EFFECTS OF TAKE-BACK LEGISLATION ON PRICING AND COORDINATION IN A CLOSED-LOOP SUPPLY CHAIN

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Abstract. This study investigates the effects of take-back legislation and channel structures on pricing, collection, and coordination in a closed-loop supply chain (CLSC). By establishing the centralized, manufacturer-led, and retailer-led CLSC models, we analyze the equilibrium solutions of channel players and the government. We obtain the following results. (1) The manufacturer can accept a higher collection target and exit the market later in the centralized model than in decentralized decision-making models. Moreover, the manufacturer exists the market earlier in the retailer-led model with regulation compared with the manufacturer-led model. (2) The government’s optimal collection target is the same under manufacturer-led and retailer-led models when the regulation comes into force. (3) Revenue-sharing and two-part tariff contracts can effectively coordinate manufacturer-led and retailer-led CLSCs under take-back legislation. Finally, we conduct several numerical examples and obtain relevant managerial insights. Our results indicate that the correlation between take-back legislation and channel structure has a significant impact on the pricing and coordination decisions of the CLSC; furthermore, the government should flexibly set the collection target when facing different supply chain and channel power structures in a CLSC.

1. Introduction. In recent decades, increased waste generation, accompanied by the rapid development of the Internet and e-commerce, has raised concern from consumers, firms, and governments [46, 52]. Given this background, many institutions worldwide have gradually enacted relevant legislation to address the waste generation problem [23, 33]. As a typical example, take-back legislation based on the EPR (extended producer responsibility) has been widely implemented across
various industries [15, 31]. The main objective of this regulation scheme is to decrease negative impacts on the environment by holding producers physically and financially responsible for collecting and recycling used products and for designing greener products [21, 25]. Early examples of such legislation include Directive 2003/108/EC on WEEE in the European Union and the take-back law in the US [3, 4]. Gradually, other countries, such as Germany and Japan, have enacted similar legislation to normalize producers’ behavior [41]. The Chinese government enacted several key laws on WEEE in response to EOL products, such as the Cleaner Production Promotion Law [55]. Many scholars have addressed the key issue of designing an efficient take-back legislation from the policymaker’s perspective.

However, in the context of CLSC management, the effect of take-back legislation on collection and coordination in a CLSC remains unclear. Examining the interplay between take-back legislation and channel players’ decisions in a CLSC is very necessary. First, from a theoretical perspective, existing studies on reverse channel selection and CLSC coordination rarely consider the government’s regulation behavior. Moreover, when governments enact a take-back regulation, traditional contracts cannot continue to effectively coordinate CLSCs. Second, take-back legislation directly affects channel players’ operations and marketing decisions, which, in turn, affects the profitability of firms. In addition, government inventions complicate the decision-making process of the CLSC.

The primary purpose of this study is to demonstrate the pricing, collection decisions, and contract design in a CLSC in the presence of take-back legislation. In describing the problem, we consider, based on observations in industries, two important factors in CLSC: the supply chain structure (centralized or decentralized) and channel power structure (manufacturer-led or retailer-led), and we investigate the effects of these factors on the equilibrium decisions of channel players and government. Following previous studies, we assume that the government sets a collection target to restrict manufacturers’ behavior under take-back legislation [3]. By establishing and comparing the centralized, manufacturer-led, and retailer-led CLSC decision-making models, we intend to answer the following questions. (1) How does take-back regulations affect manufacturers’ market behavior in a CLSC? (2) How does the government set the optimal collection target under different channel power structures? (3) How should contracts be designed to coordinate CLSCs in the presence of take-back legislation?

The main contributions of this study are as follows. First, we embed take-back legislation into a CLSC with considering different supply chain structures (centralized or decentralized) and channel power structures (manufacturer-led or retailer-led). We show that the manufacturer can choose to exit the market later in the centralized decision-making case when facing take-back regulation. Second, we endogenize the government’s collection target decision and interestingly to find that the channel power structure has no effects on the government’s optimal decisions, namely, the manufacturer optimally sets the same collection target in a CLSC. Third, we reveal that even though the take-back regulation is incorporated, revenue-sharing (RS) contract and two-part tariff (TPT) contract can also perfectly coordinate the decentralized CLSCs under different channel power structures.
by yielding the highest channel performance in the centralized decision-making case. To our knowledge, this is one of the early studies to explore the issues regarding the impacts of take-back regulation and channel structures (supply chain and channel power structures) into a CLSC and two kinds of contracts to coordinate decentralized CLSCs.

The remainder of this paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the model. Section 4 establishes three CLSC decision-making models and comprehensively compares different models. Section 5 analyzes the government’s optimal decision. Section 6 explores contract design problem for two decentralized CLSCs. Section 7 conducts several numerical examples and Section 8 concludes the study.

2. Literature review. This paper relates to the following three streams of studies: (i) closed-loop supply chain power structures, (ii) supply chain coordination mechanisms, and (iii) the role of government take-back regulations.

First, the power structure within the CLSC have been extensively investigated by relevant studies [8, 10, 11, 14, 20, 24, 34, 47, 54]. Choi et al. [14] consider a CLSC in which the collector undertakes the recycling business, and they compare supply chain profits under different types of channel leadership. Chen et al. [11] also provide important insights regarding the effects of power structures on supply chain decisions and sustainability performance. Moreover, these two studies design coordination mechanisms to improve the decentralized models to reach Pareto optimality. Zheng et al. [54] consider the manufacturer encroachment issue in a CLSC and explore how the channel power structure affects the encroachment strategy. He et al. [24] examines the channel power structure selection and pricing strategies in a dual-channel CLSC with government subsidy. Similar to these studies, we also incorporate two Stackelberg game frameworks and examine the influence of the channel power on the optimal decisions of channel members. However, few previous studies consider the important role of government intervention in the recycling process under different power channels with supply chain coordination, as we explore in this study.

Second, supply chain coordination, which is devoted to aligning incentives and improving supply chain entities’ performance, has always been an important topic [6, 7, 13, 19, 26, 27, 28, 30, 37, 40, 45, 50, 53]. Various types of coordination contracts and mechanisms (e.g., wholesale price contracts, revenue-sharing contracts, two-part tariff contracts) can be found in previous studies. Among previous studies, Biswas et al. [7] adopt the wholesale price and linear TPT contracts to establish perfect supply chain coordination from the supplier’s perspective. He and Zhao [27] discuss the several types of coordination contracts with stochastic supply and uncertain demand. Bai et al. [6] consider a sustainable supply chain and indicate that both revenue-sharing and two-part tariff contracts can achieve supply chain coordination. Yang et al. [50] explore supply chain coordination with push-pull characteristics under the allocation of inventory risk and demonstrate that both three-part tariff and revenue-sharing contracts can achieve coordination across the whole supply chain. Zheng et al. [53] investigate pricing and coordination strategies
in a dual-channel CLSC with considering different channel power structures. Wang et al. [45] investigate product collection strategy and coordination in a CLSC with considering consumer behavior and competitive dual-recycling channels. In this study, we incorporate a RS (revenue-sharing) contract and a TPT (two-part tariff) contract into a Stackelberg game and emphasize the impacts of take-back regulation within a CLSC.

Third, the literature on the government intervention in the supply chain collection business under EPR mainly includes three streams. The first stream concentrates on the construction and selection of government take-back mechanisms. Toyasaki et al. [43] compare monopolistic and competitive schemes, which are two prevailing take-back schemes, and analyze the selection of the optimal recycling mechanism. Esenduran and Kemahlioglu-Ziya [18] discuss and compare the individual and collective compliance schemes to identify which compliance scheme can achieve the optimal equilibrium under different conditions. Gui et al. [22] find that cost allocation mechanisms exert an important effect on the implementation of EPR. Moreover, Gui et al. [21] explore design incentives under the collective EPR regulation from the perspective of the network. The second stream focuses on product design and pricing strategy within manufacturing and remanufacturing systems. Esenduran et al. [17] demonstrate the strategic impacts of take-back regulations when OEM and IR (independent remanufacturer) engaged in quantity competition. Subramanian et al. [42] investigate the product design and supply chain coordination with consideration of the EPR legislation and information asymmetry. Hong et al. [29] consider the relationship between the consumer preference and product design and study the channel power selection and coordination in a green supply chain. Chen et al. [12] and Xiao et al. [48] investigate the effects of the government’s environmental subsidy on supply chain’s sustainable innovation. The last stream is related to the incentive mechanisms for supply chain cooperation. Jacobs and Subramanian [32] explore the internal relationship between government take-back legislation and responsibility sharing in a supply chain. Chen and Akmalu Ulya [9] investigate a green CLSC under a government reward-penalty mechanism that can improve the recycling rate and product’s green effort. Moreover, other studies have analyzed the influence of government reward and punishment mechanisms on pricing and recycling decisions within a CLSC. Mitra and Webster [35] consider a two-stage model with government subsidies for the manufacturer’s recycling business. Wang et al. [44] show that the reward-penalty intensity and sharing ratio significantly affect the social welfare in a multi-tier CLSC. Alizamir et al. [1] focus on the agricultural industry and investigate two government subsidy programs that are devoted to protecting farmers’ profits. However, all of these studies consider the scenario in which the collection target determined by government’s take-back legislation is exogenous. In this study, we innovatively assume that the collection target decision is endogenous.

