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Optimal timing of acquisition price announcement for used products in a dual-recycling channel reverse supply chain

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ABSTRACT

The rapid development of information technologies enables recycling companies to purchase and collect used products from consumers through both traditional and Internet-based online channels. Because an online channel transmits price information instantly to consumers, choosing the best time to announce the recycling price (i.e., acquisition price) of used products to consumers has become a critical problem for recycling companies. This paper seeks to solve this problem by developing a game-theoretic model describing a dual-channel reverse supply chain consisting of a recycling company and a third-party collector in which the recycling company purchases products not only through a third-party collector, but also directly from consumers online. We derive two major results by solving the model. The first is that first-mover advantage arises, which indicates that each firm constituting a dual-channel reverse supply chain should announce its own recycling price before the other. This first result is notable because it is exactly opposite to conventional wisdom that the second-mover advantage of pricing usually emerges when price competition occurs among firms in a horizontal relationship, which is well known in non-cooperative game theory. The second result is that the recycling company can maximize its own profit and consumers' surplus by announcing its recycling price in the online channel before or upon, but not after, determining the transfer price paid to the collector for products collected in the offline channel. Both results can be used as practical decision-making guidelines in dual-recycling channel reverse supply chain management.

1. Introduction

The rapid development of information technologies accelerates the upgrade of electrical and electronic equipment, including smartphones, tablets, and PCs used by consumers and corporations, which in turn, produces a substantial amount of waste electrical and electronic equipment (WEEE) (Feng, Govindan, & Li, 2017). Because of the economic and environmental benefits of product recycling, realizing and utilizing the economic salvage values of WEEE through an efficient collection system has become a major society-wide concern. Accordingly, management of a reverse supply chain has attracted a tremendous amount of attention from business practitioners and operational researchers (Huang, Song, Lee, & Ching, 2013). In contrast to forward supply chains involving the flow of products from manufacturers to end consumers, reverse supply chains involve the flow of used products from consumers to firms such as manufacturers, remanufacturers, and pure-play recycling companies. Meanwhile, the development of information technologies also significantly changes the method of collecting WEEE; that is, recycling companies become able to purchase and collect used products from consumers through not only traditional recycling, but also an Internet-based online channel. A *dual-channel reverse supply chain* refers to a mix of a traditional offline recycling channel and an Internet-based online direct channel developed by recycling companies (Feng et al., 2017; Wu, Chen, Li, & Zhang, 2020). The dual-channel reverse supply chain helps recycling companies obtain appropriate WEEE effectively and reduces the costs of collection and transportation.

In addition to recycling companies collecting used products both directly and indirectly, firms exclusively dedicated to recycling businesses rapidly grow in large economies by using higher acquisition prices and customer service as competitive weapons (Feng et al., 2017; Li, Feng, & Luo, 2019a; Wang, He, & Jiang, 2019a; Wang, Song, He, & Jia, 2020b). reBuy reCommerce GmbH is a company founded in Berlin in 2009 that buys used books, CDs, DVDs, hardware, and selected electronic items from consumers via its own online platform as well as third-party providers such as wholesalers (Neuhaus, 2018). reBuy is now a major company in Europe operating its recycling business in France, Germany, Italy, and the

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Netherlands. In the USA, Gazelle, operated by ecoATM LLC, is a company established in 2006 that buys used electronic equipment such as cell phones, smart tablets, and laptop PCs from consumers through direct purchasing via online and other channels. It is reported that, by 2014, Gazelle had paid consumers $200 million for their used electronic equipment and collected over 2 million devices from more than 1 million consumers (Hardcastle, 2014). ReCellular Inc., a firm that remanufactured cell phones in the USA, purchased used phones from third-party collectors as well as directly from consumers. To maintain its dual-recycling channel, ReCellular spent substantial money and time on its collectors to ensure that they could recycle a sufficient number of used products (Guide, Teunter, & van Wassenhove, 2003). In China, Loving Recycling (www.aihuishou.com), one of the largest companies that purchase and resell smartphones, is successfully operating online recycling platforms. It has more than 30 million customers and obtains 1 million orders every month (Wang et al., 2018). Because major companies engaged in the recycling business in China offer consumers not only traditional but also online methods, they have an incentive to increase the acquisition price of used products to induce more customers to choose online recycling channels (Wu et al., 2020). All of the above cases in Europe, the USA, and China demonstrate that a number of companies engaged in the recycling business also utilize dual-channel reverse supply chains to purchase and collect used products.

However, the prosperity of dual-channel reverse supply chains poses its own challenges for recycling companies. Specifically, if there are multiple collection channels that compete to purchase used products, channel conflict may arise in the reverse supply chain (Bulmus, Zhu, & Teunter, 2014; Feng et al., 2017; Kleber, Reimann, Souza, & Zhang, 2020; Li et al., 2019a). One effective measure for recycling companies to suppress the channel conflict is appropriate price control in different channels. Here, it should be noted that not only the level of the recycling prices, but also the timing of when to set and announce the prices, are critical issues for recycling companies in the era of online recycling, particularly because an online channel transmits the recycling price of used products instantly to consumers considering selling them, which a traditional channel cannot. That is, consumers can sell used products to the channel that offers a higher recycling price after easily comparing recycling prices between different channels based on the price information instantly available in, for example, their smartphones. In this situation, choosing the best time for firms constituting a reverse supply chain to determine and announce their acquisition prices to consumers becomes an important practical problem.

Given the current environment surrounding the recycling market, this paper explores the best time to announce recycling prices by developing a game-theoretic model describing a dual-channel reverse supply chain consisting of a recycling company and a third-party collector in which the recycling company purchases products not only through the third-party collector (a traditional offline channel), but also directly (a direct online channel) from consumers. We derive two major results by solving the model. The first result is that first-mover advantage arises for both firms' recycling prices, providing the practical implication that each firm constituting a dual-channel reverse supply chain should announce its own recycling price before the other. The second result is derived from a timing game in which the two firms respectively choose not only the recycling prices, but also the timing of setting their prices. Specifically, the result is that the recycling company can maximize its own profit by announcing its recycling price in the online channel before or upon, but not after, determining the transfer price paid to the collector for products collected in the offline channel. Additionally, such an early announcement of the online recycling price constitutes the unique subgame perfect Nash equilibrium (SPNE), from which neither firm deviates. Furthermore, consumers earn the highest surplus if the recycling company announces the price at this time. These results are clear-cut and robust because they are proven completely analytically even without numerical analysis.

The first result of the first-mover advantage of pricing is notable because it is exactly opposite to conventional wisdom that the second-mover advantage of pricing usually emerges when price competition occurs among firms in a horizontal relationship, which has been shown and is well known in the literature of game theory (e.g., Gal-Or, 1985; Hamilton & Slutsky, 1990). Specifically, Gal-Or (1985) analytically proves that when firms in a horizontal relationship compete on price, a second-mover advantage of pricing arises in most circumstances including cases of linear-form demand or supply functions. The basic reason for our opposite result is that the situation described by our model is not competition between firms in a completely horizontal relationship, but rather, competition that involves both horizontal and vertical relationships, because one firm (i.e., the third-party collector) plays the role of not only the competitor, but also the intermediary of the other firm (i.e., the recycling company). Because of the setting of such a competitive relationship, the conventional result is overturned in our model. Hence, the first result yields the managerial guideline that a firm constituting a dual-recycling channel should not follow the conventional game-theoretic insight, but rather, determine and announce its recycling price as early as possible.

Meanwhile, the second result indicates that the recycling company should announce its recycling price to consumers in the online channel early, before setting the transfer price in the offline channel. The reason for this result is that, by announcing the online price before the transfer price specified in the collection contract with a third-party collector, the recycling company forces the collector to set the offline price only after the recycling company sets the online price. This allows the recycling company to secure the first-mover advantage of announcing its online recycling price before the collector announces the offline price to consumers.

In this paper, we consider recycling companies in China as the case described by our model, for the following two reasons. First, competition for recycling and recovery tends to become intense especially in a growing economy like China. Second, because our model is based on Feng et al. (2017), who refer to real-life company cases in China, it is appropriate to make our cases consistent with theirs to contrast this paper with Feng et al. (2017).

More specifically, we consider each of the following companies as the recycling company that provides online collection service described by our model. That is, Xin Jinqiao Environmental Protection Company and GEM Co., Ltd. are two major recycling companies in China that not only provide collection service but also have re-manufacturing technology. First, Xin Jinqiao Environmental Protection Company, which is a state-owned certified e-waste recycler in Shanghai, established Ala Environmental Protection (xjqhb.alahb.com) as its subsidiary to collect products through an online channel. Second, GEM Co., Ltd. (en.gem.com.cn), which is the first listed company in the WEEE recycling industry, established Recycling Brother as its platform dedicated to the pure-play online collection service.[1] Because Feng et al. (2017) use Xin Jinqiao as a real-life case for their model, we also use the company as a real-life case in this paper, following Feng et al. (2017).

Because the focus of this paper is competition between a recycling company and a general third-party collector, we first clearly define the companies indicated by our model. Specifically, we de-

[1] Table 1 in Song et al. (2017, p. 3) summarizes and categorizes companies associated with the online recycling industry in China, including GEM, Ala, Loving Recycling, etc. Song et al. (2017) also describe intense acquisition price competition between these companies and collectors in detail.

fine a recycling company as used in this paper as a company that has its own specific recycling/remanufacturing technologies and collects used products via both online and offline channels; we define a third-party collector as a company that does not have such technology and only plays the role of a pure intermediary to collect products only through an offline channel. Because Xin Jinqiao and GEM, which respectively established Ala and Recycling Brother as online subsidiaries, have recycling and remanufacturing technologies, they fit the definition of the recycling company in our model.

As will be reviewed in the next section, even though the timing of the acquisition price announcement is a critical problem for recycling companies using multiple recycling channels, to our knowledge, no existing study explores the optimal timing of the price announcement in reverse supply chains comprising not only a traditional offline channel, but also an online channel. Hence, it is worthwhile to note that the current study is the first to address this issue. Moreover, no existing study has applied the framework of the timing game to identify the optimal timing of decision-making to a reverse supply chain to find an equilibrium timing of pricing. This paper is also the first to incorporate the framework of the timing game into reverse supply chain management research to identify the optimal timing of price announcements, thereby making both academic and practical contributions.

To summarize the introduction, we clarify our main research questions as follows.

- Does the timing of the acquisition price announcement by a recycling company and a collector affect their profits in a dual-channel reverse supply chain?
- If it does, when should the recycling company announce its acquisition price to maximize its profit?
- Is there a stable timing of price announcements from which neither firm deviates?

The rest of the paper is organized as follows. Section 2 provides a review of previous operational research (OR) relating to dual-channel reverse supply chain management. We delineate the fundamental settings of our model and derive equilibrium profits and prices in Section 3. Using the equilibrium results, we show that the first-mover advantage to recycling price announcement arises in Section 4. In Section 5, we explore the stable timing of prices set by applying the timing game, deriving the SPNE that determines the optimal decisions of the firms. Furthermore, we investigate how the decision timing affects consumer surplus, to consider social impact in Section 6. Section 7 presents the results from numerical study, confirming the validity of the analytical results. In Section 8, we further extend the model to show that it can describe more general situations. The final section concludes.

