Applied Mathematical Modelling 95 (2021) 484–502

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Recycling channel selection and coordination in dual sales channel closed-loop supply chains

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ARTICLE INFO

Article history:
Received 18 March 2020
Revised 5 January 2021
Accepted 14 February 2021
Available online 25 February 2021

Keywords:
Closed-loop supply chain
Direct and traditional channel competition
Recycling channel selection
Supply chain coordination

ABSTRACT

The implications of dual sales channels (direct and traditional retail channels) and closed-loop supply chains (CLSCs) have been well recognized in the literature and in practice. In this study, we explore the reverse channel choice for the manufacturer and the design of coordination mechanisms in CLSCs in the midst of dual competitive sales channels. We consider three recycling channel structures: manufacturer collecting (Model M), retailer collecting (Model R) and third-party collecting (Model C) structures. We present the following findings. The manufacturer and the retailer obtain more profits in Model M and Model R, respectively. However, from the perspective of the supply chain system, either the M model or the R model could be optimal depending on the following parameters: channel competition intensity between the direct and retail channels, collection costs and remanufacturing cost savings. Furthermore, we show that a simple price contract that consists of the wholesale price, direct channel price and transfer price of the used product (in Model R and Model C), with a complementary profit sharing mechanism can effectively coordinate dual-channel CLSCs under different recycling channel structures.

1. Introduction

In a closed-loop supply chain (CLSC), the manufacturer faces the crucial question of how to choose an effective reverse channel to collect used products? Reverse channel selection directly impacts the manufacturer's profits, environmental performance and social welfare. From industry observations, Savaskan et al. [1] are the first to put forward three reverse channel modes: (1) the manufacturer collecting mode, (2) retailer collecting mode and (3) third-party collecting mode. These three structures are extensively adopted by manufacturing firms in practice. For example, Huawei has built 705 collection centers by the end of 2016 covering 36 countries and regions. Meanwhile, the firm has developed new collection modes to improve collection efficiency such as the "online-to-offline" model and "trade-in" models, etc[1]. Fuji Photo Film also directly collects the EOL (end-of-life) products [2]. However, some popular manufacturers prefer to outsource their collection activities to other parties in the supply chain [3,4]. For example, Sony has been implementing the GreenFill Program which provides collection kiosks for its retailers to collect used electronics [5]. Similar reverse channel structures are widely adopted in the pharmaceutical industry, and some pharmaceutical producers often collaborate with the retailers to collect the unwanted or

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[1] https://www.huawei.com/cn/about-huawei/sustainability/sustainability-report/2018

https://doi.org/10.1016/j.apm.2021.02.022

unused medications [6]. Specifically, considering the scale economy effect of used product collection, a variety of independent third-party collectors have emerged to meet the rapid development of the remanufacturing industry, including IBM's Global Asset Recovery Services [7].

A number of factors affect the return efficiency of the manufacturer, such as retailer competition [8], the collection cost structure [4] and supply chain competition [2]. However, the sales channel model (single or dual sales channel model) also plays a pivotal role in the manufacturer's selection of the reverse channel. With the development of the Internet and emerging technologies, an increasing number of firms have used the direct sales channel, in addition to the traditional retail channel [9,10]. Famous electronic manufacturers (e.g., Apple, Huawei and Lenovo) have adopted the mixed channel strategy to sell products and have achieved great success. In practice, many firms with dual sales channels often collect used products for remanufacturing. The Chinese government has enacted relevant policies to encourage firms to reform traditional collection modes in order to follow trends of Internet development[2]. The introduction of the direct channel leads to channel conflict, which, in turn, influences the manufacturer's decisions regarding whether to choose the recycling channel. However, much of the existing literature on reverse channel selection assumes that presence of a single sales channel model, leaving the interplay between the forward sales channel competition and the reverse channel selection unclear. This has created a research gap in the recycling channel selection of CLSCs with dual competitive sales channels.

For a single sales channel, Savaskan et al. [1] show that the retailer collecting mode is the most efficient option for the manufacturer. The manufacturer transfers all remanufacturing cost savings to the retailer to increase demand, which alleviates the "double marginalization" effect in the channel. However, for dual competitive sales channels, the manufacturer obtains more channel power through the complete control of the direct channel. Will the manufacturer also transfer all remanufacturing cost savings to the retailer? The answer is no, we find that the manufacturer at most reimburses the retailer 75% percentage of the remanufacturing cost savings. Therefore, is the retailer collecting mode optimal for the manufacturer in a CLSC when facing two competitive sales channels? If not, how does channel competition affect the manufacturer's optimal reverse channel decisions? In addition, from the perspectives of the retailer and supply chain system, which reverse channel structure is optimal?

If the direct and traditional channels coexist, eliminating channel conflict and achieve channel coordination are crucial for each player in the supply chain. Especially in a CLSC, the forward sales channel and reverse collecting channel must coordinate before the system can achieve the optimal performance. Existing studies mainly focus on designing contracts in a CLSC with a single sales channel. Therefore, we aim to design effective contracts to coordinate CLSC with dual competitive sale channels. We further explore the effect of the reverse channel structure on the optimal contract-implementing Pareto zones of different contracts under three scenarios.

We contribute to the existing literature in the following two aspects. First, we embed the sales channel competition factor into a CLSC model and explore the manufacturer's optimal reverse channel selection. We show that in equilibrium, the manufacturer should optimally choose to collect used products directly from the consumers. Specifically, for the supply chain system, the manufacturer collecting or the retailer collecting mode could be either optimal depending on three key factors, namely, competition intensity of two sales channels, collection costs and remanufacturing cost savings. Second, we show that a simple price contract including the wholesale price, direct channel price and transfer price (under the retailer collecting and third-party collecting modes) with a complementary revenue sharing scheme can perfectly coordinate CLSCs under different reverse channel structures. To our knowledge, this is one of the early studies to address the pricing and coordination problems regarding the interaction between sales channel competition and reverse channel selection in a CLSC.

The remainder of this study proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the problem explored and presents our model assumptions. Section 4 establishes the centralized model and three decentralized dual-channel CLSC models. Section 5 compares the equilibrium outcomes and profits of the different models. Section 6 examines the coordination contract design problem. Section 7 concludes the study, provides managerial insights and discusses avenues for future research. All proofs are relegated to the online Appendices.

2. Literature review

Our study is closely related to the following three research streams: direct and traditional sales channel competition, reverse channel design and CLSC coordination. We review these areas of research sequentially.

2.1. Direct and traditional sales channel competition

The introduction of the direct channel generates channel conflict between the manufacturer and the retailer. Many studies have focused on analyzing the effects of the dual sales channel model on supply chains [11–17]. Chiang et al. [11] analyze the strategic implications of direct marketing for the manufacturer and the retailer, and find that the direct channel may not always be detrimental to the retailer due to the wholesale price reduction effect. Ofek et al. [12] consider a case involving competing retailers who manage dual channels; the authors obtain the optimal condition when the firms introduce an online channel and study the effect of product returns on channel selection strategies. Hsiao and Chen [13] examine the relationships between introducing the online channels, pricing strategies and channel structures. However, none of the above

[2] http://politics.people.com.cn/n/2015/0421/c70731-26876394.html

studies consider ways to mitigate channel conflict. Relevant literature explores coordination contract design in dual-channel supply chains [18–21,56].

Arya et al. [22] find that supplier encroachment might be beneficial to the retailer when the cost advantage of the traditional retail channel is sufficiently pronounced. Ha et al. [23] study the manufacturer encroachment problem in a supply chain when product quality is an endogenous decision. The authors show that quality differentiation may hurt the manufacturer or the retailer. Cui [24] studies how to use the quality investment to deter the contract manufacturer's channel encroachment into the original manufacturer's market. On this basis, some studies explore the channel encroachment under incomplete information scenarios [25–29]. However, these studies focus on decisions made in a forward supply chain, and we contribute to these studies by considering the effects of product collection and remanufacturing on manufacturer's optimal reverse channel selection.

2.2. Reverse channel design

Reverse channel design is a basic issue in CLSC management, and choosing the appropriate reverse channel can improve supply chain profits and environmental performance. Savaskan et al. [1] are the first to put forward three reverse channel structures: manufacture collecting, retailer collecting and third-party collecting. They conclude that the retailer, who is closer to the final market, is the most effective undertaker of used product collection. Toyasaki et al. [30] compare two prevailing take-back schemes: monopolistic and competitive. Atasu et al. [4] study the effect of the collection cost structure on reverse channel selection in a CLSC. The authors observe that the manufacturer's optimal reverse channel choice depends on how the collection cost shapes the retailer's sale and quantity decisions. De Giovanni and Zaccour [31] identify the manufacturer's optimal reverse channel choices in a two-period setting. Chuang et al. [32] consider a CLSC for high-tech products and examine the effects of collection cost structures and government regulation on the manufacturer's reverse channel selection. He et al. [33] investigate recovery strategies under the collection competition and inconvenience perceptions in collection.

Meanwhile, some researchers have extended the model to a competitive environment. Savaskan and Van Wassenhove [8] explore the problem of reverse channel design in CLSCs with competing retailers. The authors find that the scale of the collection cost determines channel profits under the direct collecting mode while supply chain profits are dominated by the degree of competition between retailers in the indirect collecting mode. Wang et al. [34] study collection and pricing decisions in a CLSC by considering competing retailers' collusion behavior. Wu and Zhou [2] examine the manufacturer's optimal reverse channel choice under supply chain competition. However, the sales channel competition factor is ignored in these studies. Specifically, few studies examine pricing and coordination strategies in CLSCs with dual sales channels [33,35–37]. Most related to our research, Saha et al. [38] investigate reverse channel selection and coordination issues in a dual-channel CLSC by considering a reward-driven remanufacturing policy. Different from Saha et al. [38], we assume that the return rate directly relates to market demand and is determined by the collection party, while the return policy depends on the remanufacturing reward in their model. In addition, we consider the interplay between CLSC environmental performance and recycling channel structures in the presence of sales channel competition, which is not considered in their study.

2.3. CLSC coordination

Many existing studies address the coordination of a CLSC in a single sales channel environment [1,31,39–42,55]. When the manufacturer introduces a direct channel, the coordination of the dual-channel CLSC becomes more complicated due to sales channel competition. Saha et al. [38] consider the reward-driven policy of collected used products for the manufacturer and find that a three-way discount mechanism can coordinate the channel and lead to “win-win” outcomes. Xie et al. [43] investigate joint pricing and advertising decisions in a dual-channel CLSC and design a revenue sharing mechanism considering the recycling rate and recycling revenue sharing ratio to coordinate a decentralized CLSC. Zheng et al. [35] explore pricing decisions and coordination in third-party collecting dual-channel CLSCs with different channel power structures. Taleizadeh et al. [36] examine the effect of marking effort investment on pricing and coordinate decisions in dual-channel CLSCs. Differing from the above studies, this study designs appropriate contracts for coordinating dual channel CLSCs under different reverse channel structures, and we further explore how the collection structure impacts the manufacturer's and retailer's bargaining power in the contracts.

2.4. Research gaps and our contributions

According to the above subsections that review the related literature, we compare our study with the above-mentioned research works in Table 1 and summarize current research gaps and our contributions as follows.

First, unlike the research on direct and traditional sales channel competition that considers sales channel competition in a forward supply chain management environment, we incorporate product collection and remanufacturing into the manufacturer's decision making in a CLSC environment. In addition, the impacts of sales channel competition on return decisions are explicitly investigated.

