The coordination model is as follows:

Since \( b_{R2}^*, S_{R2}^*, b_{T2}^*, S_{T2}^* \) are greater than 0, we get \( A (m_b - n_b) > (m_S - n_S)^2 \). Combining the convexity condition: \( 2A (m_b - n_b) > (m_S - n_S)^2 \) (proposed in Appendix B), we can get when \( A (m_b - n_b) > (m_S - n_S)^2 \), the profit function in the centralized decision-making model has the optimal solution.

Substituting \( p_2^* \), \( b_{R2}^* \), \( b_{T2}^* \), \( S_{T2}^* \) into \( q_R, q_T \) and \( \pi \), we can obtain the optimal collected quantities and profits:

Further, we have the total optimal collected quantity:

4.3. Coordination mechanism. To reduce the impact of double marginalization on the CLSC under decentralized decision-making, this paper introduces a revenue-cost sharing contract to coordinate the CLSC. So that the profit level of the supply chain under decentralized decision-making can reach the level under centralized decision-making.

Referring to Xie et al. (2018) [41], we make the contract as follows: the manufacturer gets a certain ratio \( \theta \) of the sales revenue from the retailer and bears a certain ratio \( \theta \) of the recovery costs and channel service costs from the retailer and the third-party. The profits of the CLSC members with coordination should be greater than that without coordination, so that all the members can have the incentive to implement the coordination contract. The coordination model is as follows:

\[
\pi_M = (w - c_m) d + \rho (q_R + q_T) + r (1 - \rho) (q_R + q_T) + (1 - \theta) (p - w) d - B (q_R + q_T) - (1 - \theta) \left( A \frac{S_R^2}{2} + A \frac{S_T^2}{2} \right) - (1 - \theta) (b_R q_R + b_T q_T),
\]

\[
\pi_R = \theta (p - w) d + (B - \theta b_R) q_R \theta \frac{A S_R^2}{2},
\]
Without coordination. So that we can get the constraints of the contract: CLSC members have the motivation to actively implement this contract. 

\[ \tilde{\pi}_T = (B - \theta b_T) q_T - \theta \frac{A S_T^2}{2}. \]  

(41)

Similar to the previous method for solving the decentralized model, we can use the first-order conditions of \( \tilde{\pi}_R \) and \( \tilde{\pi}_T \) to get the optimal solutions:

\[ \tilde{p} = \frac{\alpha + w \beta}{2 \beta}, \]

(42)

\[ \tilde{b}_R = \tilde{b}_T = \frac{(m_S^2 - m_S n_S - Am_b) B}{[m_S^2 - m_S n_S - A (2m_b - n_b)] \theta}, \]

(43)

\[ \tilde{S}_R = \tilde{S}_T = \frac{-m_S (m_b - n_b) B}{[m_S^2 - m_S n_S - A (2m_b - n_b)] \theta}. \]

(44)

When the equilibrium solutions satisfy \( \tilde{p} = p^*_2, \tilde{b}_R = b^*_R > 0 \) and \( \tilde{b}_T = b^*_T > 0 \), the total profit of the CLSC with coordination can reach the level which in the centralized model.

Therefore, we can get

\[ \tilde{\pi} = \tilde{\pi}_T = \frac{\bar{w} = c_m,}{(m_S - n_S)^2 - A (m_b - n_b)} (\Delta \rho + r - \rho r) \]

(45)

\[ \tilde{b}_R = \tilde{b}_T = \frac{[m_S - n_S]^2 - A (m_b - n_b)}{[m_S - n_S]^2 - 2 A (m_b - n_b)} \]

(46)

\[ \tilde{\pi} = \bar{\pi}_T = \frac{(m_S - n_S)^2 - 2 A (m_b - n_b)}{(m_S - n_S)^2 - 2 A (m_b - n_b)} \]

(47)

\[ \tilde{\pi} = \tilde{\pi}_T = \frac{(m_S - n_S)^2 - A (m_b - n_b)}{(m_S - n_S)^2 - 2 A (m_b - n_b)} \]

(48)

\[ \tilde{\pi} = \tilde{\pi}_T = \frac{(m_S - n_S)^2 - A (m_b - n_b)}{(m_S - n_S)^2 - 2 A (m_b - n_b)} \]

(49)

In order to enable each member of the CLSC to participate in the contract actively, the profit of each member with coordination should be greater than that without coordination. So that we can get the constraints of the contract: \( \tilde{\pi}_M > \pi_M^*, \tilde{\pi}_R > \pi_R^*, \tilde{\pi}_T > \pi_T^* \).

According to the constraints, we know that only when \( \theta \in [\max \{ \theta_1, \theta_2 \}, \theta_3] \), the CLSC members have the motivation to actively implement this contract.