2. Literature review

Heretofore, many OR studies have examined issues in dual-channel supply chain management using game theory to describe competitive environments. Earlier studies in this research stream have focused exclusively on forward supply chains consisting of a traditional bricks-and-mortar channel and a direct online channel (e.g., Cai, 2010; Chen, Zhao, Yan, & Zhou, 2021; Chiang & Monahan, 2005; Chiang, Chhajed, & Hess, 2003; Dumrongsiri, Fan, Jain, & Moinzadeh, 2008; Hamamura & Zennyo, 2021; Hua, Wang, & Cheng, 2010; Lee, Chang, Jean, & Kuo, 2021; Li, Zhang, Chiu, Liu, & Sethi, 2019c; Matsui, 2016, 2017, 2020; Sun, Jiao, Guo, & Yu, 2022; Wang, Jiang, & Yu, 2020a; Xu, Wang, & Zhao, 2018; Yan, Zhao, & Liu, 2018; Yang, Luo, & Zhang, 2018; Zhang & Hezarkhani, 2020). Following such dual-channel forward supply chain research, papers investigating the management of dual-channel reverse supply chains or closed-loop supply chains (CLSCs) have recently been increasing, as comprehensively reviewed in Govindan, Soleimani, and Kannan (2015) and Souza (2013). Most earlier studies assume that customers simply dispose of used products without expecting monetary compensation, and hence, the amount of the collection of used products is a function of firms' collection efforts, which can be regarded as their costs or investments, but not acquisition prices (e.g., Giri, Chakraborty, & Maiti, 2017; He, Wang, Yang, He, & Jiang, 2019; Hong, Govindan, Xu, & Du, 2017; Savaskan & van Wassenhove, 2006; Savaskan, Bhattacharya, & van Wassenhove, 2004; Taleizadeh & Sadeghi, 2019; Xie, Liang, Liu, & Ieromonachou, 2017).

In this line of research, Savaskan et al. (2004) initially develop a stylized game-theoretic model determining the desirable structure of a reverse channel for collecting used products. Specifically, they consider a manufacturer choosing one of the following three product collection modes: (i) the manufacturer collects them directly from the consumers, (ii) the manufacturer outsources collection activity to an existing retailer, or (iii) the manufacturer subcontracts collection activity to a third party. Comparing the manufacturers' optimal profits in these three environments, they conclude that outsourcing to the retailer is better than the other modes. Extending the model of Savaskan et al. (2004) by assuming that the cost structure of product collection depends on both the collection rate and collection quantity, Atasu, Toktay, and van Wassenhove (2013) examine how the collection cost structure influences the manufacturers' choice of a reverse channel between retailer- and manufacturer-managed collection channels. In a similar vein, Choi, Li, and Xu (2013) consider a CLSC consisting of a manufacturer, a retailer, and a collector, and compare the performance of CLSCs with different channel leaderships. The research by Choi et al. (2013) shows that the issue of decision sequence or timing is also important in reverse as well as in forward logistics, as they examine the influence of leaderships of channel members, which they refer to as a power structure, on profitability in the context of a CLSC. While they focus on the influence of the timing of a decision on collection efforts, we examine the optimal decision timing on acquisition prices. Hong, Wang, Wang, and Zhang (2013) examine an appropriate reverse channel structure design for used product collection from consumers in a dual-recycling channel. Their results demonstrate that the channel structure in which a manufacturer and a retailer jointly collect used products is the most effective from the manufacturer's perspective. Huang et al. (2013) study an optimal channel configuration strategy in a CLSC with a dual-recycling channel. They identify the range of the degree of competition in which the dual-recycling channel outperforms a single recycling channel from manufacturer's and consumers' perspective, respectively. He et al. (2019) consider the situation where consumers suffer inconvenience to return used products in a CLSC consisting of a manufacturer and a retailer. They show that while the retailer always has an incentive to participate in the collection competition, this competition cannot improve the efficiency of product recovery.

Overall, the previous papers overviewed above, including those examining the leadership of decisions in reverse or CLSCs, develop models assuming that collection quantity depends on firms' collection efforts. However, because the spread of Internet-based online recycling channels has now made it possible for price information to be transmitted far more quickly, which allows consumers to be able to learn and compare acquisition prices of used products easily, it is also a realistic assumption that collection quantity depends on recycling or acquisition prices rather than on collection efforts; hence, recycling firms compete on price. For this reason, an increasing number of papers develop models describing collection competition in terms of acquisition prices between firms constituting reverse supply chains, not of collection efforts (e.g., Bulmus et al., 2014; Feng et al., 2017; Kleber et al., 2020; Li, Xu, & Zhao, 2017; Liu, Lei, Deng, Leong, & Huang, 2016; Wu, 2015; Wu & Wu, 2016; Wu et al., 2020).

Bulmus et al. (2014) is an early work that develops a model of competition in acquisition price in reverse supply chains. Specifically, their model assumes that an original equipment manufacturer (OEM) and an independent remanufacturer compete in terms of both selling products and collecting returned products, which are called *cores* (Teunter & Flapper, 2011). In their dynamic model, the manufacturer offers both a new and a remanufactured product, while the remanufacturer offers only a remanufactured product. They determine both firms' optimal policies, showing that the OEM's acquisition price depends only on its own cost structure, not on the remanufacturer's acquisition price. Employing a setting similar to Bulmus et al. (2014), Hong et al. (2017) consider the case where a remanufacturer requires permission from a manufacturer to apply remanufacturing technology. They compare economic consequences of the two licensing schemes of fixed-fee and royalty under collection competition between the two firms, finding that fixed-fee licensing outperforms royalty licensing from the viewpoints of both consumer surplus and environmental protection. Feng et al. (2017) introduce the concept of an online recycling channel into a conventional two-echelon reverse supply chain with a dual-recycling channel, in which a recyclable dealer and a recycler act as a Stackelberg leader and a follower, respectively. Assuming price competition between online and offline channels and different channel preferences across consumers, they explore the reverse channel structure favorable for the recyclable dealer. Their results demonstrate that the dual-recycling channel structure always surpasses a single-channel structure from the perspectives of both the recyclable dealer and the whole system. Because Feng et al. (2017) provide a stylized model describing a dual-recycling channel under price competition between online and offline channels, Feng et al. (2017) is the most closely linked with the present paper and provides the basic foundations for our model. Meanwhile, the setting of our model, which significantly differs from that of Feng et al. (2017), is that the upstream recycling company and the downstream collector endogenously determine the equilibrium timing of price announcements within the model. We introduce the framework of the timing game into the model of Feng et al. (2017). Most recently, Kleber et al. (2020) study two-sided price competition between two remanufacturers in the acquisition of used products as well as the sales of remanufactured products. They assume that one of the two firms has a market advantage in a forward supply chain and the other has an acquisition advantage in a reverse supply chain. A major finding from their model is that the market advantage in the forward supply chain increases the competitiveness of a firm more than does the acquisition advantage in the reverse supply chain. Specifically, the firm having a market advantage can prevent the other firm's entry, even if the latter firm has a substantial acquisition advantage, but not the other way around. Comparing the papers that addressed these trade-in credit issues, we consider Bulmus et al. (2014) and Hong et al. (2017) as the earliest works that describe the collection competition. Feng et al. (2017) newly introduce the online channel into this basic model to describe a situation where collection competition takes place between online and offline channels. Kleber et al. (2020) present a comprehensive competition model in both dimensions of the forward and reverse supply chains. Each work represents a unique contribution to the literature.

Even though various issues associated with dual-channel reverse supply chain management, including channel design (Feng et al., 2017), coordination (Govindan & Popiuc, 2014), stochastic demand (Li, Li, & Cai, 2015), product quality (Cai, Lai, Li, Li, & Wu, 2014; Ferrer & Swaminathan, 2010; Örsdemir, Kemahlıoğlu-Ziya, & Parlaktürk, 2014), and government subsidies (Ma, Zhao, & Ke, 2013), have already been investigated in the literature, the appropriate timing of acquisition pricing has not been theoretically examined, despite its practical importance.

We should also be aware of an increasing number of papers that explore the favorable timing of decision-making by firms constituting supply chains (e.g., Chen, Chen, & Li, 2018; Chen et al., 2021; Li, Li, & Sun, 2019b; Matsui, 2017, 2018, 2020; Yan, Liu, Xu, & He, 2020; Zhang, Yao, & Xu, 2020). Matsui (2017) investigates the timing problem facing a manufacturer managing a dual-channel supply chain setting the direct retail price and wholesale price, showing that it should determine the direct retail price ahead of the wholesale price. He focuses on only a forward supply chain, ignoring the reverse supply chain, to explore desirable decision timing in the environment of a dual-channel supply chain. He also does not consider vertical differentiation between different channels. However, the assumption of vertical differentiation between online and offline channels is appropriate, particularly in a reverse supply chain, because the degree of accepting an online recycling channel varies substantially between consumers; that is, whether a consumer is accustomed to selling a used product through an online channel varies substantially, as indicated in previous studies (e.g., Feng et al., 2017; Li et al., 2019a). In these respects, the present paper, which considers a reverse supply chain and vertical channel differentiation, differs from Matsui (2017). While all previous papers explore the favorable timing of pricing in forward supply chains, no existing study explores the optimal timing of pricing by applying the framework of the timing game to reverse or CLSCs, even though the timing of announcing recycling prices is a critical issue for general recycling companies. Therefore, it is worthwhile to highlight that the present paper is the first to tackle this issue by applying the timing game framework to reverse supply chain management, which is also a substantial contribution to the OR literature.

3. Model

In this section, we initially delineate the settings of our model. Table 1 enumerates the notations and relevant variables used. Fig. 1 describes the reverse supply chain structure that we assume. To employ assumptions for our model, we follow previous stylized dual-recycling channel models describing competition in the literature (e.g., Feng et al., 2017; Li et al., 2019a; Wu et al., 2020). As shown in Fig. 1, we consider a dual-channel reverse supply chain consisting of two firms: a recycling company and a third-party collector.[2] We henceforth simply call the latter the collector. The recycling company purchases and collects used products from consumers not only through the collector, but also directly from consumers.[3] We call direct collection by the recycling company the direct online channel, and indirect collection through the collector the traditional offline channel, as illustrated in Fig. 1. The recycling company sets the online recycling price of a unit of a used product, p_D, and purchases these directly from consumers at that price in the online channel.[4] The recycling company also sets the transfer price of a unit of the used product paid to the collector, b, and buys products from the collector in the offline channel. Meanwhile, the collector sets the offline recycling price of a unit of products, p_T, and purchases these at the price in the offline channel. For con-

[2] While several papers develop dual-recycling channel models, the designation of these two firms is assumed to be slightly different among papers. For example, the two firms are called a recyclable dealer and a recycler in Feng et al. (2017), a remanufacturer and a recycler in Li et al. (2019a), and a recycling center and a third-party recycler in Wu et al. (2020).

[3] The term *consumers* used in our model also represents *sellers* of used products, because we focus on only reverse supply chains.

[4] The *recycling price* is also referred to as the *acquisition price* or the *collection price* in existing papers examining collection competition between different firms. All of these designations have virtually the same meaning.