Table 1
Comparison between our study and related literature.

Research paper	Sales channel competition	Multiple recycling channels	Return rate policy	Supply chain coordination	CLSC environmental performance
Chiang et al. [11]	√			√	
Hsiao and Chen [13]	√				
Shi et al. [21,56]	√			√	
Mukhopadhyay et al. [18]	√			√	
Savaskan et al. [1]		√	√	√	
Toyasaki et al. [30]		√			√
Atasu et al. [4]		√	√		
He et al. [33]		√	√	√	
Wu and Zhou [2]		√	√		
Savaskan and Van Wassenhove [8]		√	√	√	
Xie et al. [43]	√		√	√	
Choi et al. [39]			√	√	
Zheng et al. [42,55]			√	√	
Zheng et al. [35]	√		√	√	
Taleizadeh et al. [36]	√		√	√	
Saha et al. [38]	√	√		√	
Our work	√	√	√	√	√

Second, unlike the research on reverse channel design, which often studies a CLSC with a single sales channel, we study a more complex CLSC structure with sales channel competition between direct and traditional channels. Moreover, we consider the environmental performance issues that emerge within different recycling channel structures.

Third, unlike the research on CLSC coordination that considers coordination contract design in a dual-channel CLSC, we conduct a comprehensive analysis of CLSC coordination and recycling channel structures. More importantly, we compare the optimal contract-implementing Pareto zones of coordination contracts under different recycling structures. Our study offers a stronger understanding of the impacts of sales channel competition on reverse channel design and coordination in dual-channel CLSCs.

3. Model preliminaries

We consider a CLSC that consists of a manufacturer and a retailer. Differing from traditional single channel CLSC models introduced by Savaskan et al. [1], in our model the manufacturer has an alternative choice to distribute products: selling through the direct channel (direct selling mode) and wholesaling through the traditional channel (wholesaling mode). In the reverse supply chain, consistent with Savaskan et al. [1], the manufacturer has three options to collect used products: (1) the manufacturer undertakes the collection activity directly by itself, (2) the manufacturer entrusts the retailer to collect used products, or (3) the manufacturer outsources the collection activity to an independent third-party collector. We aim to explore the strategic effects of sales channel competition on the manufacturer's reverse channel selection.

Generally, manufacturing a remanufactured product from a used product costs less than manufacturing a new product from raw materials. It is estimated that remanufacturing can save a company 40% to 60% in costs relative to new product manufacturing [44]. Hence, we assume that the unit cost of remanufactured product c_r is lower than the unit cost of a new product c_m, i.e., $c_r < c_m$. Then, let Δ be the unit remanufacturing cost savings of each remanufactured product and $\Delta = c_m - c_r$. Furthermore, we assume that customers value no difference between new and remanufactured products, as this assumption is widely adopted in the CLSC literature [1,8,45]. Also, the assumption is reasonable in practice. A well-known example of an undifferentiated new and remanufactured products is the Kodak single-use camera; customers do not care whether Kodak utilizes used parts in the manufacturing of its cameras [4].

To characterize reverse channel performance, let τ be the return rate, which denotes the fraction of the sales volume remanufactured from used products, i.e., $0 \le \tau < 1$. Consistent with Savaskan et al. [1], return rate τ can be viewed as the effort the collector invests into used product collection. For simplicity, the variable cost of collecting used products is assumed to be 0, which does not alter the main results in our study. Hence, we use the quadratic function to characterize the total collection cost, which is a function of the return rate τ, that is, $C(\tau) = K\tau^2$. Parameter K is a scaling parameter that measures collection efficiency. The convex and increasing properties of this cost function capture the nature of the product collection process that achieving a small increase of the high return rate would require a substantive additional investment in collection. The validity of the quadratic collection cost structure in the CLSC context has been explicitly discussed in Atasu et al. [4], Furguson and Toktay [46] and Ovchinnikov [47]. In particular, Atasu et al. [4] empirically analyze the cost structure of the product collection with two data sets in two different industries and observe the quadratic cost curves for the both data sets. According to previous assumptions of production costs, the average production cost can be rewritten as

$c = \tau c_r + (1-\tau)c_m = c_m - \Delta\tau$[3]. In our study, to focus on analyzing the interaction between sales channel competition and reverse channel choice, we assume that all return units can be successfully remanufactured by the manufacturer consistent with many remanufacturing studies [1,8][4].

Next, we model the interplay between the direct channel and traditional channel. The addition of a direct channel leads to the channel competition, and this competition effect has a profound impact on the manufacturer's and retailer's decisions in a CLSC. The channel competition effect has been characterized by multiple ways in existing studies [11,18,22]. Consistent with Cai [19], Zheng et al. [35] and Abhishek et al. [48], we use a similar utility function for a representative consumer, which is determined by:

$$U = \sum_{i=d,t}\left(a_i q_i - \frac{q_i^2}{2}\right) - \rho q_i q_j - \sum_{i=d,t} p_i q_i \quad i, j = d, t;\ i \neq j, \tag{1}$$

The maximization of Eq. (1) yields the demand function of the direct and traditional channels, which is given by:

$$q_i = \frac{a_i - \rho a_j - p_i + \rho p_j}{1-\rho^2} \quad i, j = d, t; i \neq j. \tag{2}$$

where a_i is the potential market demand of the i channel, and p_i and q_i denote the channel price and quantity of the i channel, respectively. $\rho \in [0, 1)$ represents channel competition intensity between the direct and traditional channels. If $\rho = 0$, two channels are independent in the final market. An increase in ρ means that two channels are more competitive and that the degree of channel differentiation is decreasing. If $\rho \to 1$, two channels are perfectly substitutable. For example, the direct and traditional channels are more heterogeneous when the manufacturer and retailer sell the same products, adopt online platforms simultaneously, or develop similar promotion strategies.

To ensure the tractability and comparability of different models, we assume that the potential market demands of the direct and traditional channels are identical $a_d = a_t = 1$, denoting that the relative channel status of the direct and traditional channels is symmetric[5]. From Abhishek et al. [48], the demand function in Eq. (2) has two desirable merits. First, consumers' sensitivity to the sales channel, $\frac{1}{1-\rho^2}$, increases as the differentiation of two channels reduces. Second, the total size of potential demand, $\frac{2}{1+\rho}$, directly reveals the demand expansion effect when the manufacturer introduces the direct channel. Note that condition $c_m < 1$ must be satisfied to guarantee that each reverse channel structure can achieve positive demand.

To characterize the environmental performance of each reverse channel structure, we designate the total emissions of the manufacturer as a result of producing a new and remanufactured products as $\chi(\chi > 0)$ and $\eta\chi$, respectively, where η denotes the *emissions intensity* of a remanufactured product. For ease of exposition, we set $\chi = 1$, and the total amount of emissions linearly increases with production quantities. A similar assumption can be found in Yenipazarli [49] and Orsdemir et al. [50]. Then, the total environmental impact (EI) can be calculated as follows: $EI = \eta\chi\tau(q_d + q_t) + (1-\tau)\chi(q_d + q_t) = (1-(1-\eta)\tau)(q_d + q_t)$.

In line with Savaskan et al. [1] and Savaskan and Van Wassenhove [8], we assume that all supply chain decisions are made in a single-period setting. A market with the previous existence of the product is considered, and used products can be collected for reuse. Therefore, this study concentrates on the *average supply chain profits* made in every period when similar products are repeatedly introduced to the market.

We present three decentralized dual-channel CLSC models as shown in Fig. 1. Considering different undertakers of used products, we develop three reverse channel structures: manufacturer collecting (Model M), retailer collecting (Model R), and third-party collecting (Model C). We assume that all three CLSC models are established under the manufacturer-Stakelberg game framework. Additionally, we provide a benchmark when the manufacturer and the retailer form an alliance and jointly determine the optimal channel prices and the optimal return rate (Model I), which involves a centrally coordinated system and will be used as a benchmark to design coordination contracts in dual-channel CLSCs.

Next, we specify notations used in our model. Without loss of generality, we use π_i^j to denote the player i's profit under the j model where $i \in \{m, r, c, T\}$ denotes the manufacturer, the retailer, the third-party and the total channel system, respectively; $j \in \{M, R, C\}$ denotes the manufacturer collecting, retailer collecting and third-party collecting structures, respectively. Table 2 summarizes the notations used throughout this paper.

[3] If we consider other types of costs in the collection and production processes (e.g., the cleaning, dismantling, repairing or shipment costs of used products), the main results of our study will still be quantitively robust. The manufacturer collecting mode is its optimal reverse channel choice and the supply chain coordination contracts in Section 6 can still achieve dual-channel CLSC when considering different types of costs.

[4] If we consider the case where only part γ of collected units can be successfully remanufactured, where γ is the remanufacturing rate, we can still show that the main results in our models will not change, i.e., the manufacturer collecting mode is its optimal reverse channel choice and the supply chain coordination contracts designed in Section 6 is still applicable.

[5] In reality, when the direct and traditional channels have different market potentials and are not normalized to 1 ($a_d \neq a_t \neq 1$), we can still prove that the main findings in our study are robust, i.e., the manufactuer collecting mode is also the manufacturer's optimal reverse channel strategy. Furthermore, the designed contracts are still applicable to the CLSCs under different collecting modes.

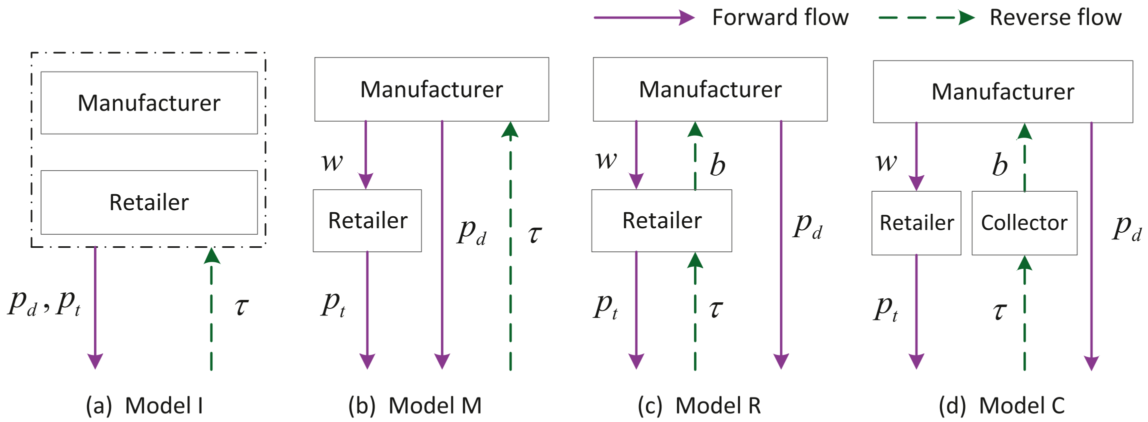


Fig. 1. Dual-channel CLSCs with product remanufacturing.

Table 2
Notations and definitions.