Unlike the above studies, our study stresses the impact that the government’s take-back legislation has on CLSC members’ pricing and coordination decisions under different different supply chain and channel power channels. Moreover, in our study, we endogenize the government’s decision and discuss the determination
of optimal collection target. We also explore the CLSC coordination problem with revenue-sharing and two-part tariff contracts in a decentralized supply chain with government intervention.

Table 1. Comparison of our study and related literature

| Research paper          | Take-back legislation | CLSC power structure | Supply chain coordination | Endogenous government’s decision |
|-------------------------|-----------------------|----------------------|---------------------------|----------------------------------|
| Choi et al. [14]        | √                     |                      |                           |                                  |
| Chen et al. [11]        | √                     |                      |                           |                                  |
| He et al. [25]          | √                     |                      |                           |                                  |
| Zheng et al. [54]       | √                     |                      |                           |                                  |
| Bai et al. [6]          | √                     |                      |                           |                                  |
| Zheng et al. [53]       | √                     | √                    |                           |                                  |
| Wang et al. [45]        | √                     |                      |                           |                                  |
| Toyasaki et al. [43]    | √                     |                      |                           |                                  |
| Esenduran and Kemahlioglu-Ziya [18] | √ |                      |                           |                                  |
| Subramanian et al. [42] | √                     |                      | √                         |                                  |
| Jacobs and Subramanian [32] | √ |                      |                           |                                  |
| Chen and Akmal Ulia [9] | √                     |                      |                           |                                  |
| Alizamir et al. [1]     | √                     | √                    | √                         |                                  |
| **Our work**            | √                     | √                    | √                         | √                                |

3. Problem description. Consider a CLSC in which a manufacturer (she) sells products to final consumers via an independent retailer (he), as well as collecting used products from consumer market. To simplify the model and obtain more managerial insights, we adopt one of the three collecting models (i.e., manufacturer-collecting model) proposed by Savaskan et al. [38]. Furthermore, we assume that there is no distinction between the new and remanufactured products. In other words, consumers have the same willingness to pay (WTP) for these two products [5, 38].

To characterize reverse channel performance, we use $\tau(0 \leq \tau \leq 1)$ to represent the return rate of used products. According to surveys, remanufacturing can save 40%-65% of a company’s costs relative to manufacturing a new product [38]. Thus, the unit production cost of a new product is higher than that of a remanufactured product. Let $c_m$ be the unit cost for the new product and $c_r$ be that for the remanufactured product. Then, the average production cost for the manufacturer is $c_m(1 - \tau) + c_r\tau$. If we use $\Delta = c_m - c_r$ to denote the unit cost savings from remanufacturing, the average production cost can be rewritten as $c_m - \Delta\tau$.

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1The main results are robust in the retailer-collecting and third party-collecting models.
According to Raz and Souza [36], the overall collection costs include the following two aspects. First, the manufacturer incurs a fixed cost $f$ to establish the collection infrastructure by, for example, building reverse channels and collection points, and purchasing required equipment. Second, depending on the return rate $\tau$, the manufacturer incurs additional collection costs $C_L \tau^2$, where $C_L$ is a scaling parameter. This function has the following properties. First, the collection cost is increasing in the return rate ($C'(\tau) > 0$). Second, subsequent efforts to increase the return rate become increasingly difficult ($C''(\tau) > 0$). This convex quadratic cost function is commonly adopted in the CLSC literature [5, 38, 39, 53]. Then, total collection costs can be characterized as $C(\tau) = f + C_L \tau^2$.

In addition to creating economic benefits for firms, the government also aims to realize both environmental and social benefits. The EPR regime has recently been widely adopted in practice. Under EPR regulation, firms are required to take charge of the whole life cycles of their products. However, considering various internal and external factors, many firms are not willing to collect used products. Hence, it is necessary for the government to take effective measures to regulate used product collection. Take-back legislation based on the EPR is a popular type of legislation and is widely adopted by many governments [3, 16]. We adopt a simple method for modelling the government’s regulation behavior and assume that the government previously sets a collection target $\tau_g$ based on industry practice. Then, the manufacturer makes pricing and collection decisions based on the collection regulation set by the government.

To maintain model tractability, we also make the following assumptions. First, all members in CLSC make their decisions in a single-period setting. Second, in all supply chain decision-making models, there is no information asymmetry between channel players. We consider a linear demand function, which is represented by $D(p) = a - bp$ [2, 5, 38], where $a(a > 0)$ is the initial demand and $b(b > 0)$ measures consumers’ sensitivity to the retail price $p$ (to ensure a nonnegative demand, the retail price $p$ is no more than the upper bound $a/b$). Then, according to above assumptions, the profit functions for channel players and supply chain system are determined by:

$$
\pi_M = (w - c_m + \Delta \tau)(a - bp) - f - C_L \tau^2, \quad (1)
$$

$$
\pi_R = (p - w)(a - bp), \quad (2)
$$

$$
\pi_T = (p - c_m + \Delta \tau)(a - bp) - f - C_L \tau^2. \quad (3)
$$

4. Model and analysis. By considering different supply chain structure (centralized vs. decentralized) and channel power structure (manufacturer-led vs. retailer-led), we present two decentralized CLSC models. We begin by analyzing the centralized CLSC model in which the manufacturer and the retailer jointly maximize their profits.

4.1. Model I–centralized model. In Model I, all supply chain members can be viewed as an alliance to optimally determine retail price $p$ and return rate $\tau$. There
is no efficiency loss in the centralized model, and the alliance optimizes:

$$\max_{p, \tau} \pi^I = (p - c_m + \Delta \tau) (a - bp) - f - C_L \tau^2. \quad (4)$$

If we do not consider the take-back regulation, it is straightforward that when 
$$4C_L - b\Delta^2 > 0, \pi_I$$ is jointly concave in $$p$$ and $$\tau$$. By using the joint FOCs, we obtain the equilibrium solutions as follows:

$$p^{I*} = \frac{2 (a + bc_m) C_L - ab\Delta^2}{b (4C_L - b\Delta^2)}, \tau^{I*} = \frac{\Delta (a - bc_m)}{4C_L - b\Delta^2}.$$

For equilibrium return rate $$\tau^{I*}$$, note that when the collection target $$\tau_g$$ satisfies 
$$\tau_g \leq \frac{\Delta (a - bc_m)}{4C_L - b\Delta^2}$$, the government regulation has no impact on the optimal decisions of the CLSC. However, if $$\tau_g > \tau^{I*}$$, the manufacturer must choose the collection target $$\tau_g$$ to meet the government regulation. Then, the retail price is determined based on the collection target. The CLSC’s optimization problem is given as follows:

$$\max_p \pi^I = (p - c_m + \Delta \tau_g) (a - bp) - f - C_L \tau_g^2. \quad (5)$$

In this case, the return rate is predetermined. Note that $$\pi^I$$ is concave in $$p$$, and solving the FOC results in:

$$p^{I*} = \frac{a + bc_m - b\Delta \tau_g}{2b}.$$ 

Note that $$p^{I*}$$ decreases in the collection target ($$\tau_g$$). If the government sets a sufficiently high collection target, the manufacturer must also incur high collection costs to meet the regulation. Hence, the CLSC exits the market if the system profit cannot cover collection costs. Proposition 1 summarizes the optimal decisions and CLSC behavior in Model I.

**Proposition 1.** In Model I,

(1) When $$\tau_g$$ satisfies $$\tau_g \leq \frac{\Delta (a - bc_m)}{4C_L - b\Delta^2}$$, the equilibrium retail price and equilibrium return rate are:

$$p^{I*} = \frac{2 (a + bc_m) C_L - ab\Delta^2}{b (4C_L - b\Delta^2)}, \tau^{I*} = \frac{\Delta (a - bc_m)}{4C_L - b\Delta^2}.$$ 

The optimal profit for the CLSC system is:

$$\pi^{I*}_T = \frac{b^2 f \Delta^2 + (a^2 - 4bf - bc_m (2a - bc_m)) C_L}{b (4C_L - b\Delta^2)}.$$ 

(2) When $$\tau_g$$ satisfies $$\frac{\Delta (a - bc_m)}{4C_L - b\Delta^2} < \tau_g \leq \tau_0$$, the equilibrium retail price and return rate are:

$$\tau^{I*} = \tau_g, p^{I*} = \frac{a + bc_m - b\Delta \tau_g}{2b}.$$ 

The supply chain system’s profit is:

$$\pi^{I*}_T = \frac{a^2 - 4bf + b \left( \frac{bc_m^2}{2c_m (a + b\Delta \tau_g) + \tau_g \left( 2a \Delta + \left( b\Delta^2 - 4C_L \right) \tau_g \right)} \right)}{4b}.$$ 

(3) When $$\tau_g > \tau_0$$, the CLSC will exit the market, where

$$\tau_0 = \frac{b\Delta (a - bc_m) + 2\sqrt{b^2 f \Delta^2 + b (a^2 - 4bf - bc_m (2a - bc_m)) C_L}}{b (4C_L - b\Delta^2)}.$$
Proof. The CLSC accepts the collection target $\tau_g$ when it exceeds the optimal return rate, i.e. $\tau_g > \tau^*_I$. Note that the CLSC will exit the market if the profit cannot cover collection costs. Then, solving the equation

$$\pi^*_T = \frac{a^2 - 4bf + b(2c_m - 2c_m(a + b\Delta \tau_g) + \tau_g(2a\Delta + (b\Delta^2 - 4CL)\tau_g))}{4b} = 0$$

yields the threshold $\tau_0$ such that when $\tau_g > \tau_0$, the CLSC withdraw from the market. □

4.2. Decentralized models. The supply chain members in CLSC make decisions independently in decentralized models. The manufacturer determines the wholesale price $w$ and return rate $\tau$, and the retailer determines the retail price $p$. According to channel power structures, we establish two decentralized models in the following two sections.