Table 1
Notations.

p_T	offline recycling price of a used product in the traditional offline channel
p_D	online recycling price of a used product in the direct online channel
b	transfer price of a unit used product paid to the collector by the recycling company
q_T	quantity of used products in the traditional offline recycling channel
q_D	quantity of used products in the direct online recycling channel
θ	hassle factor for a consumer to return a product via the online channel relative to the offline channel ($\theta > 1$)
w	revenue of the recycling company attributed to its dealing with one unit of a used product
s	consumer's willingness to return a used product
c	per unit disposal cost for one unit of used product at the recycling company
c_{RI}	inspection cost of the recycling company
c_{RS}	shipping cost from consumer to the recycling company
c_0	collection cost of one unit of product in the traditional recycling channel for the collector
c_{CI}	inspection cost of the collector
c_{CH}	handling cost of the collector
c_{CS}	shipping cost from the collector to the recycling company (including storage cost)
Δ	$c_0+c_{CI}+c_{CS}+c_{CH}$
Γ	$c_{RI}+c_{RS}$
Π	profit of the recycling company
π	profit of the third-party collector
CS	consumer surplus
t_b	period at which the recycling company determines the transfer price
t_{pD}	period at which the recycling company determines the online recycling price
t_{pT}	period at which the third-party collector determines the offline recycling price
E	sequence in which the recycling company sets the online recycling price earlier than the third-party collector sets the offline recycling price
S	sequence in which the recycling company sets the online recycling price simultaneously with the third-party collector setting the offline recycling price
L	sequence in which the recycling company sets the online recycling price later than the third-party collector sets the offline recycling price

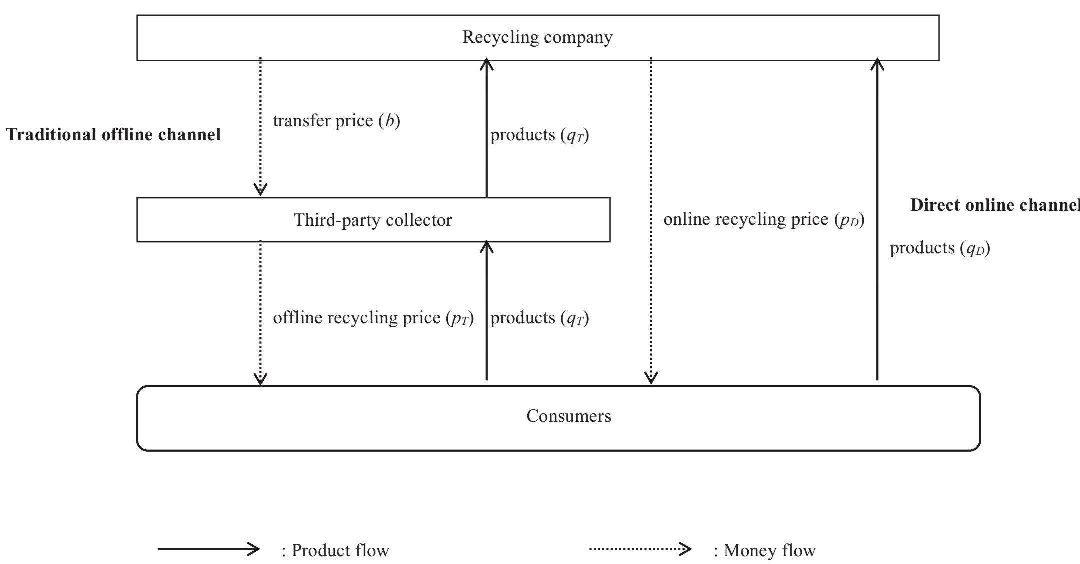

Fig. 1. Channel description.

venience, we term p_D and p_T the online price and the offline price, respectively.

As shown in Table 1, we assume the cost factors for the two firms as follows, in accordance with the literature (e.g., Feng et al., 2017). The disposal cost, inspection cost, and shipping cost per unit of used product accruing in the online channel are represented by c, c_{RI}, and c_{RS}, respectively, all of which are incurred by the recycling company. Meanwhile, c_0, c_{CI}, c_{CS}, and c_{CH} represent the collection cost, inspection cost, shipping cost from the collector to the recycling company, including the storage cost, and the handling cost per unit of used product in the offline channel, respectively, all of which are incurred by the third-party collector. For notational simplicity, let Γ and Δ denote total costs excluding the disposal cost for the recycling company and the collector, respectively; that is, $\Gamma \equiv c_{RI}+c_{RS}$ and $\Delta \equiv c_0+c_{CI}+c_{CS}+c_{CH}$.

We next lay out assumptions about consumers who sell used products. A consumer is characterized by his/her return willingness denoted by s, which is uniformly distributed with a density of unity. That is, consumers with positive net utility of collection would like to trade in used products. Therefore, s can be interpreted as the consumer's return cost, meaning that the cost to return a product varies among consumers. Let θ (> 1) denote the hassle factor of a consumer to return a product to the online recycling channel. Thus, while the willingness of a consumer to sell a used product through the offline channel is s, the willingness via the online channel is θs. Whether a consumer chooses the offline or the online channel to sell the product depends on his/her surplus. Because the collector pays consumers the offline price p_T for a used product, consumer surplus to sell a product in the offline channel is p_T-s, meaning that a consumer

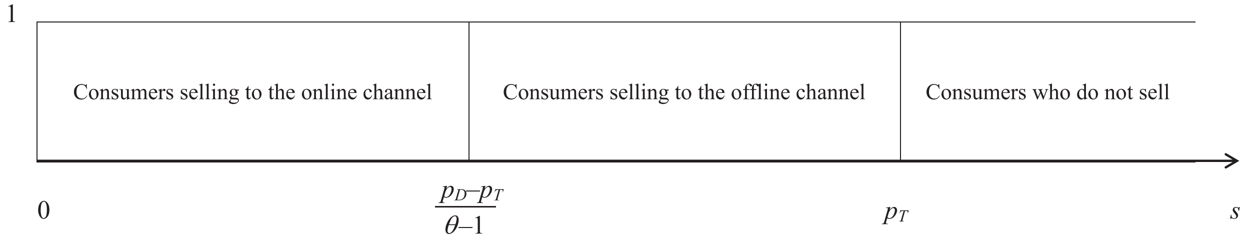

Fig. 2. Consumer segments.

has an incentive to sell if $p_T - s > 0$. Similarly, if a used product is sold through the online recycling channel at the price p_D, the surplus of a consumer with return willingness s is $p_D - \theta s$. Hence, a consumer who is indifferent between selling a product via the offline and online channel satisfies $p_D - \theta s = p_T - s$, which is restated as: $s = (p_D - p_T)/(\theta - 1)$.[5] Based on these calculations, Fig. 2 illustrates consumer segments. As shown in Fig. 2, the segment $[0, (p_D - p_T)/(\theta - 1)]$ sells to the online channel, the segment $((p_D - p_T)/(\theta - 1), p_T]$ sells to the offline channel, and the segment falling into neither of the two intervals does not sell. Consequently, we characterize consumers' supply function of used products to the offline and online channels as follows:

$$q_T = p_T - \frac{p_D - p_T}{\theta - 1} \quad (1)$$

$$q_D = \frac{p_D - p_T}{\theta - 1}. \quad (2)$$

Using Eqs. (1) and (2), we state the profits of the recycling company, denoted by Π, and the third-party collector, denoted by π, as:

$$\Pi = (w - b - c)q_T + (w - p_D - \Gamma - c)q_D = (w - b - c)\left(p_T - \frac{p_D - p_T}{\theta - 1}\right) + (w - p_D - \Gamma - c)\left(\frac{p_D - p_T}{\theta - 1}\right) \quad (3)$$

$$\pi = (b - p_T - \Delta)q_T = (b - p_T - \Delta)\left(p_T - \frac{p_D - p_T}{\theta - 1}\right). \quad (4)$$

Next, we assume that the following inequality concerning parameters is satisfied:

$$w - c - \theta(w - c - \Delta) < \Gamma < w - c - \frac{6\theta^2}{8\theta^2 - \theta - 1}(w - c - \Delta). \quad (5)$$

Inequality (5) is a condition in which the recycling cost accruing in the online channel for the recycling company (Γ) cannot be too large or too small. By solving and restating this condition for Δ, we can confirm that the condition also means that the recycling cost accruing in the offline channel for the collector (Δ) cannot be too large or too small. The basic reason to assume Inequality (5) is that if the inequality were not met, the recycling company would have the incentive to collect products through only either the online or the offline channel to prevent overly fierce competition between the two channels in equilibrium. On the one hand, if Γ were too small the recycling company would abandon collection via the offline channel and collect all products via the online channel to achieve a higher profit; the left condition of $w - c - \theta(w - c - \Delta) < \Gamma$ in Inequality (5) prevents this case. On the other hand, Γ should not be too large, as shown by the right condition of $\Gamma < (w - c - 6\theta^2/(8\theta^2 - \theta - 1))(w - c - \Delta)$ in Inequality (5), because otherwise, the recycling company would stop online collection and collect all products in the offline channel, thereby increasing its own profit.[6] If the recycling company purchased products from only one channel, our model would become meaningless because there would then be only one decision sequence; hence, the choice of decision timing, which is the most important issue in our model, would not need to be examined. In summary, we assume Inequality (5) to ensure that the recycling company purchases products via both channels in equilibrium.

Next, to discern the timing of pricing, let t_b, t_{pD}, and t_{pT} represent the timing of the transfer price, the online price, and the offline price being set, respectively. We hereafter call t_b, t_{pD}, and t_{pT} the timing variables. We assume that there are three periods in our game, because there are three decision variables, the prices, b, p_D, and p_T. Because we assume that there are three periods, in one of which the recycling company and the collector choose to set each price, each of t_b, t_{pD}, and t_{pT} is equal to 1, 2, or 3. These timing variables are assumed to satisfy:

$$t_b < t_{pT}, \quad (6)$$

such that the collector sets its offline price only after learning the transfer price set by the recycling company.[7] This assumption is usually employed in dual-channel reverse supply chain models describing collection competition between offline and online channels (e.g., Feng et al., 2017; Li et al., 2019a; Wu et al., 2020) because in practice, it is difficult and risky for the collector to offer its own recycling price to consumers before knowing the reimbursement from the upstream recycling company for the collection of used products.

Using Eqs. (3) and (4), we derive the equilibrium profits for the recycling company and the collector by decision sequence. Because there are three periods in which each of the three decision variables, b, p_D, and p_T, is set, it is necessary to analyze $3^3 = 27$ sequences of decisions to calculate all attainable payoffs. However, the assumption $t_b < t_{pT}$ in Inequality (6) means that it suffices to consider only nine sequences of decisions. Furthermore, the calcu-

[5] A consumer has an incentive to sell a used product via the online recycling channel if $p_D - \theta s > 0$ holds, which is restated as $p_D/\theta > s$. Hence, if $p_D/\theta > p_T$, all consumers would sell products through the online channel. However, we do not consider this case because the recycling company would then use only the online channel; hence, the purpose of this paper, to derive the optimal timing and sequence of pricing in the dual-channel, would become meaningless. Because we assume a relevant constraint associated with parameters represented by Inequality (5) to focus on the dual-channel case, $p_T \geq p_D/\theta$ always holds in equilibrium in our model.

[6] Indeed, if $\Gamma < w - c - ((6\theta^2)/(8\theta^2 - \theta - 1))(w - c - \Delta)$ is satisfied, q_D is positive in equilibrium in all cases summarized in Proposition 1. Similarly, if $w - c - \theta(w - c - \Delta) < \Gamma$ is satisfied, q_T is positive in equilibrium in all cases under this proposition.

