Dual-recycling channel reverse supply chain design of recycling platforms under acquisition price competition

Matsui, Kenji

(Citation)
International Journal of Production Economics,259:108769

(Issue Date)
2023-05

(Resource Type)
journal article

(Version)
Accepted Manuscript

Dual-recycling channel reverse supply chain design of recycling platforms under acquisition price competition*

Kenji Matsui

Graduate School of Business Administration, Kobe University, 2-1, Rokkodaicho, Nada-ku, Kobe, Japan

E-mail address: kmatsui@b.kobe-u.ac.jp

Telephone and fax: +81 78 803 6908

Abstract

The rapid development of information and communication technology has enabled companies establishing recycling platforms to purchase used products from end-consumers using the combination of an online collection with the Internet and a conventional offline channel, usually termed a *dual-recycling channel reverse supply chain*. By constructing a game-theoretic model, this paper explores which of the following three collection channels each of two recycling companies under acquisition price competition should use to purchase products: (i) an indirect offline channel only; (ii) a direct online channel only; or (iii) both channels. We assume that consumers perceive differentiation between the online and offline channels, but not between the recycling companies to which they sell the products. We first show that the following combinations of channel choices arise in equilibrium: (i) both recycling companies use both online and offline channels, and (ii) one recycling company uses only the online channel whereas the other recycling company uses only the offline channel. Based on this equilibrium result, we provide the central finding that the profits resulting from the first (symmetric channel) equilibrium are always Pareto-dominated by the second (asymmetric channel) equilibrium, implying that the dual-channel choice of collecting products via both offline and online channels will lead to the typical *prisoners' dilemma*. Consequently, the conventional result that a recycling company should employ both online and offline collection channels in a dual-recycling channel reverse supply chain is completely reversed when considering competition between recycling companies, some of which exit real-world recycling markets owing to excessively fierce collection competition.

Keywords: dual recycling channel; reverse supply chain; recycling platform; acquisition price competition; game theory

---

* This manuscript is the final version of the paper accepted and published in *International Journal of Production Economics*. This paper is uploaded on the repository of Kobe University under the permission of Elsevier B.V. You may download the formal version of this paper from the following URL: https://www.sciencedirect.com/science/article/pii/S0925527323000014/pdfft?md5%20=32f7fba8052f496dea7e975fea217597&pid=1-s2.0-S0925527323000014-main.pdf

Highlights

> We assume there are two recycling companies that can use dual-recycling channels.
> We also assume that the companies face price competition to collect used products.
> Both asymmetric and symmetric channel choices arise in equilibrium.
> Symmetric channel equilibrium is Pareto-dominated by asymmetric channel equilibrium.
> Use of both channels is not always profitable for a company under price competition.

1. Introduction

Rapid advances in information and communication technology promote the upgrading of personal computers, cellphones, and other electronic devices used by consumers and businesses, generating a considerable volume of waste electrical and electronic equipment (WEEE). Given that product recycling has both environmental and economic benefits, it has become a major concern for society to realize the economic salvage value of WEEE through efficient collection systems (Thierry et al., 1995). Therefore, the use of the so-called reverse supply chain is attracting a great deal of attention, not only from production researchers, but also business practitioners (Huang et al., 2013). These reverse supply chains manage the flow of the end-of-life product from end-consumers to businesses. This contrasts with forward supply chains that deal with the product flow from businesses to end-consumers.

WEEE collection methods have also changed significantly with the evolution of information technology, allowing recyclers to buy and gather end-of-life products directly from end-consumers via online channels using the Internet, along with traditional recycling channels. These *dual-recycling channel reverse supply chains* represent a mixture of an Internet-based online direct channel and a traditional offline recycling channel, which encourage recycling companies to collect WEEE more effectively, and thereby help reduce the costs of collection. In general, a dual-recycling channel is the mixed use of an online recycling channel and an offline recycling channel. In the online channel, the recycling company directly purchases used products from consumers. In the offline channel, an external offline collector acting as an intermediary purchases the products from consumers, and then the recycling company repurchases the products from the collector.[1]

Recently, recycling companies in large countries have also established online platforms that employ customer-oriented services and high acquisition prices as competitive weapons to facilitate product collection (Feng et al., 2017; Wang et al., 2019).[2] For example, Loving Recycling, the largest recycler of smartphones for purchase and resale in China, has

[1] This definition of the dual-recycling channel in our research follows from previous studies constructing game-theoretic dual-recycling channel models, including Huang et al. (2013) and Feng et al. (2017). The difference between a dual-recycling channel and a traditional offline channel is that in the former, a recycling company employs an external third-party collector for the physical collection of products via an offline channel and, at the same time, uses online technology, including the Internet, to contact consumers. In contrast, a traditional offline channel is where a recycling company physically collects used products only through an external collector without the use of online technology. Additional details are found in Huang et al. (2013) and Feng et al. (2017).

[2] While this paper focuses on companies that specialize in recycling, it should not be overlooked that general manufacturers and retailers such as Dell and Best Buy also play important roles in operating data-based real businesses for online to offline (O2O) collections. According to their official websites, Best Buy and Dell have each recycled more than 2 billion pounds of used electronics to date, respectively (https://corporate.bestbuy.com/best-buy-customers-are-part-of-the-solution-to-e-waste/ and https://www.dell.com/en-us/blog/dell-hits-2020-circular-milestones-recycles-2-billion-pounds-electronics/).

successfully operated an online recycling platform with over 40 million customers (Wang et al., 2018; Qu et al., 2019; Zuo et al., 2020; Zhao et al., 2022).[3] In 2021, Loving Recycling achieved an annual trading volume of more than 22 million units of WEEEs (Wang et al., 2022b). GEM Co., Ltd., another of the largest recycling companies in China, established Recycling Brother as its online recycling platform (Wei et al., 2021).[4] Both these and other major recycling companies have an incentive to raise the acquisition price of end-of-life products to encourage more consumers to accept online collection channels alongside conventional offline channels (Song et al., 2017; Zuo et al., 2020). In the US, Gazelle is an e-commerce company purchasing used computers, cell phones, and other electronic devices from consumers directly through online and other collection channels. By 2014, Gazelle had collected more than two million devices from over one million consumers, paying consumers approximately $200 million for their used electronics (Hardcastle, 2014). Similarly, ReCellular Inc. was a US cell phone remanufacturer that purchased used products not only directly from consumers, but also via third-party collectors, expending much effort on developing collectors so that it could gather used phones in large quantities (Guide et al., 2003). The above cases from China and the US all evidence that companies can take advantage of dual-recycling channel reverse supply chains through establishing recycling platforms.[5]

However, many recycling companies suffer from low profitability even though they collect a large volume of used products. For example, recycling companies engaging in the US collection business experience particularly fierce competition. ReCellular declared bankruptcy in 2013, and Gazelle has recently ceased trade-in services (Statt, 2020). Song et al. (2017) report fierce collection price competition also arising among recycling companies and collectors in China. Li (2019) suggests that because the acquisition price difference between companies collecting reused mobile phones in China is small, it is difficult to maintain profitability from the process of collection, maintenance, and reuse.

One possible reason for the low profitability of recycling businesses is that it is more difficult for a recycling company constituting a reverse supply chain to create customer loyalty than for a manufacturer constituting a forward supply chain. That is, because consumers usually have brand loyalty to a particular product supplied from a specific manufacturing company in forward supply chains, they perceive significant differentiation between alternative products supplied by different manufacturers. For example, a consumer

[3] Loving Recycling is the English language translation of *Aihuishou*, which is the official company name in Chinese (http://www.aihuishou.com).
[4] Recycling Brother is the English language translation of *Huishouge*, which is the official company name in Chinese (http://en.gem.com.cn).
[5] While all recycling companies shown in this section use both online and offline channels for product collection (i.e., the dual-recycling channel), the relative importance of each of the two types of channels varies across the companies. For example, Recycling Brother tends to collect more products via its offline channel using local collectors than do other recycling companies. This variation across companies is explained in detail in existing case studies by Song et al. (2017), Tong et al. (2018), and Zuo et al. (2020).

usually has a preference about whether to buy a smartphone supplied by Apple or Samsung. In contrast, consumers are likely to perceive no differentiation between recycling companies because there is usually no factor that can create consumer loyalty to a specific recycling company in a reverse supply chain. For example, consumers are less likely to have loyalty concerning whether to sell their smartphones to Loving Recycling or Recycling Brother in China. Instead, consumers are likely to simply sell their used products to a recycling company offering a higher acquisition price. Hence, it is far more difficult for firms in reverse supply chains to differentiate themselves than for firms in forward supply chains. Consequently, recycling platforms cannot help facing fierce acquisition price competition to attract consumers selling their used products.

Given the present recycling business environment, our main research questions are:

- *When recycling companies using dual-recycling channel reverse supply chains face acquisition price competition for collecting used products, which collection channel strategy is optimal for each company?*
- *What characteristics do equilibrium profits resulting from the optimal collection channel strategies have?*

More specifically, this paper explores in which of the following three channels each of two recycling companies under acquisition price competition should purchase and collect products: (i) an indirect offline channel only; (ii) a direct online channel only; or (iii) both an indirect offline channel and a direct online channel. As discussed, one distinctive feature of a reverse supply chain compared with a forward supply chain is that consumers selling used products usually perceive no differentiation between competing recycling companies. Meanwhile, consumers perceive substantial differentiation between the online and offline channels because some consumers return used products to an online channel more easily than others. Reflecting this consumer behavior, we assume in our game-theoretic model that consumers perceive differentiation between the different channels, but not between the individual recycling companies. By solving the model, we first show that the following combinations of channel choices arise in equilibrium: (i) both recycling companies use both online and offline channels, and (ii) one recycling company uses only the online channel whereas the other recycling company uses only the offline channel. Based on the equilibrium results, we provide the central finding that the profits resulting from the first (symmetric channel) equilibrium are always Pareto-dominated by the second (asymmetric channel) equilibrium, implying that the dual-channel choice of collecting products via both offline and online channels will lead to the typical *prisoners' dilemma*. Such symmetric dual-channel strategies will trigger all-out competition between the competing supply chains, such that each company will not only reduce the profit of the rival company but also its own. This yields the managerial implication that each of the two recycling companies should use only one type of channel and that this channel should differ from that of the other rival company. This choice enables the competing recycling companies to escape from the first symmetric equilibrium characterized by the prisoners' dilemma. Overall, the findings of this study suggest that in reverse supply chains where differentiation between companies is difficult, it is an effective strategy for a recycling company in a competitive environment to have only one collection channel, not both channels. Hence, recycling companies should not heedlessly use both offline and online collection channels in a competitive environment. Our findings are robust and clear because they are fully analytically proven without numerical analysis.

In practice, we intuitively infer that it would be optimal for a recycling company to use both channels to meet the needs of different types of consumers. Indeed, this has been formally shown in the literature, as will be reviewed later. However, this conventional result is completely reversed in our model when considering a competitive environment. Moreover, our finding also explains the situation in which real-world competition between recycling companies is sufficiently fierce to force several companies to exit the market.

Consistent with our finding, there exist recycling companies that differentiate their collection channels. Particularly in China, collection channels tend to vary among companies because of intense collection competition. Specifically, Wang et al. (2022a) summarize the situation in China by showing that some recycling enterprises rely on independent collectors while others use their own collection channels.[6] Moreover, Tong et al. (2018) and Zuo et al. (2020) show that Recycling Brother actively collects its products indirectly by using third-party collectors, unlike other recycling companies like Loving Recycling.[7] Elsewhere, Song et al. (2017) categorize companies engaging in recycling businesses in China, including Recycling Brother, Loving Recycling, and others, showing that the recycling channel choices differ substantially among these companies. The real-world cases of these enterprises choosing different recycling channels prove that the choice of collection channel is an important issue and highlight the need to address the above research questions.[8]

However, as we will review in the following section, no existing study describes the price competition between dual-recycling channel reverse supply chains, each of which

[6] Specifically, Wang et al. (2022a, p. 129) state: "Currently, 44% of the 109 formal recycling enterprises mainly depend on independent collectors and 33% have their own collection channels, ..."

[7] According to Tong et al. (2018, p. 671): "One exception is Huishouge in Wuhan. With door-to-door collection service in the community, Huishouge tried to open their IT platform to the urban junk buyers. They signed contracts with the junk buyers and provided information about the demands for collection of recyclable goods by household, then a nearby junk buyer would go to collect the goods door to door." Zuo et al. (2020, p. 226) also point out: "HSG [Huishouge] works with self-employed recyclers and businesses through the franchise model. After joining HSG, self-employed recyclers and businesses will receive professional training and wear uniforms to strengthen the sense of identity with HSG." Wei et al. (2021) detail the employment process for independent collectors in China.

[8] In addition, manufacturing companies other than companies specializing in recycling also choose different collection channel structures. Taleizadeh and Sadeghi (2019) detail that both Apple and Hewlett-Packard collect used products through both online and offline channels, while Dell collects only directly through its own online channel and Sony collects only offline through retail stores.

consists of one traditional offline channel and one direct online channel. Moreover, even though the optimal collection channel structure is a practical key issue for recycling companies, no existing study explores the optimal channel structure in dual-recycling channel reverse supply chains in competitive environments. As this paper is the first to address these issues, it makes a significant contribution to the literature.

The remainder of the paper is structured as follows. Section 2 reviews the literature relating to the management of reverse supply chains with dual recycling channels. Section 3 describes the basic setup of our model. Section 4 derives the equilibrium solution that identifies the optimal channel structure for each recycling company. Section 5 additionally considers a scenario in which recycling companies sequentially choose their respective channel structures. Section 6 extends the model by considering the situation where consumers can perceive that the two supply chains are differentiated, but not perfectly substitutable. Section 7 provides concluding remarks.

2. Literature review

2.1 Collection competition in reverse supply chains

Recently, a growing number of studies have considered the operation of a reverse supply chain and closed-loop supply chain (CLSC), as comprehensively reviewed in Souza (2013), Govindan et al. (2015), Chen et al. (2017), and Guo et al. (2017). Most of these assume that consumers discard used products without expectation of any financial compensation, and therefore the amount of collected products is not a function of the acquisition price, rather the efforts made by firms, which are considered to be costs or investments (e.g., Savaskan et al., 2004; Savaskan and van Wassenhove, 2006; Ferrer and Swaminathan, 2010; Atasu et al., 2013; Choi et al., 2013; Hong et al., 2013, 2017; Huang et al., 2013; Ma et al., 2013; Chuang et al., 2014; Govindan and Popiuc, 2014; Jena and Sarmah, 2014; Saha et al., 2016; Xiong et al., 2016; Giri et al., 2017; Panda et al., 2017; Xie et al., 2017; He et al., 2019a, 2019b; Taleizadeh and Sadeghi, 2019; Hosseini-Motlagh et al., 2020; Ranjbar et al., 2020; Wang et al., 2020a; Hong et al., 2021; Liu et al., 2021; Zhao et al., 2021). Within this research stream, Savaskan et al. (2004) first developed a model that determines the optimal reverse channel structure for collecting used products from customers. Specifically, they assume the situation where a manufacturer can choose one mode from the following three modes of collecting products: (i) the manufacturer directly collects products from customers, (ii) the manufacturer consigns collection operation to an external retailer, or (iii) the manufacturer consigns the collection operation to an external third-party. Comparison of the equilibrium profits of the manufacturer across these three collection modes reveals that consignment to the retailer is superior to the other modes. Atasu et al. (2013) extended the model in Savaskan et al. (2004) to investigate how the collection cost structure affects which of the manufacturer- and retailer-managed collection channels in a reverse supply chain is more profitable to the manufacturer if the collection cost structure depends on both collection rate and volume. They showed that the choice of the optimal reverse channel depends on how the cost structure adjusts the ability of the manufacturer to influence the retailer's sales and collection volume decisions.