4.2.1. Model DM—Manufacturer-led model. In the DM model, the sequence of events in the CLSC is as follows. First, taking into account the retailer’s best response, the manufacturer determines $w$ and $\tau$. Second, the retailer determines $p$. Backward induction is used to solve this Stakerlberg game, the manufacturer and the retailer optimize, respectively:

$$\max_p \pi_R = (p - w)(a - bp), \quad (6)$$

$$\max_{w, \tau} \pi_M = (w - c_m + \Delta \tau)(a - bp) - f - CL\tau^2 \quad (7)$$

First, without considering government take-back regulation, the equilibrium decisions of this model can be derived as follows by using the first-order conditions:

$$w^*_{DM} = \frac{4(a + bc_m)CL - ab\Delta^2}{b(8CL - b\Delta^2)}, \quad \tau^*_{DM} = \frac{\Delta(a - bc_m)}{8CL - b\Delta^2},$$

$$p^*_{DM} = \frac{2(3a + bc_m)CL - ab\Delta^2}{b(8CL - b\Delta^2)}.$$

A similar method can be used to analyze the optimal decisions in the CLSC in the case of government regulation, and we omit the detailed process. Proposition 2 summarizes the equilibrium solutions and boundary conditions for the CLSC exiting the market in the DM model.

**Proposition 2.** In Model DM,

1. When $\tau_g$ satisfies $\tau_g \leq \frac{\Delta(a - bc_m)}{8CL - b\Delta^2}$, the equilibrium wholesale price, return rate and retail price are:

$$w^*_{DM} = \frac{4(a + bc_m)CL - ab\Delta^2}{b(8CL - b\Delta^2)}, \quad \tau^*_{DM} = \frac{\Delta(a - bc_m)}{8CL - b\Delta^2},$$

$$p^*_{DM} = \frac{2(3a + bc_m)CL - ab\Delta^2}{b(8CL - b\Delta^2)}.$$

The manufacturer’s and retailer’s profits are:

$$\pi^{R*}_{DM} = \frac{4(a - bc_m)^2CL^2}{b(8CL - b\Delta^2)^2}, \quad \pi^{M*}_{DM} = \frac{b^2f\Delta^2 + (a^2 - 8bf - bc_m(2a - bc_m))CL}{b(8CL - b\Delta^2)}.$$
Proposition 3. In Model DR, under which the CLSC withdraw the market for Model DR.

Similar to the proof of Proposition 1, we easily prove Proposition 2.

Proof. Similar to the proof of Proposition 1, we easily prove Proposition 2.

Proposition 2 describes the interplay between collection regulation and the manufacturer’s return decisions. If the government sets a relatively low collection target \( \tau_g < \frac{a-bc_m}{8c_L-2b\Delta^2} \), the regulation has no impact on the optimal decisions in the CLSC. Furthermore, the manufacturer must meet the required return rate as \( \tau_g \) increases. However, the manufacturer exits the market if it cannot earn positive profits under the regulation \( \tau_g > \tau_1 \).

4.2.2. Model DR—Retailer-led model. In the DR model, the sequence of events in the CLSC is as follows. First, the retailer determines \( p \) in anticipation of the manufacturer’s best responses. Then, the manufacturer determines \( w \) and \( \tau \) by taking collection regulation into consideration. The manufacturer and the retailer optimize, respectively:

\[
\max_{w,\tau} \pi_M = (w - c_m + \Delta \tau) (a - bp) - f - C_L \tau^2, \tag{8}
\]

\[
\max_p \pi_R = (p - w) (a - bp). \tag{9}
\]

Backward induction method can be used to solve this model. The equilibrium outcomes of this model are given as

\[
w^{DR*} = \frac{b \Delta^2 (a + bc_m) - 2 (a + 3bc_m) C_L}{2b (b \Delta^2 - 4C_L)}, \quad \tau^{DR*} = \frac{a \Delta - b \Delta c_m}{8C_L - 2b \Delta^2}
\]

\[
p^{DR*} = \frac{(3a + bc_m) C_L - ab \Delta^2}{b (4C_L - b \Delta^2)}.
\]

Proposition 3 summarizes the equilibrium solutions and boundary conditions under which the CLSC withdraw the market for Model DR.

Proposition 3. In Model DR,

1. When \( \tau_g \) satisfies \( \frac{a \Delta - b \Delta c_m}{8C_L - 2b \Delta^2} \), the equilibrium wholesale price, return rate and retail price are:

\[
w^{DR*} = \frac{b \Delta^2 (a + bc_m) - 2 (a + 3bc_m) C_L}{2b (b \Delta^2 - 4C_L)}, \quad \tau^{DR*} = \frac{a \Delta - b \Delta c_m}{8C_L - 2b \Delta^2}
\]

2. When \( \tau_g \) satisfies \( \frac{a \Delta - b \Delta c_m}{8C_L - 2b \Delta^2} < \tau_g \leq \tau_1 \), the equilibrium wholesale price, return rate and retail price are:

\[
w^{DM*} = \frac{a + bc_m - b \Delta \tau_g}{2b}, \quad \tau^{DM*} = \tau_g, \quad p^{DM*} = \frac{3a + bc_m - b \Delta \tau_g}{4b}
\]
The optimal profits for the manufacturer and the retailer are:

\[ \pi_{M}^{DR*} = \frac{4b \Delta^2 + (a^2 - 16bf - bc_m (2a - bc_m)) C_L}{4b (4C_L - b\Delta^2)}, \]
\[ \pi_{R}^{DR*} = \frac{(a - bc_m)^2 C_L}{2b (4C_L - b\Delta^2)}. \]

(2) When \( \tau_g \) satisfy the condition \( \frac{a\Delta - b\Delta c_m}{8C_L - 2b\Delta^2} < \tau_g \leq \tau_2, \) the equilibrium wholesale price, return rate and retail price are:

\[ w_{DR*} = \frac{a + 3bc_m - 3b\Delta \tau_g}{4b}, \tau_{DR*} = \tau_g, p_{DR*} = \frac{3a + bc_m - b\Delta \tau_g}{4b}. \]

The manufacturer’s and the retailer’s profits are:

\[ \pi_{M}^{DR*} = \frac{(a - bc_m + b\Delta \tau_g)^2}{8b}, \]
\[ \pi_{R}^{DR*} = \frac{a^2 - 16bf + b (bc_m^2 - 2c_m (a + b\Delta \tau_g) + \tau_g (2a\Delta + (b\Delta^2 - 16C_L) \tau_g))}{16b}. \]

(3) When \( \tau_g \) satisfy \( \tau_g > \tau_2, \) the CLSC exit the market, where

\[ \tau_2 = \frac{b\Delta (a - bc_m) + 4\sqrt{b^2 \Delta^2 + b (a^2 - 16bf - bc_m (2a - bc_m)) C_L}}{b (16C_L - b\Delta^2)}. \]

Proof. Similar to the proof of Proposition 1, we easily prove Proposition 3. \( \square \)

4.3. Comparison of the three CLSC models. In previous sections, a centralized model and two decentralized models based on diverse power structures are analyzed. We obtain the equilibrium solutions for each model and further examine the effect of take-back legislation on the CLSC’s pricing and collection decisions. In this section, we intend to demonstrate the influences of the supply chain structure (centralized vs. decentralized) and channel power structure (manufacturer-led vs. retailer-led) on the equilibrium decisions, profits, and CLSC market behavior in different game scenarios. For ease of comparison, we assume that the government sets the same collection target (i.e., \( \tau_g \)) in the centralized and decentralized models.