[7] Inequality (6) indicates that complete simultaneous price decisions are not allowed in our model. That is, we do not consider the case of timing variables where $(t_b, t_{pD}, t_{pT}) = (1, 1, 1)$, because then the model could not be solved and hence the decision variables of prices (i.e., b, p_D, and p_T) could not be determined. The fundamental reason for this case being unsolvable is that the collector is unable to set p_T conditional on b. Hence, Inequality (6) is a necessary assumption for this type of two-echelon reverse supply chain model.

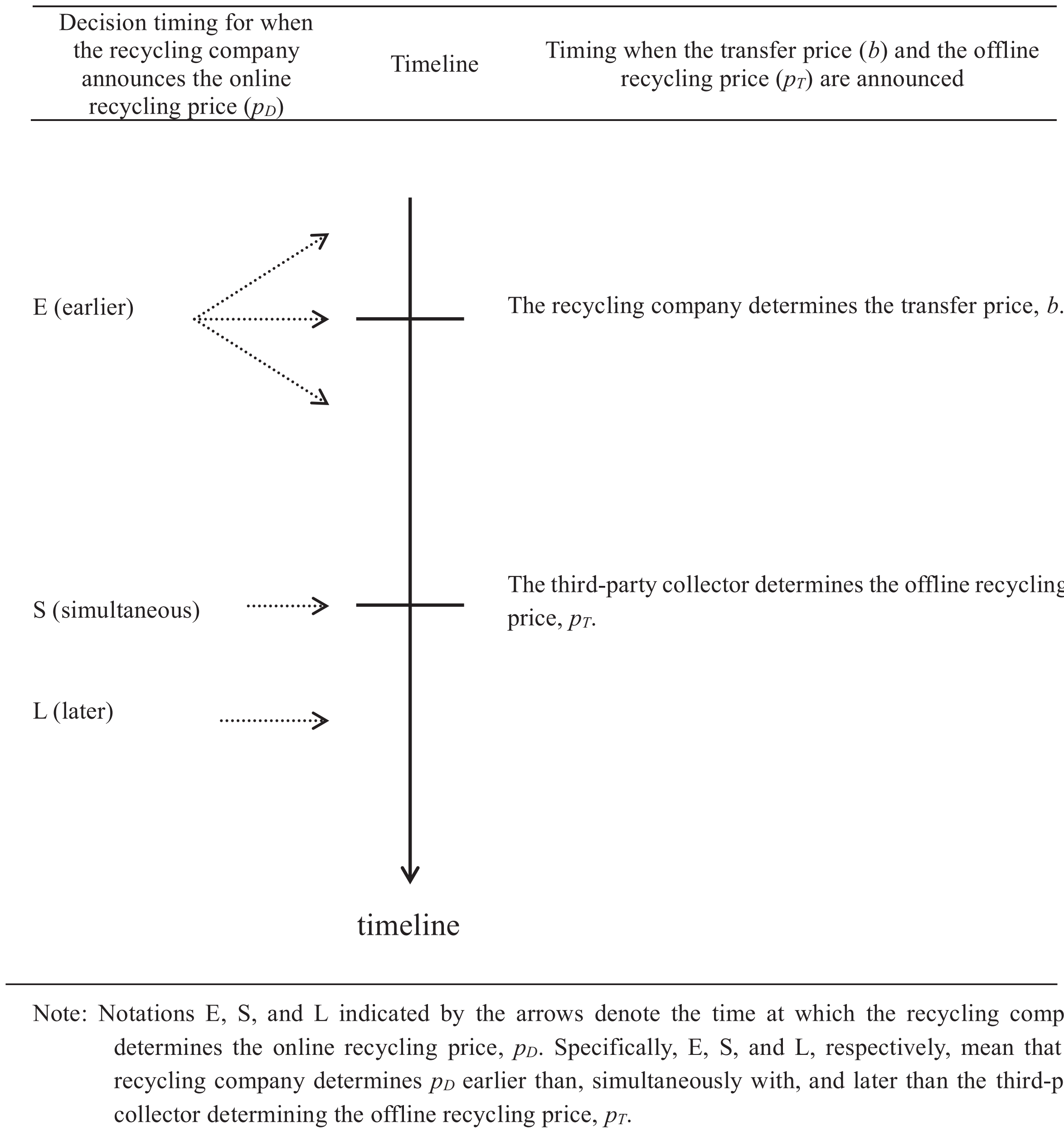

Fig. 3. Timeline of events when each price is determined.
Note: Notations E, S, and L indicated by the arrows denote the time at which the recycling company determines the online recycling price, p_D. Specifically, E, S, and L, respectively, mean that the recycling company determines p_D earlier than, simultaneously with, and later than the third-party collector determining the offline recycling price, p_T.

lation process of the equilibrium enables us to find that the nine possible timing sequences fall to only three cases of variables and payoffs in equilibrium.[8] Consequently, we discern variables and payoffs in equilibrium using the term *sequence* of b, p_D, and p_T being set. Specifically, Sequence E means that the recycling company determines the online price earlier than the collector determining the offline price, as Fig. 3 illustrates. Likewise, Sequence S means that the recycling company determines the online price simultaneously with the collector determining the offline price. Finally, Sequence L means that the recycling company determines the online price later than the collector determining the offline price. Accordingly, Sequence E is the sequence in which $(t_b, t_{pD}, t_{pT})=(1, 1, 2)$, $(1, 1, 3)$, $(1, 2, 3)$, $(2, 1, 3)$, or $(2, 2, 3)$ holds, because $t_{pD} < t_{pT}$ holds in each of the sets. Similarly, Sequence S is the sequence in which $(t_b, t_{pD}, t_{pT})=(1, 2, 2)$, $(1, 3, 3)$, or $(2, 3, 3)$ holds because $t_{pD}=t_{pT}$ holds. Lastly, Sequence L is the sequence in which $(t_b, t_{pD}, t_{pT})=(1, 3, 2)$ holds because $t_{pD} > t_{pT}$ holds. Henceforth, we append the superscript E, S, or L to the variables in equilibrium to distinguish the sequence. The equilibrium results by sequence are summarized in the next proposition. (All proofs are in the Appendix.)

Proposition 1. *The profits and prices in equilibrium are summarized in the following pricing sequences. Superscripts E, S, and L respectively indicate equilibrium in Sequences E, S, and L.*

Case (I): Sequence E

$$b^{\mathrm{E}} = \frac{w - c + \Delta}{2}$$

[8] See the proof of Proposition 1 in the Appendix for details.

$$p_D{}^{\mathrm{E}} = \frac{w-c-\Gamma}{2}$$

$$p_T{}^{\mathrm{E}} = \frac{(w-c-\Delta)\theta + (w-c-\Gamma)}{4\theta}$$

$$q_D{}^{\mathrm{E}} = \frac{\theta(w-c+\Delta-2\Gamma) - (w-c-\Gamma)}{4\theta(\theta-1)}$$

$$q_T{}^{\mathrm{E}} = \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{4(\theta-1)}$$

$$Q^{\mathrm{E}} = \frac{\theta(w-c-\Delta) + w-c-\Gamma}{4\theta}$$

$$\Pi^{\mathrm{E}} = \frac{(w-c-\Gamma)^2}{4\theta} + \frac{((w-c-\Delta)\theta - (w-c-\Gamma))^2}{8\theta(\theta-1)}$$

$$\pi^{\mathrm{E}} = \frac{((w-c-\Delta)\theta - (w-c-\Gamma))^2}{16\theta(\theta-1)}$$

Case (II): Sequence S

$$b^{\mathrm{S}} = \frac{w-c+\Delta}{2} + \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{2\theta(8\theta+1)}$$

$$p_D{}^{\mathrm{S}} = \frac{w-c-\Gamma}{2} - \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{8\theta+1}$$

$$p_T{}^{\mathrm{S}} = \frac{\theta(w-c-\Delta) + (w-c-\Gamma)}{4\theta} - \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{4\theta(8\theta+1)}$$

$$q_D{}^{\mathrm{S}} = \frac{\theta(w-c+\Delta-2\Gamma) - (w-c-\Gamma)}{4\theta(\theta-1)} - \frac{(4\theta-1)(\theta(w-c-\Delta) - (w-c-\Gamma))}{4\theta(\theta-1)(8\theta+1)}$$

$$q_T{}^{\mathrm{S}} = \frac{(2\theta+1)(\theta(w-c-\Delta) - (w-c-\Gamma))}{(\theta+1)(8\theta+1)}$$

$$Q^{\mathrm{S}} = \frac{\theta(w-c-\Delta) + w-c-\Gamma}{4\theta} - \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{4\theta(8\theta+1)}$$

$$\Pi^{\mathrm{S}} = \frac{(w-c-\Gamma)^2}{4\theta} + \frac{(\theta(w-c-\Delta) - (w-c-\Gamma))^2}{(\theta-1)(8\theta+1)}$$

$$\pi^{\mathrm{S}} = \frac{(2\theta+1)^2(\theta(w-c-\Delta) - (w-c-\Gamma))^2}{\theta(\theta-1)(8\theta+1)^2}$$

Case (III): Sequence L

$$b^{\mathrm{L}} = \frac{w-c+\Delta}{2} + \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{2\left(8\theta^2-5\theta+1\right)}$$

$$p_D{}^{\mathrm{L}} = \frac{w-c-\Gamma}{2} - \frac{(2\theta-1)(\theta(w-c-\Delta) - (w-c-\Gamma))}{2\left(8\theta^2-5\theta+1\right)}$$

$$p_T{}^{\mathrm{L}} = \frac{(1+\theta)(w-c) - \Gamma - \theta\Delta}{4\theta} + \frac{\theta(w-c-\Delta) - (w-c-\Gamma)}{2\theta(8\theta+1)}$$

$$q_D{}^{\mathrm{L}} = \frac{4\theta(w-c-2\Gamma+\Delta) + \Gamma - \Delta}{4\left(8\theta^2-5\theta+1\right)} + \frac{\Delta-\Gamma}{4(\theta-1)}$$

$$q_T{}^{\mathrm{L}} = \frac{\theta(2\theta-1)((\theta-1)(w-c) + \Gamma - \Delta\theta)}{(\theta-1)\left(8\theta^2-5\theta+1\right)}$$

$$Q^{\mathrm{L}} = \frac{4\theta^2(w-c) - \Gamma(4\theta-1) - \Delta(2\theta-1)^2}{2\left(8\theta^2-5\theta+1\right)}$$

$$\Pi^{\mathrm{L}} = \frac{(w-c-\Gamma)^2}{4\theta} + \frac{(2\theta-1)^2(\theta(w-c-\Delta) - (w-c-\Gamma))^2}{4\theta(\theta-1)\left(8\theta^2-5\theta+1\right)}$$

$$\pi^{\mathrm{L}} = \frac{2\theta^2(2\theta-1)(\theta(w-c-\Delta) - (w-c-\Gamma))^2}{(\theta-1)\left(8\theta^2-5\theta+1\right)}$$

4. Result: first-mover advantage of price announcement

We proceed to draw managerial implications from the equilibrium results. The following proposition summarizes the comparison of the variables in equilibrium shown in Proposition 1.