In which:

\[ \theta_1 = \frac{E_6}{4 E_2 E_4^2}, \]

(50)

\[ \theta_2 = \frac{E_6 [2 A \beta E_3 E_9 E_5^2 + E_2^2 E_{10}]}{4 E_2^2 [2 A \beta E_7 E_8 E_9 + E_6 E_{10}]} \]

(51)

\[ \theta_3 = \frac{4 A \beta E_4 E_9 E_5^2 [2 A m_b E_1 - m_S^2 E_4]}{4 A \beta E_7 E_8 E_9 + E_6 E_{10}} + \frac{E_6 E_{10}}{8 A \beta E_7 E_8 E_9 + 2 E_6 E_{10}} + \frac{2 A \beta m_b (m_b - n_b) E_6 E_5^2}{(4 A \beta E_7 E_8 E_9 + E_6 E_{10}) E_2}. \]

(52)

Note that

\[ E_1 = m_S^2 - m_S n_S - A m_b, \]

(53)

\[ E_2 = m_S^2 - m_S n_S - A (2m_b - n_b), \]

(54)
\[ E_3 = (m_S - n_S)^2 - 2A(m_b - n_b), \]  
\[ E_4 = (m_S - n_S)^2 - A(m_b - n_b), \]  
\[ E_5 = \Delta \rho + r - \rho r, \]  
\[ E_6 = E_1^2 E_3^2, \]  
\[ E_7 = E_4^2 E_5^2, \]  
\[ E_8 = 2Am_b - m_S^2, \]  
\[ E_9 = (m_b - n_b)^2, \]  
\[ E_{10} = (\alpha - \beta c_m)^2. \]  

Since the analytical solutions of \( \theta_1 \), \( \theta_2 \) and \( \theta_3 \) are too complicated, we will discuss the value range of \( \theta \) and describe the profit changes of the supply chain with contract coordination by a numerical study in Section 6.

5. Analysis. In this section, we compare the optimal collecting decisions of the retailer and the third-party collector, and analyze the effects of remanufacturable ratio, collecting price and service competition factors on collecting decisions and profits of the CLSC in the decentralized model. Note that the proofs of the propositions presented in this section are included in Appendix C. As for the comparison of centralized and decentralized CLSC models, we will expand it in the next section.

**Proposition 1.** The optimal collection decisions between the retailer and the third-party collector satisfies the following relationship: \( b_{R_1}^* = b_{T_1}^* \), \( S_{R_1}^* = S_{T_1}^* \), \( q_{R_1}^* = q_{T_1}^* \).

Proposition 1 shows that the recovery price, service level and collected quantity of the third-party collector are the same as those of the retailer. Because collecting used products can bring profits, the third-party collector always wants to participate in the collection activity, and compete with the retailer in the recovery market by providing different collecting price and service. In the Stackelberg game under the leadership of the manufacturer, in order to maximize the profits, the third-party collector and the retailer provide consumers with the same collecting price and service level, so as to obtain no less than the other party’s collection volume from the recovery market.

**Proposition 2.** The optimal recovery transfer price \( B \) is only related to \( \rho \) and increases in \( \rho \).

Proposition 2 indicates that the manufacturer’s transfer price related to the remanufacturing ratio has nothing to do with the collection competition between the retailer and the third-party collector in the recovery market. Due to the uneven quality of collected products, high-quality used products can be used for remanufacturing after collecting, while low-quality used products can only be recycled by disassembly. Compared with the disassembly of collected products, remanufacturing has more value and benefit for the manufacturer, which can help the manufacturer obtain more profits. The higher the utilization degree of collected products is, the more cost can be saved by remanufacturing. Therefore, when the remanufacturing ratio of collected products is high, the manufacturer is willing to recover used products from the retailer and the third-party collector with high collecting price.
Proposition 3. (i) The optimal collection decisions $b_{R1}^*$, $b_{T1}^*$, $S_{R1}^*$ and $S_{T1}^*$ are increasing in $\rho$. (ii) The optimal collected quantities $q_{R1}^*$ and $q_{T1}^*$ are increasing in $\rho$. (iii) The optimal profits $\pi_M^*$, $\pi_R^*$ and $\pi_T^*$ are increasing in $\rho$.

Proposition 3 shows that with the remanufacturable ratio increasing, the collecting prices and service levels provided by the retailer and the third-party collector to consumers will be improved. Combined with Proposition 2, when the proportion of collected products that can be used for remanufacturing is high, the manufacturer can save more costs via remanufacturing, which inevitably increases its collecting transfer price to encourage the retailer and the third-party collector to carry out collecting activity. In recovery market, the consumers, who are sensitive to the recovery price and service, are more willing to resell their used products to the collector who provides high recovery price and service. Therefore, the retailer and the third-party collector seek to recover more used products from consumers by improving their collecting price and service level. Due to the high remanufacturable ratio and the many collection quantities, the manufacturer can obtain the more profits from remanufacturing, and transfer a part of the remanufacturing profits to the retailer and the third-party collector through the collecting price $B$, so the profits of all the CLSC members increase.