**Proposition 4.** When the CLSC’s decisions are not affected by take-back regulation, the equilibrium solutions and the profits of channel members and the whole system satisfy the following relationships:

1. \( w_{DR}^{DM*} > w_{DR}^{DM*}, p_{DR}^{DM*} > p_{DR}^{DR*}, p_{DR}^{I*} > \tau_{DR*}^{DR*} > \tau_{DR*}^{DM*}. \)
2. \( \pi_{R}^{DR*} > \pi_{R}^{DM*}. \) When \( 3b\Delta^2 \leq 8C_L, \pi_{M}^{DM*} > \pi_{M}^{DR*}; \) otherwise, \( \pi_{M}^{DM*} < \pi_{M}^{DR*}. \)

When the CLSC’s decision is affected by take-back regulation, the profits of channel members and the whole system satisfy the following relationships:

1. \( w_{DR}^{DM*} > w_{DR}^{DM*}, p_{DR}^{DM*} = p_{DR}^{DR*} = p_{DR}^{I*} = \tau_{DR*}^{DR*} = \tau_{DR*}^{DM*} = \tau_{R}. \)
2. \( \pi_{R}^{DR*} > \pi_{R}^{DM*}; \pi_{M}^{DR*} > \pi_{M}^{DM*}; \pi_{I}^{DR*} > \pi_{I}^{DM*} = \pi_{I}^{DR*}. \)

Proof. When the CLSC’s decisions are not affected by the regulation, we have

\[ w_{DR}^{DM*} - w_{DR}^{DR*} = \frac{(a - bc_m) (b^2 \Delta^4 - 6b \Delta^2 C_L + 16C_L^2)}{2b (8C_L - b \Delta^2) (4C_L - b \Delta^2)} > 0; \]
Similarly, the results in Proposition 4 under the regulation can also be proved. \(\square\)

Proposition 4 shows that the centralized model leads to the highest channel efficiency for the CLSC system and for consumers. In decentralized decision-making models, as in most current studies, the retail price is lower and return rate is higher in the DR model than that in the DM model. This result is because the manufacturer reduces the wholesale price when the retailer has more channel power, which, in turn, increases market demand. Hence, higher demand results in higher channel performance for the CLSC system in the DR model. However, the manufacturer does not always obtain higher profits when he is the channel leader. Note that when the condition \(3b\Delta^2 \geq 8C_L\) is satisfied, the DR model is more beneficial to the manufacturer. This result holds because the manufacturer’s profit is a tradeoff between the collection cost and the remanufacturing cost savings. The manufacturer tries to increase the return rate to improve firm profit when the remanufacturing cost savings are sufficiently large. The return rate is higher in the DR model than in the DM model, and the higher return rate leads to higher profit for the manufacturer in the DR model when remanufacturing cost savings are sufficiently high.

When the CLSC’s decision is affected by take-back regulation, the main results are consistent with those in the non-regulation case. The differences are as follows. First, the optimal retail prices are the same in the two decentralized models. Second, the manufacturer always obtains a higher profit in the DM model. Furthermore, the channel power structure does not affect the supply chain system’s profit (i.e., \(\pi_T^{DM*} = \pi_T^{DR*}\)).

Proposition 5. The boundary conditions under which the CLSC exits the market in the three models satisfy the following relationship: \(\tau_0 > \tau_1 > \tau_2\).
Proof. Assuming
\[ h_0 (f) = \tau_0 = \frac{b \Delta (a - bc_m) + 2 \sqrt{b^2 f \Delta^2 + b (a^2 - 4bf - bc_m (2a - bc_m)) C_L}}{b (4C_L - b \Delta^2)}, \]
\[ h_1 (f) = \tau_1 = \frac{b \Delta (a - bc_m) + 2 \sqrt{2b^3 f \Delta^2 + 2b (a^2 - 8bf - bc_m (2a + bc_m)) C_L}}{b (8C_L - b \Delta^2)}. \]

The partial derivatives of \( h_0(f) \) and \( h_1(f) \) on \( f \) are:
\[ \frac{\partial h_0 (f)}{\partial f} = -\frac{b}{\sqrt{b^3 f \Delta^2 + b (a^2 - 4bf - bc_m (2a - bc_m)) C_L}}, \]
\[ \frac{\partial h_1 (f)}{\partial f} = -\frac{b}{\sqrt{\frac{1}{2} b^3 f \Delta^2 + \frac{1}{2} b (a^2 - 8bf - bc_m (2a - bc_m)) C_L}}. \]

Furthermore, let
\[ g_1 = b^3 f \Delta^2 + b (a^2 - 4bf - bc_m (2a - bc_m)) C_L, \]
\[ g_2 = \frac{1}{2} b^3 f \Delta^2 + \frac{1}{2} b (a^2 - 8bf - bc_m (2a - bc_m)) C_L, \]
we have \( g_1 - g_2 = \frac{1}{2} b \left( b^2 f \Delta^2 + (a - bc_m)^2 C_L \right) > 0 \). Hence, \( \left| \frac{\partial h_0 (f)}{\partial f} \right| < \left| \frac{\partial h_1 (f)}{\partial f} \right| \), which indicates that the slope of \( h_0(f) \) is lower than that of \( h_1(f) \).

\[ h_0 (0) = \frac{ab \Delta - b^3 \Delta c_m + 2 \sqrt{b(a - bc_m)^2 C_L}}{b(4C_L - b \Delta^2)}, \quad h_1 (0) = \frac{ab \Delta - b^3 \Delta c_m + 2 \sqrt{b(a - bc_m)^2 C_L}}{b(8C_L - b \Delta^2)}, \]
we obtain the following relationship:
\[ h_0 (0) - h_1 (0) = \frac{2 (a - bc_m) \sqrt{bC_L} ((\sqrt{2} - 1) b \Delta^2 + 2C_L (b \Delta + 2 (2 - \sqrt{2})))}{b (8C_L - b \Delta^2) (4C_L - b \Delta^2)} > 0. \]

Hence, \( \tau_0 > \tau_1 \). In a similar way, we can prove \( \tau_1 > \tau_2 \). \( \square \)

As discussed earlier, in both the centralized and decentralized models, the CLSC exits the market if the government sets a sufficiently high collection target. However, the boundary conditions are not the same in the three decision-making models, implying that the supply chain and channel power structures have significant impacts on the CLSC’s marketing and operational decisions. Proposition 5 shows that, because \( \tau_0 \) is the highest, the CLSC can accept a higher collection target set by the government than that in a decentralized model because there is no double marginalization effect in a centralized decision-making system and all decisions in the CLSC are optimal. In the centralized model, all channel players form an alliance and exit the market if they cannot obtain positive profits. Under decentralized models, however, the manufacturer exits the market if he cannot obtain positive profits. Furthermore, when we compare the DM and DR models, it is interesting to find that the CLSC exits the market earlier in the DR model with the regulation. This result can be explained by the following fact. Whether the CLSC exits the market under a decentralized model depends on the manufacturer’s profit, and the manufacturer has relatively less bargaining power in the DR model than in the case in which she acts as the channel leader. Proposition 4 shows that the manufacturer obtains a lower profit in the DR model and, thus, exits the market earlier in that case.
5. The government’s optimal decision. The previous section analyzes the pricing and collection decisions of the CLSC in various decision-making scenarios. Next, we investigate the government’s determination of the optimal collection target and the impacts of the supply chain structure and channel power structure on the government’s decisions. Without loss of generality, the government aims to maximize the total social welfare, which includes three relevant parts: the producer surplus, consumer surplus and environmental performance.

A large body of literature address the inclusion of environmental performance in supply chain management [49, 51]. In line with Yenipazarli [51], it is plausible to assume that each remanufactured product has less environmental impact than a new one. Accordingly, if we do not consider the environmental costs of new or remanufactured products in the production and usage processes. Without loss of generality, we assume that the environmental performance of unit new product is 0, which is viewed as a benchmark compared with the remanufactured product. Then, if we define κ(κ > 0) as the unit environmental performance per remanufactured product, the total environmental performance of the CLSC can be represented as κτ(a − bp).

Further, the producer surplus is the sum of the manufacturer’s and retailer’s profits, and the consumer surplus is \( \frac{1}{2\tau}(a - bp)^2 \). Then, the social welfare is given as:

\[
SW = EP + CS + PS = \kappa\tau^* \left( a - bp^* \right) + \frac{1}{2\tau} \left( a - bp^* \right)^2 + \pi^*_T, \quad i \in \{I, DM, DR\}
\]

(10)

There are two ways to increase social welfare: increasing the producer and consumer surpluses or increasing environmental performance. It is not difficult to see that these two methods conflicts. To represent the government’s heterogenous preferences, we define χ as the preference for producer and consumer surpluses and 1 − χ as the preference for environmental performance. Then, the objective function of the government is:

\[
\max_{\tau_g} SW = (1 - \chi) \kappa\tau_g \left( a - bp^* \right) + \chi \left( \frac{1}{2\tau} \left( a - bp^* \right)^2 + \pi^*_T \right) \\
s.t. \quad \tau_g \geq 0, \quad \frac{1}{2\tau} \left( a - bp^* \right)^2 + \pi^*_T \geq 0.
\]

(11)

In the above optimization problem, χ = 0 implies that the government fully cares about increasing environmental performance, and χ = 1 implies that the government seeks to maximize producer and consumer surpluses. The following proposition summarizes the government’s optimal decisions.

**Proposition 6.** (1) In Model I, when \( \tau_g \leq \frac{\Delta(a-bc_m)}{4C_L-b\Delta} \), the optimal collection target is: \( \tau^*_g = \frac{\Delta(a-bc_m)}{4C_L-b\Delta} \). When \( \frac{\Delta(a-bc_m)}{4C_L-b\Delta} < \tau_g \leq \tau_0 \), if \( \chi > \frac{4b\Delta}{b\Delta(4k-3\Delta)+8C_L} \), \( \tau^*_g = \frac{2(2x(1-\chi)+3\Delta)(a-bc_m)}{8\chi C_L-6\Delta(4x(1-\chi)+3\Delta)} \); otherwise, no equilibrium \( \tau^*_g \) exists.