Proposition 2. *The following inequalities regarding the equilibrium profits and prices hold.*

$$\Pi^{\mathrm{E}} > \Pi^{\mathrm{S}} > \Pi^{\mathrm{L}}$$

$$\pi^{\mathrm{E}} < \pi^{\mathrm{S}} < \pi^{\mathrm{L}}$$

$$b^{\mathrm{E}} < b^{\mathrm{S}} < b^{\mathrm{L}}$$

$$p_D{}^{\mathrm{E}} > p_D{}^{\mathrm{S}} > p_D{}^{\mathrm{L}}$$

$$p_T{}^{\mathrm{E}} > p_T{}^{\mathrm{S}} > p_T{}^{\mathrm{L}}$$

Let us interpret the meaning of the relationships shown in Proposition 2 with reference to the timeline of decision sequences in Fig. 3. $\Pi^{\mathrm{E}} > \Pi^{\mathrm{S}} > \Pi^{\mathrm{L}}$ in the proposition means that the recycling company generates its largest profit by determining the online price before the collector determines the offline price, as illustrated in Fig. 3. Meanwhile, $\pi^{\mathrm{E}} < \pi^{\mathrm{S}} < \pi^{\mathrm{L}}$ means that the collector generates the highest profit by determining the offline price before the recycling company determines the online price, as shown in Fig. 3. Therefore, Proposition 2 indicates that the first-mover advantage arises for both the recycling company and the collector determining and announcing their respective recycling prices. That is, we draw the implication that each firm can achieve a higher profit by determining and announcing its own recycling price before the other firm does.

Notice that this result is the exact opposite of the conventional result, in which a second-mover advantage under price competition has been shown and is well known in the literature of game theory (e.g., Gal-Or, 1985; Hamilton & Slutsky, 1990). Specifically, Gal-Or (1985) proves that when firms in a horizontal relationship compete in terms of price, the firm deciding the price later achieves a higher profit under price competition.[9] The basic reason for our opposite result is that the situation described by our model is not competition between firms in a horizontal relationship, but rather, competition that involves both horizontal and vertical relationships, because the collector plays the role of not only

[9] More precisely, this second-mover advantage arises in a noncooperative game if the decision variables are strategic complements, which means that if a player involved in the game increases its decision variable, another player correspondingly increases its decision variable. The extant literature proves that prices controlled by multiple competing firms are mostly characterized by strategic complements (e.g., Gal-Or, 1985). In reality, when recycling price competition occurs between two firms, it is generally conceivable that if one firm raises its price, the other rival firm also raises its price to attract consumers in response, meaning that the prices have a positive correlation. In this way, prices tend to have the characteristic of strategic complements.

the competitor, but also the intermediary of the recycling company. Because of the setting of such a competitive relationship, our model overturns the conventional result.

While Proposition 2 is the first basic result derived from Proposition 1, it also delivers the following corollary.

Corollary 1. *The following inequalities hold.*

$$p_D{}^{E} - p_T{}^{E} > 0, \quad p_D{}^{S} - p_T{}^{S} > 0, \quad p_D{}^{L} - p_T{}^{L} > 0$$

Corollary 1 shows that the online price is always higher than the traditional channel offline price, irrespective of the timing of pricing. Hence, we obtain a result that is consistent with empirical evidence shown in the literature that the online recycling price is higher, on average, than that for traditional recycling methods (e.g., Wang, Ren, Dong, Zhang, & Wang, 2019b). Note that this result is associated with the effect of *double marginalization* arising in the offline channel as well as with the hassle cost itself in the online channel. That is, the third-party collector earns its profit by extracting the margin between the transfer price paid by the recycling company (b) and the offline price (p_T). Hence, the acquisition price in the offline channel decreases by the amount of the margin extracted by the collector. As a result, in equilibrium, the acquisition price in the online channel is relatively high compared with the acquisition price in the offline channel.

To demonstrate the effect of this double marginalization formally, we show that the collector's margin (b–p_T) is monotonically increasing with respect to the hassle factor (θ), as the partial derivative of b^{E}–$p_T{}^{E}$ in Sequence E with respect to θ gives the following:

$$\partial(b^{E} - p_T{}^{E})/\partial\theta = (w - c - \Gamma)/(4\theta^2) > 0.$$

This inequality shows that the collector's margin increases as the hassle factor (θ) increases, which means that the double marginalization increases as the consumers' hassle cost in the online channel increases. Hence, there exists a mechanism that, because double marginalization is more pronounced and the collector extracts a higher margin as the hassle factor increases, the acquisition price in the offline channel decreases and hence the price in the online channel becomes relatively high.

5. Result: equilibrium timing of price announcement

Based on the above settings, we proceed to formulate a timing game, which was originally proposed by Hamilton and Slutsky (1990).[10] Specifically, the timing game consists of two stages. The second stage corresponds to the basic model assumed in Section 3; that is, it consists of three periods in one of which the recycling company and the collector set and announce each price. Hence, in the timing game, the first stage is newly added to the basic model described in Section 3. At the first stage, the recycling company and the third-party collector state which of the three periods in the second stage each of the two firms will set and announce each price and commit to the statement. Namely, the recycling company chooses t_b and t_{pD} from {1, 2, 3} and the collector chooses t_{pT} from {1, 2, 3} at the first stage of the whole game. At the second stage, subsequent to the statement, the recycling company sets the transfer price (b) and the online price (p_D), and the collector sets the offline price (p_T) in one of these three periods.[11] Because the timing game consists of two stages, we first solve the problem in the second stage and then solve the problem in the first stage backwardly, deriving the SPNE of the whole game. This allows us to determine the equilibrium values of not only the price variables, b, p_D, and p_T, but also the timing variables, t_b, t_{pD}, and t_{pT}.

Recall that a first-mover advantage in pricing arises in Proposition 2 in the previous section. Given this result, we identify the equilibrium timing of pricing from which neither firm deviates, based on the timing game. The equilibrium results of Proposition 1 enable us to identify the equilibrium timing, as shown in the next proposition.

Proposition 3. *The combinations of timing variables constituting the SPNE include:* $(t_b, t_{pD}, t_{pT})=(1, 1, 2), (1, 1, 3), (2, 1, 3)$, *or* $(2, 2, 3)$. *This suggests that in equilibrium the recycling company sets the online price,* p_D, *(i) before or when the company sets the transfer price,* b, *and (ii) before the collector sets the offline price,* p_T.

Proposition 3 is the second major result in this paper. Notice that $t_{pD} < t_{pT}$ holds in all the combinations of equilibrium timings shown in Proposition 3, meaning that only Sequence E can constitute the SPNE. Additionally, the proposition also shows that no SPNE arises if the recycling company sets the online price after the company sets the transfer price (i.e., $t_b < t_{pD}$). Specifically, if the recycling company sets $(t_b, t_{pD})=(1, 2)$ or $(1, 3)$, the collector correspondingly sets $t_{pT}=2$ to achieve a higher profit, because the collector can gain the first-mover advantage as suggested in Proposition 2 by accelerating the timing of setting the offline price so that $t_{pT} \leq t_{pD}$ holds. Proposition 3 suggests that the recycling company should determine and announce the online price before or upon, but not after, determining the transfer price to prevent this collector's behavior. By announcing the online price before the transfer price, the recycling company forces the collector to set the offline price only after the recycling company sets the online price. This allows the recycling company to secure the first-mover advantage of announcing its online recycling price before the collector announces the offline price.

Finally, we examine whether our optimal timing of pricing result is consistent with the decision sequence setting assumed in previous models in the literature. First, in Feng et al. (2017), from which we borrowed basic assumptions, a recyclable dealer sets its online price upon setting the transfer price applied to a downstream recycler. Also observe that, while the notation is slightly different, our quantitative results in Case (I): Sequence E of Proposition 1 are basically the same as those in Theorem 2 of Feng et al. (2017), p. 606). Li et al. (2019a) assume that a remanufacturer sets its online price upon setting its transfer price applied to a recycler. Furthermore, Wu et al. (2020) also assume that a recycling center sets its online price upon setting its transfer price applied to a third-party recycler. Therefore, our result proves that the decision timing considered in all of the previous studies, including Feng et al. (2017), Li et al. (2019a), and Wu et al. (2020), is optimal for the recycling company using a dual-recycling channel because the timing constitutes the SPNE in the timing game of our model. Consequently, our results also establish the appropriateness of models and results in preceding research of dual-channel reverse supply chain management.

6. Result: consumer surplus

While we have examined the impact of decision timing only from the perspective of company profitability up to the previous section, social impact is also an important issue to examine in the context of reverse supply chain research. The benchmark model of Feng et al. (2017), which provides the foundations for our model, assumes that firms incur all environmental costs, which are captured by variables c, Δ, and Γ. Therefore, the environmental im-

[10] More formally, pioneering work on the timing game by Hamilton and Slutsky (1990) formulates two types of noncooperative games in which the decision timings of players are endogenously determined: (i) an observable delay game, and (ii) an action commitment game. We adopt the observable delay game as the framework of the timing game in this paper.

[11] Lu (2006) similarly develops a model of a timing game in which three decision variables are decided in three discrete periods. To assure consistency with earlier studies, we adopt the identical setting of the existence of three periods.

pact is already considered and internalized in our model, similar to Feng et al. (2017). Hence, we investigate how consumers' surplus, which is also regarded as a social impact, depends on the timing of price announcements in this section. Analysis of consumer surplus is important particularly from the perspective of the reverse supply chain, because consumer surplus represents how much money (i.e., pecuniary benefit) consumers directly earn from selling used products through the reverse supply chain. Namely, consumers using the reverse supply chain play the role of sellers, but not buyers.

First, the following proposition summarizes the equilibrium consumer surplus realized in each of the decision sequences.

Proposition 4. *The consumer surplus in equilibrium is summarized in the following pricing sequences. Superscripts E, S, and L respectively indicate equilibrium in Sequences E, S, and L.*

Case (I): Sequence E

$$CS^{E}=(\theta^{2}(w-c-\Delta)^{2}-2\theta(w-c-\Gamma)(w-c-\Delta)+(4\theta-3)(w-c-\Gamma)^{2})/(32\theta(\theta-1))$$

Case (II): Sequence S

$$CS^{S}=(4\theta^{3}(5+4\theta)(w-c-\Delta)^{2}-4\theta\left(16\theta^{2}+3\theta-1\right)\times(w-c-\Gamma)(w-c-\Delta)+\left(64\theta^{3}-23\theta-5\right)(w-c-\Gamma)^{2})/(8\theta(\theta-1)(8\theta+1)^{2})$$

Case (III): Sequence L

$$CS^{L}=\theta(2\theta-1)^{2}\left(4\theta^{2}+\theta-1\right)(w-c-\Delta)^{2}-2\left(32\theta^{3}-46\theta^{2}+21\theta-3\right)(w-c-\Gamma)(w-c-\Delta)+\left(64\theta^{3}-96\theta^{2}+41\theta-5\right)(w-c-\Gamma)^{2})/\left(8(\theta-1)\left(8\theta^{2}-5\theta+1\right)^{2}\right)$$

Comparing consumer surplus by the sequence, we derive the following proposition.