Later, Choi et al. (2013) examined how the profitability of a CLSC consisting of one manufacturer, one retailer, and one collector depends on their decision leadership within the CLSC. They showed that the retailer-led model, in which the retailer is the first mover, leads to the most effective CLSC. They also demonstrated that the order of decision-making significantly influences CLSC profitability, whether in a reverse or forward supply chain. Hong et al. (2013) explored a desirable reverse channel structure for collecting end-of-life products from consumers in a dual-channel supply chain, assuming that a manufacturer chooses one of the three following reverse hybrid structures for product collection: (i) both manufacturer and retailer collect end-of-life products; (ii) the manufacturer outsources the collection of end-of-life products to the retailer and a third-party; or (iii) the manufacturer and an external third-party collect end-of-life products. They showed that the hybrid collection channel structure by the manufacturer and retailer is the most profitable to the manufacturer. In other work, Huang et al. (2013) explored the optimal channel configuration strategy of a CLSC with a dual-recycling channel, in which a manufacturer sells products through a retailer in a forward supply chain while the retailer and a third-party compete for the collection of used products in a reverse supply chain. Their results identified the range of competitive intensity in which a CLSC with a dual-recycling channel is superior to a CLSC with a single recycling channel from the perspective of the manufacturer and consumers. Wu and Zhou (2017) extended the model in Savaskan et al. (2004) by assuming the existence of two supply chains and investigated the influence of supply chain competition on the manufacturers' choice on reverse channel structure. They showed that asymmetric equilibria can arise in strategic reverse channel selection, with one manufacturer preferring retailer-managed collections and the other preferring manufacturer-managed collections. They further revealed that the prisoners' dilemma arises because the choice of manufacturer-managed collection results in a Pareto-optimal solution for both manufacturers. Whereas their model demonstrated that the prisoners' dilemma arises regarding collection channel choice with the assumption of collection effort being the decision variable, we assume that the acquisition price is the decision variable, and that dual-channel collection is available. In this respect, our model also differs from that of Wu and Zhou (2017). He et al. (2019b) assumed that consumers facing a CLSC consisting of one manufacturer and one retailer experience inconvenience in returning used products. They demonstrated that while competition does not enhance the efficiency of product collection, the retailer always has the incentive to join collection competition, which can reduce the cost advantage of remanufacturing. Most recently, He et al. (2022) constructed a closed-loop supply chain model involving one manufacturer and one third-party collector to analyze the effects of collection competition and channel convenience for consumers to return used products. By comparing monopolistic and competitive scenarios, they found that channel differentiation and collection convenience promote collection competition. Specifically, while extreme channel differentiation mitigates competition, a more competitive market with appropriate channel differentiation leads to a higher level of collection convenience.

The above preceding studies, including those exploring desirable collection channel structure in reverse or CLSCs, have developed models based on the assumption that the amount of collection hinges on the collection efforts of firms. However, with the proliferation of online recycling channels using the Internet, the transmission of price information has become much faster, and consumers can more easily learn and compare present acquisition prices. Hence, it is realistic that recycling companies engage in price competition because acquisition prices influence collection quantity. Accordingly, a growing number of studies construct models that describe situations where firms in reverse supply chains compete in terms of acquisition price rather than collection effort (e.g., Minner and Kiesmüller, 2012; Bulmus et al., 2014; He, 2015; Wu, 2015; Hu et al., 2016; Liu et al., 2016; Feng et al., 2017; Gan et al., 2017; Li et al., 2017; Heydari et al., 2018; Taleizadeh and Sadeghi, 2019; Jin et al., 2021; Matsui, 2022).

In this stream, Minner and Kiesmüller (2012) considered a closed-loop supply chain in which demand is satisfied either by manufacturing new products or by buying used products from consumers and remanufacturing them. Taking into account dynamic parameters including seasonal factors and product life cycles, they developed a model that jointly determines the buy-back price and manufacturing–remanufacturing. Their model shows that an optimal policy includes time intervals where returns are acquired to synchronize demand and remanufacturing, and time intervals where demand is satisfied by a mixture of manufactured and remanufactured products. Bulmus et al. (2014) constructed a reverse supply chain model in which firms compete in terms of their acquisition prices. Specifically, they described competition between an original equipment manufacturer (OEM) and a remanufacturer, not only in terms of the sale of their products but also the collection of used products. They assumed that the OEM sells both new and remanufactured products, whereas the remanufacturer sells only remanufactured products. Identifying the optimal strategies for both firms, they revealed that the acquisition price from the OEM depends on its cost structure, but not on the acquisition price from the remanufacturer. Hong et al. (2017) adopted a similar setup to Bulmus et al. (2014) and considered the situation in which a remanufacturer needs a license from a manufacturer to use some remanufacturing technologies. They compared the economic outcomes resulting from the two types of licensing, either a fixed fee license or a royalty license, and found that the former was superior to the latter in terms of both environmental protection and consumer surplus.

2.2 Acquisition price competition in dual-recycling channel reverse supply chains

Given models describing competitive environments in reverse supply chains operated primarily by manufacturers, Feng et al. (2017) introduced the idea of an Internet-based direct recycling channel in a typical two-level dual-channel reverse supply chain, where a recyclable dealer is a Stackelberg leader, and a recycler is a follower. They investigated the preferred structure of the reverse channel for the recyclable dealer, assuming different channel preferences among consumers and price competition between the online and offline channels. Their results showed that the choice of the dual-channel structure always earns both the recyclable dealer and the entire supply chain higher profits than a single-channel structure. Feng et al. (2017) is most closely related to this paper in the sense that they developed a stylized model to describe price competition between an offline channel and an online channel in a reverse supply chain, and hence their model is the basis for ours.

Later, Taleizadeh and Sadeghi (2019) formulated a game-theoretic model of two reverse supply chains, each of which consists of a manufacturer and a retailer competing to collect more used products by paying higher rewards to customers. They considered three decision sequences to determine the optimal level of the rewards: Nash; Nash–Stackelberg–first supply chain; and Nash–Stackelberg–second supply chain. By comparing the equilibrium outcomes resulting from these three sequences, they showed that a direct online collection channel offers a more appropriate reward to customers than a traditional collection channel and thus the former channel enables a supply chain to achieve a higher share of the market. Jin et al. (2021) assumed a reverse supply chain consisting of competing online and offline recycling channels, examining how the power structure of supply chain members affects their decisions on pricing and coordination. Specifically, they constructed one centralized reverse supply chain model and three decentralized reverse supply chain models under three power structures: remanufacturer-led; collector-led; and vertical Nash. Their main conclusion was that either the remanufacturer or the collector has an incentive to make its decision first in the reverse supply chain, while the balanced power structure (i.e., vertical Nash) is more advantageous for the entire reverse supply chain system. Most recently, Matsui (2022) explored the desirable timing of announcing the acquisition price of used products to consumers by constructing a model that describes a dual-recycling channel reverse supply chain consisting of one recycling company and one third-party collector, where the recycling company purchases the products directly from consumers online as well as through the third-party collector. Matsui (2022) showed that the recycling company should announce the acquisition price in the online channel before or upon rather than after setting the transfer price paid to the collector in the offline channel in order to maximize its own profit and consumer surplus.[9]

2.3 Summary

Table 1 provides a summary of the relevant literature, highlighting the main features of this paper when compared to previous studies, which can be categorized by several characteristics. First, there are two types of models that can be distinguished by the decision variable: models in which the collection effort that affects collection quantity is the decision variable, and models in which the acquisition price is the decision variable. Second, the models can be classified by whether the channel structure is endogenously chosen or not.

[9] It should also be noted that the focus of earlier studies on dual-channel supply chain management was on the forward supply chain selling products to consumers (e.g., Chiang et al., 2003; Dumrongsiri et al., 2008; Cai et al., 2009; Hua et al., 2010; Dan et al., 2012; Matsui, 2016, 2017; Yan et al., 2018, 2020; Yang et al., 2018; Jabarzare and Rasti-Barzoki, 2020; Shi et al., 2020; Wang et al., 2020b; Zhang et al., 2020). Accordingly, early game-theoretic models describing dual-recycling channel reverse supply chains have used the framework of those describing dual-channel forward supply chains.

Third, some models assume the existence of multiple supply chains while others only a single supply chain. Hence, Table 1 reveals that, unlike previous studies, only this paper simultaneously considers acquisition price as the decision variable, channel structure to be endogenously determined, and the existence of multiple supply chains.

In summary, although previous studies have investigated the issue of dual-recycling channel reverse supply chain management from a variety of viewpoints, no existing research explores the optimal collection channel structure under acquisition price competition, even though the recycling channel choice is a key issue for companies establishing recycling platforms. Hence, it is worth highlighting that this paper is the first to address this problem by applying noncooperative game theory to reverse supply chain management, thereby making a unique contribution to the production economics literature.

3. Model

This section describes the setup of our model. Fig. 1 depicts the structure of the reverse supply chains assumed, and Table 2 enumerates the variables and notations used in the model. Our model follows the assumptions of existing stylized game-theoretic models for dual-channel reverse supply chains (e.g., Feng et al., 2017; Li et al., 2019; Wu et al., 2020; Matsui, 2022). Whereas Feng et al. (2017), Li et al. (2019), Wu et al. (2020), and Matsui (2022) assume only a single supply chain composed of one recycling company and one third-party collector, we assume that two dual-channel supply chains are competing in the purchase and collection of used products from consumers, as illustrated in Fig. 1.

For simplicity, we henceforth refer to a recycling company and a third-party collector simply as a company and a collector, respectively. Because we assume that two supply chains exist, we index the first chain consisting of Company 1 and Collector 1 as Supply chain 1 and the second chain consisting of Company 2 and Collector 2 as Supply chain 2, also as shown in Fig. 1.[10] Each company can buy and collect used products directly from consumers and/or indirectly via a collector.[11] We call this a *direct online channel* or just an *online channel* when a recycling company collects directly from consumers, and a *traditional offline channel* or just an *offline channel* when a collector collects indirectly.

Because both recycling companies can use dual channels, Company i (where i = 1 or 2) chooses one of the following three strategies as its channel strategy concerning which channel to use, denoted by S_i. Strategy T is purchasing used products only through the

[10] Although several previous studies construct models of dual-recycling channels, the designations of the two firms differ slightly. For example, Feng et al. (2017) refer to them as the recycling dealer and the recycler, Li et al. (2019) as the remanufacturer and the recycler, Wu et al. (2020) as the recycling center and the third-party recycler, and Matsui (2022) as the recycling company and the third-party collector. Following the models in He et al. (2022) and Mastui (2022), we refer to the two firms in our model as the recycling company and the third-party collector.

[11] Because our focus is only on reverse supply chains, the term *consumers* also denotes *sellers* of used products in our model.

offline channel, Strategy D is purchasing products only through the online channel, and Strategy TD is purchasing products through both the offline and online channels. If Company i chooses Strategy TD, Company i and Collector i will compete to purchase used products from consumers between the online and offline channels within the same Supply chain i. Henceforth, we refer to this type of competition as *channel competition*.[12] Meanwhile, competition also arises between Companies 1 and 2 (or Collectors 1 and 2) to purchase used products within the same type of channel. We refer to this type of competition as *supply chain competition*. Accordingly, in our model, we distinguish between these two types of competition. If Company i chooses Strategy T or TD, the company determines the transfer price b_i of the used product to pay to Collector i and purchases the product in the offline channel. Subsequently, Collector i determines the offline recycling price per used product, p_i^T, and purchases the product through the offline channel at that price. Meanwhile, if Company i chooses Strategy D or TD, it determines the online recycling price per used product, p_i^D, and purchases the product directly through the online channel.[13] For convenience, we refer to p_i^T and p_i^D as the offline and the online price in Supply chain i, respectively.

Next, we assume that the disutility of a consumer to return products is specified as:

$$\begin{aligned}&\alpha(q_1^T+q_2^T+q_1^D+q_2^D)+\beta(((q_1^T)^2+(q_2^T)^2+(q_1^D)^2+(q_2^D)^2)/2+\lambda(q_1^Tq_2^T+q_1^Dq_2^D)\\&+\theta(q_1^Tq_1^D+q_2^Tq_2^D)+\lambda\theta(q_1^Tq_2^D+q_1^Dq_2^T)),\end{aligned} \tag{1}$$

where q_i^T and q_i^D respectively denote the quantity collected via the offline channel and the online channel in Supply chain i. α and β are positive constants. $\theta \in (0, 1)$ denotes substitutability between the online and offline channels and $\lambda \in (0, 1]$ denotes substitutability between different supply chains within the same type of channel. Thus, consumers perceive that the two channels and the two supply chains become more differentiated as θ and λ decrease, respectively. We henceforth refer to θ as *channel substitutability* and λ as *supply chain substitutability*. Equation (1) indicates that a higher disutility means the consumer is more reluctant to return or is more addicted to end-of-life products (Simpson et al., 2019). Meanwhile, the total amount of money that the consumer receives is stated as: $p_1^Tq_1^T+p_2^Tq_2^T+p_1^Dq_1^D+p_2^Dq_2^D$. Given these functions, consumer surplus denoted by S is described as:

$$\begin{aligned}S = {}&(p_1^Tq_1^T+p_2^Tq_2^T+p_1^Dq_1^D+p_2^Dq_2^D)\\&-(\alpha(q_1^T+q_2^T+q_1^D+q_2^D)+\beta(((q_1^T)^2+(q_2^T)^2+(q_1^D)^2+(q_2^D)^2)/2+\lambda(q_1^Tq_2^T+q_1^Dq_2^D)\\&+\theta(q_1^Tq_1^D+q_2^Tq_2^D)+\lambda\theta(q_1^Tq_2^D+q_1^Dq_2^T))).\end{aligned} \tag{2}$$

[12] The assumption that third-party collectors possess the pricing power follows the assumption of previous models describing acquisition price competition in dual-recycling channel reverse supply chains (e.g., Feng et al., 2017; Li et al., 2019; Wu et al., 2020; Matsui, 2022). There is also empirical evidence that intense price competition arises between collection channels because general collectors possess pricing power, especially in China (Song et al., 2017; Bai et al., 2022).