(2) In Model DM, when \( \tau_g \leq \frac{\Delta(a-bc_m)}{8C_L-b\Delta} \), \( \tau^*_g = \frac{\Delta(a-bc_m)}{8C_L-b\Delta} \). When \( \frac{\Delta(a-bc_m)}{8C_L-b\Delta} < \tau_g \leq \tau_1 \), if \( \chi > \frac{8b\Delta}{b\Delta(8k-\Delta)+82C_L} \), \( \tau^*_g = \frac{4k(1-\chi)+7\Delta)(a-bc_m)}{32\chi C_L-6\Delta(8k(1-\chi)+7\Delta)} \); otherwise, no equilibrium \( \tau^*_g \) exists.

(3) In Model DR, when \( \tau_g \leq \frac{a\Delta-bc_m}{8C_L-2b\Delta} \), \( \tau^*_g = \frac{a\Delta-bc_m}{8C_L-2b\Delta} \). When \( \frac{a\Delta-bc_m}{8C_L-2b\Delta} < \tau_g \leq \tau_2 \), the government’s optimal policy is the same as that in Model DM.
Proof. In Model I, according to Proposition 1, when \( \tau_g < \frac{\Delta (a - bc_m)}{4cL - b\Delta} \), the government’s regulation doesn’t affect the CLSC’s decisions. Because social welfare \( SW \) increases in \( \tau_g \), hence, the government optimal decision is to choose \( \tau_g = \tau^* = \frac{\Delta (a - bc_m)}{4cL - b\Delta} \). Furthermore, when \( \tau_g \geq \frac{\Delta (a - bc_m)}{4cL - b\Delta} \), we can verify that when \( \chi > \frac{4}{b\Delta (4\kappa - 3\Delta) + 8cL} \), social welfare \( SW \) is concave in \( \tau_g \). Then, the FOC is:

\[
\frac{1}{4} ((2\kappa (1 - \chi) + 3\Delta \chi) (a - bc_m) + (b\Delta (4\kappa (1 - \chi) - 3\Delta \chi) + 8\chi CL) \tau_g) = 0.
\]

Solving the equation yields the optimal collection target:

\[
\tau^*_g = \frac{(2\kappa (1 - \chi) + 3\Delta \chi) (a - bc_m)}{8\chi CL - b\Delta (4\kappa (1 - \chi) + 3\Delta \chi)}.
\]

Similarly, we can prove Proposition 6(2) and 6(3).

The social welfare increases in the collection target if the regulation has no impact on the CLSC’s decisions. Hence, the government optimally sets \( \tau_g^* = \tau_i^*, i \in \{I, DM, DR\} \) to maximize social welfare. However, if the government increases the collection target, the environmental performance is higher (more used products), and producer and consumer surpluses are lower (less demand). Consequently, the government’s optimal policy involves a tradeoff between the above two factors. From Proposition 6, it is important to note that the government’s decision is related to its different preferences regarding environmental performance and surplus when the collection target exceeds a specific threshold.

The government’s equilibrium exists only when its preference for producer and consumer surpluses are relatively high, implying that the government should attach enough importance on CLSC firms when setting the collection regulation policy, as the firms will have no incentive to join the market if they cannot obtain positive profit. Furthermore, it is interesting that the government faces the same choice when the regulation come into force regardless of power structure. The power structure only affects the relative states of channel members in the CLSC, and the whole system’s profit is the same in the manufacturer-led and retailer-led models (see Proposition 4). Hence, the government should set the same collection target under both power structures.

6. Closed-loop supply chain coordination. The comparative results in Proposition 4 indicate that decentralized CLSCs have a double marginalization effect, which, in turn, results in an inefficient supply chain system. Thus, it is essential to design appropriate contracts to coordinate decentralized CLSCs. Particularly, the complexity of CLSC coordination increases because we consider the effect of take-back regulation from the government and power structures on the optimal decisions of the CLSC. Next, we examine the use of revenue-sharing (RS) and two-part tariff (TPT) contracts to effectively coordinate the decentralized models considering take-back regulation and power structure. To realize CLSC coordination, the optimal retail price and optimal return rate in contracts must be the same as those in the centralized model, that is, \( p^* = p^I, \tau^* = \tau^I \), where \( i \in \{DM, DR\} \).
6.1. Coordination of model DM. First, we analyze the use of the RS contract for coordinating the manufacturer-led CLSC. The logic of this coordination contract is that the manufacturer promises to offer a lower wholesale price \( w^{CM*} \) to the retailer, and the retailer promises to transfer \( 1 - \phi \) of its sales revenue to the manufacturer. The decision model of the CLSC under this coordination contract is:

\[
\max_{w, \phi} \pi^{CM}_{M} = (w - c_m + \Delta\tau + (1 - \phi) p)(a - bp) - f - C_L\tau^2, \\
\begin{align*}
p^{CM*} &= p^{I*}, \tau^{CM*} = \tau^{I*}, \\
(\phi p - w)(a - bp) &\geq \pi^{DM*}_{R}, \\
(w - c_m + \Delta\tau + (1 - \phi) p)(a - bp) - f - C_L\tau^2 &\geq \pi^{DM*}_{M}, \\
0 &\leq \phi \leq 1.
\end{align*}
\] (12)

When the CLSC is not restricted by take-back regulation, the equilibrium wholesale price under the contract is:

\[
w^{CM*} = \phi \left(4c_m C_L - a\Delta^2\right) \frac{4C_L - b\Delta^2}{4C_L - b\Delta^2}.
\] (13)

If the contract can be implemented, then the manufacturer and retailer need to obtain at least the reservation profits under the decentralized decision-making setting. The range of \( \phi \) can be obtained as follows:

\[
\left(4C_L - b\Delta^2\right)^2 \leq \phi \leq \frac{4C_L - b\Delta^2}{8C_L - b\Delta^2}.
\]

When the CLSC is restricted by take-back regulation, \( \tau^* = \tau_g \). The equilibrium wholesale price \( w^{CM*} \) and equilibrium return rate \( \phi \) under the RS contract are as follows:

\[
w^{CM*} = \phi (c_m - \Delta\tau_g), \frac{1}{4} \leq \phi \leq \frac{1}{2}.
\]

Proposition 7. When the CLSC is not restricted by take-back regulation, the equilibrium wholesale price under the RS contract is \( w^{CM*} = \frac{\phi (4c_m C_L - a\Delta^2)}{4C_L - b\Delta^2} \), and the range of \( \phi \) is \( \left(\frac{4C_L - b\Delta^2}{8C_L - b\Delta^2}\right)^2 \leq \phi \leq \frac{4C_L - b\Delta^2}{8C_L - b\Delta^2} \). When the CLSC is restricted by take-back regulation, the equilibrium wholesale price under the RS contract is \( w^{CM*} = \phi (c_m - \Delta\tau_g) \), and the range of \( \phi \) is \( \frac{1}{4} \leq \phi \leq \frac{1}{2} \).

Next, we consider the coordination by using the TPT contract in the manufacturer-led model. Under this contract, the manufacturer is contracted to offer the wholesale price \( w^{CM*} \) to the retailer, and the retailer then transfers a fixed fee \( F \) to the manufacturer as compensation. The decision model of the CLSC under this contract is as follows:

\[
\max_{w, F} \pi^{CM}_{M} = (w - c_m + \Delta\tau)(a - bp) - f - C_L\tau^2 + F, \\
\begin{align*}
p^{CM*} &= p^{I*}, \tau^{CM*} = \tau^{I*}, \\
\pi^{R}_{R} &= (p - w)(a - bp) - F \geq \pi^{DM*}_{R}, \\
(w - c_m + \Delta\tau)(a - bp) - f - C_L\tau^2 + F &\geq \pi^{DM*}_{M}.
\end{align*}
\] (14)

The equilibrium decisions of the CLSC under the TPT contract are given in the following proposition.
Proposition 8. When the CLSC is not restricted by the take-back regulation, the equilibrium wholesale price under the TPT contract is $w_{CM}^* = \frac{4c_m C_L - a\Delta^2}{4C_L b - b\Delta^2}$, and the parameter $F$ satisfies $16(a-bc_m)^2C_L^2 \leq F_{CR}^* \leq \frac{32(a-bc_m)^2(6C_L - b\Delta^2)C_L^2}{b(8C_L - b\Delta^2)(4C_L - b\Delta^2)^2}$.

When the CLSC is restricted by the take-back regulation, the equilibrium wholesale price under the TPT contract is $w_{CM}^* = c_m - \Delta\tau$, and the range of parameter $F$ satisfies $\frac{(a-bc_m+b\Delta\tau)^2}{8b} \leq F_{CR}^* \leq \frac{3(a-bc_m+b\Delta\tau)^2}{16b}$.

The analysis shows that the manufacturer-led CLSC can be effectively coordinated in the centralized model and that the system profit reaches that under centralized decision-making. The contract parameters $\phi$ and $F$ depend on the bargaining power of each channel member.