Proposition 5. *The following inequalities regarding the equilibrium consumer surplus hold.*

$CS^{E}>CS^{S}>CS^{L}$

Proposition 5 shows the notable result that Sequence E, which is chosen in equilibrium as a result of optimal strategies of companies, also maximizes consumers' surplus. Namely, the consumer surplus in equilibrium is also higher in the order of Sequence E, S, and L as shown in Proposition 5, which is exactly the same order of the ranking of the recycling company's profit shown in Proposition 2. This result provides the implication that the recycling company maximizes not only its own profit but also consumer surplus by announcing its acquisition price in the online channel before determining the transfer price in the offline channel. Hence, the main conclusion in this paper remains valid even if we take consumer surplus into account.

Note additionally that this result is practically useful especially for a state-owned recycling company like Xin Jinqiao Environmental Protection in China, which is used as the real-life company case in our model, following Feng et al. (2017), because state-owned companies usually aim not only to increase their own profits but also to contribute to society as a whole. Therefore, it is important for state-owned enterprises like Xin Jinqiao to announce acquisition prices as early as possible in order to increase not only their own profits but also consumers' benefits. Finally, the result that Sequence E maximizes consumer surplus in Proposition 5 also reinforces the appropriateness of the timing of decision-making on acquisition prices in the previous models of Feng et al. (2017), Li et al. (2019a), and Wu et al. (2020).

7. Numerical study

In this section, we perform numerical study to verify the correctness of our analytical results and illustrate them intuitively. While there are five exogenous parameters of w, Δ, Γ, c, and θ in our model, they are reduced to the three elements θ, w–c–Γ, and w–c–Δ. This is because all the equilibrium values of both Π and CS shown in Propositions 1 and 4 consist of only the three elements of θ, w–c–Γ, and w–c–Δ, meaning that only the three elements determine equilibrium results.

Because our analytical model uses basic settings employed in Feng et al. (2017), we also apply the benchmark values of exogenous parameters used in the numerical analysis of Feng et al. (2017), p. 606). We set the benchmark values of parameters $w=4.2$, $\Delta=1.8$, $\Gamma=1.6$, $c=0.8$, and $\theta=2$, following actual data from the real-life recycling company shown in Feng et al. (2017).[12]

Figs. 4 and 5 illustrate the numerical results of the recycling company's profit (Π) and consumer surplus (CS), respectively. Specifically, to construct Panel (i) in Figs. 4 and 5, we first substitute $w=4.2$, $\Delta=1.8$, $c=0.8$, and $\Gamma=1.6$ into Π^E, Π^S, Π^L, CS^E, CS^S, and CS^L shown in Propositions 1 and 4, and then vary θ to draw the graph of each value. To draw panel (ii) in the two figures, we substitute $w=4.2$, $\Delta=1.8$, $c=0.8$, and $\theta=2$ into the profits and consumer surplus, varying Γ to draw the graphs against the horizontal axis of w–c–Γ because w–c–Γ appears as the only exogenous element in the equilibrium values of Π and CS. Similarly, in panel (iii), we substitute $w=4.2$, $\Gamma=1.6$, $c=0.8$, and $\theta=2$ and vary Δ, thereby drawing the graphs of equilibrium profits and consumer surplus against the horizontal axis of w–c–Δ. Each graph is depicted only in the range that the assumption of Inequality (5) is satisfied. Observe that the numerical results in all the panels in both figures are consistent with the analytical results shown in Proposition 2 regarding the profit and Proposition 5 regarding consumer surplus. Namely, the graphs demonstrate that the results $\Pi^E > \Pi^S > \Pi^L$ and $CS^E > CS^S > CS^L$ are robust. Consequently, the numerical analysis shows our major conclusions intuitively and verifies the correctness of Propositions 2 and 5.

8. Generalization

8.1. Forward supply chain

In this section, we consider further generalization of our model to show that the model can describe more general situations that are possible in reality. First, the issue of the closed-loop supply chain, which integrates both forward and reverse supply chains, has been modeled and discussed substantially in the OR literature (e.g., Chuang, Wang, & Zhao, 2014; Giovanni, Reddy, & Zaccour, 2016; Jena & Sarmah, 2014; Saha, Sarmah, & Moon, 2016; Xiong, Zhao, & Zhou, 2016). We can extend our model to consider a closed-loop supply chain by incorporating the forward supply chain into the present model involving only the reverse supply chain. Our central results regarding optimal timing of pricing can be derived independently of whether a forward supply chain is incorporated or not, as is shown below.

If incorporating a forward supply chain into our reverse supply chain model, we need to consider and investigate the recycling company's decision-making to sell its remanufactured products in the forward supply chain as an additional optimization problem. Recall that our basic model assumes that the recycling company

[12] More specifically, Feng et al. (2017, p. 606) state, "Suppose $w=4.2$, $\Delta=1.8$, $\Gamma=1.6$, $c_{pd}=0.8$ ... the above condition is consistent with the reality as seen by Changhong Green Group Company Limited and Shanghai Xin Jinqiao Environmental Protection Company Limited," which are real-life cases also used in our paper. Note that c_{pd} in the quotation corresponds to c in our model.

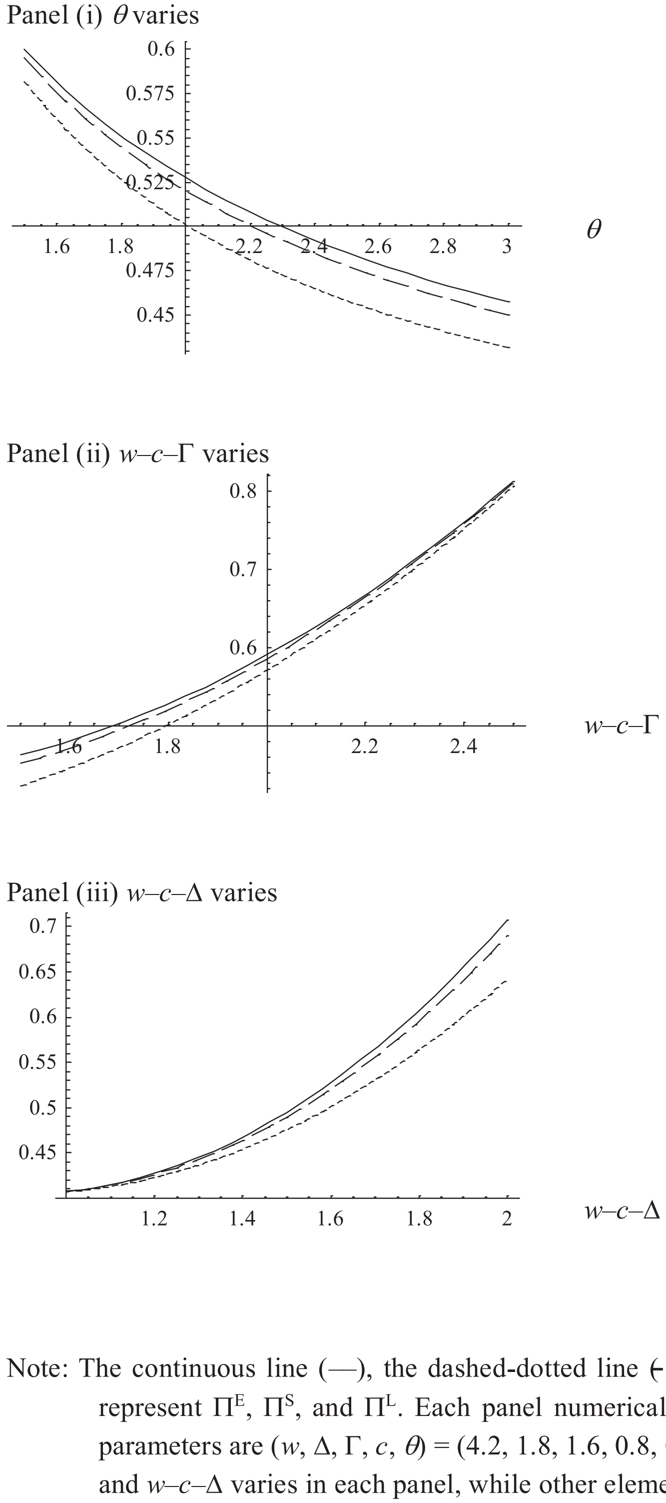

Fig. 4. Effects of parameters on the recycling company's profit, Π.
Note: The continuous line (–), the dashed-dotted line (– – –), and the dotted line (·····) respectively represent Π^E, Π^S, and Π^L. Each panel numerically shows that $\Pi^E > \Pi^S > \Pi^L$ holds. Benchmark parameters are (w, Δ, Γ, c, θ) = (4.2, 1.8, 1.6, 0.8, 0.5). Only one of the three elements of θ, w–c–Γ, and w–c–Δ varies in each panel, while other elements are fixed.

is a price taker regarding the selling price of a remanufactured product denoted by w due to perfect competition in the forward supply chain, following Feng et al. (2017). Using this assumption, we demonstrate that Sequence E is the best timing for the recycling company to maximize its own profit in the reverse supply chain, as shown in Proposition 2. If the assumption of perfect competition is changed so that the recycling company has the power to control w in the market of the forward supply chain because of, for example, its monopoly, then it remanufactures all the collected quantity through both channels and sells them at the monopoly price based on a demand schedule in the forward supply chain. Therefore, even if the recycling company can make