[13] In previous studies investigating collection competition among different firms, the term *recycling price* has also been known as the *collection price* or *acquisition price*. All three terms have the same meaning.

The consumer maximizes S by solving $\partial S/\partial q_1{}^T = \partial S/\partial q_1{}^D = \partial S/\partial q_2{}^T = \partial S/\partial q_2{}^D = 0$, which yields the following supply functions that the recycling companies and third-party collectors, respectively, face.[14]

$$\begin{aligned}
p_1{}^T &= \alpha+\beta(q_1{}^T+\lambda q_2{}^T+\theta(q_1{}^D+\lambda q_2{}^D)) \\
p_2{}^T &= \alpha+\beta(q_2{}^T+\lambda q_1{}^T+\theta(q_2{}^D+\lambda q_1{}^D)) \\
p_1{}^D &= \alpha+\beta(q_1{}^D+\lambda q_2{}^D+\theta(q_1{}^T+\lambda q_2{}^T)) \\
p_2{}^D &= \alpha+\beta(q_2{}^D+\lambda q_1{}^D+\theta(q_2{}^T+\lambda q_1{}^T))
\end{aligned} \tag{3}$$

Equation (3) indicates that $q_i{}^T$ and $q_i{}^D$ increase as $p_i{}^T$ and $p_i{}^D$ increase, respectively. This is because the higher the purchase price offered in a channel, the stronger the incentive for consumers to sell and return their used products to that channel.

We employ the linear-form inverse supply function shown in Equation (3) following existing dual-recycling channel models that adopt linear supply functions (e.g., Wu et al., 2020; Jin et al., 2021). The form of the inverse supply function in Equation (3) implies that the two channels are differentiated in terms of variety rather than quality. Namely, the function implies that channel preferences vary among consumers, and therefore the value of returning a product to one channel is not always higher than the value of returning it to the other channel for all consumers. In reality, some consumers may prefer an online channel because new technology allows them to return used products more conveniently, whereas other consumers, such as the elderly, may prefer an offline channel because they find the process of returning products using unfamiliar new technology inconvenient. As a result, channel preferences can vary substantially across consumers. Given the variance of consumers' channel preferences, we adopt the supply function form expressed in Equation (3), which describes the situation where consumers who prefer the online channel and those who prefer the offline channel coexist.

Next, we assume that a recycling company pays disposal, shipping, and inspection costs per product incurred in an online channel following the assumptions of existing models (e.g., Feng et al., 2017). We denote these by c, c_{RS}, and c_{RI}, respectively. Moreover, a collector incurs the collection, inspection, shipping, and handling cost per product incurred in an offline channel. We denote these by c_0, c_{CI}, c_{CS}, and c_{CH}, respectively. To simplify the notation, we denote the total cost excluding the disposal cost as Γ and Δ, respectively. Namely, $\Gamma \equiv c_{RI}+c_{RS}$ and $\Delta \equiv c_0+c_{CI}+c_{CS}+c_{CH}$. Thus, Γ represents the total marginal cost for the recycling company to collect one unit of used product in the online channel, and Δ

[14] Also see Singh and Vives (1984) that first explore and identify which specific utility function form of a representative consumer is needed to derive linear-form demand functions for two horizontally differentiated products. While Singh and Vives (1984) originally show the derivation process of the linear-form *demand* functions from the specific *utility* function, we here show that this process can be adopted in a similar way to the derivation of the linear-form *supply* functions for differentiated used products (i.e., Equation (3)) from the specific *disutility* function (i.e., Equation (1)). Because several recent dual-recycling channel reverse supply chain models describing horizontal differentiation between channels use the linear-form supply functions (e.g., Wu et al., 2020; Jin et al., 2021), we provide the theoretical foundation of the underlying disutility function

represents the total marginal cost for the collector to collect one unit of used product in the offline channel. This assumption regarding the cost structure completely follows the stylized dual-recycling channel model constructed by Feng et al. (2017). In practice, there are several factors affecting the total cost to a recycling company and a collector. For example, when a recycling company has more advanced online information technology, Γ is smaller relative to Δ. When a collector is more efficient in physical collection activity than a recycling company, Δ is smaller relative to Γ. Here, it is important to note that all main results of this paper shown later hold independent of Δ and Γ. Namely, no matter which of Γ and Δ is bigger, the main results in the paper hold.

Given the above settings, the profit of Company *i*, Π_i, that has chosen Strategy T, Strategy D, and Strategy TD, respectively, is stated as:

$$\Pi_i = (w - b_i - c)q_i^T, \qquad \text{if } S_i = \text{T} \tag{4}$$

$$\Pi_i = (w - p_i^D - \Gamma - c)q_i^D, \qquad \text{if } S_i = \text{D} \tag{5}$$

$$\Pi_i = (w - b_i - c)q_i^T + (w - p_i^D - \Gamma - c)q_i^D, \qquad \text{if } S_i = \text{TD} \tag{6}$$

where *w* is the revenue that a recycling company earns by handling a unit of used product.[15] Meanwhile, the profit of Collector *i*, π_i, is:

$$\pi_i = (b_i - p_i^T - \Delta)q_i^T, \qquad \text{if } S_i = \text{TD or T} \tag{7}$$

$$\pi_i = 0. \qquad \text{if } S_i = \text{D} \tag{8}$$

As shown in Equation (8), the profit of Collector *i* is zero if Company *i* chooses Strategy D and hence does not employ Collector *i*.

To simplify the notation of variables, we additionally define the following two variables.

$$\begin{aligned} X &\equiv w - c - \alpha - \Delta \\ Y &\equiv w - c - \alpha - \Gamma \end{aligned} \tag{9}$$

Intuitively, *X* and *Y* represent net profitability in offline and online channels, which is revenue minus total cost per product from each channel, respectively. We also assume the following inequality is satisfied with respect to the parameters of *X*, *Y*, and *θ*:

$$\theta X < Y < X/\theta. \tag{10}$$

Inequality (10) is the condition ensuring that the net profitability *Y* for a recycling company from handling one product in an online channel is neither too large nor too small. By solving Inequality (10) for *X*, we verify that this condition also indicates that the profitability *X* for a recycling company from handling one product via the offline channel is also neither excessively large nor small. The underlying reason for assuming Inequality (10)

for such existing reverse supply chain models, which is also a contribution of this paper.

[15] Following Feng et al. (2017), we assume that the price of the recycled product is determined in a perfectly competitive market. Hence, each company is considered a price-taker for the recycled product and the price of *w* is identical.

is that if this inequality were not satisfied, both recycling companies would achieve higher profits by purchasing products from only one channel, either online or offline, in all circumstances. That is, if Y were too small, both recycling companies would stop collecting from online channels and collect all products from offline channels because the online channel is not sufficiently profitable; the left condition of Inequality (10), $\theta X < Y$, prevents this case. At the same time, Y must not be excessively large, as indicated by the condition on the right-hand side in Inequality (10), $Y < X/\theta$, because otherwise, a recycling company would purchase all the products from the online channel by abandoning the offline channel. If a recycling company only collected products through one channel regardless of circumstances, our model would become meaningless because there would then be no choice for a recycling company regarding which channel(s) to use; hence, we would not need to examine the choice of channel structure, which is the most central issue in our model. In summary, the assumption of Inequality (10) guarantees that there never exists a situation in which a recycling company always collects only from one channel regardless of circumstances.

We assume the event timeline illustrated in Fig. 2 following the stylized dual-channel reverse supply chain model in Feng et al. (2017). Initially, each of the two companies determines its channel strategy from Strategy T, D, or TD at Stage 1. At Stage 2, a company determines the transfer price if it uses an offline channel, and a company determines the online price if it uses an online channel. Finally, a collector employed by a recycling company determines its offline price at Stage 3. Given our model is based on the framework of a dynamic noncooperative game with complete information, we adopt subgame perfect Nash equilibrium (SPNE) as the equilibrium concept of our model.

4. Basic results: Substitutable supply chains

As discussed, a distinctive feature of the reverse supply chain compared with the forward supply chain is that consumers usually perceive no brand loyalty to a particular company. Hence, consumers are likely to simply sell their used products to the company that offers and purchases their used product at the highest acquisition price irrespective of the brand of the recycling company. To reflect this consumer behavior, we restrict our analysis to the case where consumers perceive the two supply chains are perfectly substitutable by assuming $\lambda = 1$ in this section.[16] Substituting $\lambda = 1$ into Equation (3) makes them imply that Supply chains 1 and 2 are substitutable for consumers as long as the channel type is the same, which reflects no consumer loyalty to a specific recycling company. We derive the equilibrium decision of each company resulting from each pair of channel strategies, as shown in the lemma below (the Appendix summarizes all proofs).[17]

[16] In Section 6, we extend our analysis to consider the case where λ is less than one. We then show that even if the recycling companies are not perfectly substitutable, all the main results from the basic model under $\lambda = 1$ hold provided λ is sufficiently large.

[17] It should be noted that the solving process for equilibrium in the case of $\lambda = 1$ as the basic

Lemma 1. The equilibrium prices determined by a recycling company in each of the channel strategy combinations are summarized as follows. The first notation in the superscript parentheses attached to p^D, p^T, and b signifies the strategy chosen by the own company, and the second notation signifies the strategy chosen by the rival company.

$$p^{D(\mathrm{D,\,D})} = w-\Gamma-c$$

$$p^{T(\mathrm{T,\,T})} = w-c-\Delta, \quad b^{(\mathrm{T,\,T})} = w-c$$

$$p^{D(\mathrm{TD,\,TD})} = w-\Gamma-c, \quad p^{T(\mathrm{TD,\,TD})} = w-c-\Delta, \quad b^{(\mathrm{TD,\,TD})} = w-c$$

$$p^{D(\mathrm{D,\,T})} = \frac{2(2-\theta^2)Y+\theta X}{8-5\theta^2}+\alpha$$

$$p^{T(\mathrm{T,\,D})} = \frac{(4-\theta^2)X+3\theta(2-\theta^2)Y}{2(8-5\theta^2)}+\alpha, \quad b^{(\mathrm{T,\,D})} = w-c+\frac{\theta(2-\theta^2)Y-(4-3\theta^2)X}{8-5\theta^2}$$

$$p^{D(\mathrm{TD,\,D})} = w-\Gamma-c, \quad p^{T(\mathrm{TD,\,D})} = \frac{X+3\theta Y}{4}+\alpha, \quad b^{(\mathrm{TD,\,D})} = w-c+\frac{\theta Y-X}{2}$$

$$p^{D(\mathrm{D,\,TD})} = w-\Gamma-c$$

$$p^{D(\mathrm{TD,\,T})} = \frac{Y+\theta X}{2}+\alpha, \quad p^{T(\mathrm{TD,\,T})} = w-c-\Delta, \quad b^{(\mathrm{TD,\,T})} = w-c$$

$$p^{T(\mathrm{T,\,TD})} = w-c-\Delta, \quad b^{(\mathrm{T,\,TD})} = w-c$$

Lemma 1 suggests that if a recycling company has the same type of channel as the rival company, the acquisition price will be equal to the revenue minus cost per unit of product in equilibrium. For example, $p^{D(\mathrm{D,\,D})}$ and $p^{D(\mathrm{D,\,TD})}$ are the equilibrium prices when a company has an online channel in response to the rival company also having an online channel. In this case, the online acquisition price rises to $w-\Gamma-c$, which is equal to the revenue minus cost per unit, meaning that the company generates no profit from the online channel. This also applies to the equilibrium price in the offline channel. Given the equilibrium prices, we next show the equilibrium profit in the following proposition.

Proposition 1. The equilibrium profit of a recycling company in each of the channel strategy combinations is summarized as follows. The first notation in the superscript parentheses attached to Π signifies the strategy chosen by the own company, and the second notation signifies the strategy chosen by the rival company.

$$\Pi^{(\mathrm{TD,\,TD})} = \Pi^{(\mathrm{D,\,TD})} = \Pi^{(\mathrm{D,\,D})} = \Pi^{(\mathrm{T,\,TD})} = \Pi^{(\mathrm{T,\,T})} = 0$$

$$\Pi^{(\mathrm{TD,\,D})} = \frac{(X-\theta Y)^2}{8\beta(1-\theta^2)}$$

---

result in this section is significantly different from that in the case of $0 < \lambda < 1$ as the extension considered in Section 6. This is because when $\lambda = 1$, the system of inverse supply functions of Equation (3) cannot be solved for quantities (i.e., q_1^T, q_2^T, q_1^D, and q_2^D) as the supply functions including prices (i.e., p_1^T, p_2^T, p_1^D, and p_2^D), which are the decision variables in our model. See the proof of Lemma 1 and Proposition 1 in the Appendix for details of the solving process.

$$\Pi^{(\mathrm{TD,\,T})} = \frac{(Y-\theta X)^2}{4\beta(1-\theta^2)}$$

$$\Pi^{(\mathrm{D,\,T})} = \frac{(2-\theta^2)\left((4-3\theta^2)Y-\theta X\right)^2}{2\beta(1-\theta^2)(8-5\theta^2)^2}$$

$$\Pi^{(\mathrm{T,\,D})} = \frac{\left((4-3\theta^2)X-\theta(2-\theta^2)Y\right)^2}{2\beta(1-\theta^2)(8-5\theta^2)^2}$$

Proposition 1 shows that the profits of both companies fall to zero if they choose the symmetric channel strategies of (TD, TD), (T, T), and (D, D) because perfect price competition arises in every channel.[18] Bertrand (1883) originally points out that the selling price falls to marginal cost when price-cutting competition takes place in a forward supply chain, which is usually referred to as *Bertrand competition*. Although Bertrand competition originally represents price-cutting sales competition in forward supply chains, this logic can be directly applied to price-raising purchase competition driving up acquisition prices in reverse supply chains. If consumers perceive that different companies are substitutable, as assumed in this section, then there arises an acquisition price competition between the same type of channels that raises the price until it matches the marginal revenue for each company. As a result, neither company generates a positive profit if both companies use the same type of channel(s). By contrast, if a company uses a channel not used by the other company, Bertrand competition never arises at least in that channel and the company can earn a positive profit as shown in Proposition 1.

A comparison of the equilibrium profits presented in Proposition 1 leads to the following proposition.

Proposition 2. The relationships below hold with respect to the profit ranking of the company.

$$\Pi^{(\mathrm{T,\,D})} > \Pi^{(\mathrm{TD,\,D})} > \Pi^{(\mathrm{D,\,D})} = 0$$
$$\Pi^{(\mathrm{D,\,T})} > \Pi^{(\mathrm{TD,\,T})} > \Pi^{(\mathrm{T,\,T})} = 0$$
$$\Pi^{(\mathrm{TD,\,TD})} = \Pi^{(\mathrm{T,\,TD})} = \Pi^{(\mathrm{D,\,TD})} = 0$$

[18] Because we take the approach of constructing an economic model to describe acquisition price competition occurring in reverse supply chains, the equilibrium economic profit is obtained as zero in several cases. Here, we must note that even if the economic profit of a firm is zero in equilibrium, the firm has an incentive to operate because its accounting profit can be calculated as positive. This is because economic profit is defined as the excess profit that remains after subtracting dividend payments to shareholders from accounting profit. Indeed, it is common in economic models for the economic profit of a firm to be zero in the long-run equilibrium. For a more detailed explanation see, for example, Besanko et al. (2017, p. 28), a leading textbook on how economic models can be applied to practical strategic management.