Notation	Definition
w	Wholesale price
p_d	Direct channel price
p_t	Traditional channel price
b	Transfer price payed by the manufacturer to the collector
τ	Return rate
K	Cost scaling parameter
c_m	Unit manufacturing cost of a new product
c_r	Unit manufacturing cost of a remanufactured product
Δ	Unit remanufacturing cost savings
ρ	Channel competition intensity
q_d	Sales volume of the direct channel
q_t	Sales volume of the traditional channel
π_m	Manufacturer's profit
π_r	Retailer's profit
π_c	Third-party's profit
π_T	Chain system's profit
EI	Environmental impact

4. Four closed-loop supply chain models

In this section, we establish three different dual-channel CLSC models for different reverse channel structures. In addition to calculating equilibrium solutions for different decision-making models, we aim to determine the optimal transfer prices for Model R and Model C. We begin by analyzing the centralized decision-making model. The proofs of the concavity for all objective functions and detailed derivation processes of the four models are provided in online Appendix A.

4.1. Centralized model (model I)

To avoid channel conflicts, it is not uncommon for the manufacturer and the retailer to form an alliance jointly determining pricing and return decisions in some industries [1,39]. In a centralized dual-channel CLSC, the manufacturer and the retailer jointly choose the optimal direct and traditional channel prices p_d, p_t and the optimal return rate τ. Wholesale price w and transfer price b can be considered as internal transfer prices, which have no effect on channel prices and return rate. The optimization model of the centralized dual-channel CLSC is written as follows:

$$\max_{p_d,p_t,\tau} \pi^I = (p_t - c_m + \Delta\tau)\left(\frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right) + (p_d - c_m + \Delta\tau)\left(\frac{1-\rho-p_d+\rho p_t}{1-\rho^2}\right) - K\tau^2. \tag{3}$$

The first and second terms denote sales profits from the direct and traditional channels, respectively, and the third term denotes the collection cost, which has been defined in Section 3. Because the objective function is jointly concave in p_d, p_t and τ, by utilizing the first-order conditions of Eq. (3) and solving them simultaneously, we obtain the optimal channel prices (p_d^{I*}, p_t^{I*}), return rate τ^{I*}, profit of supply chain π^{I*}, and environmental impact EI^{I*}, which are shown in Table 3.

To maintain model rationality, the optimal return rate $\tau^{I*} \in [0,1)$ leads to the following condition for the parameter K.

Lemma 1. *The parameter K defined in the collection cost function must satisfy* $K > \dfrac{\Delta(1+\Delta-c_m)}{2(1+\rho)}$ *such that* $0 \le \tau^{I*} < 1$.

Table 3
Equilibrium outcomes of centralized and decentralized dual-channel CLSCs .

Equilibrium	Model I	Model M	Model R	Model C
w^*	-	$\frac{4Kx_1(1+c_m)-\Delta^2x_2}{8x_1K-x_2\Delta^2}$	$\frac{64x_1^3(1+c_m)K-\Delta^2x_2^2y_1}{4\left(32x_1^3K-\Delta^2x_1x_2^2\right)}$	$\frac{8x_1K(1+c_m)-\Delta^2x_2}{16x_1K-\Delta^2x_2}$
p_d^*	$\frac{(1+c_m)x_1K-\Delta^2}{2x_1K-\Delta^2}$	$\frac{4Kx_1(1+c_m)-\Delta^2x_2}{8x_1K-x_2\Delta^2}$	$\frac{64x_1^3(1+c_m)K-\Delta^2x_2^2y_1}{4\left(32x_1^3K-\Delta^2x_1x_2^2\right)}$	$\frac{8x_1K(1+c_m)-\Delta^2x_2}{16x_1K-\Delta^2x_2}$
p_t^*	$\frac{(1+c_m)x_1K-\Delta^2}{2x_1K-\Delta^2}$	$\frac{2x_1y_3K-\Delta^2x_2}{8x_1K-x_2\Delta^2}$	$\frac{32x_1^3Ky_3+\Delta^2x_2^2y_2}{4\left(32x_1^3K-\Delta^2x_1x_2^2\right)}$	$\frac{4x_1Ky_3-\Delta^2x_2}{16x_1K-\Delta^2x_2}$
τ^*	$\frac{\Delta(1-c_m)}{2x_1K-\Delta^2}$	$\frac{\Delta x_2(1-c_m)}{8x_1K-x_2\Delta^2}$	$\frac{\Delta x_2^2(1-c_m)}{32x_1^2K-\Delta^2x_2^2}$	$\frac{\Delta x_2(1-c_m)}{16x_1K-\Delta^2x_2}$
b^*	-	-	$\frac{\Delta x_2}{4x_1}$	$\frac{\Delta}{2}$
π_m^*	-	$\frac{Kx_2(1-c_m)^2}{8x_1K-x_2\Delta^2}$	$\frac{4x_1x_2K(1-c_m)^2}{32x_1^2K-\Delta^2x_2^2}$	$\frac{2x_2K(1-c_m)^2}{16x_1K-\Delta^2x_2}$
π_r^*	-	$\frac{4K^2\left(1-\rho^2\right)(1-c_m)^2}{\left(8x_1K-x_2\Delta^2\right)^2}$	$\frac{z_1(1-c_m)^2}{8\left(\Delta^2x_1x_2^2-32x_1^3K\right)^2}$	$\frac{16\left(1-\rho^2\right)K^2(1-c_m)^2}{\left(16x_1K-\Delta^2x_2\right)^2}$
π_c^*	-	-	-	$\frac{\Delta^2x_2^2K(1-c_m)^2}{\left(16x_1K-\Delta^2x_2\right)^2}$
π_T^*	$\frac{K(1+c_m)^2}{2x_1K-\Delta^2}$	$\frac{Ks_1(1-c_m)^2}{\left(8x_1K-\Delta^2x_2\right)^2}$	$\frac{z_2(1-c_m)^2}{8\left(32x_2^3K-\Delta^2x_1x_2^2\right)^2}$	$\frac{Ks_2(1-c_m)^2}{\left(16x_1K-\Delta^2x_2\right)^2}$
EI^*	$\frac{2K(1-c_m)h_1}{\left(2(1+\rho)K-\Delta^2\right)^2}$	$\frac{2(3+\rho)K(1-c_m)h_2}{\left(8(1+\rho)K-\Delta^2(3+\rho)\right)^2}$	$\frac{8(1+\rho)(3+\rho)K(1-c_m)h_3}{\left(32(1+\rho)^2K-\Delta^2(3+\rho)^2\right)^2}$	$\frac{4(3+\rho)K(1-c_m)h_4}{\left(16(1+\rho)K-\Delta^2(3+\rho)\right)^2}$

$x_1=1+\rho$; $x_2=3+\rho$; $y_1=(1-\rho)c_m-3-5\rho$; $y_2=(1-\rho)c_m-5+3\rho$, $y_3=3-\rho+x_1c_m$; $s_1=4x_1(7+\rho)K-\Delta^2x_2^2$, $s_2=16x_1(7+\rho)K-\Delta^2x_2^2$; $z_1=512(1-\rho)x_1^5K^2+8\Delta^2x_1^2x_2^2(7+(10-\rho)\rho)K-\Delta^4(1-\rho)x_2^4$, $z_2=512x_1^5(7+\rho)K^2-\Delta^4(1+\rho)x_2^4-8\Delta^2x_1^2x_2^2(5+\rho(6+5\rho))K$. $h_1=2(1+\rho)K-\Delta(1-\eta)(1-c_m)-\Delta^2$, $h_2=8(1+\rho)K-\Delta(1+\Delta-\eta)(3+\rho)+\Delta(1-\eta)(3+\rho)c_m$, $h_3=32(1+\rho)^2K-\Delta(1+\Delta-\eta)(3+\rho)^2+\Delta(1-\eta)(3+\rho)^2c_m$, $h_4=16(1+\rho)K-\Delta(1+\Delta-\eta)(3+\rho)+\Delta(1-\eta)(3+\rho)c_m$

From a practical viewpoint, it is not economically viable to collect or remanufacture all used products from the final market for all collecting parties. The parameter K is large enough to ensure that the optimal return rate under Model I is less than 1, which further guarantees the existence of equilibrium solutions for the three decentralized dual-channel CLSC models. This assumption is widely adopted in the CLSC literature [1,8,51].

4.2. Manufacturer collecting mode (Model M)

In Model M, the products are distributed through two separate channels: direct and traditional channels. In addition, the manufacturer is responsible for collecting used products. The sequence of events is as follows. The manufacturer first determines direct channel price p_d, wholesale price w and return rate τ. Then, the retailer chooses traditional channel price p_t. The backward induction method is used to solve this dynamic game. Given w, p_d and τ, the retailer's optimization problem is to choose $p_t(w, p_d, \tau)$ to maximize its profit:

$$\max_{p_t} \pi_r^M = (p_t - w)\left(\frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right). \tag{4}$$

Because the objective function π_r^M is concave in p_t, using the first-order condition of Eq. (4) yields the retailer's best response function $p_t(w, p_d) = \frac{1}{2}(1+w-\rho+\rho p_d)$. Then, in anticipating the retailer's best response, the manufacturer chooses wholesale price w^{M*}, direct channel price p_d^{M*} and return rate τ^{M*} to maximize its profit:

$$\begin{aligned}\max_{w,p_d,\tau} \pi_m^M = {} & (w-c_m+\Delta\tau)\left(\frac{1-\rho-p_t(w,p_d,\tau)+\rho p_d}{1-\rho^2}\right)\\ & +(p_d-c_m+\Delta\tau)\left(\frac{1-\rho-p_d+\rho p_t(w,p_d,\tau)}{1-\rho^2}\right)-K\tau^2\\ \text{s.t.}\quad & w \le p_d.\end{aligned} \tag{5}$$

Note that, the first and second terms of π_m denote profits from traditional and direct channels, respectively; the third term is the manufacturer's collection costs. Constraint $w \le p_d$ ensures the coexistence of direct and traditional channels. Problem (5) is a constrained optimization problem, and we must establish a Lagrange function and find the corresponding optimal Karush-Kuhn-Tucker (KKT) conditions. The detailed proof for the model is shown in online Appendix A. Then, from the concavity of the objective function in w, p_d, τ we can obtain the optimal wholesale price w^{M*}, direct channel price p_d^{M*}

and return rate τ^{M*} for the manufacturer. Next, the optimal traditional channel price p_t^{M*}, the optimal profits for the manufacturer π_m^{M*}, the retailer π_r^{M*} and the chain system π_T^{M*} and the total environmental impact EI^{M*} are obtained according to the manufacturer's optimal decisions. All equilibrium outcomes of the Model M are shown in Table 3.

4.3. Retailer collecting mode (Model R)

In Model R, the retailer manages the traditional channel and simultaneously collects used products. The manufacturer, on the one hand, sells products through the traditional channel and wholesales products through the direct channel; on the other hand, it buys back used products from the retailer at a price b. To ensure the manufacturer has an incentive to collect and remanufacture used products, the transfer price b should not exceed unit remanufacturing cost savings Δ (i.e., $b \le \Delta$). The sequence of events is as follows. First, the manufacturer determines wholesale price w, direct channel price p_d and transfer price b. Then, the retailer chooses traditional channel price p_t and return rate τ. We first optimize the retailer's problem.