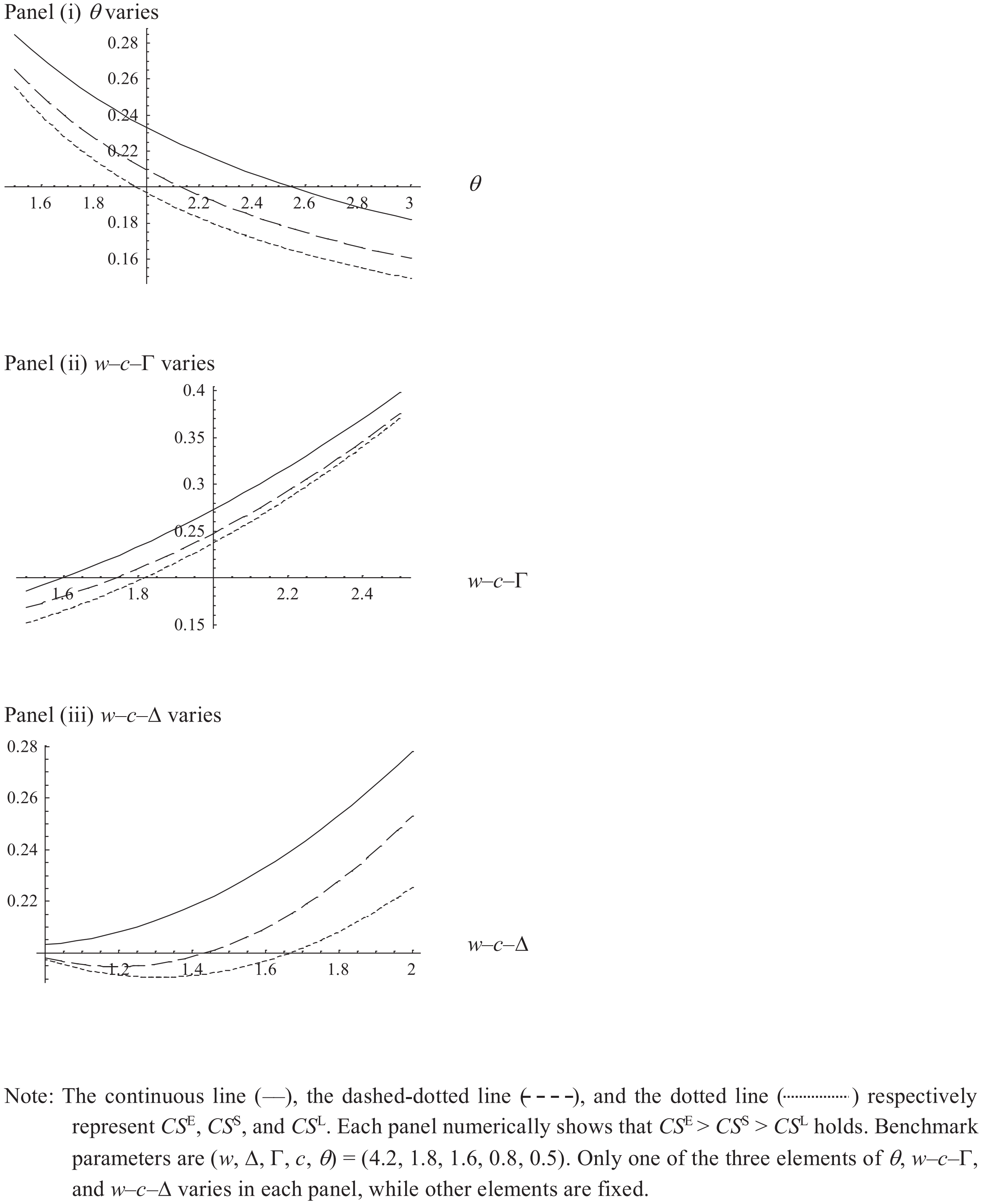

Fig. 5. Effects of parameters on consumers' surplus, CS.

Note: The continuous line (—), the dashed-dotted line (–––), and the dotted line (·····) respectively represent CS^E, CS^S, and CS^L. Each panel numerically shows that $CS^E > CS^S > CS^L$ holds. Benchmark parameters are $(w, \Delta, \Gamma, c, \theta) = (4.2, 1.8, 1.6, 0.8, 0.5)$. Only one of the three elements of θ, w–c–Γ, and w–c–Δ varies in each panel, while other elements are fixed.

its optimal decision including the selling price also in the forward supply chain, the result that the recycling company should announce the direct acquisition price in the online channel before the transfer price in the offline channel continues to hold. Stated differently, the central result derived from our reverse supply chain model holds even if a forward supply chain is incorporated into the model and hence a closed-loop supply chain is considered.

8.2. Repeated game

Next, actual collection competition in reality arises not only once but is usually repeated multiple times unless a firm exits the recycling business. Hence, we consider another possible scenario in which the whole game is repeated over multiple periods. Specifically, let us consider the scenario in which all the events shown in Fig. 3 are repeated over n periods, but not one-shot. In this dynamic game, we first derive the equilibrium of collection competition in the last period and then solve the problems backwardly in order from the later to the earlier period. That is, we first find the equilibrium in the game described in Fig. 3 in the last period, i.e., period n. Because the game in period n is regarded as only one-shot, which corresponds to the basic model in Section 3, Sequence E constitutes the equilibrium as shown in Proposition 2. Subsequently, we use this solution to solve the problem in period n–1. Because the optimal timing of pricing in period n–1 is independent of that in period n due to the principle of optimization, Sequence E still constitutes the equilibrium in period n–1. Solving games backwardly in order similarly, we find that the equilibrium sequence of pricing in the period of n–2, n–3, ..., 2, and 1 is also Sequence E. That is, the announcement of the online acquisition price before the transfer price by the recycling company (i.e., Sequence E) shown in Fig. 3 in each of the multiple periods always exists on the equilibrium path, thereby constituting the SPNE of the whole repeated game. Consequently, the major result that Sequence E is the optimal timing for the recycling company continues to hold, even if the setting of the basic model is changed so that the game is repeated over multiple periods.

9. Conclusion and discussion

The recent rapid development of information technologies encourages recycling companies to collect used products from consumers through a mix of traditional offline and Internet-based online channels, which is called a dual-channel reverse supply chain. Because an online channel transmits price information instantly to consumers considering selling products, the exploration of the best time to announce the acquisition price of used products to consumers is now a critical problem for recycling companies. To solve this problem, the present paper develops a game-theoretic model describing a dual-channel reverse supply chain consisting of a recycling company and a third-party collector, in which the recycling company purchases products not only through the third-party collector in an offline channel, but also directly in an online channel. Now, recall the following three research questions raised at the end of Section 1. (i) Does the timing of the acquisition price announcement by a recycling company and a collector affect their profits? (ii) If it does, when should the recycling company announce its acquisition price to maximize its profit? (iii) Is there a stable timing of price announcements from which neither firm deviates? We summarize the major results of our model, thereby answering each of the questions. First, first-mover advantage arises for the two firms to determine their respective recycling prices, indicating that the decision timing affects their profits. Second, the recycling company can maximize its own profit by announcing its recycling price in the online channel before or upon, but not after, determining the transfer price paid to the collector for a product collected in the offline channel. Third, such an early announcement of the online recycling price by the recycling company constitutes the unique SPNE, from which neither firm deviates, in the timing game. It should also be noted that even though we consider a variety of cost factors, including disposal, inspection, and shipping costs, incurred by the two respective firms as exogenous parameters following previous studies (e.g., Feng et al., 2017), the major results above are not affected by any cost factors, which proves the robustness of the result.

While our results are useful as practical guidelines for decisions made in dual-channel reverse supply chains, they are also academically novel from the perspective of game theory. As discussed earlier, it has been commonly known that a second-mover advantage emerges in price competition under general environments; namely, the later a firm sets a price, the higher the profit it generates (e.g., Gal-or, 1985; Hamilton & Slutsky, 1990). Our results suggest that a recycling company must beware of the contrary insight gained in this study; that is, a second-mover disadvantage of announcing the online price after the collector announces the offline price. Consequently, the present paper warns that if a recycling company defers announcing the online price by unwaveringly espousing the conventional insight found in the game theory literature, the company's profit will deteriorate.

Moreover, our reverse supply chain model critically differs from a forward supply chain model in the following model setup. Because consumers play the role not of buyers but sellers in our reverse supply chain model, we consider the consumers' supply system represented by supply functions in Eqs. (1) and (2), which is different from the demand system usually used to describe a forward supply chain. While the existence of the first-mover advantage has been shown in previous papers considering a forward supply chain assuming a demand system, there is no existing paper that has formally shown a first-mover advantage arising in an acquisition price competition in a reverse supply chain assuming a supply system. This is also regarded as a unique contribution of the present paper from the theoretical perspective.

Finally, while our research is motivated by the rapid growth of recycling companies collecting WEEE, its insights are useful for not only pure-play recycling companies, but also general manufacturing firms who outsource collection activity to a third-party collector or retailer. For instance, Xerox outsources vendors to collect used products concurrently when they sell and install new products. Kodak authorizes its retailers to collect the end-of-use cores of single-used cameras from customers (Bulmus et al., 2014). As a result, Kodak produces approximately 90% of single-use cameras from disposed cameras, and new products are produced by the reuse of about 76% of used cameras by weight. When such a manufacturer collects used products via an external collector, the transfer price of the product is usually specified in a contract signed between the firms. Our results suggest that to secure its own first-mover advantage, it is essential for a general manufacturing firm, similarly to a recycling company, to announce online price information before concluding the contract of collection activity specifying a transfer price with an external collector.

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Appendix

Proof of Proposition 1. We derive the equilibrium solution by the sequence of prices being set using backward induction.
Case (I): Sequence E; if (t_b, t_{pD}, t_{pT})=(1, 1, 2), (1, 1, 3), (1, 2, 3), (2, 1, 3), or (2, 2, 3)

Whereas the sequence of prices being determined varies across the five sets of timings in this case, we will later prove that all of the five timing strategies result in the same profits by further breaking down the case into three cases referred to as Case (I)-(i), (ii), and (iii).

The collector sets p_T at the last move. We first solve $\partial\pi/\partial p_T = 0$ to maximize Eq. (4) with respect to p_T, obtaining:

$$p_T = (p_D + \theta(b - \Delta)). \tag{A1}$$

Note that all objective functions of maximization problems in the Appendix are quadratic and thus concave with respect to the decision variables (prices) because we use the system of linear supply functions described by Eqs. (1) and (2). This means that the second-order conditions are satisfied in all maximization problems below. Hence, we leave out the second-order conditions.

We next investigate the recycling company's decision on its online price. Substituting Eq. (A1) into Eq. (3) yields:

$$\Pi = \frac{(w - c - b)(b - \Delta)}{2} + \frac{p_D(w - c - p_D - \Gamma)}{2\theta} - \frac{(p_D - b + \Gamma)(p_D - b + \Delta)}{2(\theta - 1)}. \tag{A2}$$

We derive the equilibrium by further classifying this case into the following three cases; that is, the recycling company sets the online price (i) earlier than, (ii) simultaneously with, and (iii) later than setting the transfer price.

Case (I)-(i): if $(t_b, t_{pD}, t_{pT}) = (2, 1, 3)$

The recycling company sets the online price before the company sets the transfer price. We solve $\partial\Pi/\partial b = 0$ to maximize Eq. (A2) on b, having:

$$b = ((\theta - 1)(w - c) + 2p_D + \Gamma + \theta\Delta)/(2\theta). \tag{A3}$$

Then, after inserting Eq. (A3) into Eq. (A2), we solve $\partial\Pi/\partial p_D = 0$ to maximize it with respect to p_D, having:

$$p_D = (w - c - \Gamma)/2. \tag{A4}$$

We replace p_D in Eq. (A3) with Eq. (A4), obtaining:

$$b = (w - c + \Delta)/2. \tag{A5}$$

Inserting Eqs. (A4) and (A5) into Eq. (A1) gives:

$$p_T = ((\theta + 1)(w - c) - \Gamma - \theta\Delta)/(4\theta). \tag{A6}$$

Case (I)-(ii): when $(t_b, t_{pD}, t_{pT}) = (1, 1, 2)$, $(1, 1, 3)$, or $(2, 2, 3)$

The recycling company sets the online price simultaneously with the company setting the transfer price. Therefore, we solve $\partial\Pi/\partial b = \partial\Pi/\partial p_D = 0$ to maximize Eq. (A2) on both b and p_D, having:

$$b = (w - c + \Delta)/2,\ p_D = (w - c - \Gamma)/2. \tag{A7}$$

Because this problem is a simultaneous decision on two variables of b and p_D to maximize Π, the Hessian matrix of the objective function must be negatively defined. Using Eq. (A2), we show that the determinant of the Hessian matrix is positive as follows.

$$\begin{vmatrix} \partial^2\Pi/\partial b^2 & \partial\Pi/\partial b\partial p_D \\ \partial\Pi/\partial b\partial p_D & \partial^2\Pi/\partial {p_D}^2 \end{vmatrix} = \frac{2}{\theta - 1} > 0,$$

Therefore, the Hessian Matrix of this objective function is negatively defined, ensuring that Π is maximized with respect to both b and p_D.