The ranking of the equilibrium profit shown in Proposition 2 enables us to determine the company channel strategies constituting the SPNE. To facilitate identifying the equilibrium channel strategy, we construct a payoff matrix classified by the channel strategy in Table 3 and circle the payoff resulting from the best-response strategy using the results shown in Proposition 2. Because the left and right variables in the parentheses of each cell in the table represent the profit of the own company and the profit of the rival company, respectively, the cell with both payoffs in parentheses circled constitutes the SPNE. By referring to Table 3, we obtain the following theorem.

Theorem 1. The pairs of channel strategies always constituting the SPNE are the following three:
(S_i, S_j) = (TD, TD), (T, D), (D, T) $(i, j) = (1, 2), (2, 1)$.

Theorem 1 shows that the following combinations of both symmetric and asymmetric channel choices arise in equilibrium: (i) both recycling companies use both online and offline channels (i.e., strategies (TD, TD)), and (ii) one recycling company uses only the online channel whereas the other recycling company uses only the offline channel (i.e., strategies (T, D) and (D, T)). Comparing profits between the equilibrium strategies, we obtain the following theorem summarizing the Pareto-dominance relationship between the profits.

Theorem 2. The symmetric channel strategies (TD, TD) are always Pareto-dominated by the two asymmetric channel strategies (T, D) and (D, T).

Theorem 2, together with Theorem 1, provides the central result of this paper. Intuitively, it seems more advantageous for a company to use both channels because this channel strategy enables the company to cover a larger number of consumers. However, the result of Theorem 2 shows the opposite. As shown in Proposition 1, if the two companies use completely symmetric channel forms under a duopoly, the most intense competition for product acquisition will arise between the channels, and hence the profits of both companies fall to zero. For this reason, having both channels for both recycling companies (i.e., (TD, TD)) would lead to a typical prisoners' dilemma. To avoid this, having only one channel that differs (i.e., (D, T) or (T, D)) is better because it ensures positive profit margins. That is, the strategy to collect products only from either channel is more profitable for a company than the strategy of collecting products from both channels.

Additionally, note that the strategy of using both channels (i.e., TD) is weakly dominated by the strategy of using only one channel (i.e., T or D) because $\Pi^{(T, D)} > \Pi^{(TD, D)}$, $\Pi^{(D, T)} > \Pi^{(TD, T)}$, and $\Pi^{(TD, TD)} = \Pi^{(T, TD)} = \Pi^{(D, TD)}$ hold as shown in Proposition 2. This is also significantly different from the conventional result that Strategy TD is always the dominant strategy shown in the stylized model by Feng et al. (2017) that considers the existence of only one supply chain. As discussed earlier, constructing both online and offline channels is an inferior strategy for a recycling company when there is a competing recycling company because this strategy triggers the most intense supply chain competition.

Finally, because Theorem 1 suggests that asymmetric channel strategies taken by the two companies arise in equilibrium, it is worthwhile to examine which of the two equilibrium strategies—(D, T) or (T, D)—is more profitable for a company. The next proposition answers this question.

Proposition 3. In the asymmetric strategies in equilibrium of either Strategy (D, T) or (T, D), the following relationship holds.

$$\Pi^{(T,\,D)} \gtreqless \Pi^{(D,\,T)} \qquad \text{if } X \gtreqless \sqrt{2-\theta^2}\,Y$$

Proposition 3 indicates that whether strategy T or strategy D is more profitable depends on whether X is greater or less than the threshold of $\sqrt{2-\theta^2}\,Y$. Because X represents profitability in an offline channel, strategy T is more profitable if X is relatively large compared to Y. Conversely, if X is relatively small compared to Y, the recycling company should choose strategy D to achieve a higher profit.

5. Extension: Sequential channel choice

In the basic model, we assumed that both recycling companies simultaneously choose their respective channel strategies, as shown in Fig. 2. However, it may be more realistic to assume that recycling companies choose the channel strategies sequentially, but not at the same time, because different companies usually commence their recycling businesses at different points in time. In this case, one company chooses its channel structure first, and then the other company chooses its channel structure. Accordingly, we consider this realistic sequential channel design in this section.

To consider the sequential channel choice, we change Stage 1 of the event timeline in Fig. 2 so that one company is the first mover, and the other company is the second mover in choosing each channel form. We obtain the following theorem characterizing the equilibrium.

Theorem 3. Under the assumption that the two recycling companies sequentially choose their respective channel structures, the equilibrium is characterized as follows.

(i) If $X \geq \sqrt{2-\theta^2}\,Y$, the first-moving recycling company chooses Strategy T and the second-moving recycling company chooses Strategy D in SPNE.

(ii) If $X \leq \sqrt{2-\theta^2}\,Y$, the first-moving recycling company chooses Strategy D and the second-moving recycling company chooses Strategy T in SPNE.

(iii) No SPNE arises in which the two companies choose symmetric channel strategies, including strategies (TD, TD).

Theorem 3 suggests that whereas the first and second movers can choose the asymmetric channel strategies of (T, D) or (D, T) in equilibrium, each company never chooses Strategy TD. This is because if the first mover chooses Strategy TD, it anticipates that an optimal reaction strategy of the second mover will also be Strategy TD, and as a result, its profit will be zero. Therefore, Theorem 3 shows that only asymmetric channel strategies are always realized in equilibrium if channel choice decisions are made sequentially, but not simultaneously. Because the SPNE involving the asymmetric channel strategies are Pareto-dominant, as shown in Theorem 2, the companies can completely escape from the prisoners' dilemma.

Theorem 3 also suggests that the first-moving company should choose Strategy T if the value of X is relatively greater than Y, whereas it should choose Strategy D if X is relatively smaller than Y. That is, if the profitability from collecting through an offline channel is relatively large (small), the company should build and use only the offline (online) channel because it earns the company more profit than the online (offline) channel. In either case, it is at least better for the first-moving recycling company intentionally to build and use only one type of channel. This first mover's choice enables the competing companies to avoid completely the prisoners' dilemma. Therefore, the theorem provides the managerial implication that the first mover commencing recycling business should not greedily adopt all types of channels, even though this multichannel strategy is seemingly appealing to the first mover. This is because if the first-moving company heedlessly builds and uses both channels aiming to attract more consumers, the second mover will also build both channels as its best response, and the typical prisoners' dilemma will arise preventing both companies from earning positive profits. To summarize, the notable implication of this section is that if companies can sequentially choose their respective forms of channels, they completely escape from the equilibrium of the prisoners' dilemma and arrive at the Pareto-superior equilibrium involving asymmetric channel structures.

6. Extension: Differentiated supply chains

In previous sections, we focused only on the case of $\lambda = 1$ to reflect the realistic situation where consumers perceive no differentiation between reverse supply chains, thereby deriving basic results. However, there may be a situation in which consumers perceive some differentiation between supply chains composed of different recycling companies. Accordingly, we consider the case $0 < \lambda < 1$ in this section as an extension, where consumers perceive that the supply chains are not perfectly substitutable but are instead differentiated. Deriving the equilibrium decisions for this case, we obtain the following lemma.

Lemma 2. When consumers perceive that companies are differentiated so that $0 < \lambda < 1$, the equilibrium prices determined by a recycling company in each of the channel strategy combinations are summarized as follows.

$$p^{D(\mathrm{D,\ D})} = \frac{Y}{2-\lambda}+\alpha$$

$$p^{T(\mathrm{T,\ T})} = \frac{(2-\lambda^2)X}{(2-\lambda)(4-\lambda-2\lambda^2)}+\alpha, \quad b^{(\mathrm{T,\ T})} = w-c-\frac{(2-\lambda-\lambda^2)X}{4-\lambda-2\lambda^2}$$

$$p^{D(\mathrm{TD,\ TD})} = \frac{Y}{2-\lambda}+\alpha, \quad p^{T(\mathrm{TD,\ TD})} = \frac{(2-\lambda^2)X+(2-\lambda-\lambda^2)\theta Y}{(2-\lambda)(4-\lambda-2\lambda^2)}+\alpha$$

$$b^{(\mathrm{TD,\ TD})} = w-c-\frac{(1-\lambda)((4-\lambda^2)X-\lambda(1+\lambda)\theta Y)}{(2-\lambda)(4-\lambda-2\lambda^2)}$$

$$p^{D(\mathrm{D,\ T})} = \frac{2(2-\theta^2\lambda^2)Y+\theta\lambda X}{8-5\theta^2\lambda^2}+\alpha$$

$$p^{T(\mathrm{T,\ D})} = \frac{(4-\theta^2\lambda^2)X+3\theta\lambda(2-\theta^2\lambda^2)Y}{2(8-5\theta^2\lambda^2)}+\alpha, \quad b^{(\mathrm{T,\ D})} = w-c+\frac{\theta\lambda(2-\theta^2\lambda^2)Y-(4-3\theta^2\lambda^2)X}{8-5\theta^2\lambda^2}$$

$$p^{D(\mathrm{TD,\ D})} = \frac{Y}{2-\lambda}+\alpha, \quad p^{T(\mathrm{TD,\ D})} = \frac{(2-\lambda)X+\theta(2+\lambda)Y}{4(2-\lambda)}+\alpha, \quad b^{(\mathrm{TD,\ D})} = w-c+\frac{\theta\lambda Y-(2-\lambda)X}{2(2-\lambda)}$$

$$p^{D(\mathrm{D,\ TD})} = \frac{Y}{2-\lambda}+\alpha$$

$$p^{D(\mathrm{TD,\ T})} = \frac{\theta\lambda(4+\lambda-2(1+\theta^2)\lambda^2-\theta^2\lambda^3)X+(16-(17+8\theta^2)\lambda^2+(4+5\theta^2)\lambda^4)Y}{2(16-(17+9\theta^2)\lambda^2+(4+6\theta^2)\lambda^4)}+\alpha$$

$$p^{T(\mathrm{TD,\ T})} =$$
$$(\theta(8-(3+5\theta^2)\lambda^2)(2-3\lambda^2+\lambda^4)Y+(16+4(3-\theta^2)\lambda-2(7+13\theta^2)\lambda^2-2(5+4\theta^2-$$
$$\theta^4)\lambda^3+(3+19\theta^2+10\theta^4)\lambda^4+2(1+\theta^2)^2\lambda^5-\theta^2(3+5\theta^2)\lambda^6)X)$$
$$/((4-(1+3\theta^2)\lambda^2)(16-(17+9\theta^2)\lambda^2+(4+6\theta^2)\lambda^4))+\alpha$$

$$b^{(\mathrm{TD,\ T})} = w-c+\frac{(1-\lambda)(\theta\lambda^2(1+\lambda)Y-(16+12\lambda-(6+9\theta^2)\lambda^2-(4+7\theta^2)\lambda^3)X)}{2(16-(17+9\theta^2)\lambda^2+(4+6\theta^2)\lambda^4)}$$

$$p^{T(\mathrm{T,\ TD})} =$$
$$(2\theta\lambda(3-(1+2\theta^2)\lambda^2)(2-3\lambda^2+\lambda^4)Y+(16+12\lambda-2(7+11\theta^2)\lambda^2-$$
$$10(1+2\theta^2)\lambda^3+(3+14\theta^2+7\theta^4)\lambda^4+2(1+7\theta^2+4\theta^4)\lambda^5-2\theta^2(1+\theta^2)\lambda^6-2\theta^2(1+2\theta^2)\lambda^7)X)$$
$$/((4-(1+3\theta^2)\lambda^2)(16-(17+9\theta^2)\lambda^2+(4+6\theta^2)\lambda^4))+\alpha$$

$$b^{(\mathrm{T,\ TD})} = w-c+\frac{(1-\lambda)(\theta\lambda(1+\lambda)(2-\lambda^2)Y-(8+6\lambda-(3+5\theta^2)\lambda^2-(2+3\theta^2)\lambda^3+\theta^2\lambda^4)X)}{16-(17+9\theta^2)\lambda^2+(4+6\theta^2)\lambda^4}$$

Unlike the results in Lemma 1, Lemma 2 shows that even if a company has the same type of channel as the rival company, the former company can charge an acquisition price that is lower than the revenue per unit of a used product and hence obtain a positive profit from the channel. The fundamental reason for why the company obtains a positive profit is that consumers perceive supply chain differentiation between the recycling companies and, hence, there exist consumers that have preferences for selling used products to one company over the other. The equilibrium profits in the presence of this supply chain differentiation are summarized in the following proposition.

Proposition 4. When consumers perceive that companies are differentiated so that $0 < \lambda <$

1, the equilibrium profits of a recycling company in each of the channel strategy combinations are summarized as follows.