Given the manufacturer's decisions (w, p_d, b), the retailer chooses p_t and τ to maximize its profit:

$$\max_{p_t,\tau} \pi_r^R = (p_t - w)\left(\frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right) + b\tau\left(\frac{1-\rho-p_d+\rho p_t}{1-\rho^2} + \frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right) - K\tau^2. \tag{6}$$

Because the objective function in Eq. (6) is jointly concave in p_t and τ, from the first-order conditions, we obtain the retailer's best response functions $p_t(w, p_d, b)$ and $\tau(w, p_d, b)$ based on the manufacturer's decisions. Then, in anticipating the retailer's optimal decisions, the manufacturer determines wholesale price w, direct channel price p_d and transfer price b to maximize its profit:

$$\begin{aligned} \max_{w,p_d,b} \pi_m^R = &(w - c_m + (\Delta - b)\tau(w, p_d, b))\left(\frac{1-\rho-p_t(w,p_d,b)+\rho p_d}{1-\rho^2}\right) \\ &+(p_d - c_m + (\Delta - b)\tau(w, p_d, b))\left(\frac{1-\rho-p_d+\rho p_t(w,p_d,b)}{1-\rho^2}\right) \\ \text{s.t.} \quad & w \le p_d \end{aligned} \tag{7}$$

Similar to Savaskan et al. [1], we optimize the manufacturer's problem in two steps. First, for a given b, because the objective function in is jointly concave in w and p_d, the first-order conditions characterize the manufacturer optimal wholesale price $w^{R*}(b)$ and direct channel price $p_d^{R*}(b)$ from the first-order conditions of Problem (7). The manufacturer's optimal profit, for a given b, is as follows:

$$\pi_m^{R*}(b) = \frac{(3+\rho)K(1-c_m)^2}{4b^2(1+\rho) - 2b\Delta(3+\rho) + 8(1+\rho)K}. \tag{8}$$

Because $\pi_m^{R*}(b)$ is concave in b, we can derive the optimal transfer price b^{R*} that maximizes the manufacturer's profit, which is shown in Observation 1.

Observation 1. Under Model R, the optimal transfer price for the manufacturer is $b^{R*} = \frac{\Delta(3+\rho)}{4(1+\rho)}$. Specifically, b^{R*} increases as unit remanufacturing cost savings Δ increase and decreases as the channel competition intensity ρ increases.

Observation 1 shows an interesting result for the transfer price under the retailer collecting dual-channel CLSC model. From Observation 1, note that the optimal transfer price depends on two factors: channel competition intensity (i.e., ρ) and unit remanufacturing cost savings (i.e., Δ). Because $\rho \in [0, 1]$, $b^{R*} \in \left[\frac{\Delta}{2}, \frac{3\Delta}{4}\right]$. Specifically, when the direct and traditional channels become more competitive, the manufacturer reduces the transfer price. In contrast, if remanufacturing leads to higher cost savings, the manufacturer increases the transfer price.

First, we explore the effect of channel competition intensity on the transfer price. When two sales channels are independent (i.e., $\rho = 0$), the traditional channel has no effect on the direct channel and the manufacturer pays the highest transfer price to motivate the retailer to collect more used products. At this point, the optimal transfer price is maximized with $b^{R*} = \frac{3\Delta}{4}$. As channel competition intensity increases (i.e., $0 < \rho < 1$), the sales quantity (i.e., q_d^{R*}) and profit margin (i.e., $p_d^{R*} - c_m + (\Delta - b^{R*})\tau^{R*}$) for the direct channel decreases; the profit margin for the traditional channel (i.e., $w^{R*} - c_m + (\Delta - b^{R*})\tau^{R*}$) also decreases. In other words, the profit reduction effect originating from intensified channel competition dominates the profit increasing effect originating from remanufacturing cost savings. Hence, the manufacturer will reduce the transfer price for the retailer to reduce buy-back costs as ρ increases. When two sales channels are purely substitutable (i.e., $\rho \to 1$), the optimal transfer price reaches the lowest value with $b^{R*} = \frac{\Delta}{2}$.

Second, we explore the effect of unit remanufacturing cost savings on the transfer price. As Δ increases, a higher transfer price leads to a higher profit margin for the traditional channel (i.e. $p^{R*} - w^{R*}$), which, in turn, motivates the retailer to collect more used products. The cost increasing effect is dominated by the demand and collection volume expansion effects, which results in more profit for the manufacturer. Furthermore, higher remanufacturing cost savings lead to a lower wholesale price and a higher transfer price, which reduces the double marginalization effect in the traditional channel (i.e., $\dfrac{p^{R*} - w^{R*} + b^{R*}\tau^{R*}}{p^{R*} - c_m + \Delta\tau^{R*}}$ decreases). As a result, the traditional channel price is lower and the demand is higher in the R model. Finally, raising the transfer price to some extent compensates for the channel disadvantage for the retailer, which alleviates channel conflict and thus benefits the manufacturer.

Compared with the retailer collecting mode developed by Savaskan et al. [1], our study shows different results that are of high importance from theoretical and practical perspectives. For a single-channel CLSC, Savaskan et al. [1] point out that the manufacturer's optimal choice is to directly transfer all remanufacturing cost savings to the retailer under retailer collecting mode (i.e., $b^* = \Delta$). However, in the retailer collecting dual-channel CLSC model, Observation 1 shows that the upper and lower bounds of the transfer price are $\frac{3\Delta}{4}$ and $\frac{\Delta}{2}$, respectively. The reason for this is as follows. If the transfer price is too low (i.e., $b^{R*} < \frac{\Delta}{2}$), the manufacturer does not provide sufficient incentive for the retailer to increase collection quantity and demand. In contrast, if the transfer price is too large (i.e., $b^{R*} > \frac{3\Delta}{4}$), the profit reduction effect resulting from a higher buy-back price dominates the profit increasing effect led by collection volume and demand expansion effects, which lowers the manufacturer's profits. In summary, the manufacturer should strategically choose the optimal transfer price for the retailer depending on different levels of competition intensity between the direct and traditional channels.

Finally, according to the optimal transfer price b^{R*} given in Observation 1, the optimal channel prices (i.e., w^{R*}, p_d^{R*}, p_t^{R*}), return rate (i.e., τ^{R*}), profits for the manufacturer, the retailer and the supply chain system (i.e., π_m^{R*}, π_r^{R*}, π_T^{R*}) and environmental impact EI^{R*} for Model R are shown in Table 3.

4.4. Third-party collecting mode (Model C)

In Model C, the manufacturer outsources the collection activity to an independent third-party collector, the direct and traditional channels are managed by the manufacturer and the retailer, respectively. The sequence of events is as follows. First, the manufacturer determines direct channel price p_d, wholesale price w and transfer price b. Then, the retailer sets traditional channel price p_t; meanwhile, the third-party collector determines the return rate τ. We begin by optimizing the retailer's and third-party's problems.

Given w, p_d and b, the third-party collector chooses return rate τ to maximize its profit:

$$\max_{\tau} \pi_c^C = b\tau\left(\frac{1-\rho-p_d+\rho p_t}{1-\rho^2} + \frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right) - K\tau^2. \tag{9}$$

Meanwhile, the retailer sets traditional channel price p_t to maximize its profit:

$$\max_{p_t} \pi_r^C = (p_t - w)\left(\frac{1-\rho-p_t+\rho p_d}{1-\rho^2}\right). \tag{10}$$

Because π_c^C in Eq. (9) is concave in τ and π_r^C in Eq. (10) is concave in p_t, the retailer's and third-party collector's best response, given the manufacturer's decisions w, p_d and b, are given by $p_t(w, p_d, b) = \frac{1}{2}(1 + w - \rho + \rho p_d)$ and $\tau(w, p_d, b) = \dfrac{b(3 - w + \rho - (2+\rho)p_d)}{4(1+\rho)K}$. Then, in anticipating the retailer's and third-party collector's optimal decisions, the manufacturer's optimization problem is:

$$\begin{aligned} \max_{w, p_d, b} \pi_m^C = {} & (w - c_m + (\Delta - b)\tau(w, p_d, b))\left(\frac{1-\rho-p_t(w, p_d, b)+\rho p_d}{1-\rho^2}\right) \\ & + (p_d - c_m + (\Delta - b)\tau(w, p_d, b))\left(\frac{1-\rho-p_d+\rho p_t(w, p_d, b)}{1-\rho^2}\right) \\ \text{s.t.} \quad & w \le p_d. \end{aligned} \tag{11}$$

From the concavity of the objective function in w, p_d, we obtain the optimal solutions ($w^{C*}(b)$, $p_d^{C*}(b)$) for a given fixed transfer price b. The manufacturer's optimal profit, for a given b, is determined by:

$$\pi_m^{C*}(b) = \frac{(3+\rho)K(1-c_m)^2}{2b(b-\Delta)(3+\rho) + 8(1+\rho)K}. \tag{12}$$

The objective function in Eq. (12) is concave in b, and we then obtain the optimal transfer price b^{C*} in Model C, which is given in Observation 2.

Observation 2. In Model C, the manufacturer's profit is maximized when the optimal transfer price satisfies $b^{C*} = \frac{\Delta}{2}$.

Observation 2 shows how the manufacturer strategically determines the transfer price under the third-party collecting dual-channel CLSC model, and its optimal decision is to transfer half of remanufacturing cost savings to the third-party collector. Specifically, note that in Model C, the optimal transfer price is independent of channel competition intensity ρ. This

Table 4
Comparisons between the optimal wholesale prices.

Case	Δ	K	ρ	Relationships
Case 1	$\Delta > 8(1-c_m)$	$\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9\Delta^2}{16}$	–	$w^{M*} < w^{R*} < w^{C*}$
Case 2	$\Delta \le 8(1-c_m)$	–	$0 < \rho \le \rho^w$	$w^{M*} < w^{C*} < w^{R*}$
Case 3			$\rho^w < \rho < 1$	$w^{M*} < w^{R*} < w^{C*}$
Case 4	$\Delta > 8(1-c_m)$	$K \ge \frac{9\Delta^2}{16}$	$0 < \rho \le \rho^w$	$w^{M*} < w^{C*} < w^{R*}$
Case 5			$\rho^w < \rho < 1$	$w^{M*} < w^{R*} < w^{C*}$

where ρ^w is one solution of equation $16(1-\rho^2)K - \Delta^2(3+\rho)^2 = 0$.

result differs from that of Model R illustrated in Observation 1. The reasons for this are as follows. In Model C, the independent third-party manages the collection process, and the manufacturer and the retailer are responsible for the retailing of products through the direct and traditional channels. Obviously, the forward sales channel and the reverse collecting channel in Model C are separate, thus the third-party collector's profit only depends on the transfer price. However, in Model R, the retailer manages the reverse channel and traditional sales channel simultaneously. The retailer's optimal pricing and return rate decisions are shaped by the channel competition intensity and transfer price, and the manufacturer's relative channel power reduces when the retailer acts as both the collector and distributor. Therefore, the manufacturer will strategically adjust the wholesale price based on different levels of competition intensity between the direct and traditional channels.

Compared with the third-party collecting mode given in Savaskan et al. [1], note that without taking the variable cost of the used product into consideration, our result is identical to theirs. This comparison reveals an interesting result. In the dual sales channel CLSC environment, the optimal transfer price is independent of the channel competition intensity when the third-party acts as the collector. Regardless of whether it is operating in a single or dual channel CLSC, the manufacturer should optimally choose the transfer price $b^{C*} = \frac{\Delta}{2}$ under the third-party collecting mode.