6.2. Coordination of model DR. Next, we examine the coordination issue in the retailer-led CLSC. Under the RS contract, the retailer sets the wholesale price $w_{CR}^*$, and the manufacturer transfers a fixed fee $F$ to the retailer as compensation. The decision model of the CLSC under this contract is expressed as:

$$\max_{w, F} \pi_{CR}^* = (p - (1-\phi)w) (a - bp),$$

subject to:

$$p_{CR}^* = p^{I^*}, \tau_{CM}^* = \tau^{I^*},$$
$$w - c_m + \Delta\tau (a - bp) - f - C_L \tau^2 \geq \pi_{DR}^*,$$
$$0 \leq \phi \leq 1.$$ \hspace{1cm} (15)

Under the TPT contract, the retailer sets the wholesale price $w_{CM}^*$, and the manufacturer transfers a fixed fee $F$ to the retailer as compensation. The decision model of the CLSC under this contract is expressed as:

$$\max_{w, F} \pi_{CR}^* = (p - w) (a - bp) + F,$$

subject to:

$$p_{CM}^* = p^{I^*}, \tau_{CM}^* = \tau^{I^*},$$
$$w - c_m + \Delta\tau (a - bp) - f - C_L \tau^2 \geq \pi_{DR}^*,$$
$$0 \leq \phi \leq 1.$$ \hspace{1cm} (16)

The following proposition gives the equilibrium decisions for the above two models.

Proposition 9. (1) Under the RS contract, when the CLSC is not restricted by take-back regulation, $w_{CR}^* = \frac{2(a+\phi+b(2-\phi)c_m)C_L - a\Delta^2}{b\phi(4C_L - b\Delta^2)}$, and the contract parameter $\phi$ satisfies $\frac{1}{4} + \frac{3\phi^2}{16C_L} \leq \phi \leq \frac{1}{2} + \frac{\Delta^2}{8C_L}$. When the CLSC is restricted by take-back regulation, the equilibrium wholesale price is $w_{CR}^* = \frac{a\phi + b(2-\phi)(c_m - \Delta\tau)}{be\phi}$, and the contract parameter satisfies $\frac{1}{3} < \phi < \frac{1}{2}$.

(2) Under the TPT contract, when the CLSC is not restricted by take-back regulation, $w_{CR}^* = \frac{2(a-bc_m)C_L - a\Delta^2}{b(4C_L - b\Delta^2)}$, and contract parameter $F$ satisfies $\frac{(a-bc_m)^2C_L^2}{2b(4C_L - b\Delta^2)} \leq F_{CR}^* \leq \frac{3(a-bc_m)^2C_L^2}{4b(4C_L - b\Delta^2)}$. When the CLSC is restricted by take-back regulation, $w_{CR}^* =$.
and the contract parameter $F$ satisfies $$\frac{a+bcm-b\Delta \tau_g}{3(a-bcm+b\Delta \tau_g)^2} \leq F^{CR^*} \leq \frac{(a-bcm+b\Delta \tau_g)^2}{8b}\frac{a+bcm-b\Delta \tau_g}{3(a-bcm+b\Delta \tau_g)^2}.$$

7. Numerical analysis. Relevant decision-making models have been established in the previous sections, and some basic conclusions have been drawn, but these conclusions are not sufficient to fully understand the impacts of changes in some model parameters on CLSC decision-making and the practical managerial significance of the model. Specifically, we need to investigate the impact of the collection target and power structure on CLSC equilibrium decisions and profits, the government’s optimal decision, and the coordination performance of the contracts. Considering the characteristics of the model and the managerial background of the problem, the numerical analysis focuses on (1) the effects of parameters on the equilibrium decisions and performance of the CLSC, (2) the influence of the parameters $\kappa$ and $\chi$ on the government’s optimal collection target, and (3) the coordination effect of RS and TPT contracts on the decentralized CLSC system.

From the previous analysis, we can see that the government’s take-back regulation has different effects in centralized and decentralized models. However, in the example analysis, to facilitate comparison between the models and determine the managerial significance, we compare the CLSC system across different decision models when it is or is not constrained by the regulation. Following the numerical analyses of [3, 35] and to ensure the feasibility of the theoretical model, the basic parameters are set as follows:

| Parameter | $a$ | $b$ | $cm$ | $\Delta$ | $f$ | $CL$ |
|-----------|-----|-----|------|----------|-----|-----|
| Initial value | 200 | 10  | 10   | 8        | 10  | 900 |

7.1. The influence of parameters on the CLSC and government’s decision. First, as can be seen from Figure 1, when $\tau_g$ is small enough, the take-back regulation generates no effects on the CLSC. The manufacturer and the retailer choose balanced prices and return rates with the aim of maximizing firm profits. When it exceeds a certain threshold, the CLSC is influenced by the take-back regulation. In the case of CLSC decisions based on the government’s collection target, the CLSC’s recovery cost moves inversely with channel revenue. When the recovery cost is large enough, the CLSC opts to withdraw from the market. Based on the analysis, the equilibrium prices $w^*$ and $p^*$ of the manufacturer decrease as $\tau_g$ increases because the regulation limits the pricing power of both channel members, weakening the entire supply chain’s control over the terminal market. In this circumstance, the manufacturer and the retailer can only increase their purchases by reducing the price; otherwise, they incur greater losses. When $\tau_g$ exceeds the acceptable boundary of the CLSC, the manufacturer cannot earn a profit and opts to withdraw from the market.

Next, we analyze the influence of the channel power structure on equilibrium solutions of the CLSC. When the CLSC is not affected by the take-back regulation, the equilibrium retail price is the lowest in centralized decision-making, and the
wholesale price and the retail price are lower in the retailer-led model than that in the manufacturer-led model. This result is because the existence of the double marginalization effect in the decentralized CLSC distorts the optimal pricing of the supply chain, and, thus, the CLSC cannot achieve optimal decision-making efficiency. Moreover, this marginalization effect is clearer in the manufacturer-led CLSC. However, when the CLSC is constrained by the take-back regulation, the channel power structure does not affect the equilibrium price decisions of the CLSC.

Figure 2 analyzes the effect of the parameter $\tau_g$ on the optimal profits of each channel member and the CLSC system. First, each channel member obtains higher profits in the CLSC when they are the leaders because channel leaders can control the pricing and return decisions of the CLSC to achieve higher profits. However, from the perspective of the CLSC system, the profit of the supply chain is highest under centralized decision-making. Further, the supply chain profit is higher in the retailer-led model without take-back regulation, whereas it is the same in the two decentralized models in the take-back regulation. Second, we can observe that the regulation has different effects on the manufacturer and the retailer. The manufacturer’s profit decreases as $\tau_g$ increases, whereas the retailer’s profit increases as $\tau_g$ increases. The reason is that when the CLSC is constrained by the take-back regulation, the government stipulates a higher recycling rate, which directly leads to an increase in the manufacturer’s recycling cost. Thus, the manufacturer’s profit continues to decline. When $\tau_g$ is large enough, the manufacturer cannot make profits and withdraws from the market. However, from the retailer’s perspective, an increase in $\tau_g$ causes the manufacturer to reduce wholesale price and, thus, resulting
in a lower retail price. Thus, the government’s regulation is actually more beneficial to consumers, and the increase in terminal demand leads to an increase in the retailer’s profit.

Figure 3 analyzes the influence of the parameters $\kappa$ and $\chi$ on the government’s optimal collection target decision when the CLSC decision is constrained by the take-back regulation. The parameter $\chi$ indicates the government’s preference for producer and consumer surplus in the case of regulation. Figure 3(a) shows that $\tau_g^*$ declines with $\chi$, which means that if the government prefers to pursue the improvement of profit and consumer surplus in the CLSC system, it chooses to reduce the collection target. This conclusion reflects the impact of the government’s take-back regulation on the remanufacturing industry in different regions of the world.

In countries with earlier government recycling control, such as European countries and the US, governments usually set stricter industry collection targets to improve the recycling efficiency of products. In developing countries, the basic development goal is to increase total GDP, and this goal largely ignores environmental and social benefits in the process of development. Thus, lower collection targets are set. Further comparison shows that the government sets a higher collection target under centralized decision-making because the decision-making efficiency of the CLSC system in this case reaches the optimal level, and the government has more opportunity to choose a higher collection target and to maximize the overall social welfare level. However, in the two decentralized decision-making models, the government’s optimal choice is completely consistent, which shows that the change in the channel power structure does not affect the government’s choice of collection target.

Figure 3(b) reflects the influence of the unit environmental performance of remanufacturing on the government’s optimal decision. The figure shows that if the remanufactured product can bring a better environmental performance, the government sets a higher collection target because the increase in environmental performance achieves a synchronous increase in overall social welfare. In general, the determination of the government’s optimal collection target is the result of a trade-off between economic and environmental benefits. The specific choice should be considered in combination with the actual situation and the development strategy.