$\Pi^{(TD, TD)} =$

$$\frac{1-\lambda}{\beta(2-\lambda)(1+\lambda)\left(4-\lambda-2\lambda^2\right)^2}\left(\frac{\left(8-8\lambda-9\lambda^2+4\lambda^3+3\lambda^4\right)Y^2}{2-\lambda}+\frac{(2+\lambda)\left(2-\lambda^2\right)\left(X^2+Y^2-2\theta XY\right)}{1-\theta^2}\right)$$

$$\Pi^{(D, TD)} = \frac{(1-\lambda)Y^2}{\beta(2-\lambda)^2(1+\lambda)}$$

$$\Pi^{(D, D)} = \frac{(1-\lambda)Y^2}{\beta(1+\lambda)(2-\lambda)^2}$$

$\Pi^{(T, TD)} =$

$$\frac{(1-\lambda)\left(2-\left(1+\theta^2\right)\lambda^2\right)\left(\left(8+6\lambda-\left(3+5\theta^2\right)\lambda^2-\left(2+3\theta^2\right)\lambda^3+\theta^2\lambda^4\right)X-\theta\lambda\left(2+2\lambda-\lambda^2-\lambda^3\right)Y\right)^2}{\beta(1+\lambda)\left(4-\left(1+3\theta^2\right)\lambda^2\right)\left(16-\left(17+9\theta^2\right)\lambda^2+\left(4+6\theta^2\right)\lambda^4\right)^2}$$

$$\Pi^{(T, T)} = \frac{(1-\lambda)(2+\lambda)\left(2-\lambda^2\right)X^2}{\beta(2-\lambda)(1+\lambda)\left(4-\lambda-2\lambda^2\right)^2}$$

$$\Pi^{(TD, D)} = \frac{X^2+Y^2-2\theta XY}{8\beta\left(1-\theta^2\right)}+\frac{\left(4-8\lambda+3\lambda^2-\lambda^3\right)Y^2}{8\beta(2-\lambda)^2(1+\lambda)}$$

$\Pi^{(TD, T)} =$

$$\frac{(1-\lambda)\left(2-\left(1+\theta^2\right)\lambda^2\right)\left(\left(8+6\lambda-\left(3+5\theta^2\right)\lambda^2-\left(2+3\theta^2\right)\lambda^3+\theta^2\lambda^4\right)X-\theta\lambda\left(2+2\lambda-\lambda^2-\lambda^3\right)Y\right)^2}{\beta(1+\lambda)\left(4-\left(1+3\theta^2\right)\lambda^2\right)\left(16-\left(17+9\theta^2\right)\lambda^2+\left(4+6\theta^2\right)\lambda^4\right)^2}+$$

$$\frac{\theta^2\left(8-\left(9+4\theta^2\right)\lambda^2+\left(4+\theta^2\right)\lambda^4\right)X^2-2\theta\left(8-5\lambda^2\right)\left(1-\theta^2\lambda^2\right)XY+\left(16-17\lambda^2+4\lambda^4-\theta^2\left(8-4\lambda^2-\lambda^4\right)\right)Y^2}{4\beta\left(1-\theta^2\right)\left(16-\left(17+9\theta^2\right)\lambda^2+\left(4+6\theta^2\right)\lambda^4\right)}$$

$$\Pi^{(D, T)} = \frac{\left(2-\lambda^2\theta^2\right)\left(\left(4-3\lambda^2\theta^2\right)Y-\lambda\theta X\right)^2}{2\beta\left(1-\lambda^2\theta^2\right)\left(8-5\lambda^2\theta^2\right)^2}$$

$$\Pi^{(T, D)} = \frac{\left(\left(4-3\lambda^2\theta^2\right)X-\theta\left(2-\lambda^2\theta^2\right)\lambda Y\right)^2}{2\beta\left(1-\lambda^2\theta^2\right)\left(8-5\lambda^2\theta^2\right)^2}$$

Proposition 4 shows the equilibrium profits in the general situation of λ taking a value between 0 and 1. Because the profit in each case of Proposition 4 contains five parameters of β, θ, λ, X, and Y, unlike Proposition 2 for the case of $\lambda = 1$, it is not possible to compare specific pairs of two profits in Proposition 4 to determine which profit is greater than another, meaning that it is also not possible to identify the channel strategy that constitutes the SPNE. For this reason, we henceforth limit our discussion of the results to the case of $Y = X$ (i.e., $\Gamma = \Delta$), in which the profitability is equal between the online and offline channels. The reason for assuming this is that it allows us to multiplicatively separate X, Y, and β from the profits in all the cases of Proposition 4 and hence to compare the equilibrium profits between the channel strategies by using only two parameters of θ and λ. Using this assumption, we have the following corollary.

Corollary 1. When $Y = X$, five regions emerge within the domain of λ and θ as drawn in Fig. 3, which have the following characteristics.
• Regions I and II: The asymmetric channel strategies (D, T) and (T, D) arise in SPNE.
• Regions II, III, IV, and V: The symmetric channel strategies (TD, TD) arise in SPNE.
• Regions I, II, III, and IV: The combination of profits resulting from the symmetric channels strategies (TD, TD) is not Pareto optimal.

The results in Corollary 1 are illustrated in Fig. 3. Note that each of the five regions in Fig. 3 does not include the four side lines of the square because they are drawn within the domain of $0 < \lambda < 1$ and $0 < \theta < 1$ as assumed in this section. Thus, Fig. 3 shows that even when λ is smaller than 1 so that the channels are not perfectly substitutable, all of the central results of Theorems 1 and 2 obtained in the basic model of the previous section can hold. Specifically, Fig. 3 suggests that in Region II, the three combinations of channel strategies (TD, TD), (D, T), and (T, D) arise in the SPNE, and strategies (TD, TD) are Pareto-dominated by strategies (D, T), and (T, D). Namely, in Region II, both asymmetric and symmetric channel strategies arise in SPNE and the symmetric equilibrium is a prisoner's dilemma, which is completely the same results as in Theorems 1 and 2. This means that even when consumers perceive the supply chains as not fully substitutable, the same results as in the basic model are equally valid if the channels are only moderately differentiated so that λ is sufficiently large. This result indicates that Theorems 1 and 2, which are the main results in this paper, can hold under more general circumstances in the presence of supply chain differentiation where $\lambda < 1$.

While we focused only on the case of $Y = X$ to obtain clear-cut analytical results in this section, we have at least confirmed the existence of environments where Theorems 1 and 2 continue to hold even when all the parameters including λ vary.

7. Conclusion

The rapid development of information and communication technology has enabled companies establishing recycling platforms to purchase end-of-life products from consumers using a combination of conventional Internet-based online and offline collection channels, usually referred to as a dual-recycling channel reverse supply chain. Despite collecting increasingly larger volumes of used products, many recycling companies suffer from low profitability. Given this business environment, we explore the optimal collection channel structure for recycling companies using dual-channel reverse supply chains. By solving our game-theoretic model, we find that the following combinations of channel choices arise in equilibrium: (i) both recycling companies use both online and offline channels, and (ii) one recycling company uses only the online channel whereas the other recycling company uses only the offline channel. Drawing on this finding, the symmetric channel equilibrium is always Pareto-dominated by the asymmetric channel equilibrium because the symmetric channel strategies yield lower profits for both companies than the asymmetric strategies, meaning that the dual-channel choice of collecting products via both the offline and online channels leads to the typical prisoners' dilemma. As we already obtained clear-cut results completely in the analytical form only by solving our model, we do not conduct numerical analysis in this paper.

Given the above results, the managerial implication derived from our model is that it is desirable for the two competing recycling companies to make decisions so that the companies reach one of the two asymmetric channel equilibria among the three equilibria. Namely, each of the recycling companies should build and use only one type of collection channel that differs from each other, rather than collecting through both channels. Having both offline and online channels for one of the competing recycling companies would induce the rival recycling company to also have both channels, leading to a symmetric channel equilibrium corresponding to the prisoner's dilemma. Therefore, a recycling company should intentionally have only one of the two types of channels to reach a Pareto-dominant equilibrium. In summary, the result of this paper suggests useful measures regarding which recycling channel each of the recycling companies should have to avoid falling into a prisoner's dilemma equilibrium before the recycling companies make their respective recycling channel choices. In this respect, the results have significant usefulness as a managerial guideline.

Our results also caution real-life recycling companies facing acquisition price competition that a dual-channel strategy of both online and offline channels is not necessarily optimal. Intuitively, using both online and offline channels to collect products seems advantageous because it would allow the company to collect products from a wider range of consumers. However, our results suggest the contrary: if both recycling companies use both channels, the most destructive collection competition between recycling companies arises in which neither company generates profit. To avoid this all-out acquisition price competition between supply chains, a recycling company should instead use only either of the two channels, thereby inducing the other recycling company to use the remaining type of channel. Consequently, the conventional finding in the literature that a recycling company should use both online and offline collection channels in a dual-recycling channel reverse supply chain is completely reversed in our model considering competition between recycling companies. In only changing the assumption of a single supply chain in earlier models to two competing supply chains in our model, it has completely overturned important prevailing findings, thereby making a significant contribution to the literature.

Finally, our results explain the real-world situation where collection competition is so fierce that several recycling companies in large countries such as China and the US have exited the market. Therefore, our model provides useful managerial guidelines for existing recycling companies that adequate differentiation between them is a key issue, and that differentiation in collection methods and channels can help them to escape from the predicament of excessive acquisition price competition.

Acknowledgments

The author gratefully acknowledges four anonymous reviewers for their insightful comments. Needless to say, the author is solely responsible for any remaining errors. The author also greatly appreciates Financial support of Grant-in Aid for Scientific Research (B) (20H01551, 22H00863) and (C) (18K01568) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

Appendix

Proof of Lemma 1 and Proposition 1.

In this proof, we obtain the equilibrium decisions (prices) and profits resulting from each combination of channel strategies.

Case (i): Strategy (D, D)

Because only online channels exist in this case, consumers can sell used products only to an online channel. Hence, the profit of Company i (= 1, 2) is described as Equation (5). Companies 1 and 2 determine p_1^D and p_2^D, which are their respective decision variables. We prove below that the only equilibrium acquisition price is $p_1^D = p_2^D = w–\Gamma–c$. To show this, we first prove that the state $p_1^D < p_2^D$ is not an equilibrium. First, because a consumer's preference for returning a product to an online channel is indifferent between Companies 1 and 2, a consumer simply sells to that company offering a higher acquisition price. Given this consumer behavior, Company 1 is unable to purchase any return product at all and hence its profit is zero if $p_1^D < p_2^D$. However, by driving up p_1^D to a slightly higher price than p_2^D, Company 1 increases its profit to a positive value because then the company collects all products from consumers. Therefore, the state of $p_1^D < p_2^D$ is not an equilibrium. Similarly, the state $p_2^D < p_1^D$ is not a stable equilibrium from which neither company deviates. This competition between the two companies to raise their respective acquisition prices continues until its upper limit, $p_1^D = p_2^D = w–\Gamma–c$, is reached. Neither company can raise the purchase price above this level because if it did, its profit margin would fall to negative. Consequently, the following equation holds in equilibrium in the case of Strategy (D, D).

$$p_1^D = p_2^D = w–\Gamma–c. \tag{A1}$$

Substituting Equation (A1) into Equation (5) yields equilibrium profits as: $\Pi_1 = \Pi_2 = 0$.

Case (ii): Strategy (T, T)

Because only offline channels exist in this case, consumers can return products only to an offline channel. Accordingly, the profit for Collector i (= 1, 2) is Equation (7). Because consumers perceive that the two chains are substitutable, each of the two collectors offers as high an offline price as possible unless the profit becomes negative in equilibrium. Because this corresponds to the perfect price competition described in Case (i): Strategy (D, D), the equilibrium purchase price is determined by the collectors' lower marginal revenue of $b_1–\Delta$ or $b_2–\Delta$. That is, the equilibrium acquisition price at Stage 3 is:

$$\begin{array}{ll} p_1{}^T = p_2{}^T = b_2-\Delta & \text{if } b_1 > b_2 \\ p_1{}^T = p_2{}^T = b_1-\Delta & \text{if } b_1 \leq b_2. \end{array} \tag{A2}$$

Next, the profit of Company i (= 1, 2) is Equation (4). At Stage 2, Company 1 determines b_1 and Company 2 determines b_2. Here, Equations (4) and (7) indicate that the only combination of transfer prices constituting the SPNE is $b_1 = b_2$. This is because if $b_1 > b_2$, Collector 2 can collect no product in the later stage and hence the profit of Company 2 collecting products via Collector 2 is zero. In this case, Company 2 drives up its transfer price of b_2 to a level slightly higher than b_1 so that it deprives Collector 1 of the collection of all products at the later stage, which obviously increases its profit. This competition between the companies to drive up their respective transfer prices continues until the prices reach the level of $b_1 = b_2 = w–c$, at which neither company has an incentive to raise nor reduce its transfer price. Consequently, only this state constitutes a stable equilibrium. Substituting $b_1 = b_2 = w–c$ into Equation (A2) gives $p_1{}^T = p_2{}^T = w–c–\Delta$. Substituting $b_1 = b_2 = w–c$ into Equation (4) gives equilibrium profits as $\Pi_1 = \Pi_2 = 0$.

Case (iii): Strategy (TD, TD)

In this case, both companies use both offline and online channels. Accordingly, the profits of Company i and Collector i (= 1, 2) are described as Equations (6) and (7). At Stage 3, Collector i maximizes Equation (7). Here, like Case (ii): (T, T), the collectors need to announce their respective acquisition prices as high as possible in equilibrium to the extent that profit does not become negative. Hence, equilibrium offline prices are:

$$\begin{array}{ll} p_1{}^T = p_2{}^T = b_2-\Delta & \text{if } b_1 > b_2 \\ p_1{}^T = p_2{}^T = b_1-\Delta & \text{if } b_1 \leq b_2 \end{array} \tag{A3}$$

At Stage 2, Company 1 determines b_1 and Company 2 determines b_2. Like Case (ii): (T, T), the only combination of transfer prices constituting the SPNE is $b_1 = b_2 = w–c$ because the competition between the companies to drive up their respective transfer prices continues until they reach the level of $b_1 = b_2 = w–c$, at which neither company has an incentive to change its transfer price. Hence, the following equation holds in equilibrium in this case of Strategy (TD, TD).

$$b_1 = b_2 = w-c. \tag{A4}$$

Substituting Equation (A4) into Equation (A3) gives $p_1{}^T = p_2{}^T = w–c–\Delta$.

Next, we consider the online price choice by the recycling company. Completely similar to Case (i): (D, D), this competition between the two companies to raise the purchase price continues until its upper limit, $p_1{}^D = p_2{}^D = w–c–\Gamma$, is reached. Therefore, the following equation holds in equilibrium.

$$p_1{}^D = p_2{}^D = w-c-\Gamma. \tag{A5}$$

Substituting Equations (A4) and (A5) into Equation (6) yields equilibrium profits as: $\Pi_1 = \Pi_2 = 0$.

Case (iv): Strategy (T, D)

The two companies choose asymmetric channel strategies in this case. Without loss of generality, we consider the situation where Company 1 chooses Strategy T and Company 2 chooses Strategy D. Accordingly, substituting $q_1^D = 0$ and $q_2^T = 0$ into Equation (3) and solving the equation for q_1^T and q_2^D, we obtain the following supply function:

$$q_1^T = (p_1^T - \theta p_2^D - (1-\theta)\alpha)/(\beta(1-\theta^2)) \tag{A6}$$

$$q_2^D = (p_2^D - \theta p_1^T - (1-\theta)\alpha)/(\beta(1-\theta^2)). \tag{A7}$$

Using Equations (4), (5), (7), the profits for Collector 1 and the companies are:

$$\pi_1 = (b_1 - p_1^T - \Delta)q_1^T \tag{A8}$$

$$\Pi_1 = (w - b_1 - c)q_1^T \tag{A9}$$

$$\Pi_2 = (w - p_2^D - \Gamma - c)q_2^D. \tag{A10}$$

Substituting the supply function of Equation (A6) into Equation (A8), we restate the profit of Collector 1 as follows:

$$\pi_1 = (b_1 - p_1^T - \Delta)(p_1^T - \theta p_2^D - (1-\theta)\alpha)/(\beta(1-\theta^2)). \tag{A11}$$

Collector 1 maximizes its own profit with respect to p_1^T by solving $\partial\pi_1/\partial p_1^T = 0$ at Stage 3, which yields:

$$p_1^T = (b_1 + \theta p_2^D - \Delta + (1-\theta)\alpha)/2. \tag{A12}$$

Hereafter, we perform the concavity test in all the maximization problems throughout this proof. The second-order derivative of Equation (A11) is $\partial^2\pi_1/\partial(p_1^T)^2 = -2/(\beta(1-\theta^2)) < 0$, which guarantees that π_1 is maximized at p_1^T shown in Equation (A12).