Proposition 4. (i) $b_{R1}^*$ and $b_{T1}^*$ are increasing in $n_b$, but $S_{R1}^*$ and $S_{T1}^*$ are decreasing in $n_b$. (ii) $b_{R1}^*$ and $b_{T1}^*$ are increasing in $n_S$, but $S_{R1}^*$ and $S_{T1}^*$ are decreasing in $n_S$.

Proposition 4 (i) shows that with the intensification of collecting price competition, the collecting prices of the retailer and the third-party collector are increasing, but the collecting service levels are decreasing. The competition in the recovery market is mainly reflected in price competition, and the most effective incentive to attract consumers to resell used products is to increase the collecting price. Therefore, the retailer and the third-party collector constantly increase their collecting prices in order to gain advantages in recovery competition. However, due to the large amount of capital investment in recovery price, it is bound to affect the capital investment of the retailer and the third-party collector in the construction of recovery channel services, which makes the collecting service level of the retailer and the third-party collector continue to decline.

Proposition 4 (ii) shows that with the intensification of collecting service competition, the collecting prices of the retailer and the third-party collector are increasing, but the collecting service levels are still decreasing. The competition of recovery market is mainly reflected in the competition of collecting service. However, due to the high investment cost of channel service, the retailer and the third-party collector will choose to reduce their service level to reduce the construction expenditure of collecting service, and then use the saved cost to increase their own recovery price, in order to attract consumers to resell the used products, so as to gain advantages in the competition. Therefore, the competition of collecting service will eventually evolve into the competition of collecting price.

Proposition 5. (i) $q_{R1}^*$ and $q_{T1}^*$ are decreasing in $n_b$. (ii) $q_{R1}^*$ and $q_{T1}^*$ are decreasing in $n_S$. (iii) $\pi_M^*$, $\pi_R^*$ and $\pi_T^*$ are decreasing in $n_b$. (iv) $\pi_M^*$, $\pi_R^*$ and $\pi_T^*$ are decreasing in $n_S$.

As can be seen in Proposition 5, the collected quantities of the retailer and the third-party collector are decreasing with the intensification of recovery price
competition or recovery service competition. With the aid of Proposition 4, as the collecting competition intensifies in the recovery market, the retailer and the third-party collector will increase the collecting price of used products in order to obtain more collection volume, and reduce the expenditure of channel service construction by decreasing the collecting service level. The vicious price competition in the recovery market leads to the reduction of the collection quantities of used products collected by the retailer and the third-party collector, which not only reduces the profits of the retailer and third-party collector, but also indirectly affects the profit of the manufacturer.

6. Numerical analysis. In order to describe the results more intuitively and effectively, we provide a numerical study in this section to enrich the content of Section 5 and supplement the analysis of the comparisons between the collecting decisions and profits of the CLSC members in the centralized and decentralized models. We also discuss the profit changes with or without coordination to further verify the validity of the contract.

Because the convexity conditions (proposed in Appendix A, Appendix B) and positive conditions (proposed in Section 4) must be guaranteed, we notice that

\[2Am_b > m_S^2, \quad Am_b > m_S^2 - m_Sn_S, \quad A(m_b - n_b) > (m_S - n_S)^2.\]

Therefore, we select a set of parameters considering the practice: \(\alpha = 100, \beta = 2, c_m = 8, c_r = 4, \rho = 0.7, r = 2, m_b = 10, n_b = 2, A = 30, m_S = 12, n_S = 3.\) The following numerical operations are carried out in MATLAB 2016.

6.1. The comparisons of the two models. According to the results in Table 3, the optimal collecting prices and service levels of the retail and the third-party collector in the centralized model are higher than those in the decentralized model, while the optimal sales price in the centralized model is lower than that in the decentralized model. It shows that compared to decentralized decision-making, centralized decision-making is beneficial to consumers on forward sales and reverse collecting.

Table 3. The comparisons between the optimal collection decisions and profits of the two models.

|       |  \(p\) |  \(b_R\) |  \(b_T\) |  \(S_R\) |  \(S_T\) |  \(q_R\) |  \(q_T\) |  \(q_C\) | \(\pi_C\) |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| DM    | 39.5   | 0.76   | 0.76   | 0.38   | 0.38   | 9.44   | 9.44   | 18.89  | 707.17 |
| CM    | 29     | 1.35   | 1.35   | 0.61   | 0.61   | 16.36  | 16.36  | 32.72  | 937.63 |

The collected quantity and profit of the CLSC under centralized decision-making are greater than those under decentralized decision-making. That is because the double marginal effect problem under decentralized decision-making makes the retailer and the third-party collector provide lower collecting prices and collecting service levels, resulting in poor collecting of used products and hindering the sales of new and remanufactured products.