Observations 1 and 2 have significant implications for the manufacturer involved in the CLSC management. When the manufacturer faces the direct and traditional sale channels simultaneously, it should strategically make the collecting decisions based on different reverse channel structures. If the retailer collects the used product, the transfer price has a direct impact on the demand of the two sale channels. However, if the manufacturer outsources the collection activity to an independent third-party collector, the transfer price is the direct cost for the manufacturer and is not affected by channel competition.

Next, according to the optimal transfer price (i.e., b^{C*}) in Observation 2, we obtain the equilibrium prices (i.e., w^{C*}, p_d^{C*} and p_t^{C*}), return rate τ^{C*}, profits for each player and supply chain system (i.e., π_m^{C*}, π_r^{C*}, π_c^{C*} and π_T^{C*}) and environmental impact EI^{C*}, which are shown in Table 3.

5. Comparisons of four CLSC models

In this section, we compare the optimal wholesale prices, direct and traditional channel prices and return rates in the centralized and three decentralized dual-channel CLSC models. Moreover, we explore which collecting mode is preferable from the perspectives of the manufacturer, retailer and supply chain system.

Proposition 1. *The relationship between the optimal wholesale prices under the three dual-channel CLSC models is summarized in Table 4.*

Proposition 1 indicates that the optimal wholesale price is the lowest in the M model compared with other two models. The wholesale price depends on direct channel price p_d and return rate τ. When the manufacturer directly collects the used product, it obtains the whole profits (i.e., $\Delta\tau^{M*}(q_r^* + q_t^*)$) of product remanufacturing. Hence, the manufacturer reduces the wholesale price to increase the demand and the collection volume. Even though a lower wholesale price reduces the competitive advantage of the tradition channel, this effect is dominated by the increased profits from higher return rate. In addition, this result can be explained by "double marginalization effect" in a dual-channel CLSC. In Model M, there is no "double marginalization effect" in reverse supply chain, and the manufacturer has enough incentives to reduce the wholesale price for the retailer.

The comparison of the optimal wholesale prices of the R and C models depends on remanufacturing cost savings Δ, collection cost K and channel competition intensity ρ. The proposition shows that if the remanufacturing cost savings are sufficiently high and the collection cost is sufficiently low (i.e., $\Delta > 8(1-c_m)$ and $\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9\Delta^2}{16}$), the optimal wholesale price is higher in Model C than that in Model R. Moreover, when the remanufacturing cost savings are relatively low (i.e., $\Delta \le 8(1-c_m)$), or the collection cost is relatively high but the remanufacturing cost savings are sufficiently high

Table 5
Comparisons between the optimal channel prices.

Case	Δ	K	ρ	Relationships
Case 1	$\Delta > 8(1-c_m)$	$\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9\Delta^2}{16}$	–	$p_d^{I*} < p_d^{M*} < p_d^{R*} < p_d^{C*}$
Case 2	$\Delta \le 8(1-c_m)$	–	$0 < \rho \le \rho^w$	$p_d^{I*} < p_d^{M*} < p_d^{C*} < p_d^{R*}$
Case 3			$\rho^w < \rho < 1$	$p_d^{I*} < p_d^{M*} < p_d^{R*} < p_d^{C*}$
Case 4	$\Delta > 8(1-c_m)$	$K \ge \frac{9\Delta^2}{16}$	$0 < \rho \le \rho^w$	$p_d^{I*} < p_d^{M*} < p_d^{C*} < p_d^{R*}$
Case 5			$\rho^w < \rho < 1$	$p_d^{I*} < p_d^{M*} < p_d^{R*} < p_d^{C*}$
Case	Δ	K	ρ	Relationships
Case 1	$\Delta > 8(1-c_m)$	$\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9\Delta^2}{16}$	–	$p_t^{I*} < p_t^{M*} < p_t^{R*} < p_t^{C*}$
Case 2	$\Delta \le 8(1-c_m)$	–	$0 < \rho \le \rho^p$	$p_t^{I*} < p_t^{R*} < p_t^{M*} < p_t^{C*}$
Case 3			$\rho^p < \rho < 1$	$p_d^{I*} < p_d^{M*} < p_d^{R*} < p_d^{C*}$
Case 4	$\Delta > 8(1-c_m)$	$K \ge \frac{9\Delta^2}{16}$	$0 < \rho \le \rho^p$	$p_t^{I*} < p_t^{R*} < p_t^{M*} < p_t^{C*}$
Case 5			$\rho^p < \rho < 1$	$p_t^{I*} < p_t^{M*} < p_t^{R*} < p_t^{C*}$

where ρ^w is one solution of equation $16(1-\rho^2)K - \Delta^2(3+\rho)^2 = 0$; ρ^p is one solution of equation $\Delta^2(1-\rho)(3+\rho)^2 - 8(1+\rho)(2-\rho(7+\rho(8+3\rho)))K = 0$.

(i.e., $\Delta > 8(1-c_m)$ and $K \ge \frac{9\Delta^2}{16}$), the optimal wholesale price is higher in Model R when the two channels are more monopolistic and lower when the two channels become more competitive.

Proposition 2. *The optimal direct and traditional channel prices satisfy the following relationships, which are summarized in Table 5.*

Proposition 2 compares the optimal direct and traditional channel prices under the centralized and three decentralized dual-channel CLSC models. Note that for the centralized decision-making case, the optimal direct channel price is lower than that under the three decentralized models. Furthermore, in a dual-channel CLSC, the manufacturer strategically chooses the direct channel price to compete with the tradition channel, and the results indicate that the direct channel price should be set equal to the wholesale price. This finding echoes the results presented for the forward dual-channel supply chain by Chiang et al. [11], who show that the manufacturer views the direct channel as playing a strategic role in competing with the traditional channel.

Next, we compare the optimal traditional channel prices under different CLSC models. First, the optimal traditional channel price for the centralized case is lower than that under the three decentralized models. Second, the optimal traditional channel price is higher in the C model than that in the R and M models. This is the case for two reasons. When the third-party collects the used product, the forward selling and reverse collecting are two independent activities in the CLSC. Hence, we find a "repeated double marginalization effect" in the C model that is more pronounced than that found in the M and R models. Furthermore, in the C model, the investment in the used product collection has only an indirect effect on the channel price; while in the M and R models, this effect is more direct and the retailer can offer a lower channel price.

For optimal traditional channel prices in the M and R models, the comparison hinges on remanufacturing cost savings, collection costs and channel competition intensity. When remanufacturing cost savings are high enough and collection costs are low (i.e., $\Delta > 8(1-c_m)$ and $\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9\Delta^2}{16}$), note that the manufacturer sets a higher wholesale price in the R model than that in the M model (see Proposition 1). Hence, the retailer responds by setting a higher channel price in the R model. When remanufacturing cost savings are relatively low (i.e., $\Delta \le 8(1-c_m)$), or the remanufacturing cost savings and collection costs are sufficiently high (i.e., $\Delta > 8(1-c_m)$ and $K \ge \frac{9\Delta^2}{16}$), the optimal traditional prices in the M and R models depend on the channel competition intensity. If two channels are more monopolistic, the optimal price is higher in the M model; otherwise, the retailer sets a higher retail price in the R model.

Proposition 3. *The optimal return rates and environmental impacts under the three decentralized models satisfy the following relationships: $\tau^{I*} > \tau^{M*} > \tau^{R*} > \tau^{C*}$ and $EI^{I*} < EI^{M*} < EI^{R*} < EI^{C*}$.*

Proposition 3 indicates that the Model I achieves a higher return rate than that in the decentralized CLSC models. This is because the total demands of the direct and traditional channels in Model I are higher than those in the three decentralized models.

In comparing the three decentralized CLSC models, we find that the return rate is the highest in the M model, which is inconsistent with common results in existing CLSC studies [1,35,39]. This can be explained as follows. On the one hand, the manufacturer extracts all remanufacturing cost savings in the M model unlike in the R and C models. On the other hand, when the retailer or third-party collects used products, a "repeated double marginalization effect" of the traditional and reverse collecting channels, respectively, occurs. However, there is no double marginalization effect in the reverse channel in the M model. In addition, the optimal return rate is higher in the R model than that in the C model. The reason for

Table 6
Comparisons between the optimal profits for supply chain system .

Case	Δ	K	ρ	Relationships
Case 1	$\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	$\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9}{40}(4+\sqrt{6})\Delta^2$	–	$\pi_T^{C*} < \pi_T^{R*} < \pi_T^{M*} < \pi_T^{I*}$
Case 2	$\Delta \le \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	–	$0 < \rho \le \rho^\pi$	$\pi_T^{C*} < \pi_T^{M*} < \pi_T^{R*} < \pi_T^{I*}$
Case 3			$\rho^\pi < \rho < 1$	$\pi_T^{C*} < \pi_T^{R*} < \pi_T^{M*} < \pi_T^{I*}$
Case 4	$\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	$K \ge \frac{9}{40}(4+\sqrt{6})\Delta^2$	$0 < \rho \le \rho^\pi$	$\pi_T^{C*} < \pi_T^{M*} < \pi_T^{R*} < \pi_T^{I*}$
Case 5			$\rho^\pi < \rho < 1$	$\pi_T^{C*} < \pi_T^{R*} < \pi_T^{M*} < \pi_T^{I*}$

where ρ^π is one solution of equation $\pi_T^{M*} - \pi_T^{R*} = 0$.

this is as follows. The used product investment made by the retailer has a direct impact on channel demand in the Model R. However, the investment made by the third-party collector only has a second-degree effect on channel demand. This explains why the manufacturer transfers a large percentage of the remanufacturing cost savings to the collector in the R model (i.e., $b^{R*} > b^{C*}$), even though the manufacturer obtains a lower profit margin from product remanufacturing (i.e., $\Delta - b^{R*} < \Delta - b^{C*}$).

Proposition 3 also shows which reverse channel structure can generate higher environmental performance. As environmental impact is negatively related to the return rate (i.e., the more used products are collected, the lower the environmental impact generated), we find that the manufacturing-collecting mode is the optimal choice. This result is meaningful to regulators and policy makers. With the rapid development of e-commerce and the dual-channel CLSC model being adopted by increasing number of industries, the government should take effective measures to encourage manufacturers to collect used products in the market.

Proposition 4. *(1) The manufacturer's and retailer's optimal profits under the three decentralized models are related as:* $\pi_m^{C*} < \pi_m^{R*} < \pi_m^{M*}$ *and* $\pi_r^{C*} < \pi_r^{M*} < \pi_r^{R*}$*, respectively. (2) The supply chain system's optimal profit under the three decentralized models satisfy the following relationship, which is summarized in Table 6.*

Proposition 4 compares channel players' and supply chain system's profits under different collecting models. The result indicates that manufacturer collecting mode is its dominant strategy, which is in contrast to conventional wisdom. The total demand of the direct and traditional channels (i.e., $q_T^{M*} > q_T^{R*} > q_T^{C*}$) and the collection quantity (see Proposition 3) are higher in the M model than those in the R and C models. Therefore, the manufacturer obtains the highest profit when it collects used products directly. From the retailer's perspective, the retailer obtains direct profit from the investment that has been put in used product collection in the R model. Even if the traditional channel demand is higher and the wholesale price is lower (see Proposition 1) in the M model, the R model is preferable for the retailer due to the increased profit from the collection. The C model is the least preferable for both the manufacturer and the retailer due to the repeated double marginalization effect. According to Table 6, to meet the conditions in Cases 1, 4 and 5, we set $c_m, \Delta = 0.7, 0.6$; to meet the condition in Cases 2 and 3, we set $c_m, \Delta = 0.5, 0.3$. We draw the region plots to compare the supply chain profits under the three collecting modes in Figure 2.