After substituting Equations (A6), (A7), and (A12) into Π_1 and Π_2 of Equations (A9) and (A10), we solve $\partial\Pi_1/\partial b_1 = \partial\Pi_2/\partial p_2^D = 0$ at Stage 2 to yield:

$$\begin{aligned} b_1 &= w - c + (\theta(2-\theta^2)Y - (4-3\theta^2)X)/(8-5\theta^2), \\ p_2^D &= (2(2-\theta^2)Y + \theta X)/(8-5\theta^2) + \alpha. \end{aligned} \tag{A13}$$

The second-order derivatives of Π_1 and Π_2 are $\partial^2\Pi_1/\partial b_1^2 = -1/(\beta(1-\theta^2)) < 0$ and $\partial\Pi_2^2/\partial(p_2^D)^2 = -(2-\theta^2)/(\beta(1-\theta^2)) < 0$, which guarantee that Π_1 and Π_2 are maximized at b_1 and p_2^D shown in Equation (A13), respectively.

Substituting Equations (A6), (A7), (A12), and (A13) into Equations (A9) and (A10) yields the equilibrium profits.

$$\Pi_1 = \frac{\left((4-3\theta^2)X - \theta(2-\theta^2)Y\right)^2}{2\beta(1-\theta^2)(8-5\theta^2)^2} \tag{A14}$$

$$\Pi_2 = \frac{(2-\theta^2)\left((4-3\theta^2)Y - \theta X\right)^2}{2\beta(1-\theta^2)(8-5\theta^2)^2} \tag{A15}$$

Given we have assumed that Company 1 chooses T and Company 2 chooses D, Equation (A14) and Equation (A15) respectively represent $\Pi^{(T,\,D)}$ and $\Pi^{(D,\,T)}$.

Case (v): Strategy (TD, D)

We assume in this case that Company 1 chooses TD and Company 2 chooses D without loss of generality. In this case, substituting $q_2^T = 0$ into Equation (3) and solving the equation for q_1^T, q_1^D, and q_2^D, we obtain the following supply function:

$$q_1^T = (p_1^T - \theta p_1^D - (1-\theta)\alpha)/(\beta(1-\theta^2)) \tag{A16}$$

$$q_1^D + q_2^D = ((1+\theta^2)p_1^D + (1-\theta^2)p_2^D - 2\theta p_1^T - 2(1-\theta)\alpha)/(2\beta(1-\theta^2)). \tag{A17}$$

Using Equations (5), (6), and (7), the profits of Collector 1 and recycling companies are:

$$\pi_1 = (b_1 - p_1^T - \Delta)q_1^T \tag{A18}$$

$$\Pi_1 = (w - b_1 - c)q_1^T + (w - p_1^D - \Gamma - c)q_1^D \tag{A19}$$

$$\Pi_2 = (w - p_2^D - \Gamma - c)q_2^D. \tag{A20}$$

Substituting the supply function of Equation (A16) into Equation (A18), we restate the profit of Collector 1 as follows:

$$\pi_1 = (b_1 - p_1^T - \Delta)(p_1^T - \theta p_1^D - (1-\theta)\alpha)/(\beta(1-\theta^2)). \tag{A21}$$

Collector 1 maximizes its profit with respect to p_1^T by solving $\partial\pi_1/\partial p_1^T = 0$, yielding:

$$p_1^T = (b_1 + \theta p_1^D - \Delta + (1-\theta)\alpha)/2. \tag{A22}$$

The second-order derivative of π_1 is $\partial^2\pi_1/\partial(p_1^T)^2 = -2/(\beta(1-\theta^2)) < 0$, which guarantees that π_1 is maximized at p_1^T shown in Equation (A22).

Next, we consider the maximization problem for the companies to determine their online prices of p_1^D and p_2^D. Completely like Case (i) (D, D), price competition between the companies raises the direct price until it reaches the level of $w-c-\Gamma$ as follows:

$$p_1^D = p_2^D = w - c - \Gamma. \tag{A23}$$

Substituting Equations (A16), (A22) and (A23) into Equation (A19) and then solving for $\partial\Pi_1/\partial b_1 = 0$, we have:

$$b_1 = w - c + (\theta Y - X)/2. \tag{A24}$$

The second-order derivative of Π_1 is $\partial^2\Pi_1/\partial b_1^2 = -1/(\beta(1-\theta^2)) < 0$, which guarantees that Π_1 is maximized at b_1 shown in Equation (A24). Inserting Equations (A16), (A22), (A23) and (A24) into Equations (A19) and (A20), we derive the equilibrium profits as follows:

$$\Pi_1 = \frac{(X - \theta Y)^2}{8\beta(1-\theta^2)}, \tag{A25}$$

$$\Pi_2 = 0. \tag{A26}$$

Because we assumed that Company 1 chooses TD and Company 2 chooses D, Equation (A25) and Equation (A26), respectively, represent $\Pi^{(TD, D)}$ and $\Pi^{(D, TD)}$.

Case (vi): Strategy (TD, T)

We assume in this case that Company 1 chooses TD and Company 2 chooses T without loss of generality. Substituting $q_2^D = 0$ into Equation (3) and solving the equation for q_1^T, q_1^D, and q_2^T, we obtain the following supply function:

$$q_1^D = (p_1^D - \theta p_1^T - (1-\theta)\alpha)/(\beta(1-\theta^2))$$

$$q_1^T + q_2^T = ((1+\theta^2)p_1^T + (1-\theta^2)p_2^T - 2\theta p_1^D - 2(1-\theta)\alpha)/(2\beta(1-\theta^2)).$$

With the use of the supply function and Equations (4), (6) and (7), the profits of recycling companies and Collector i are:

$$\Pi_1 = (w - b_1 - c)q_1^T + (w - p_1^D - \Gamma - c)q_1^D$$

$$= (w - b_1 - c)q_1^T + (w - p_1^D - \Gamma - c)\left(\frac{p_1^D - \theta p_1^T - (1-\theta)\alpha}{\beta(1-\theta^2)}\right) \tag{A27}$$

$$\Pi_2 = (w - b_2 - c)q_2^T, \tag{A28}$$

$$\pi_i = (b_i - p_i^T - \Delta)q_i^T \tag{A29}$$

At Stage 3, Collector i maximizes Equation (A29). Here, like Case (ii): (T, T), equilibrium offline prices are: $p_1^T = p_2^T = b_2 - \Delta$ if $b_1 \geq b_2$ and $p_1^T = p_2^T = b_1 - \Delta$ if $b_1 < b_2$ because the collectors need to set as high an acquisition price as possible in equilibrium to the extent that profit does not become negative. Anticipating the collectors' optimal decisions in the next stage, Company 1 determines b_1 and Company 2 determines b_2 at Stage 2. The only combination of prices constituting the SPNE is $b_1 = b_2$ because the competition between companies to drive up their respective transfer prices continues until the prices attain the level of $b_1 = b_2 = w-c$, at which neither company has an incentive to change its transfer price. Hence, the following equation holds in equilibrium.

$$b_1 = b_2 = w - c. \tag{A30}$$

Next, consider the maximization problem for Company 1 to determine p_1^D at Stage 2. After substituting Equation (A30) into Π_1 of Equation (A27), we solve $\partial\Pi_1/\partial p_1^D = 0$ at Stage 2 to yield:

$$p_1^D = (\theta(w-c-\Delta)+(w-c-\Gamma)+(1-\theta)\alpha)/2. \tag{A31}$$

The second-order derivative of Π_1 is $\partial^2\Pi_1/\partial(p_1^D)^2 = -2/(\beta(1-\theta^2)) < 0$, which guarantees that Π_1 is maximized at p_1^D shown in Equation (A31). Inserting $p_1^T = w-c-\Delta$ and Equations (A30) and (A31) into Equations (A27) and (A28) yields the equilibrium profits.

$$\Pi_1 = \frac{(Y - \theta X)^2}{4\beta(1-\theta^2)} \tag{A32}$$

$$\Pi_2 = 0 \tag{A33}$$

Because we assumed that Company 1 chooses TD and Company 2 chooses T, Equation (A32) and Equation (A33), respectively, represent $\Pi^{(TD,\,T)}$ and $\Pi^{(T,\,TD)}$. □

Proof of Proposition 2.

(i) Proof of $\Pi^{(T,\,D)} > \Pi^{(TD,\,D)}$

Proposition 1 suggests that the following equation holds.

$\Pi^{(\mathrm{T,\ D})} - \Pi^{(\mathrm{TD,\ D})}$

$$= \frac{\theta(-(16\theta - 11\theta^3)X^2 + 2(32 - 40\theta^2 + 13\theta^4)XY - \theta(48 - 64\theta^2 + 21\theta^4)Y^2)}{8\beta(1-\theta^2)(8-5\theta^2)^2} \tag{A34}$$

Let us determine the sign of $-(16\theta-11\theta^3)X^2+2(32-40\theta^2+13\theta^4)XY-\theta(48-64\theta^2+21\theta^4)Y^2$ in the numerator of Equation (A34). Because $\theta > 1$, $-(16\theta-11\theta^3)$ that is the coefficient of X^2 is negative, indicating that Equation (A34) is concave with respect to X. Therefore, Equation (A34) takes its minimum value when X is equal to the value of the endpoint in its domain of definition, which is either $X = \theta Y$ or $X = Y/\theta$ assumed in Inequality (10). We substitute each value into Equation (A34). First, substituting $X = \theta Y$ into Equation (A34) gives $16\theta(1-\theta^2)^2Y^2$, which is positive. Second, substituting $X = Y/\theta$ into Equation (A34) gives $3(1-\theta^2)^2(16-7\theta^2)Y^2/\theta$, which is also positive. Therefore, Equation (A34) is always positive within the domain of $\theta Y < X < Y/\theta$, meaning that $\Pi^{(\mathrm{T,\ D})} - \Pi^{(\mathrm{TD,\ D})} > 0$ holds.

(ii) Proof of $\Pi^{(\mathrm{TD,D})} > \Pi^{(\mathrm{D,D})}$

$\Pi^{(\mathrm{TD,D})} > \Pi^{(\mathrm{D,D})}$ holds because Proposition 1 suggests that $\Pi^{(\mathrm{TD,\ D})} = (X-\theta Y)^2/(8\beta(1-\theta^2))$ and $\Pi^{(\mathrm{D,\ D})} = 0$.

(iii) Proof of $\Pi^{(\mathrm{D,\ T})} > \Pi^{(\mathrm{TD,\ T})}$

Proposition 1 suggests that the following equation holds.

$\Pi^{(\mathrm{D,\ T})} - \Pi^{(\mathrm{TD,\ T})}$

$$= \frac{\theta(-\theta(48 - 59\theta^2 + 18\theta^4)Y^2 + 2(48 - 60\theta^2 + 19\theta^4)XY - \theta(60 - 78\theta^2 + 25\theta^4)X^2)}{4\beta(1-\theta^2)(8-5\theta^2)^2} \tag{A35}$$

Let us determine the sign of $-\theta(48-59\theta^2+18\theta^4)Y^2+2(48-60\theta^2+19\theta^4)XY-\theta(60-78\theta^2+25\theta^4)X^2$ in the numerator of Equation (A35). Because $0 < \theta < 1$, $-\theta(60-78\theta^2+25\theta^4)$ that is the coefficient of X^2 is negative, indicating that Equation (A35) is concave with respect to X. Therefore, Equation (A35) takes its minimum value when X is the endpoint of either $X = \theta Y$ or $X = Y/\theta$ assumed in Inequality (10). We substitute each value into Equation (A35). First, substituting $X = \theta Y$ into Equation (A35) gives $\theta(1-\theta^2)^2(48-25\theta^2)Y^2$, which is positive. Second, substituting $X = Y/\theta$ into Equation (A35) gives $(18(2-\theta^2)(1-\theta^2)^2Y^2)/\theta$, which is also positive. Therefore, Equation (A35) is always positive within the domain of $\theta Y < X < Y/\theta$, meaning that $\Pi^{(\mathrm{T,\ D})} - \Pi^{(\mathrm{TD,\ D})} > 0$ holds.

(iv) Proof of $\Pi^{(\mathrm{TD,\ T})} > \Pi^{(\mathrm{T,\ T})}$

$\Pi^{(\mathrm{TD,\ T})} > \Pi^{(\mathrm{T,\ T})}$ holds because Proposition 1 suggests that $\Pi^{(\mathrm{TD,\ T})} = (Y-\theta X)^2/(4\beta(1-\theta^2))$ and $\Pi^{(\mathrm{T,\ T})} = 0$.

(v) Proof of $\Pi^{(TD, TD)} = \Pi^{(T, TD)} = \Pi^{(D, TD)}$

Proposition 1 shows $\Pi^{(TD, TD)} = \Pi^{(T, TD)} = \Pi^{(D, TD)} = 0$. □

Proof of Theorem 1.

Table 3 shows the payoff matrix for the companies in Stage 1. The circled payoffs represent each company's best-response strategy. Because the variable on the left in parentheses represents Company 1's profit and the variable on the right represents Company 2's profit, the cell with both payoffs in parentheses circled corresponds to the SPNE. □

Proof of Theorem 2.

Proposition 2 indicates that $\Pi^{(T, D)}–\Pi^{(TD, TD)} > 0$ and $\Pi^{(D, T)}–\Pi^{(TD, TD)} > 0$. These inequalities imply that both companies earn greater profits in the equilibrium of (T, D) or (D, T) than in the equilibrium of (TD, TD), indicating that the equilibrium of either (T, D) or (D, T) Pareto dominates the equilibrium of (TD, TD). □

Proof of Proposition 3.

Using the values of $\Pi^{(T, D)}$ and $\Pi^{(D, T)}$ in Proposition 1, we equivalently transform the inequality of $\Pi^{(T, D)} \gtreqless \Pi^{(D, T)}$ as the following inequality, which is the condition shown in this proposition.

$X \gtreqless \sqrt{2-\theta^2}Y$ □

Proof of Theorem 3.

If the first mover chooses Strategy D, the second mover will subsequently choose Strategy T in response because the latter generates the highest profit among strategies T, D, and TD according to Proposition 2. Meanwhile, if the first mover chooses Strategy T, the second mover will subsequently choose Strategy D among the three feasible channel strategies because the latter generates the highest profit according to Proposition 2. The first mover never chooses TD because then its profit is the lowest as a result of TD being chosen by the second mover according to Proposition 2. Therefore, the first mover chooses either Strategy T or D. Next, by substituting the profits in Proposition 1 into $\Pi^{(T, D)} \gtreqless \Pi^{(D, T)}$, the inequality is equivalently transformed as:

$X \gtreqless \sqrt{2-\theta^2}Y$.

This inequality corresponds to the inequality shown in this theorem. □

Proof of Lemma 2 and Proposition 4.