7.2. Analysis of the coordination performance of the CLSC. This section verifies the coordinating effect of contracts on the decentralized CLSC system. The
calculation shows that in the manufacturer-led model, the parameter range for a RS contract in the CLSC is \( \phi^* \in [0.2036, 0.4512] \) when the CLSC is not constrained by the take-back regulation and \( \phi^* \in [0.25, 0.5] \) when the CLSC is constrained by the regulation. In the retailer-led model, the parameter range for the RS contract in the CLSC is \( \phi^* \in [0.3833, 0.5899] \) when the CLSC is not constrained by the take-back regulation and \( \phi^* \in [0.25, 0.5] \) when the CLSC is constrained by the regulation. Combining coordination contracts in different decision models, we assume that \( \phi^* = 0.4 \). In the manufacturer-led model, the parameter \( F \) for the TPT contract in the CLSC should satisfy \( F^* \in [202.937, 294.505] \) when it is not constrained by the take-back regulation and should satisfy \( F^* \in [192.2, 288.3] \) when it is constrained by the regulation. In the retailer-led model, the parameter \( F \) for the TPT contract in the CLSC should satisfy \( F^* \in [152.027, 228.041] \) when it is not constrained by the take-back regulation and should satisfy \( F^* \in [192.2, 288.3] \) when it is constrained by the regulation. Combining the coordination contracts in different decision models, we assume that \( F^* = 215 \). Tables 2 and 3 show the equilibrium decisions results of the CLSC under RS and TPT contracts.

**Table 3. Comparison of equilibrium decisions in CLSC under RS contract**

| Model  | DM | DR | CM | CR | \( I \) | Model  | DM | DR | CM | CR | \( I \) |
|--------|----|----|----|----|------|--------|----|----|----|----|------|
| \( w^* \) | 14.51 | 11.96 | 3.14 | 25.68 | - | \( w^* \) | 13.80 | 10.70 | 3.04 | 25.20 | - |
| \( p^* \) | 17.26 | 16.96 | 13.92 | 13.92 | 13.92 | \( p^* \) | 16.90 | 16.90 | 13.80 | 13.80 | 13.80 |
| \( \tau^* \) | 0.12 | 0.14 | 0.27 | 0.27 | 0.27 | \( \tau^* \) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| \( \pi^*_M \) | 127.20 | 66.01 | 146.14 | 72.18 | - | \( \pi^*_M \) | 101.20 | 5.10 | 139.64 | 62.76 | - |
| \( \pi^*_R \) | 75.29 | 152.00 | 147.92 | 221.88 | - | \( \pi^*_R \) | 96.10 | 192.20 | 153.76 | 230.64 | - |
| \( \pi^*_T \) | 202.49 | 218.01 | 294.10 | 294.10 | 294.10 | \( \pi^*_T \) | 197.30 | 197.30 | 293.40 | 293.40 | 293.40 |

**Table 4. Comparison of equilibrium decisions under TPT contract**

| Model  | DM | DR | CM | CR | \( I \) | Model  | DM | DR | CM | CR | \( I \) |
|--------|----|----|----|----|------|--------|----|----|----|----|------|
| \( w^* \) | 14.51 | 11.96 | 7.84 | 13.92 | - | \( w^* \) | 13.80 | 10.70 | 7.60 | 13.80 | - |
| \( p^* \) | 17.26 | 16.96 | 13.92 | 13.92 | 13.92 | \( p^* \) | 16.90 | 16.90 | 13.80 | 13.80 | 13.80 |
| \( \tau^* \) | 0.12 | 0.14 | 0.27 | 0.27 | 0.27 | \( \tau^* \) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| \( \pi^*_M \) | 127.20 | 66.01 | 139.30 | 79.05 | - | \( \pi^*_M \) | 101.20 | 5.10 | 124.00 | 78.40 | - |
| \( \pi^*_R \) | 75.29 | 152.00 | 154.80 | 215.05 | - | \( \pi^*_R \) | 96.10 | 192.20 | 169.40 | 215.00 | - |
| \( \pi^*_T \) | 202.49 | 218.01 | 294.10 | 294.10 | 294.10 | \( \pi^*_T \) | 197.30 | 197.30 | 293.40 | 293.40 | 293.40 |

Tables 2 and 3 show that in a decentralized CLSC, considering the government’s take-back regulation and the channel power structure, both RS and TPT contracts can achieve CLSC coordination. Under these contracts, the equilibrium price and recovery rate in the CLSC are the same as those under centralized decision-making. Both channel members increase their profits, and the profit of the CLSC system reaches the optimal value in the centralized model. The determination of the optimal parameter in the RS contract \( \phi^* \) and the optimal transfer payment scale \( F^* \)
in the TPT contract depends on the negotiation power of the manufacturer and the retailer in the contract implementation. Figure 4 analyzes the influence of the parameter $\Delta$ on the parameters $\phi^*$ and $F^*$ of the coordination contract in the CLSC without any regulation. The figure shows that under a PS contract, when the remanufacturing cost saving $\Delta$ is low enough, a change in the channel power structure has little effect on the optimal revenue sharing ratio $\phi^*$. However, with an increase in $\Delta$, in the manufacturer-led model, the proportion $(1 - \phi^*)$ of the retailer’s sales revenue to the manufacturer continues increasing, whereas, in the retailer-led model, the proportion $(1 - \phi^*)$ of the manufacturer’s wholesale revenue to the retailer continues decreasing. Similarly, the optimal transfer payment scale $F^*$ under the TPT contract increases with an increase in $\Delta$, and the difference $\bar{F}_{CM}^* - \bar{F}_{CR}^*$ also continues to increase. Thus, the contract plays a more significant role in coordinating the CLSC under the manufacturer-led model.

![Figure 4](image_url)

**Figure 4.** Effects of $\Delta$ on contract parameters $\phi^*$ and $F^*$

8. **Concluding remarks.** Focusing on the two-tier CLSC composed of a manufacturer and a retailer, this study explores the impact of a take-back regulation and the channel structure on pricing and return decisions and coordination of the CLSC. First, we establish a centralized decision-making model and two decentralized models based on different power structures. The model is solved using backward induction, and the equilibrium decisions of different models are compared. The results show that the government’s take-back regulation has an important impact on the channel players’ optimal decisions. Specifically, the government can set a higher collection target under centralized decision-making than under decentralized decision-making. Compared with the two decentralized decision-making models, the government’s take-back regulation has a more significant impact on the retailer-led model, and the CLSC withdraws from the market earlier. Second, we analyze the determination of the government’s optimal collection target. The goal of government decision-making is based on the comprehensive consideration of the producer surplus, the consumer surplus, and environmental performance. The analysis shows that the government’s optimal choice depends on the government’s preference for economic and environmental benefits. When the decision-making of the CLSC is constrained by the take-back regulation, the government’s optimal collection target is not affected by the channel power structure of the CLSC. Third, we find RS and TPT contracts can effectively coordinate the CLSC with the take-back regulation.
under different power structures. Finally, numerical examples are provided to analyze the impacts of key parameters on the equilibrium outcomes and the CLSC’s profit, and relevant management implications are obtained.

The managerial insights of this study are as follows. First, the manufacturers’ pricing and return decisions are affected by the government’s take-back legislations as well as supply chain/channel power structures. When determining whether to implement product collection and remanufacturing activities, manufacturers should take the above factors into consideration and then make strategic decisions, namely, choosing to exit the market earlier in the decentralized decision-making models compared with the centralized model. Second, from the perspective of governments, they play an essential role in adjusting the manufacturers’ pricing and return decisions via setting a flexible collection target. For example, in a retailer-led CLSC model, the government can set a lower collection target. Third, even though facing the government’s take-bake regulation, the decentralized CLSC models still can be coordinated by a revenue-sharing or a two-part tariff contract, manufacturers and retailers are suggested to proactively achieve supply chain coordination by implementing the above two contracts.

In sum, although this study offers a preliminary discussion of the coordination of the CLSC under take-back legislation and draws relevant conclusions, this topic still merits further discussion. First, this study does not consider the differences between new and remanufactured products, and it is of greater practical significance to discuss the interplay between the take-back regulation and CLSC’s decisions in that case. Second, this study does not consider the impact of information uncertainty on CLSC decision-making, and understanding this question in the context of asymmetric demand or cost information is a topic for future study.

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REFERENCES

[1] S. Alizamir, F. Iravani and H. Mamani, An analysis of price vs. revenue protection: Government subsidies in the agriculture industry, Management Science, 65 (2018), 1–18.
[2] A. Arya and B. Mittendorf, Supply chain consequences of subsidies for corporate social responsibility, Production and Operations Management, 24 (2015), 1346–1357.
[3] A. Atasu, L. N. Van Wassenhove and M. Sarvary, Efficient take-back legislation, Production and Operations Management, 18 (2009), 243–258.
[4] A. Atasu and L. N. Van Wassenhove, An operations perspective on product take-back legislation for e-waste: Theory, practice, and research needs, Production and Operations Management, 21 (2012), 407–422.
[5] A. Atasu, L. B. Toktay and L. N. Van Wassenhove. How collection cost structure drives a manufacturer’s reverse channel choice, Production and Operations Management, 22 (2013), 1089–1102.
[6] Q. G. Bai, M. Y. Chen and L. Xu, Revenue and promotional cost-sharing contract versus two-part tariff contract in coordinating sustainable supply chain systems with deteriorating items, *International Journal of Production Economics*, 187 (2017), 85–101.