From the supply chain system's perspective, the centralized model is more efficient than the decentralized models. In addition, the C model is the least preferred of the three decentralized models due to the strong double marginalization effect found in this channel. Note that the optimality between the M and R models for the supply chain system depends on remanufacturing cost savings, collection costs and channel competition intensity. The M model is the dominant strategy for the supply chain system if and only if remanufacturing cost savings are sufficiently high and collection costs are sufficiently low. Otherwise, the channel competition intensity determines the optimal channel strategy for the supply chain system. When the efficiency of the used-product collection and remanufacturing is sufficiently high, the demands from the direct and traditional channels as well as the return rate are higher in the M model (i.e., $q_t^{M*} > q_t^{R*} > q_t^{C*}$, $q_d^{M*} > q_d^{R*} > q_d^{C*}$ and $\tau^{M*} > \tau^{R*} > \tau^{C*}$), which jointly leads to a higher profit for the supply chain system. (see Case 1 in Fig. 2(a)) However, when the remanufacturing cost savings are low (i.e., $\Delta \le \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$) or remanufacturing cost savings and collection costs are high (i.e., $\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$ and $K \ge \frac{9}{40}(4+\sqrt{6})\Delta^2$), the demand of the traditional channel in the M model is lower than that in the R model (i.e., $q_t^{R*} > q_t^{M*} > q_t^{C*}$) if the channel competition is relatively low (i.e., $\rho < \rho^\pi$). (see Case 4 in Fig. 2(a) and Case 2 in Fig. 2(b)) The increased profit from direct channel and remanufacturnig cannot offset the decreased profit originating from a lower sales quantity of the traditional channel, which leads to a lower supply chain system profit in the M model when two channels are more monopolistic. Instead, when two channels are more competitive (i.e., $\rho \ge \rho^\pi$), the M model achieves higher demand in the two sales channels, which leads to a higher profit for the supply chain system. (see Case 5 in Fig. 2(a) and Case 3 in Fig. 2(b)).

Proposition 4 has practical implications for manufacturers and the supply chain system. First, manufacturers should consider the reverse channel structure when making pricing decisions because who acts as the collector heavily impacts their profits. We find that the manufacturer collecting mode is always the dominant strategy from the manufacturer's perspective.

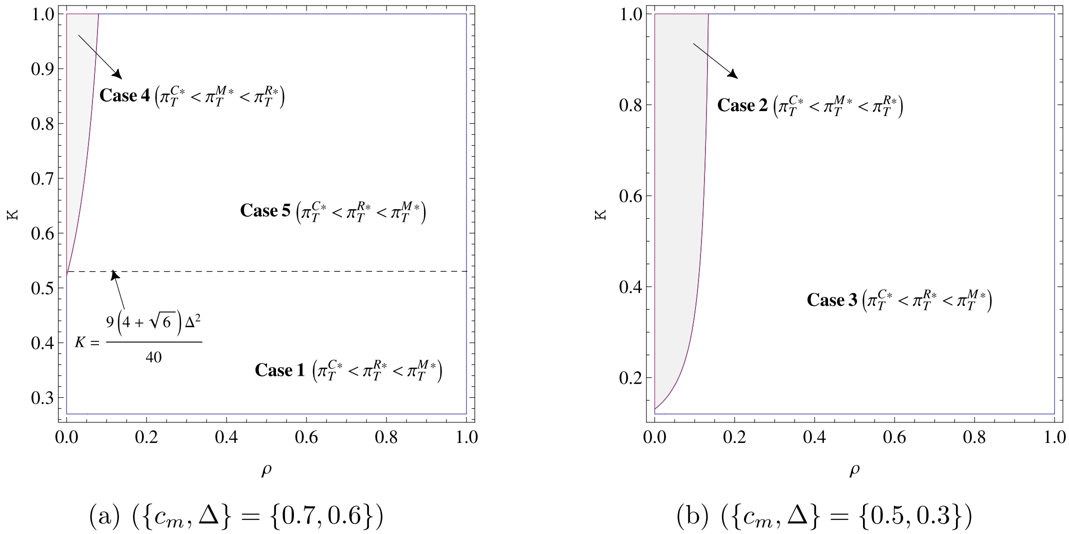


Fig. 2. Supply chain profits under three collecting modes.

This is in fact in line with the practice as an increasing number of manufacturers adopt dual sales channels and collect used products directly. Second, we find that the third-party collecting mode is the least preferred from the supply chain system's point of view. This explains why a growing number of firms choose manufacturer collecting mode (e.g., Apple, Huawei and Lenovo etc.) or retailer collecting mode (e.g., Sony) rather than the third-party collecting mode. Finally, we characterize the optimal reverse channel choice under different conditions, from which we can provide valuable suggestions for different recycling industries. For example, when remanufacturing cost savings are high and collection costs are low, the government should proactively advocate for the manufacturing-collecting mode, which benefits the supply chain, environment and society. Otherwise, which collecting mode is optimal for the supply chain system depends on channel competition between the direct and retail channels. Taking the automobile industry as an example (high remanufacturing cost savings and collection costs), it is optimal for the supply chain system to choose the retrier-collecting mode when the direct and retail channels are sufficiently differentiated; otherwise, the manufacturer collecting mode is superior.

6. Dual-channel closed-loop supply chain coordination

Previous analysis shows that the decentralized dual-channel CLSCs cannot achieve the optimal performance as in the centralized model. Hence, it is essential to design appropriate mechanisms to coordinate the decentralized dual-channel CLSCs. In a dual-channel CLSC, supply chain coordination is more complex due to the existence of the direct channel. Many studies explore the coordination of a CLSC under different decision-making environments. However, few studies consider the issue of coordinating a dual-channel CLSC. We aim to analyze the effects of reverse channel structure on the optimal wholesale prices and contract-implementing Pareto zones in coordination contracts under the three decentralized models.

Consistent with Chen et al. [20], we coordinate the dual-channel CLSC sequentially. First, the manufacturer offers a simple price scheme that consists of the wholesale price and the transfer price (Model R and C). Subsequently, all supply chain members reallocate the optimal profit by using a revenue sharing scheme. To achieve supply chain coordination, the optimal prices of the direct and traditional channels and the optimal return rate should be equal to those in the centralized model (Model I). Specifically, since the manufacturer has complete control over the direct channel, it can strategically set the direct channel price. Hence, the manufacturer first sets the optimal direct channel price $p_d^{i*} = p_d^{I*}, i \in \{MC, RC, CC\}$ before offering the retailer a contract, where the superscripts MC, RC and CC denote coordination models for the manufacturer collecting, retailer collecting and third-party collecting modes, respectively. For notational convenience, let $x_1 = 1 + \rho, x_2 = 3 + \rho$.

6.1. Coordinating of the M model (Model MC)

In the MC Model, the manufacturer first sets $p_d^{MC*} = p_d^{I*}$, $\tau^{MC*} = \tau^{I*}$. Then, the manufacturer provides the retailer a contract (p_d^{MC*}, w^{MC}). Then, given p_d^{MC*}, τ^{MC*} and w^{MC}, the traditional channel price determined by the retailer is:

$$p_t\left(w^{CC}\right) = \frac{1}{2}\left(1 + w - \rho + \rho\left(\frac{\Delta^2 - x_1K - x_1Kc_m}{\Delta^2 - 2x_1K}\right)\right). \tag{13}$$

To guarantee supply chain coordination, the retailer sets $p_t(w^{MC}) = p_t^{I*}$, where p_t^{I*} is the optimal traditional channel price in Model I. Then, we obtain the optimal wholesale price under the contract as follows:

$$w^{MC*} = \frac{x_1(\rho + (2-\rho)c_m)K - \Delta^2}{2x_1K - \Delta^2}. \tag{14}$$

We observe that in the contract (p_d^{MC*}, w^{MC*}), the supply chain system's profit is the same as that of the I model, i.e., $\pi_T^{MC*} = \pi_T^{I*}$. Hence, the contract (p_d^{MC*}, w^{MC*}) can effectively coordinate Model M. It is also observed that the retailer is better off while the manufacturer is worse off compared with the uncoordinated case, that is:

$$\pi_r^{MC*} - \pi_r^{M*} = \frac{x_1\left(1-\rho^2\right)(1-c_m)^2K^2\left(4K-\Delta^2\right)\left(12x_1K - \Delta^2(5+\rho)\right)}{\left(8x_1K - \Delta^2x_2\right)^2\left(2x_1K-\Delta^2\right)^2} > 0,$$

$$\pi_m^{MC*} - \pi_m^{M*} = -\frac{(1-\rho){x_1}^2\left(4K-\Delta^2\right)K^2(1-c_m)^2}{\left(8x_1K-\Delta^2x_2\right)\left(2x_1K-\Delta^2\right)^2} < 0.$$

The contract (p_d^{MC*}, w^{MC}) cannot be implemented since the manufacturer cannot obtain the reservation profits (i.e., π_m^{M*}). Hence, we use a complementary revenue sharing contract to ensure a win-win outcome for the manufacturer and retailer, which is widely adopted in existing studies [52–54]. Under the complementary revenue sharing scheme, let $\gamma^{MC}(0 \le \gamma^{MC} \le 1)$ and $1-\gamma^{MC}$ be the proportion of supply chain profit for the manufacturer and retailer, respectively. Then, solving inequations $\gamma^{MC}\pi_T^{MC*} \ge \pi_m^{M*}$ and $(1-\gamma^{MC})\pi_T^{MC*} \ge \pi_r^{M*}$, we obtain the lower and upper bounds for the revenue sharing rate γ^{MC}, which are given as follows.

$$\frac{x_2\left(2x_1K-\Delta^2\right)}{8x_1K-\Delta^2x_2} = \underline{\gamma}^{MC} \le \gamma^{MC} \le \bar{\gamma}^{MC} = \frac{\Delta^4{x_2}^2 - 4\Delta^2x_1(11+5\rho)K + 8{x_1}^2(7+\rho)K^2}{\left(8x_1K-\Delta^2x_2\right)^2}. \tag{15}$$

Lemma 2. *In Model M, if the revenue sharing rate γ^{MC} satisfies $\gamma^{MC} \in [\underline{\gamma}^{MC}, \bar{\gamma}^{MC}]$, the contract $(p_d^{MC*}, w^{MC*}, \gamma^{MC})$ can effectively coordinate the dual-channel CLSC with manufacturer collecting, where w^{MC*} is given in Eq. (14), and $\underline{\gamma}^{MC}$ and $\bar{\gamma}^{MC}$ are given in Eq (15).*

6.2. Coordinating of the R model (Model RC)

Differing from the M model, the retailer sets the traditional channel price and return rate decisions simultaneously in the R model. Similar to the analysis of the M model, the manufacturer first sets $p_d^{RC*} = p_d^{I*}$. Then, the manufacturer offers contract $(p_d^{RC*}, w^{RC}, b^{RC})$ to the retailer. Given p_d^{RC*}, w^{RC} and b^{RC}, we obtain the traditional channel price and return rate as follows:

$$\tau\left(w^{RC}, b^{RC}\right) = \frac{b(x_2 - w)}{4x_1K - b^2(1-\rho)} - \frac{b(2+\rho)\left(x_1K + x_1Kc_m - \Delta^2\right)}{\left(2x_1K-\Delta^2\right)\left(4x_1K - b^2(1-\rho)\right)}, \tag{16}$$

$$p_t\left(w^{RC}, b^{RC}\right) = \frac{2(1+w-\rho)x_1K - 2b^2(1-\rho)}{4x_1K - b^2(1-\rho)} - \frac{b\left(2\rho x_1K - b^2(1-\rho)\right)\left(x_1K(1+c_m) - \Delta^2\right)}{\left(2x_1K-\Delta^2\right)\left(4x_1K - b^2(1-\rho)\right)}. \tag{17}$$