As in Proof of Lemma 1 and Proposition 1, the objective functions (i.e., profits) are sequentially maximized with use of backward induction to obtain SPNE in each case of the channel strategies. Note that because $\lambda < 1$ holds in this section, we can sequentially maximize each profit function by using corresponding first-order conditions. Here as an example, we show the solving process in the case of (TD, T). We first substitute $q_2^D = 0$ into Equation (3) and solving the equation for q_1^T, q_1^D, and q_2^T, obtaining the supply function. Then, by substituting the supply function into the collectors' profits of π_1 and π_2, we express the profits as the functions of p_1^D, p_1^T, p_2^T, b_1, and b_2. At Stage 3, Collectors 1 and 2 maximize their respective profits by solving $\partial\pi_1/\partial p_1^T = \partial\pi_2/\partial p_2^T = 0$. After substituting these p_1^T and p_2^T derived at Stage 3 and the supply function into Π_1 and Π_2, we solve $\partial\Pi_1/\partial p_1^D = \partial\Pi_1/\partial b_1 = \partial\Pi_2/\partial b_2 = 0$ at Stage 2 to yield p_1^D, b_1, and b_2. Finally, inserting p_1^D, p_1^T, p_2^T, b_1, and b_2 derived above into Π_1 and Π_2 yields the equilibrium profits. Similarly, in each case of channel strategies other than (TD, D), we can obtain equilibrium profits by sequentially maximizing the objective functions of companies' and collectors' profits in completely the same order of function maximization as in the proof of Proposition 1. □

Proof of Corollary 1.

First, we substitute $Y = X$ into the profits of all the cases obtained in Proposition 4. Then, each difference between two profits (e.g., $\Pi^{(D,\,T)}-\Pi^{(TD,\,T)}$) is expressed as a polynomial containing four exogenous parameters of θ, λ, X, and β. Multiplying this polynomial by β/X^2, we can eliminate β and X from the polynomial. By using this expression (e.g., $(\Pi^{(D,\,T)}-\Pi^{(TD,\,T)})\times(\beta/X^2)$), we can determine the region of the two parameters of θ and λ in which the profit in one case is higher than the profit in another case. Specifically, by setting the expression equaling to 0, we can draw a locus of θ and λ that satisfies this equation in a two-dimensional space of θ and λ, which represents the boundary that distinguishes whether the profit in one case is greater or less than the profit in another case. For example, because all the four inequalities of $\Pi^{(D,\,T)} > \Pi^{(T,\,T)}$, $\Pi^{(D,\,T)} > \Pi^{(TD,\,T)}$, $\Pi^{(T,\,D)} > \Pi^{(D,\,D)}$, and $\Pi^{(T,\,D)} > \Pi^{(TD,\,D)}$ hold in Regions I and II, strategies (T, D) and (D, T) constitute SPNE there. The boundaries that distinguish SPNE and Pareto optimality in all cases are drawn in Fig. 3. □

References

Atasu, A., Toktay, L.B., van Wassenhove, L.N., 2013. How collection cost structure drives a manufacturer's reverse channel choice. Production and Operations Management 22 (5), 1089–1102.

Bai, S., Ge, L., Zhang, X., 2022. Platform or direct channel: Government-subsidized recycling strategies for WEEE. Information Systems and e-Business Management 20, 347–369.

Bertrand, J., 1883. Théorie mathématique de la richesse sociale. Journal des Savants 67, 499–508.

Besanko, D., Dranove, D., Shanley, M., 2017. Economics of Strategy, 7th Edition. Wiley.

Bulmus, S.C., Zhu, S.X., Teunter, R.H., 2014. Competition for cores in remanufacturing. European Journal of Operational Research 233 (1), 105–113.

Cai, G., Zhang, Z.G., Zhang, M., 2009. Game theoretical perspectives on dual-channel supply chain competition with price discounts and pricing schemes. International

Journal of Production Economics 117 (1), 80–96.
Chen, L., Zhao, X., Tang, O., Price, L., Zhang, S., Zhu, W., 2017. Supply chain collaboration for sustainability: A literature review and future research agenda. International Journal of Production Economics 194, 73–87.
Chiang, W.-Y.K., Chhajed, D., Hess, J.D., 2003. Direct marketing, indirect profits: A strategic analysis of dual-channel supply-chain design. Management Science 49 (1), 1–20.
Choi, T.-M., Li, Y., Xu, L., 2013. Channel leadership, performance and coordination in closed loop supply chains. International Journal of Production Economics 146 (1), 371–380.
Chuang, C.-H., Wang, C.X., Zhao, Y., 2014. Closed-loop supply chain models for a high-tech product under alternative reverse channel and collection cost structures. International Journal of Production Economics 156, 108–123.
Dan, B., Xu, G., Liu, C., 2012. Pricing policies in a dual-channel supply chain with retail services. International Journal of Production Economics 139 (1), 312–320.
Dumrongsiri, A., Fan, M., Jain, A., Moinzadeh, K., 2008. A supply chain model with direct and retail channels. European Journal of Operational Research 187 (3), 691–718.
Feng, L., Govindan, K., Li, C., 2017. Strategic planning: Design and coordination for dual-recycling channel reverse supply chain considering consumer behavior. European Journal of Operational Research 260 (2), 601–612.
Ferrer, G., Swaminathan, J.M., 2010. Managing new and differentiated remanufactured products. European Journal of Operational Research 203 (2), 370–379.
Gan, S.-S., Pujawan, I.N., Suparno, Widodo, B., 2017. Pricing decision for new and remanufactured product in a closed-loop supply chain with separate sales-channel. International Journal of Production Economics 190, 120–132.
Giri, B.C., Chakraborty, A., Maiti, T., 2017. Pricing and return product collection decisions in a closed-loop supply chain with dual-channel in both forward and reverse logistics. Journal of Manufacturing Systems 42, 104–123.
Govindan, K., Popiuc, M.N., 2014. Reverse supply chain coordination by revenue sharing contract: A case for the personal computers industry. European Journal of Operational Research 233 (2), 326–336.
Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. European Journal of Operational Research 240 (3), 603–626.
Guide, V.D.R., Teunter, R.H., van Wassenhove, L.N., 2003. Matching demand and supply to maximize profits from remanufacturing. Manufacturing & Service Operations Management 5 (4), 303–316.
Guo, S., Shen, B., Choi, T.-M., Jung, S., 2017. A review on supply chain contracts in reverse logistics: Supply chain structures and channel leaderships. Journal of Cleaner Production 144, 387–402.
Hardcastle, J.L., 2014. Gazelle pays $200M for used electronic devices. Environmental+Energy Leader, November 20, 2014,

https://www.environmentalleader.com/2014/11/gazelle-pays-200m-for-used-electronic-devices/

He, Y., 2015. Acquisition pricing and remanufacturing decisions in a closed-loop supply chain. International Journal of Production Economics 163, 48–60.

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

He, Q., Wang, N., Browning, T.R., Jiang, B., 2022. Competitive collection with convenience-perceived customers. European Journal of Operational Research 303 (1), 239–254.

He, Q., Wang, N., Yang, Z., He, Z., Jiang, B., 2019b. Competitive collection under channel inconvenience in closed-loop supply chain. European Journal of Operational Research 275 (1), 155–166.

Heydari, J., Govindan, K., Sadeghi, R., 2018. Reverse supply chain coordination under stochastic remanufacturing capacity. International Journal of Production Economics 202, 1–11.

Hong, X., Cao, X., Gong, Y., Chen, W., 2021. Quality information acquisition and disclosure with green manufacturing in a closed-loop supply chain. International Journal of Production Economics 232, 107997.

Hong, X., Govindan, K., Xu, L., Du, P., 2017. Quantity and collection decisions in a closed-loop supply chain with technology licensing. European Journal of Operational Research 256 (3), 820–829.

Hong, X., Wang, Z., Wang, D., Zhang, H., 2013. Decision models of closed-loop supply chain with remanufacturing under hybrid dual-channel collection. International Journal of Advanced Manufacturing Technology 68 (5–8), 1851–1865.

Hosseini-Motlagh, S.-M., Ebrahimi, S., Zirakpourdehkordi, R., 2020. Coordination of dual-function acquisition price and corporate social responsibility in a sustainable closed-loop supply chain. Journal of Cleaner Production 251, 119629.

Hu, S., Dai, Y., Ma, Z.-J., Ye, Y.-S., 2016. Designing contracts for a reverse supply chain with strategic recycling behavior of consumers. International Journal of Production Economics 180, 16–24.

Hua, G., Wang, S., Cheng, T.C.E., 2010. Price and lead time decisions in dual-channel supply chains. European Journal of Operational Research 205 (1), 113–126.

Huang, M., Song, M., Lee, L.H., Ching, W.K., 2013. Analysis for strategy of closed-loop supply chain with dual recycling channel. International Journal of Production Economics 144 (2), 510–520.

Jabarzare, N., Rasti-Barzoki, M., 2020. A game theoretic approach for pricing and determining quality level through coordination contracts in a dual-channel supply chain including manufacturer and packaging company. International Journal of Production Economics 221, 107480.

Jena, S.K., Sarmah, S.P., 2014. Price competition and co-operation in a duopoly closed-loop supply chain. International Journal of Production Economics 156, 346–360.

Jin, L., Zheng, B., Huang, S., 2021. Pricing and coordination in a reverse supply chain with online and offline recycling channels: A power perspective. Journal of Cleaner Production 298, 126786.
Li, N., 2019. From mobile phone recycling to appliance recycling: "Flash Recycling" completes series B1 financing. 36Krypton First, October 31, 2019, https://36kr.com/p/1724599123969
Li, C., Feng, L., Luo, S., 2019. Strategic introduction of an online recycling channel in the reverse supply chain with a random demand. Journal of Cleaner Production 236, 117683.
Li, Y., Xu, F., Zhao, X., 2017. Governance mechanisms of dual-channel reverse supply chains with informal collection channel. Journal of Cleaner Production 155 (2), 125–140.
Liu, Z., Chen, J., Diallo, C., Venkatadri, U., 2021. Pricing and production decisions in a dual-channel closed-loop supply chain with (re)manufacturing. International Journal of Production Economics 232, 107935.
Liu, H., Lei, M., Deng, H., Leong, G.K., Huang, T., 2016. A dual channel, quality-based price competition model for the WEEE recycling market with government subsidy. Omega 59 (B), 290–302.
Ma, W., Zhao, Z., Ke, H., 2013. Dual-channel closed-loop supply chain with government consumption-subsidy. European Journal of Operational Research 226 (2), 221–227.
Matsui, K., 2016. Asymmetric product distribution between symmetric manufacturers using dual-channel supply chains. European Journal of Operational Research 248 (2), 646–657.
Matsui, K., 2017. When should a manufacturer set its direct price and wholesale price in dual-channel supply chains? European Journal of Operational Research 258 (2), 501–511.
Matsui, K., 2022. Optimal timing of acquisition price announcement for used products in a dual-recycling channel reverse supply chain. European Journal of Operational Research 300 (2), 615–632.
Minner, S., Kiesmüller, G.P., 2012. Dynamic product acquisition in closed loop supply chains. International Journal of Production Research 50 (11), 2836–2851.
Panda, S., Modak, N.M., Cárdenas-Barrón, L.E., 2017. Coordinating a socially responsible closed-loop supply chain with product recycling. International Journal of Production Economics 188, 11–21.
Qu, Y., Wang, W., Liu, Y., Zhu, Q., 2019. Understanding residents' preferences for e-waste collection in China–A case study of waste mobile phones. Journal of Cleaner Production 228, 52–62.
Ranjbar, S., Sahebi, H., Ashayeri, J., Teymouri, A., 2020. A competitive dual recycling channel in a three-level closed loop supply chain under different power structures: Pricing and collecting decisions. Journal of Cleaner Production 272, 122623.
Saha, S., Sarmah, S.P., Moon, I., 2016. Dual channel closed-loop supply chain coordination with a reward-driven remanufacturing policy. International Journal of Production

Research 54 (5), 1503–1517.
Savaskan, R.C., Bhattacharya, S., van Wassenhove, L.N., 2004. Closed-loop supply chain models with product remanufacturing. Management Science 50 (2), 239–252.
Savaskan, R.C., van Wassenhove, L.N., 2006. Reverse channel design: The case of competing retailers. Management Science 52 (1), 1–14.
Shi, S., Sun, J., Cheng, T.C.E., 2020. Wholesale or drop-shipping: Contract choices of the online retailer and the manufacturer in a dual-channel supply chain. International Journal of Production Economics 226, 107618.
Simpson, D., Power, D., Riach, K., Tsarenko, Y., 2019. Consumer motivation for product disposal and its role in acquiring products for reuse. Journal of Operations Management 65 (7), 612–635.
Singh, N., Vives, X., 1984. Price and quantity competition in a differentiated duopoly. RAND Journal of Economics 15 (4), 546–554.
Song, X., Wang, J., Yang, J., Lu, B., 2017. An updated review and conceptual model for optimizing WEEE management in China from a life cycle perspective. Frontiers of Environmental Science & Engineering 11 (5), 3.
Souza, G.C., 2013. Closed-loop supply chains: A critical review, and future research. Decision Sciences 44 (1), 7–38.
Statt, N., 2020. Trade-in site Gazelle is ending trade-ins. The Verge. https://www.theverge.com/2020/12/30/22206779/gazelle-smartphone-used-trade-in-program-shut-down
Taleizadeh, A.A., Sadeghi, R., 2019. Pricing strategies in the competitive reverse supply chains with traditional and e-channels: A game theoretic approach. International Journal of Production Economics 215, 48–60.
Thierry, M., Salomon, M., van Nunen, J., van Wassenhove, L., 1995. Strategic issues in product recovery management. California Management Review 37 (2), 114–136.
Tong, X., Tao, D., Lifset, R., 2018. Varieties of business models for post-consumer recycling in China. Journal of Cleaner Production 170, 665–673.
Wang, H., Han, H., Liu, H., Tian, X., Xu, M., Wu, Y., Gu, Y., Liu, Y., Zuo, T., 2018. "Internet +" recyclable resources: A new recycling mode in China. Resources, Conservation & Recycling 134, 44–47.
Wang, N., He, Q., Jiang, B., 2019. Hybrid closed-loop supply chains with competition in recycling and product markets. International Journal of Production Economics 217, 246–258.
Wang, Q., Hong, X., Gong, Y., Chen, W., 2020a. Collusion or Not: The optimal choice of competing retailers in a closed-loop supply chain. International Journal of Production Economics 225, 107580.
Wang, J., Jiang, H., Yu, M., 2020b. Pricing decisions in a dual-channel green supply chain with product customization. Journal of Cleaner Production 247, 119101.
Wang, J., Li, W., Mishima, N., Adachi, T., 2022a. Exploring the optimal reverse supply chain for e-waste treatment under Chinese government subsidy. Waste Management 137, 128–138.

Wang, N., Zhang, M., He, Z., 2022b. Development trends of enterprises' green growth model. in: Enterprises' Green Growth Model and Value Chain Reconstruction, pp. 49–66, Springer.

Wei, F., Zhu, Q., Pourhejazy, P., Liu, C., 2021. Contract vs. recruitment: Integrating an informal waste merchant to a formal collector for collection of municipal solid waste. Journal of Cleaner Production 287, 125004.