Whether in the centralized model or in the decentralized model, the retailer and the third-party collector have the same collection strategies and collected quantities, which is consistent with Proposition 1 in Section 5.

6.2. The impact of key parameters on the CLSC. In order to investigate the impact of the collecting quality and competition on the CLSC, we use MATLAB
Effects of remanufacturable ratio $\rho$. Figure 3 shows that as $\rho$ increases, the transfer price of the manufacturer, as well as the collecting prices, collecting service levels and collected quantities of the retailer and third-party collector will increase, and the total supply chain profit and the chain members’ profits are also increasing. This is in accordance with Proposition 2, 3 in Section 5. Compared with the retailer and the third-party collector, the manufacturer is more sensitive to the change of remanufacturing ratio because of the remanufacturing activity. With the increase of remanufacturing ratio, the profit growth of the manufacturer is more obvious than that of the retailer and the third-party, and the transfer price $B$ increases more than the collecting price $b$.

In addition, with the remanufacturable ratio increasing, the collecting prices and service levels of the collecting subjects increase, which improves consumers’ willingness to resell their used products, so that the collected quantities of the CLSC increase. And the demand of products influenced by the recovery market also increases. Therefore, to a certain extent, the increase of the remanufacturable ratio brings more sales profits to the manufacturer and the retailer, making the total profit of the CLSC increased.

Effects of competition coefficients $n_b$ and $n_S$. As shown in Figure 4 and Figure 5, with the increase of $n_b$ or $n_S$, the recovery prices of the retailer and the third-party collector are increasing, but the service levels and recovery quantities are decreasing, which leads to the decrease of the CLSC members’ profits. Faced with the
intensification of collecting price or collecting service competition, the retailer and the third-party collector have the same strategy, which is to increase the collecting price and reduce the collecting service level. Therefore, the recovery competition of used products is essentially the competition between collecting prices. And the vicious price competition is not conducive to the collection of used products, which leads to the reduction of the collection quantities of the retailer and the third-party collector, and reduces the CLSC members’ profits. This is in agreement with Proposition 4, 5 in Section 5.

Effects of sensitivity coefficients $m_b$ and $m_S$. From Figure 6 and Figure 7, we observe that the collected quantities of the retailer and the third-party collector increase in $m_b$ and $m_S$, and the profits of the CLSC members also increase in $m_b$ and $m_S$. Compared with the retailer and the third-party collector, the manufacturer’s profit and the total CLSC profit increase more obviously. This is because when consumers are more sensitive to the recovery price and service level, the retailer and the third-party collector must provide consumers with higher collecting price and service level to encourage consumers to resell their used products. When the consumers’ willingness to resell becomes high, the retailer and the third-party collector can obtain the more collected quantities of used products, and make more profits. As the reverse recovery of used products can promote the forward sales of products, the manufacturer will usher in a broader market demand. Therefore, the cost-savings of remanufacturing and the sales of products make the profit growth of the manufacturer higher than that of the other supply chain members. Due to the recovery expenses and channel service costs brought by the increase of recovery
volume, the profit growth rates of the retailer and the third-party collector are relatively slow.

6.3. Analysis of contract coordination. According to the values of the related parameters, we can get $\theta_1 = 0.3110$, $\theta_2 = 0.2515$, $\theta_3 = 0.5017$ via calculation. Therefore, when the sharing ratio satisfies $\theta \in [0.3110, 0.5017]$, the profits of the CLSC and chain members with coordination are greater than those without coordination.
And the total profit of the CLSC in the decentralized model with coordination is almost equal to the total profit of the CLSC in the centralized model.

As shown in Figure 8, when the sharing ratio satisfies \( \theta \in [0.3110, 0.5017] \), the coordination contract is valid. Selecting the median \( \theta = 0.4063 \), we get the whole CLSC profit and the chain members’ profits with coordination. The results are as follows.

**Table 4.** The comparison between the profits of the CLSC with coordination and that without coordination.

| Profit     | \( \pi_T \) | \( \pi_R \) | \( \pi_M \) | \( \pi \) | Supply chain efficiency |
|------------|-------------|-------------|-------------|---------|------------------------|
| Without coordination | 6.78       | 227.28      | 473.11      | 707.17  | 75.42%                 |
| With coordination    | 8.86       | 367.21      | 561.44      | 937.51  | 99.99%                 |

It can be seen from Table 4 that the profits of the manufacturer, the retailer and the third-party collector with contract coordination are significantly greater than those without coordination, and the efficiency of the CLSC rises from 75.42% to 99.99%. Due to the contract coordination, the problem of double marginalization effect in the decentralized decision-making system can be effectively improved, which increases the supply chain members’ profits. Therefore, the manufacturer, the retailer and the third-party collector have more motivation to participate in coordination activity.
7. Conclusions and future research. Considering the collecting competition between the retailer and third-party collector, and the different quality of collected used products, we study the collecting decisions and profits of different members in a CLSC. More specifically, two CLSC models are proposed to study the impact of some key parameters ($\rho$, $m_b$, $n_b$, $m_S$, $n_S$) on the supply chain members’ collecting decisions and profits. This paper also provides numerical analysis to further verify the theoretical analysis and coordination efficiency, and proposes some interesting managerial insights.