To achieve supply chain coordination, the retailer sets $p_t(w^{RC}) = p_t^{I*}$ and $\tau^{RC*} = \tau^{I*}$. By solving equations $p_t(w^{RC}) = p_t^{I*}$ and $\tau(b^{RC}) = \tau^{I*}$, we obtain the equilibrium wholesale price and transfer price under the contract, which are given by:

$$w^{RC*} = \frac{(\rho x_1 + (2-\rho)x_1c_m)K - (\rho + (1-\rho)c_m)\Delta^2}{2x_1K - \Delta^2}, \quad b^{RC*} = \Delta. \tag{18}$$

With w^{RC*} and b^{RC*}, we can obtain the optimal profits for the manufacturer and retailer in the RC model. Similar to the MC model, we observe that the manufacturer cannot obtain the reservation profit in the uncoordinated case. Hence, we use a complementary revenue sharing scheme to reallocate the supply chain profit. Assuming that the manufacturer and the retailer share $\gamma^{RC}(0 \le \gamma^{RC} \le 1)$ and $1-\gamma^{RC}$ percentage of the supply chain profit π_T^{RC*}, respectively. The contract can be implemented when conditions $\gamma^{RC}\pi_T^{RC*} \ge \pi_m^{R*}$ and $(1-\gamma^{RC})\pi_T^{RC*} \ge \pi_r^{R*}$ are satisfied, thus we obtain the optimal range of revenue sharing rate in the RC model, which is given by:

$$\frac{4x_1x_2\left(2x_1K-\Delta^2\right)}{32{x_1}^2K - \Delta^2{x_2}^2} = \underline{\gamma}^{RC} \le \gamma^{RC} \le \bar{\gamma}^{RC} = 1 - \frac{\left(2x_1K-\Delta^2\right)z_1}{8K\left(32{x_1}^3K - \Delta^2x_1{x_2}^2\right)^2}, \tag{19}$$

where $z_1 = 512(1-\rho)x_1^5K^2 + 8\Delta^2x_1^2x_2^2(7+(10-\rho)\rho)K - \Delta^4(1-\rho)x_2^4$.

Lemma 3. *In Model R, when the revenue sharing rate γ^{RC} satisfies $\gamma^{RC} \in [\underline{\gamma}^{RC}, \bar{\gamma}^{RC}]$, the contract $(p_d^{RC*}, w^{RC*}, b^{RC*}, \gamma^{RC})$ can effectively coordinate the dual-channel CLSC with retailer collecting, where $w^{MC*}$is given in Eq. (18), and $\underline{\gamma}^{RC}$ and $\bar{\gamma}^{RC}$ are given in Eq (19).*

Table 7
Comparisons between optimal contract-implementing Pareto zones in the three contracts .

Case	Δ	K	ρ	Relationships
Case 1	$\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	$\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9}{40}(4+\sqrt{6})\Delta^2$	–	$N\gamma^{MC} < N\gamma^{RC} < N\gamma^{CC}$
Case 2	$\Delta \le \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	–	$0 < \rho \le \rho^{\gamma}$	$N\gamma^{RC} < N\gamma^{MC} < N\gamma^{CC}$
Case 3			$\rho^{\gamma} < \rho < 1$	$N\gamma^{MC} < N\gamma^{RC} < N\gamma^{CC}$
Case 4	$\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$	$K \ge \frac{9}{40}(4+\sqrt{6})\Delta^2$	$0 < \rho \le \rho^{\gamma}$	$N\gamma^{RC} < N\gamma^{MC} < N\gamma^{CC}$
Case 5			$\rho^{\gamma} < \rho < 1$	$N\gamma^{MC} < N\gamma^{RC} < N\gamma^{CC}$

where ρ^{γ} is one solution of equation $N\gamma^{MC} - N\gamma^{RC} = 0$.

6.3. Coordinating of the C model (Model CC)

In Model C, the independent third-party collector is responsible for collecting used products, and the manufacturer must coordinate the traditional forward and reverse channels separately. The manufacturer first sets $p_d^{CC*} = p_d^{I*}$ and then offers the retailer and third-party collector the contract $(p_d^{CC*}, w^{CC}, b^{CC})$. Given $p_d^{CC*}, w^{CC}, b^{CC}$, the traditional channel price and transfer price are:

$$p_t\left(w^{CC}, b^{CC}\right) = \frac{1}{2}\left(1 + w - \rho + \frac{\rho\left(x_1K + x_1Kc_m - \Delta^2\right)}{2x_1K - \Delta^2}\right), \tag{20}$$

$$\tau\left(w^{CC}, b^{CC}\right) = \frac{b(3 - w + \rho)}{4x_1K} - \frac{b\left(x_1K(1 + c_m) - \Delta^2\right)(2 + \rho)}{4x_1K\left(2x_1K - \Delta^2\right)}. \tag{21}$$

To achieve supply chain coordination, the retailer sets $p_t^{CC*} = p_t^{I*}$ and the third-party chooses $\tau^{CC*} = \tau^{I*}$. By solving equations $p_t(w^{CC}, b^{CC}) = p_t^{I*}$ and $\tau(b^{CC}, b^{CC}) = \tau^{I*}$, we obtain the optimal wholesale price and optimal transfer price in the contract, which are given as follows:

$$w^{CC*} = \frac{x_1K(\rho + (2-\rho)c_m) - \Delta^2}{2x_1K - \Delta^2}, \quad b^{CC*} = \Delta. \tag{22}$$

We can prove that $\pi_m^{CC*} < \pi_m^{C*}$, $\pi_c^{CC*} > \pi_c^{C*}$ and $\pi_r^{CC*} > \pi_r^{C*}$, meaning that the retailer and third-party collector are better off while the manufacturer is worse off compared with the uncoordinated case. Similar to Model M and Model R, we also use a complementary revenue sharing scheme to achieve a win-win-win outcome for the manufacturer, retailer and third-party collector. Assuming that the manufacturer shares γ^{CC} percentage of the supply chain profit π_T^{CC*}, the retailer and the third-party are viewed as an alliance to share the remaining $1 - \gamma^{CC}$ percentage of the supply chain profit. Then, by solving inequations $\gamma^{CC}\pi_T^{CC*} \ge \pi_m^{C*}$ and $(1-\gamma^{CC})\pi_T^{CC*} \ge \pi_r^{C*} + \pi_c^{C*}$, we derive the lower and upper bounds for the revenue sharing rate γ^{CC}, which are given as follows:

$$\frac{2x_2\left(2x_1K - \Delta^2\right)}{16x_1K - \Delta^2x_2} = \underline{\gamma}^{CC} \le \gamma^{CC} \le \bar{\gamma}^{CC} = \frac{2\Delta^4x_2^2 - 2\Delta^2x_1(49 + \rho(30+\rho))K + 32x_1^2(7+\rho)K^2}{\left(16x_1K - \Delta^2x_2\right)^2}. \tag{23}$$

Lemma 4. *In Model C, if the revenue sharing rate γ^{CC} satisfies $\gamma^{CC} \in [\underline{\gamma}^{CC}, \bar{\gamma}^{CC}]$, the contract $(p_d^{CC*}, w^{CC*}, b^{CC*}, \gamma^{CC})$ can effectively coordinate the dual-channel CLSC with third-party collecting, where w^{CC*} is given in Eq. (22), and $\underline{\gamma}^{CC}$ and $\bar{\gamma}^{CC}$ are given in Eq. (23).*

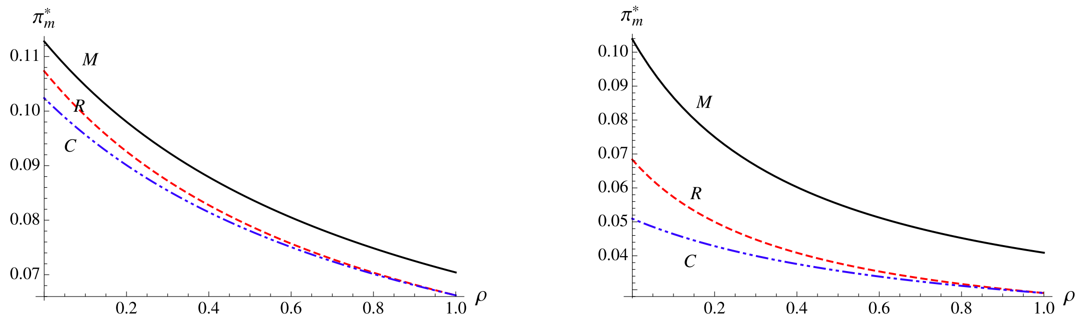
Next, we analyze the impacts of the reverse channel structure on the contracts of dual-channel CLSCs. In consistent with Cai [19], let $N\gamma^i = \bar{\gamma}^i - \underline{\gamma}^i, i \in \{MC, RC, CC\}$ denote the optimal contract-implementing Pareto zones of coordination contracts under the different collecting modes.

Proposition 5. *(1) The optimal wholesale prices and transfer prices in the three contracts satisfy: $w^{MC*} = w^{CC*} < w^{RC*}$ and $b^{RC*} = b^{CC*}$.*

(2) The optimal contract-implementing Pareto zones in the three contracts satisfy the following relationship, which is shown in Table 7.

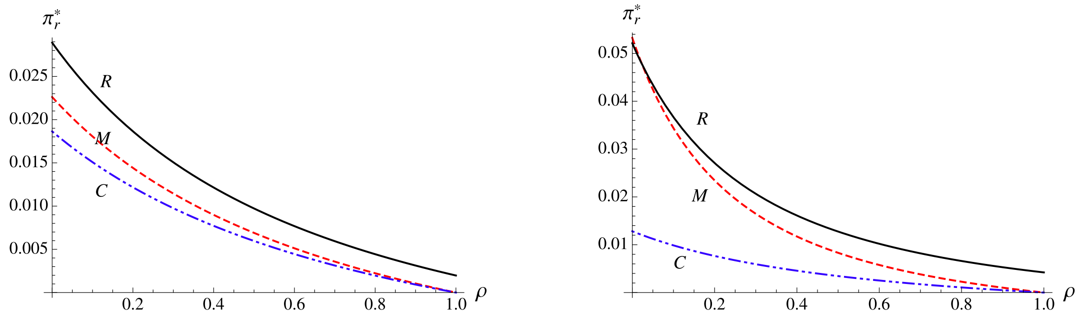
Proposition 5(1) compares the optimal wholesale prices and optimal transfer prices in the three contracts. We find that the manufacturer offers a higher wholesale price under the RC model than that under the MC and CC models, implying that the manufacturer sacrifices less to coordinate the channel when the retailer is the collector. In addition, the manufacturer transfers total remanufacturing cost savings to the retailer and third-party under the RC and CC models. The manufacturer benefits from supply chain coordination at the cost of giving up remanufacturing cost savings.