Wu, C.-H., 2015. Strategic and operational decisions under sales competition and collection competition for end-of-use products in remanufacturing. International Journal of Production Economics 169, 11–20.

Wu, D., Chen, J., Li, P., Zhang, R., 2020. Contract coordination of dual channel reverse supply chain considering service level. Journal of Cleaner Production 260, 121071.

Wu, X., Zhou, Y., 2017. The optimal reverse channel choice under supply chain competition. European Journal of Operational Research 259 (1), 63–66.

Xie, J., Liang, L., Liu, L., Ieromonachou, P., 2017. Coordination contracts of dual-channel with cooperation advertising in closed-loop supply chains. International Journal of Production Economics 183 (B), 528–538.

Xiong, Y., Zhao, Q., Zhou, Y., 2016. Manufacturer-remanufacturing vs supplier-remanufacturing in a closed-loop supply chain. International Journal Production Economics 176, 21–28.

Yan, N., Liu, Y., Xu, X., He, X., 2020. Strategic dual-channel pricing games with e-retailer finance. European Journal of Operational Research 283 (1), 138–151.

Yan, Y., Zhao, R., Liu, Z., 2018. Strategic introduction of the marketplace channel under spillovers from online to offline sales. European Journal of Operational Research 267 (1), 65–77.

Yang, H., Luo, J., Zhang, Q., 2018. Supplier encroachment under nonlinear pricing with imperfect substitutes: Bargaining power versus revenue-sharing. European Journal of Operational Research 267 (3), 1089–1101.

Zhang, L.-H., Yao, J., Xu, L., 2020. Emission reduction and market encroachment: Whether the manufacturer opens a direct channel or not? Journal of Cleaner Production 269, 121932.

Zhao, S., You, Z., Zhu, Q., 2021. Quality choice for product recovery considering a trade-in program and third-party remanufacturing competition. International Journal Production Economics 240, 108239.

Zhao, S., You, Z., Zhu, Q., 2022. Effects of asymmetric cost information on collection outsourcing of used products for remanufacturing. Transportation Research Part E 162, 102729.

Zuo, L., Wang, C., Sun, Q., 2020. Sustaining WEEE collection business in China: The case of online to offline (O2O) development strategies. Waste Management 101, 222–230.

Table 1. Comparison with the literature

	Decision variable		Channel structure decision	Competition between supply chains
	Effort (quantity)	Price		
Savaskan et al. (2004), Savaskan and van Wassenhove (2006), Atasu et al. (2013), Choi et al. (2013), Hong et al. (2013), Huang et al. (2013), Chuang et al. (2014), Jena and Sarmah (2014), Saha et al. (2016), Giri et al. (2017), Panda et al. (2017), He et al. (2019b), Ranjbar et al. (2020), He et al. (2022)	✓		✓	
Hong et al. (2017), Hosseini-Motlagh et al. (2020), Wang et al. (2020a), Zhao et al. (2021)	✓			
Wu and Zhou (2017)	✓		✓	✓
Minner and Kiesmüller (2012), Bulmus et al. (2014), He (2015), Wu (2015), Hu et al. (2016), Liu et al. (2016), Gan et al. (2017), Li et al. (2017), Heydari et al. (2018), Jin et al. (2021)		✓		
Taleizadeh and Sadeghi (2019)		✓		✓
Feng et al. (2017), Li et al. (2019), Wu et al. (2020), Matsui (2022)		✓	✓	
This paper		✓	✓	✓

Table 2. Notations

p_i^T	offline recycling price offered by Collector *i* in an offline channel
p_i^D	online recycling price offered by Company *i* in an online channel
b_i	transfer price paid from Company *i* to Collector *i*
q_i^T	used product quantity collected from Company *i*'s offline channel
q_i^D	used product quantity collected from Company *i*'s online channel
θ	substitutability between an online channel and an offline channel within the same supply chain ($0 < \theta < 1$)
λ	substitutability between supply chains within the same type of channel ($0 < \lambda \leq 1$)
α	intercept of an inverse supply function
β	slope of an inverse supply function
w	recycling company revenue from handling one used product
c	recycling company's disposal cost per product
c_{RI}	recycling company's inspection cost
c_{RS}	recycling company's shipping cost
c_0	collector's product collection cost from the offline channel
c_{CI}	collector's inspection cost
c_{CH}	collector's handling cost
c_{CS}	collector's shipping cost
Δ	$c_0+c_{CI}+c_{CH}+c_{CS}$
Γ	$c_{RS}+c_{RI}$
X	$w-c-\alpha-\Delta$
Y	$w-c-\alpha-\Gamma$
Π	recycling company's profit
π	collector's profit
i	subscript indexing a supply chain (i = 1 or 2)
D	strategy of collecting products only from an online channel
T	strategy of collecting products only from an offline channel
TD	strategy of collecting products from both offline and online channels
S_i	channel strategy chosen by Company *i*
SPNE	subgame perfect Nash equilibrium

Table 3. Payoff matrix for the two recycling companies

		Recycling company 2		
	Channel strategy	T	D	TD
Recycling company 1	T	$(\Pi^{(T, T)}, \Pi^{(T, T)})$	$(\Pi^{(T, D)}, \Pi^{(D, T)})$	$(\Pi^{(T, TD)}, \Pi^{(TD, T)})$
	D	$(\Pi^{(D, T)}, \Pi^{(T, D)})$	$(\Pi^{(D, D)}, \Pi^{(D, D)})$	$(\Pi^{(D, TD)}, \Pi^{(TD, D)})$
	TD	$(\Pi^{(TD, T)}, \Pi^{(T, TD)})$	$(\Pi^{(TD, D)}, \Pi^{(D, TD)})$	$(\Pi^{(TD, TD)}, \Pi^{(TD, TD)})$

Note: The first and second variables in parentheses in each cell represent the profits of Recycling company 1 and Recycling company 2, respectively. The profit circled represents the best-response strategy of the company.

Fig. 1. Description of supply chains

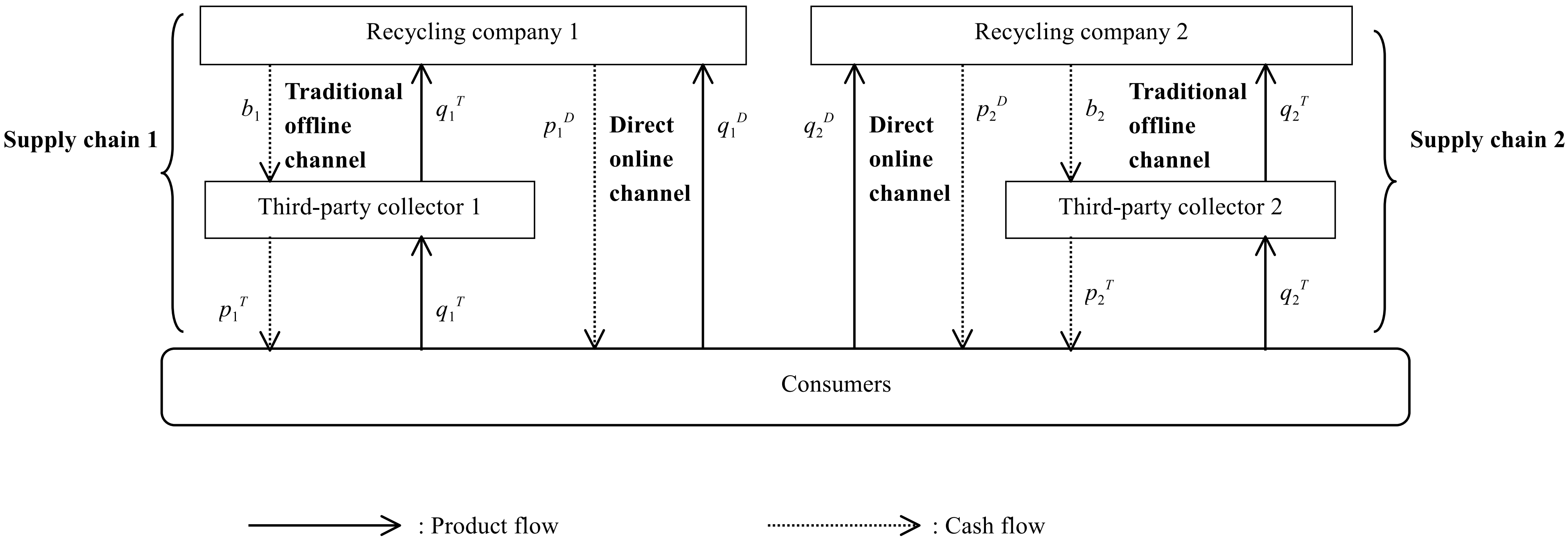


Fig. 2. Event timeline

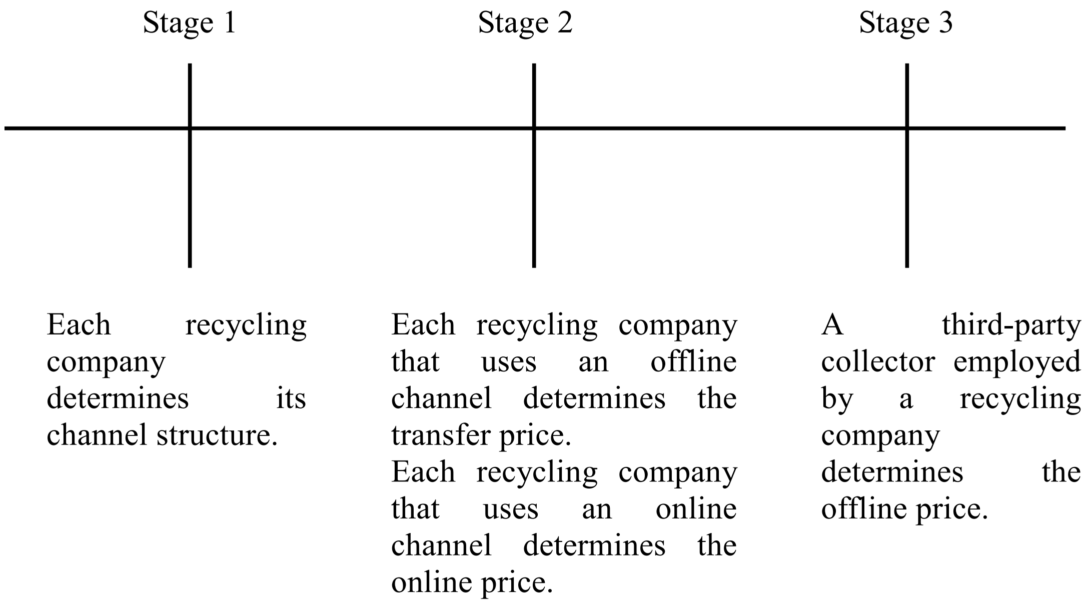
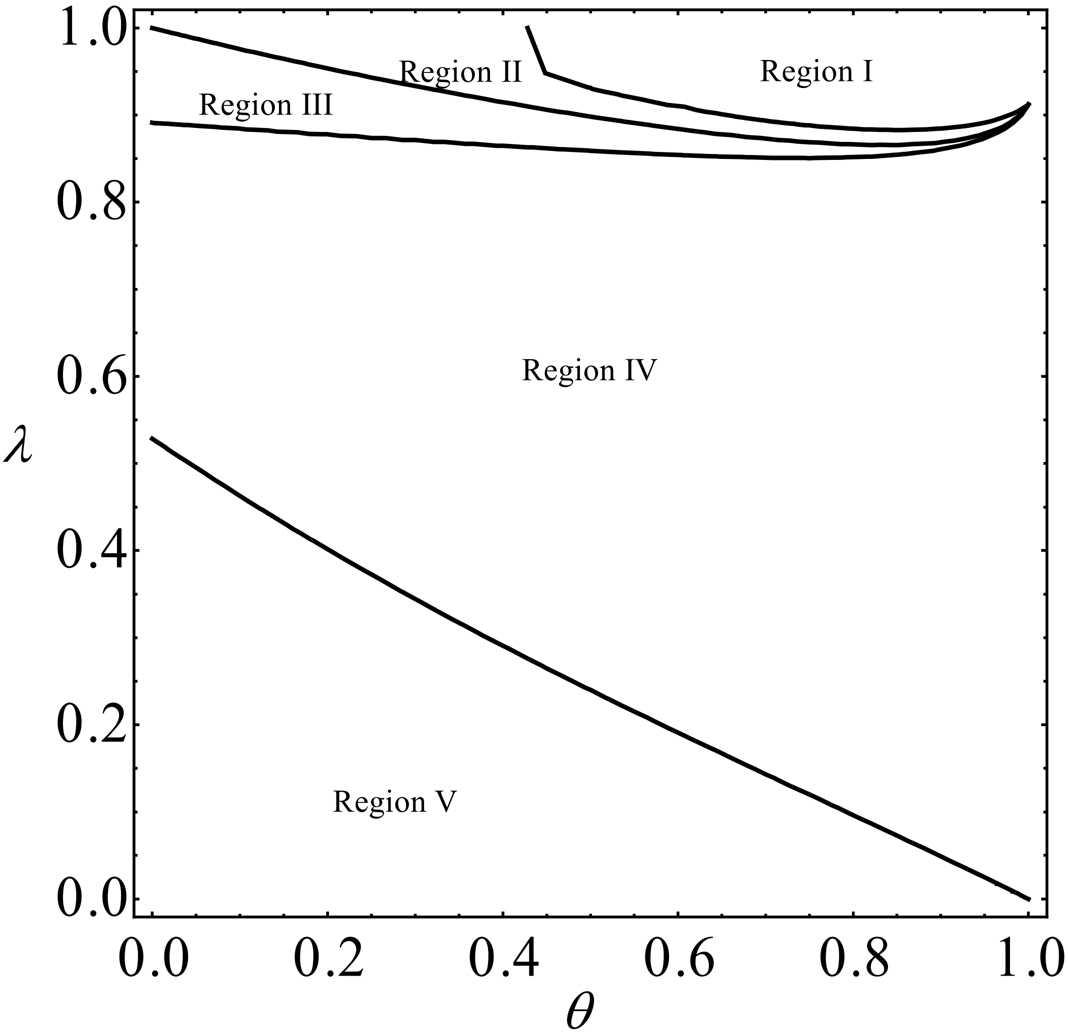


Fig. 3. Characterization of SPNE when consumers perceive differentiation between supply chains ($0 < \lambda < 1$)



Notes: The figure is drawn under the condition of $Y = X$ so that both online and offline channels are equally profitable.

Asymmetric channel strategies (D, T) and (T, D) arise in SPNE in Regions I and II, while not in Regions III, IV, and V.

Symmetric channel strategies (TD, TD) arises in SPNE in Regions II, III, IV, and V, while not in Region I.

Symmetric channel strategies (TD, TD) is Pareto optimal only in Region V, while not in Regions I, II, III, and IV.