Summarizing the above, we can get the following conclusions:

(1) In the recovery market with unimpeded information, the retailer and third-party collector have the same collecting strategies, and have the same coping strategies when the competition intensifies.

(2) The collected quantities and profits of the CLSC members are positively correlated with the remanufacturable ratio $\rho$. Compared with the retailer and third-party collector, the manufacturer’s profit is more sensitive to the change of $\rho$.

(3) The CLSC members participating in collecting can improve the collected quantities by properly increasing the collecting price and service level. However, as competition intensifies, the collecting price plays a major role in the competition. The collectors mainly hope to obtain more collecting volume by increasing the collecting price. Compared with collecting price, collecting service has higher channel construction cost, which is often reduced by the collectors in the competition.

(4) The changes of collecting decisions caused by collection competition have a negative impact on consumers on the whole, which severely dampens consumers’ enthusiasm for collecting and reduces the collecting volume and profits of supply chain members.

(5) The collection decisions and profits of the CLSC members under centralized decision-making are better than those under decentralized decision-making. Moreover, the revenue-cost sharing contract can effectively coordinate the supply chain under decentralized decision-making, which can increase the collected quantities and profits of the CLSC.

For the manufacturer, it should try to increase the remanufacturable ratio of collected products by improving remanufacturing technology. As for the third-party collector and retailer, they can occupy an advantage by increasing the collecting price in recovery market. In addition, the third-party and retailer should actively sign contracts with the manufacturer to build the better recovery channel, which can increase the collected quantities. The cooperation among the CLSC members can increase the profits of each party and achieve a win-win situation.

In the future, this research may be continued as follows: 1) Compared with deterministic demand, random demand analysis is more practical and suitable to explain realistic economic activities. Moreover, robust optimization and fuzzy control can be used to analyze the random demand [7, 25]. 2) Considering qualified third-party remanufacturer and its collection competition with manufacturers in a CLSC can enrich existing research. 3) Considering the different power structure among supply chain members is very helpful for supply chain members to make decisions.

Author contributions. Dingzhong Feng: Conceptualization, Validation, Formal analysis, Writing - original draft, Funding acquisition. Xiaofeng Zhang: Validation, Formal analysis, Investigation, Writing - review & editing, Supervision. Ye Zhang: Revision.
Declaration of competing interest. The authors declare no conflict of interest.

Acknowledgments. This research was funded by the Natural Science Foundation of Zhejiang Province, China (No. LY18G010019). The authors gratefully acknowledge financial support from the Zhejiang Province Public Welfare Technology Application Research Project (No. 2015C33014).

Appendix A.

$$\max_{w,B} \pi_M = (w - c_m)(\alpha - \beta p) + [\rho \Delta + r(1 - \rho) - B]$$

$$\begin{align*}
    &\max_{p,b,R,S_R} \pi_R = (p - w)(\alpha - \beta p) + (B - b_R) \\
    &\max_{b_T,S_T} \pi_T = (B - b_T)(m_b b_R - n_b b_T + m_S S_R - n_S S_T) - \frac{A}{2} S_T^2
\end{align*}$$

Taking the second-order partial derivatives of $\pi_R$ with respect to $p$, $b_R$, and $S_R$, we can obtain the Hessian matrix

$$H_R = \begin{bmatrix}
    \frac{\partial^2 \pi_R}{\partial p^2} & \frac{\partial^2 \pi_R}{\partial p \partial b_R} & \frac{\partial^2 \pi_R}{\partial p \partial S_R} \\
    \frac{\partial^2 \pi_R}{\partial p \partial b_R} & \frac{\partial^2 \pi_R}{\partial b_R^2} & \frac{\partial^2 \pi_R}{\partial b_R \partial S_R} \\
    \frac{\partial^2 \pi_R}{\partial p \partial S_R} & \frac{\partial^2 \pi_R}{\partial b_R \partial S_R} & \frac{\partial^2 \pi_R}{\partial S_R^2}
\end{bmatrix} = \begin{bmatrix}
    -2\beta & 0 & 0 \\
    0 & -2m_b & -m_S \\
    0 & -m_S & -A
\end{bmatrix}.$$  

When satisfying the conditions (i) $|H_R1| < 0$, (ii) $|H_R2| > 0$ and (iii) $|H_R3| < 0$, the $H_R$ is negative definite. Since $H_R1 = -2\beta$ and $|H_R1| = -2\beta < 0$, condition (i) is satisfied. Since $H_R2 = \begin{bmatrix}
    -2\beta & 0 \\
    0 & -2m_b
\end{bmatrix}$ and $|H_R2| = 4\beta m_b > 0$, condition (ii) is satisfied. Since $H_R3 = \begin{bmatrix}
    0 & -2m_b & -m_S \\
    0 & -m_S & -A
\end{bmatrix}$ and $|H_R3| = -2\beta(2Am_b - m_S^2)$, Therefore, if $2Am_b > m_S^2$, condition (iii) is satisfied. Therefore, we prove that $\pi_R$ is strictly concave in $p$, $b_R$ and $S_R$.