Proposition 5(2) compares the optimal contract-implementing Pareto zones in the three contracts. The result indicates that the contract-implementing Pareto zone is wider under the CC model than that under the other two models, suggesting



(a) $(\{c_m, K, \Delta\} = \{0.5, 0.2, 0.3\})$ (b) $(\{c_m, K, \Delta\} = \{0.7, 0.2, 0.6\})$

Fig. 3. The impact of ρ on π_m^*.



(a) $(\{c_m, K, \Delta\} = \{0.5, 0.2, 0.3\})$ (b) $(\{c_m, K, \Delta\} = \{0.7, 0.2, 0.6\})$

Fig. 4. The impact of ρ on π_r^*.

that the negotiation power of the manufacturer is lower in the third-party collecting mode. When the third-party collects used products, the manufacturer's preemptive channel power is reduced by the retailer and third-party collector. However, the power of the alliance of the retailer and third-party in the CC model increases compared with that under the other two models. Moreover, the contract-implementing Pareto zones under the MC and RC models depend on the following parameters: remanufacturing cost savings (Δ), collection cost (K) and channel competition intensity (ρ), which indicates that the reverse channel structure has a significant impact on the optimal contract-implementing Pareto zones of the three contracts, and each channel member's negotiation power under the contract changes with the three reverse channel structures.

7. Numerical analysis

In this section, we consider some numerical examples to gain deeper managerial insights of our models. The numerical analysis aims to analyze the impacts of the key parameters (i.e., Δ, K and ρ) on supply chain profit and coordination contracts. Considering the constraints of parameters outlined in Propositions 1–4, we give the following two parameter sets[6], which are of similar changing tendency and comparative relationship as the data considered in [58,59]. To meet conditions $\Delta > \frac{2(9\sqrt{6}-16)}{23}(1-c_m)$ and $\frac{\Delta(1+\Delta-c_m)}{2} \le K < \frac{9}{40}(4+\sqrt{6})\Delta^2$, we set $\{c_m, K, \Delta\} = \{0.7, 0.2, 0.6\}$; otherwise, the parameter set is designed as $\{c_m, K, \Delta\} = \{0.5, 0.2, 0.3\}$.

Fig. 3 shows that the manufacturer collecting mode always outperforms the other two collecting modes for the manufacturer. Moreover, as the remanufacturing cost savings Δ increase, the manufacturer prefers to collect used products by itself, because it can extract all the remanufacturing savings in this case and the investment in collection has a direct effect to increase channel demand. Fig. 4 illustrates that the R model is more preferable for the retailer than the other two models. Furthermore, as Δ increases, the profit difference between the M and R models becomes smaller, and converges when the

[6] All parameters (the initial demands of the direct and traditional channels, product costs of new and remanufactured products and remanufacturing cost savings) set in the numerical analysis are under the conditions outlined in the Model preliminaries section. Hence, we show some numerical results in Figures 2–5 in this part. It should be noted that the optimal profits in these numerical experiments may not reflect the actual profits for manufacturers or retailers in practice since we assume the normalized market demands for both direct and traditional channels (thus all the parameters need to be normalized to the same order of magnitude to be meaningful). However, our numerical results can still show the comparative relationships between the supply chain members under different collection types.

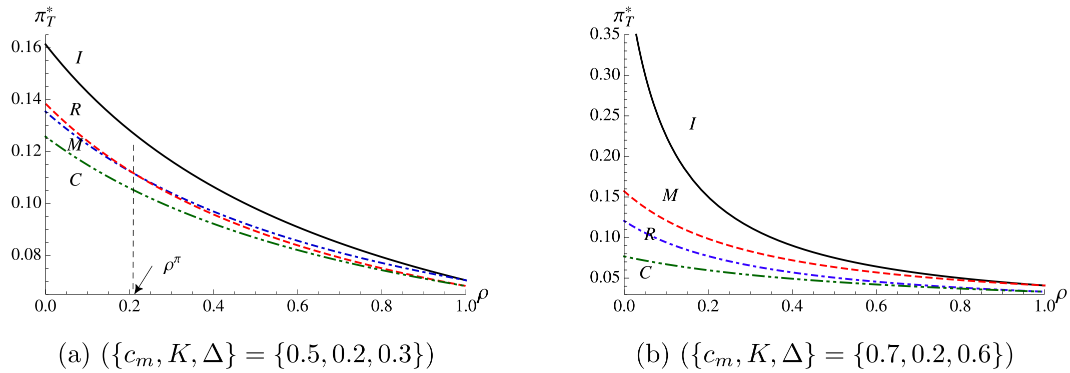


Fig. 5. The impact of ρ on π_T^*.

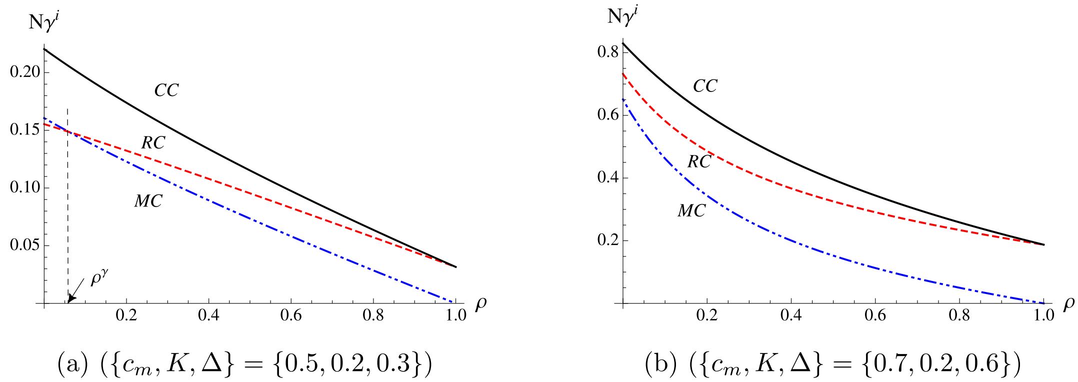


Fig. 6. The impact of ρ on $N\gamma^i$, $i \in \{MC, RC, CC\}$.

two sales channels are monopolistic (i.e., $\rho \to 0$). This result can be explained as follows. The manufacturer prefers to reduce the wholesale price to the retailer when the remanufacturing is more profitable. In Model M, this wholesale price reduction effect is significant in improving the retailer's profit. We see that the manufacturer's and retailer's profits decrease with channel competition intensity ρ, because the increasing channel conflict leads to a higher "double marginalization" effect in dual-channel CLSCs.

Fig. 5 compares the optimal profits of the total channel under the three dual-channel CLSC models. First, the centralized model leads to the highest profit, because the channel demand and return rate are higher than those in the decentralized models. Second, when the collection and remanufacturing efficiencies are sufficiently high, the M model is preferred for the supply chain; otherwise, the M or the R model might be the optimal channel structure, depending on the channel competition intensity, the remanufacturing cost savings and the collection cost. This result completely matches Proposition 4. Finally, note that the C model is the least preferred option for the total channel due to the existence of the "repeated double marginalization" effect in the third-party collecting dual-channel CLSC.

Fig. 6 compares the contract-implementing Pareto zones under the three dual-channel CLSC models. First, the revenue sharing contract can be implemented in the third-party collecting mode, because the negotiation power of the manufacturer in the C model is smaller than that in the other two CLSC models. In addition, the contract-implementing Pareto zones under the M and R models depends on the channel competition intensity and collection and remanufacturing costs. Second, as the channel competition intensity increases, the contract-implementing Pareto zones become narrower in the three contracts due to the fact that an increase in channel conflict makes it more difficult in achieving supply chain coordination. Finally, when two channels are purely competitive (i.e., $\rho \to 1$), the contract-implementing Pareto zone of the M model converges to that of the R model. In summary, compared with the C model, the negotiation power of the manufacturer is impaired in the R Model when the two channels become more competitive.

8. Managerial insights and concluding remarks

It has been well documented that the selection of efficient reverse channels is critical to firms. Existing studies show that the retailer collecting mode is the most effective way for supply chain members and the system [1,8]. However, the introduction of direct channels alters the channel structure of the CLSC. In this case, the manufacturer may need to adjust its strategies in selecting the optimal reverse channel. In this paper, by comparing the optimal profits under different reverse channel structures, we find that, in the dual-channel CLSCs, the manufacturer should directly collect used products by itself. From the perspective of the supply chain system, either the manufacturer collecting or retailer collecting mode could be optimal, depending on the key factors, i.e., the channel competition between the direct and traditional channels, collection costs and remanufacturing cost savings. Second, the supply chain coordination contracts are designed to improve the channel efficiency of the dual-channel CLSCs, and we find that a simple price contract, embeded with a complementary revenue sharing scheme, can perfectly coordinate the dual-channel CLSCs.

Our work has direct practical relevance for firms that are engaged in used product collection and remanufacturing in the context of multiple sales channels. The results offer several implications for managers and policy makers in the CLSC management. First, we find that the manufacturer should collect used products directly from consumers when facing dual sales channels. This result is in line with the fact that an increasing number of manufacturers have been building their own collection channels in the era of e-commerce, such as Huawei, Apple and Dell etc. Second, from the supply chain system's perspective, we find that the key parameters (e.g., channel competition intensity, collection costs and remanufacturing cost savings) play a strategic role in selecting the optimal reverse channel. To improve supply chain surplus and reduce environmental impact, policy makers should consider the interactions between these factors and manufacturers' reverse channel selection, and reasonably set reward or penalty schemes to facilitate product reuse. Third, our results suggest that all supply chain members can collaborate to increase collection efficiency and performance by implementing certain coordination contracts, regardless of the underlying reverse channel structure. For example, China Household Electrical Appliances Association (CHEAA) established the China WEEE Recycling Union (CWRU) to promote the recycling and reuse of electrical appliances by uniting manufacturers such as Haier, Changhong, Hisense, TCL, Chuangwei, Skyworth, and Huawei [57].

We have made some assumptions which can be relaxed in the future research. First, we assume that there is no distinction between the new and remanufactured products. However, consumers often value the remanufactured product less than the new product [58,59]. Under this assumption, who is the best undertaker for collection activity for the manufacturer needs further analysis. Second, we assume that the manufacturer plays the dominant role in the CLSC, but in reality it is not uncommon to observe the retailer-led or third party-led CLSC [35]. Therefore, it would be more practical to build alternative models by incorporating these factors. Third, since we assume the non-cooperative behavior between the manufacturer and the retailer in our models, it would be interesting to analyze the strategic impacts of the channel member collusion behavior on the manufacturer optimal reverse channel choice in the dual-channel CLSC. Fourth, future research can also explore reverse channel selection and coordination issues of dual-channel CLSCs under incomplete cost/demand information. Finally, we assume that all channel members are risk-neutral, thus an extension of this study could consider the case where the manufacturer or retailer is a risk-averse decision-maker.

Acknowledgments

The authors thank the Associate Editor and the three anonymous reviewers for their valuable comments, which significantly improve the quality of this paper. This paper has been supported by the Social Science Foundation of Education Ministry of China [No. 19YJC630229], Natural Science Foundation of Hubei Province [No. 2019CFB120], the Fundamental Research Funds for the Central Universities [No. 2662020JGPYG14], the National Natural Science Foundation of China [No. 71902079] and the Philosophy and Social Science Project of Hubei Province [No. 20G032].

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.apm.2021.02.022

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