[7] I. Biswas, A. Raj and S. K. Srivastava, Supply chain channel coordination with triple bottom line approach, *Transportation Research Part E: Logistics and Transportation Review*, 115 (2018), 213–226.

[8] G. S. Cai, Z. G. Zhang and M. Zhang, Game theoretical perspectives on dual-channel supply chain competition with price discounts and pricing schemes, *International Journal of Production Economics*, 117 (2009), 80–96.

[9] C. K. Chen and M. Akmalul Ulya, Analyses of the reward-penalty mechanism in green closed-loop supply chains with product remanufacturing, *International Journal of Production Economics*, 210 (2019), 211–223.

[10] X. Chen and X. J. Wang, Free or bundled: Channel selection decisions under different power structures, *Omega*, 53 (2015), 11–20.

[11] X. Chen, X. J. Wang and H. K. Chan, Manufacturer and retailer coordination for environmental and economic competitiveness: A power perspective, *Transportation Research Part E: Logistics and Transportation Review*, 97 (2017), 268–281.

[12] J. Y. Chen, S. Dimitrov and H. Pun, The impact of government subsidy on supply Chains’ sustainability innovation, *Omega*, 86 (2019), 42–58.

[13] P. Chintapalli, S. M. Disney and C. S. Tang, Coordinating supply chains via advance-order discounts, minimum order quantities, and delegations, *Production and Operations Management*, 26 (2017), 2175–2186.

[14] T. M. Choi, Y. J. Li and L. Xu, Channel leadership, performance and coordination in closed loop supply chains, *International Journal of Production Economics*, 146 (2013), 371–380.

[15] J. Ding, W. Chen and W. Wang, Production and carbon emission reduction decisions for remanufacturing firms under carbon tax and take-back legislation, *Computers & Industrial Engineering*, 143 (2020), 106419.

[16] G. Esenduran, A. Atasu and L. N. Van Wassenhove, Valuable e-waste: Implications for extended producer responsibility, *IISE Transactions*, 51 (2019), 382–396.

[17] G. Esenduran, E. Kemahlioglu-Ziya and J. M. Swaminathan, Impact of take-back regulation on the remanufacturing industry, *Production and Operations Management*, 26 (2017), 924–944.

[18] G. Esenduran and E. Kemahlioglu-Ziya, A comparison of product take-back compliance schemes, *Production and Operations Management*, 24 (2015), 71–88.

[19] L. Feng, K. Govindan and C. Li, Strategic planning: Design and coordination for dual-recycling channel reverse supply chain considering consumer behavior, *European Journal of Operational Research*, 260 (2017), 601–612.

[20] J. H. Gao, H. S. Han, L. T. Hou and H. Y. Wang, Pricing and effort decisions in a closed-loop supply chain under different channel power structures, *Journal of Cleaner Production*, 112 (2016), 2043–2057.

[21] L. Y. Gui, A. Atasu, O. Ergun and L. Toktay, Design incentives under collective extended producer responsibility: A network perspective, *Management Science*, 64 (2018), 5083–5104.

[22] L. Y. Gui, A. Atasu, O. Ergun and L. B. Toktay, Efficient implementation of collective extended producer responsibility legislation, *Management Science*, 62 (2015), 1098–1123.

[23] P. Hasanov, M. Y. Jaber and N. Tahirov, Four-level closed loop supply chain with remanufacturing, *Applied Mathematical Modelling*, 66 (2019), 141–155.

[24] P. He, Y. He and H. Xu, Channel structure and pricing in a dual-channel closed-loop supply chain with government subsidy, *International Journal of Production Economics*, 213 (2019), 108–123.

[25] Q. He, N. Wang, Z. Yang, Z. He, Zheng and B. Jiang, Competitive collection under channel inconvenience in closed-loop supply chain, *European Journal of Operational Research*, 275 (2019), 155–166.
26. Y. He, Acquisition pricing and remanufacturing decisions in a closed-loop supply chain, *International Journal of Production Economics*, 163 (2015), 48–60.
27. Y. He, X. Zhao, Contracts and coordination: Supply chains with uncertain demand and supply, *Naval Research Logistics*, 63 (2016), 305–319.
28. X. Hong, L. Wang, Y. Gong and W. Chen, What is the role of value-added service in a remanufacturing closed-loop supply chain?, *International Journal of Production Research*, 59 (2020), 3342–3361.
29. Z. Hong, H. Wang and Y. Gong, Green product design considering functional-product reference, *International Journal of Production Economics*, 210 (2019), 155–168.
30. L. Hsiao, Y. J. Chen and H. Xiong, Supply chain coordination with product line design and a revenue sharing scheme, *Naval Research Logistics*, 66 (2019), 213–229.
31. X. Huang, A. Atasu and L. B. Toktay, Design implications of extended producer responsibility for durable products, *Management Science*, 65 (2019), 2573–2590.
32. B. W. Jacobs and R. Subramanian, Sharing responsibility for product recovery across the supply chain, *Production and Operations Management*, 21 (2012), 85–100.
33. Z. J. Ma, Y. S. Ye, Y. Dai and H. Yan, The price of anarchy in closed-loop supply chains, *International Transactions in Operational Research*, 2019.
34. T. Maiti and B. C. Giri, A closed loop supply chain under retail price and product quality dependent demand, *Journal of Manufacturing Systems*, 37 (2015), 624–637.
35. S. Mitra and S. Webster, Competition in remanufacturing and the effects of government subsidies, *International Journal of Production Economics*, 111 (2008), 287–298.
36. G. Raz and G. C. Souza, Recycling as a strategic supply source, *Production and Operations Management*, 27 (2018), 902–916.
37. S. Sarkar, S. Tiwari, H. M. Wee and B. C. Giri, Channel coordination with price discount mechanism under price–sensitive market demand, *International Transactions in Operational Research*, 27 (2020), 2509–2533.
38. R. C. Savaskan, S. Bhattacharya and L. N. Van Wassenhove, Closed-loop supply chain models with product remanufacturing, *Management Science*, 50 (2004), 133–279.
39. R. C. Savaskan and L. N. Van Wassenhove, Reverse channel design: The case of competing retailers, *Management Science*, 52 (2006), 1–14.
40. M. A. Sieke, R. W. Seifert and U. W. Thonemann, Designing service level contracts for supply chain coordination, *Production and Operations Management*, 21 (2012), 698–714.
41. R. Sousa, E. Agante, J. Cerejeira and M. Portela, EEE fees and the WEEE system-A model of efficiency and income in European countries, *Waste Management*, 79 (2018), 770–780.
42. R. Subramanian, S. Gupta and F. B. Talbot, Product design and supply chain coordination under extended producer responsibility, *Production and Operations Management*, 18 (2009), 259–277.
43. F. Toyasaki, T. Boyaci and V. Verter, An analysis of monopolistic and competitive take-back schemes for WEEE recycling, *Production and Operations Management*, 20 (2011), 805–823.
44. W. B. Wang, S. Q. Yang, L. Xu and X. L. Yang, Carrot/stick mechanisms for collection responsibility sharing in multi-tier closed-loop supply chain management, *Transportation Research Part E: Logistics and Transportation Review*, 125 (2019), 366–387.
45. N. Wang, Y. Song, Q. He and T. Jia, Competitive dual-collecting regarding consumer behavior and coordination in closed-loop supply chain, *Computers & Industrial Engineering*, 144 (2020), 106481.
46. J. Wei and J. Zhao, Reverse channel decisions for a fuzzy closed-loop supply chain, *Applied Mathematical Modelling*, 37 (2013), 1502–1513.
47. C. H. Wu, Price and service competition between new and remanufactured products in a two-echelon supply chain, *International Journal of Production Economics*, 140 (2012), 496–507.
48. W. Xiao, C. Gaimon, R. Subramanian and M. Biehl, Investment in environmental process improvement, *Production and Operations Management*, 28 (2019), 407–420.
49. G. Xie, Modeling decision processes of a green supply chain with regulation on energy saving level, *Computers & Operations Research*, 54 (2015), 266–273.
[50] L. Yang, G. S. Cai and J. Chen, Push, pull, and supply chain risk averse attitude, *Production and Operations Management*, 27 (2018), 1534–1552.

[51] A. Yenipazarli, Managing new and remanufactured products to mitigate environmental damage under emissions regulation, *European Journal of Operational Research*, 249 (2016), 117–130.

[52] C. T. Zhang, M. L. Ren, Closed-loop supply chain coordination strategy for the remanufacture of patented products under competitive demand, *Applied Mathematical Modelling*, 40 (2016), 6243–6255.

[53] B. Zheng, C. Yang, J. Yang and M. Zhang, Dual-channel closed loop supply chains: Forward channel competition, power structures and coordination, *International Journal of Production Research*, 55 (2017), 3510–3527.

[54] B. Zheng, N. Yu, L. Jin and H. Xia, Effects of power structure on manufacturer encroachment in a closed-loop supply chain, *Computers & Industrial Engineering*, 137 (2019), 106062.

[55] J. Zhu, C. Fan, H. Shi and L. Shi, Efforts for a circular economy in China: A comprehensive review of policies, *Journal of Industrial Ecology*, 23 (2019), 110–118.

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