Taking the second-order partial derivatives of $\pi_T$ with respect to $b_T$ and $S_T$, we can obtain the Hessian matrix

$$H_T = \begin{bmatrix}
    \frac{\partial^2 \pi_T}{\partial b_T^2} & \frac{\partial^2 \pi_T}{\partial b_T \partial S_T} \\
    \frac{\partial^2 \pi_T}{\partial b_T \partial S_T} & \frac{\partial^2 \pi_T}{\partial S_T^2}
\end{bmatrix} = \begin{bmatrix}
    0 & -m_S \\
    -m_S & -A
\end{bmatrix}.$$  

Then we obtain $|H_T1| = -2m_b < 0$ and $|H_T2| = 2Am_b - m_S^2 > 0$. Therefore, we prove that $\pi_T$ is strictly concave in $b_T$ and $S_T$.

According to the FOC of $\max_{p,b,R,S_R} \pi_R$ and $\max_{b_T,S_T} \pi_T$, we have $p^* = \frac{\alpha + \beta w}{2\beta}$, $b_R^* = \frac{(m_S^2 - m_S n_S - Am_b)B}{m_s^2 - m_S n_S - A(2m_b - n_b)}$, $S_R^* = \frac{-m_S(m_b - n_b)B}{m_s^2 - m_S n_S - A(2m_b - n_b)}$,

$b_T^* = \frac{(m_S^2 - m_S n_S - Am_b)B}{m_s^2 - m_S n_S - A(2m_b - n_b)}$, $S_T^* = \frac{-m_S(m_b - n_b)B}{m_s^2 - m_S n_S - A(2m_b - n_b)}$.

Substituting the above optimal solution into $\max_{w,B} \pi_M$, we can get the Hessian matrix

$$H_M = \begin{bmatrix}
    \frac{\partial^2 \pi_M}{\partial w^2} & \frac{\partial^2 \pi_M}{\partial w \partial B} \\
    \frac{\partial^2 \pi_M}{\partial w \partial B} & \frac{\partial^2 \pi_M}{\partial B^2}
\end{bmatrix} = \begin{bmatrix}
    -\beta & 0 \\
    0 & \frac{4Am_b(m_b - n_b)}{m_s^2 - m_S n_S - A(2m_b - n_b)}
\end{bmatrix}.$$
For $\pi_M$ to be concave in $w$ and $B$, the $H_M$ should satisfy conditions: $|H_{M1}| = -\beta < 0$ and $|H_{M2}| = \frac{43A_n - 4\gamma A_m (m_b - n_b)}{m_S^2 - m_S S_n - A (2m_b - n_b)} > 0$. Therefore, if $m_S^2 - m_S S_n - A (2m_b - n_b) < 0$, we prove that $\pi_M$ is strictly concave in $w$ and $B$.

Appendix B.

$$
\max_{p, b_R, S_R, b_T, S_T} \pi_C = (p - c_m) (\alpha - \beta p) + [(\Delta \rho + r - \rho r)] [m_b (b_R + b_T) - n_b (b_T + b_R)] + m_S (S_R + S_T) - n_S (S_T + S_R) - b_R q_R - b_T q_T
$$

$$
- \frac{A}{2} S_R^2 - \frac{A}{2} S_T^2
$$

Taking the second-order partial derivatives of $\pi_C$ with respect to $p$, $b_R$, $S_R$, $b_T$ and $S_T$, we can obtain the Hessian Matrix

$$
H_C = 
\begin{bmatrix}
\frac{\partial^2 \pi_C}{\partial p^2} & \frac{\partial^2 \pi_C}{\partial p \partial S_R} & \frac{\partial^2 \pi_C}{\partial p \partial S_T} & \frac{\partial^2 \pi_C}{\partial p \partial b_T} & \frac{\partial^2 \pi_C}{\partial p \partial b_T} \\
\frac{\partial^2 \pi_C}{\partial S_R \partial p} & \frac{\partial^2 \pi_C}{\partial S_R^2} & \frac{\partial^2 \pi_C}{\partial S_R \partial S_T} & \frac{\partial^2 \pi_C}{\partial S_R \partial b_T} & \frac{\partial^2 \pi_C}{\partial S_R \partial b_T} \\
\frac{\partial^2 \pi_C}{\partial S_T \partial p} & \frac{\partial^2 \pi_C}{\partial S_T \partial S_R} & \frac{\partial^2 \pi_C}{\partial S_T^2} & \frac{\partial^2 \pi_C}{\partial S_T \partial b_T} & \frac{\partial^2 \pi_C}{\partial S_T \partial b_T} \\
\frac{\partial^2 \pi_C}{\partial b_T \partial p} & \frac{\partial^2 \pi_C}{\partial b_T \partial S_R} & \frac{\partial^2 \pi_C}{\partial b_T \partial S_T} & \frac{\partial^2 \pi_C}{\partial b_T^2} & \frac{\partial^2 \pi_C}{\partial b_T^2} \\
\frac{\partial^2 \pi_C}{\partial b_T \partial p} & \frac{\partial^2 \pi_C}{\partial b_T \partial S_R} & \frac{\partial^2 \pi_C}{\partial b_T \partial S_T} & \frac{\partial^2 \pi_C}{\partial b_T^2} & \frac{\partial^2 \pi_C}{\partial b_T^2}
\end{bmatrix}
$$

$$
= 
\begin{bmatrix}
-2\beta & 0 & 0 & 0 & 0 \\
0 & -2m_b & 2n_b & -m_S & n_S \\
0 & 2n_b & -2m_b & n_S & -m_S \\
0 & -m_S & n_S & -A & 0 \\
0 & n_S & -m_S & 0 & -A
\end{bmatrix}
$$

For $\pi_C$ to be concave in $p$, $b_R$, $S_R$, $b_T$ and $S_T$, the $H_C$ should satisfy the conditions as following:

$|H_1| = -2\beta < 0$,

$|H_2| = 4\beta m_b > 0$,

$|H_3| = -8\beta (m_b^2 - n_b^2) < 0$,

$|H_4| = -4\beta [m_S^2 m_b + n_S^2 m_b - 2m_S n_S n_b - 2A (m_b^2 - n_b^2)] > 0$,

$|H_5| = -2\beta \left[ (m_S^2 - n_S^2)^2 - 4A m_b (m_S^2 + n_S^2) + 8A m_S n_S n_b + 4A^2 (m_b^2 - n_b^2) \right] < 0$.

Therefore, the $H_C$ is negative definite as long as

$$
\begin{cases}
m_S^2 m_b + n_S^2 m_b - 2m_S n_S n_b - 2A (m_b^2 - n_b^2) < 0 \\
(m_S^2 - n_S^2)^2 - 4A m_b (m_S^2 + n_S^2) + 8A m_S n_S n_b + 4A^2 (m_b^2 - n_b^2) > 0
\end{cases}
$$

Simplifying the above inequalities, we can get $2A (m_b - n_b) > (m_S - n_S)^2$.

Therefore, we prove that $\pi_C$ is strictly concave in $p$, $b_R$, $S_R$, $b_T$ and $S_T$.

Appendix C.

**Proof of Proposition 2.** Taking the first derivative of $B^*$ with respect to $\rho$, we obtain $\frac{\partial B^*}{\partial \rho} = \Delta - r$. According to assumption 5, we can easily get $\frac{\partial B^*}{\partial \rho} > 0$. Thus $B^*$ is increasing in $\rho$. \qed
Proof of Proposition 3. The first derivatives of $b_{R_1}^*$, $b_{T_1}^*$, $S_{R_1}^*$ and $S_{T_1}^*$ with respect to $\rho$ are as follows:
\[
\frac{\partial b_{R_1}^*}{\partial \rho} = \frac{\partial b_{T_1}^*}{\partial \rho} = \frac{(m_S^2 - m_S n_S - A m_b) (\Delta - r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]} > 0, \\
\frac{\partial S_{R_1}^*}{\partial \rho} = \frac{\partial S_{T_1}^*}{\partial \rho} = \frac{-m_S (m_b - n_b) (\Delta - r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]} > 0.
\]
The proof of (i) is completed.

Taking the derivatives of $q_{R_1}^*$ and $q_{T_1}^*$ with respect to $\rho$ yields
\[
\frac{\partial q_{R_1}^*}{\partial \rho} = \frac{\partial q_{T_1}^*}{\partial \rho} = \frac{-A m_b (m_b - n_b) (\Delta - r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]} > 0.
\]
The proof of (ii) is completed.

The derivatives of $\pi_M^*$, $\pi_R^*$ and $\pi_T^*$ respect to $\rho$ are given by
\[
\frac{\partial \pi_M^*}{\partial \rho} = \frac{-A m_b (m_b - n_b) (\Delta + r - \rho r) (\Delta - r)}{[m_S^2 - m_S n_S - A (2 m_b - n_b)]} > 0, \\
\frac{\partial \pi_R^*}{\partial \rho} = \frac{A (2 A m_b - m_S^2) (m_b - n_b)^2 (\Delta + r - \rho r) (\Delta - r)}{4 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} > 0, \\
\frac{\partial \pi_T^*}{\partial \rho} = \frac{A (2 A m_b - m_S^2) (m_b - n_b)^2 (\Delta + r - \rho r) (\Delta - r)}{4 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} > 0.
\]
The proof of (iii) is completed.

Proof of Proposition 4. We first consider the derivatives of the optimal collection decisions with respect to $n_b$. The first derivatives of $b_{R_1}^*$, $b_{T_1}^*$, $S_{R_1}^*$ and $S_{T_1}^*$ with respect to $n_b$ are as follows:
\[
\frac{\partial b_{R_1}^*}{\partial n_b} = \frac{\partial b_{T_1}^*}{\partial n_b} = \frac{-A (m_S^2 - m_S n_S - A m_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} > 0, \\
\frac{\partial S_{R_1}^*}{\partial n_b} = \frac{\partial S_{T_1}^*}{\partial n_b} = \frac{m_S (m_S^2 - m_S n_S - A m_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} < 0.
\]
$b_{R_1}^*$ and $b_{T_1}^*$ are increasing in $n_b$, but $S_{R_1}^*$ and $S_{T_1}^*$ are decreasing in $n_b$.

Then we turn our attention to the derivatives of the optimal collection decisions with respect to $n_S$.
\[
\frac{\partial b_{R_1}^*}{\partial n_S} = \frac{\partial b_{T_1}^*}{\partial n_S} = \frac{A m_b (m_b - n_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} > 0, \\
\frac{\partial S_{R_1}^*}{\partial n_S} = \frac{\partial S_{T_1}^*}{\partial n_S} = \frac{-m_S^2 (m_b - n_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} < 0.
\]
$b_{R_1}^*$ and $b_{T_1}^*$ are increasing in $n_S$, but $S_{R_1}^*$ and $S_{T_1}^*$ are decreasing in $n_S$.

Proof of Proposition 5. Consider the following derivatives:
\[
\frac{\partial q_{R_1}^*}{\partial n_b} = \frac{\partial q_{T_1}^*}{\partial n_b} = \frac{A m_b (m_b - n_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} < 0, \\
\frac{\partial q_{R_1}^*}{\partial n_S} = \frac{\partial q_{T_1}^*}{\partial n_S} = \frac{-A b_{R_1} m_S (m_b - n_b) (\Delta + r - \rho r)}{2 [m_S^2 - m_S n_S - A (2 m_b - n_b)]^2} < 0.
\]
Then we obtain that \( q_{R1} \) and \( q_{T1} \) are decreasing in \( n_b \), and \( q_{R1} \) and \( q_{T1} \) are decreasing in \( n_s \). The proof of (i) and (ii) are completed.

The derivatives of \( \pi_M^* \), \( \pi_R^* \) and \( \pi_T^* \) respect to \( n_b \) are given by

\[
\begin{align*}
\frac{\partial \pi_M^*}{\partial n_b} &= \frac{A m_b \left( m_s^2 - m_s n_S - A m_b \right) (\Delta \rho + r - \rho r)^2}{2 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^2} < 0, \\
\frac{\partial \pi_R^*}{\partial n_b} &= -A \left( 2Am_b - m_s^2 \right) \left( m_s^2 - m_s n_S - A m_b \right) (m_b - n_b) (\Delta \rho + r - \rho r)^2 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^3 < 0, \\
\frac{\partial \pi_T^*}{\partial n_b} &= -A \left( 2Am_b - m_s^2 \right) \left( m_s^2 - m_s n_S - A m_b \right) (m_b - n_b) (\Delta \rho + r - \rho r)^2 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^3 < 0.
\end{align*}
\]

The proof of (iii) is completed.

Taking the first derivatives of \( \pi_M^* \), \( \pi_R^* \) and \( \pi_T^* \) respect to \( n_S \) then yields

\[
\begin{align*}
\frac{\partial \pi_M^*}{\partial n_S} &= -\frac{Am_b m_S (m_b - n_b) (\Delta \rho + r - \rho r)^2}{2 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^2} < 0, \\
\frac{\partial \pi_R^*}{\partial n_S} &= \frac{Am_S \left( 2Am_b - m_s^2 \right) (m_b - n_b)^2 (\Delta \rho + r - \rho r)^2}{4 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^3} < 0, \\
\frac{\partial \pi_T^*}{\partial n_S} &= \frac{Am_S \left( 2Am_b - m_s^2 \right) (m_b - n_b)^2 (\Delta \rho + r - \rho r)^2}{4 \left[ m_s^2 - m_s n_S - A (2m_b - n_b) \right]^3} < 0.
\end{align*}
\]

The proof of (iv) is completed.

\[\square\]

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Received December 2020; 1st revision February 2021; final revision April 2021.

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