Inserting Eq. (A7) into (A1) gives:

$$p_T = ((1 + \theta)(w - c) - \Gamma - \theta\Delta)/(4\theta). \tag{A8}$$

Case (I)-(iii): if $(t_b, t_{pD}, t_{pT}) = (1, 2, 3)$

The recycling company sets its online price after setting its transfer price and before the collector sets the offline price in this case. We solve $\partial\Pi/\partial p_D = 0$ to maximize Eq. (A2) with respect to p_D, yielding:

$$p_D = ((\theta - 1)(w - c) + 2\theta(b - \Gamma) + \Gamma - \theta\Delta)/(2(2\theta - 1)). \tag{A9}$$

After substituting Eq. (A9) into Eq. (A2), we maximize it on b by solving $\partial\Pi/\partial b = 0$, having:

$$b = (w - c + \Delta)/2. \tag{A10}$$

We replace b in Eq. (A9) with Eq. (A10), obtaining:

$$p_D = (w - c - \Gamma)/2. \tag{A11}$$

Inserting Eq. (A10) and (A11) into Eq. (A1) gives:

$$p_T = ((\theta + 1)(w - c) - \Gamma - \theta\Delta)/(4\theta). \tag{A12}$$

Lastly, we substitute either Eqs. (A4)–(A6) of Case (I)-(i), Eqs. (A7)–(A8) of Case (I)-(ii), or Eqs. (A10)–(A12) of Case (I)-(iii) into Eqs. (3) and (4), obtaining the equilibrium profits of the recycling company and the collector as: $\Pi^E = (w - c - \Gamma)^2/(4\theta) + ((w - c - \Delta)\theta - (w - c - \Gamma))^2/(8\theta(\theta - 1))$ and $\pi^E = ((w - c - \Delta)\theta - (w - c - \Gamma))^2/(16\theta(\theta - 1))$. Observe that the envelope theorem results in the identical equilibrium profits in Cases (I)-(i), (ii), and (iii).

Case (II): Sequence S; if $(t_b, t_{pD}, t_{pT}) = (1, 2, 2)$, $(1, 3, 3)$, or $(2, 3, 3)$

We respectively maximize Eq. (3) and Eq. (4) to p_D and p_T by solving $\partial\Pi/\partial p_D = \partial\pi/\partial p_T = 0$, having:

$$p_D = \theta(3b - 2\Gamma - \Delta)/(4\theta - 1)$$

$$p_T = (b - \Gamma + 2\theta(b - \Delta))/(4\theta - 1). \tag{A13}$$

After substituting Eq. (A13) into Eq. (3), we maximize it on b by solving $\partial\Pi/\partial b = 0$, yielding:

$$b = \frac{w - c + \Delta}{2} + \frac{\theta(w - c - \Delta) - (w - c - \Gamma)}{2\theta(8\theta + 1)}. \tag{A14}$$

Lastly, substituting Eqs. (A13) and (A14) into Eqs. (3) and (4) gives the profits of the recycling company and the collector in equilibrium as: $\Pi^S = \frac{(w-c-\Gamma)^2}{4\theta} + \frac{(\theta(w-c-\Delta)-(w-c-\Gamma))^2}{(\theta-1)(8\theta+1)}$ and $\pi^S = \frac{(2\theta+1)^2(\theta(w-c-\Delta)-(w-c-\Gamma))^2}{\theta(\theta-1)(8\theta+1)^2}$.

Case (III): Sequence L; if $(t_b, t_{pD}, t_{pT}) = (1, 3, 2)$

We solve $\partial\Pi/\partial p_D = 0$ to maximize Eq. (3) with respect to p_D, having:

$$p_D = (b + p_T - \Gamma)/2. \tag{A15}$$

We replace p_D in Eq. (4) with Eq. (A15) and maximize it with respect to p_T by solving $\partial\pi/\partial p_T = 0$, having:

$$p_T = (2\theta(b - \Delta) + \Delta - \Gamma)/(2(2\theta - 1)). \tag{A16}$$

After substituting Eqs. (A15) and (A16) into Eq. (3), we solve $\partial\Pi/\partial b = 0$ to maximize it with respect to b, having:

$$b = \frac{w - c + \Delta}{2} + \frac{\theta(w - c - \Delta) - (w - c - \Gamma)}{2\left(8\theta^2 - 5\theta + 1\right)}. \tag{A17}$$

Lastly, substituting Eqs. (A15), (A16), and (A17) into Eqs. (3) and (4) gives the profits of the recycling company and the collector in equilibrium as: $\Pi^L = \frac{(w-c-\Gamma)^2}{4\theta} + \frac{(2\theta-1)^2(\theta(w-c-\Delta)-(w-c-\Gamma))^2}{4\theta(\theta-1)(8\theta^2-5\theta+1)}$ and

$$\pi^L = \frac{2\theta^2(2\theta - 1)(\theta(w - c - \Delta) - (w - c - \Gamma))^2}{(\theta - 1)\left(8\theta^2 - 5\theta + 1\right)}.$$

Proof of Proposition 2. The following inequalities hold from the results shown in Proposition 1. Note that the inequalities below hold because of the assumption of $w - c - \theta(w - c - \Delta) < \Gamma$ represented by Inequality (5).

$$\Pi^E - \Pi^S = (\theta(w-c-\Delta)-(w-c-\Gamma))^2/(8\theta(8\theta^2-7\theta-1)) > 0$$

$$\Pi^S - \Pi^L = (8\theta^2-1)(\theta(w-c-\Delta)-(w-c-\Gamma))^2/(4\theta(\theta-1)(8\theta+1)(8\theta^2-5\theta+1)) > 0$$

$$\pi^E - \pi^S = -3(16\theta+5)(\theta(w-c-\Delta)-(w-c-\Gamma))^2/(16\theta(\theta-1)(8\theta+1)^2) < 0$$

$$\pi^S - \pi^L = -(64\theta^4-46\theta^3-5\theta^2+6\theta-1)(\theta(w-c-\Delta)-(w-c-\Gamma))^2/(\theta(\theta-1)(8\theta+1)^2(8\theta^2-5\theta+1)^2) < 0$$

$$b^E - b^S = -(\theta(w-c-\Delta)-(w-c-\Gamma))/(2\theta(8\theta+1)) < 0$$

$$b^S - b^L = -(6\theta-1)(\theta(w-c-\Delta)-(w-c-\Gamma))/(2\theta(8\theta+1)(8\theta^2-5\theta+1)) < 0$$

$$p_D{}^E - p_D{}^S = (\theta(w-c-\Delta)-(w-c-\Gamma))/(8\theta+1) > 0$$

$$p_D{}^S - p_D{}^L = (4\theta-3)(\theta(w-c-\Delta)-(w-c-\Gamma))/(2(8\theta+1)(8\theta^2-5\theta+1)) > 0$$

$$p_T{}^E - p_T{}^S = (\theta(w-c-\Delta)-(w-c-\Gamma))/(4\theta(8\theta+1)) > 0$$

$$p_T{}^S - p_T{}^L = (8\theta^2-1)(\theta(w-c-\Delta)-(w-c-\Gamma))/(2\theta(8\theta+1)(8\theta^2-5\theta+1)) > 0$$

□

Proof of Corollary 1. The following three inequalities hold, which prove this corollary.

$$p_D{}^E - p_T{}^E = ((w-c)(\theta-1)+\theta\Delta-\Gamma(2\theta-1))/(4\theta) > (w-c-\Delta)(4\theta^2-5\theta+1)/(4(8\theta^2-\theta-1)) > 0$$

$$p_D{}^S - p_T{}^S = ((w-c)(2\theta^2-\theta-1)+6\theta^2\Delta-\Gamma(8\theta^2-\theta-1))/(2\theta(8\theta+1)) > 0$$

$$p_D{}^L - p_T{}^L = (2(w-c)\theta(\theta-1)-(8\theta^2-7\theta+1)\Gamma+(6\theta^2-5\theta+1)\Delta)/(2(8\theta^2-5\theta+1))$$

$$> (\theta-1)(\theta+1)(4\theta-1)/(2(1-5\theta+8\theta^2)(8\theta^2-\theta-1)) > 0$$

Note that the first inequality in each of the three Eqs. above holds because of the assumption that $\Gamma < w-c-(6\theta^2/(8\theta^2-\theta-1))(w-c-\Delta)$ represented by Inequality (5). □

Proof of Proposition 3. We determine whether each of the nine possible sequences constitutes the SPNE. The below cases prove that $(t_b, t_{pD}, t_{pT}) = (1, 1, 2)$, $(1, 1, 3)$, $(2, 1, 3)$, and $(2, 2, 3)$ constitute the SPNE.

(i): $(t_b, t_{pD}, t_{pT}) = (1, 1, 2)$

The recycling company has no incentive to change its timing strategy from $(t_b, t_{pD}) = (1, 1)$ to the other possible strategy of $(t_b, t_{pD}) = (1, 2)$ or $(1, 3)$ that satisfies $t_b < t_{pT}$ in Inequality (6). This is because if the recycling company changed the strategy, its profit would decrease from Π^E to Π^S or Π^L. Next, the collector also has no incentive to change its timing strategy from $t_{pT} = 2$ to the other possible strategy of $t_{pT} = 3$ that is consistent with the constraint of $t_b < t_{pT}$ in Inequality (6). This is because the collector's profit would remain unchanged as π^E even if the collector changed the strategy. Consequently, $(t_b, t_{pD}, t_{pT}) = (1, 1, 2)$ constitutes the SPNE because neither firm has an incentive to change its timing strategy in this state.

(ii): $(t_b, t_{pD}, t_{pT}) = (1, 1, 3)$

The recycling company has no incentive to alter the timing strategy from $(t_b, t_{pD}) = (1, 1)$ to the other possible strategies of $(t_b, t_{pD}) = (1, 2)$, $(1, 3)$, $(2, 1)$, $(2, 2)$, or $(2, 3)$ that satisfy $t_b < t_{pT}$. This is because if the recycling company changed the strategy, its profit would decrease from Π^E to Π^S or remain unchanged. Next, the collector also has no incentive to change its timing strategy from $t_{pT} = 3$ to the other possible strategy of $t_{pT} = 2$ that satisfies $t_b < t_{pT}$. This is because the collector's profit would remain unchanged as π^E even if the collector changed the strategy. Consequently, $(t_b, t_{pD}, t_{pT}) = (1, 1, 3)$ constitutes the SPNE because neither firm has the incentive to alter the timing strategy in this state.

(iii): $(t_b, t_{pD}, t_{pT}) = (1, 2, 2)$

The recycling company has the incentive to alter its timing strategy from $(t_b, t_{pD}) = (1, 2)$ to the other possible strategy $(t_b, t_{pD}) = (1, 1)$ that satisfies $t_b < t_{pT}$, because then, its profit increases from Π^S to Π^E. Hence, $(t_b, t_{pD}, t_{pT}) = (1, 2, 2)$ does not constitute the SPNE.

(iv): $(t_b, t_{pD}, t_{pT}) = (1, 2, 3)$

The collector has an incentive to alter the timing strategy from $t_{pT} = 3$ to the other possible strategy $t_{pT} = 2$ that is consistent with the constraint of $t_b < t_{pT}$, because then its profit increases from π^E to π^S. Hence, $(t_b, t_{pD}, t_{pT}) = (1, 2, 3)$ does not constitute the SPNE.

(v): $(t_b, t_{pD}, t_{pT}) = (1, 3, 2)$

The recycling company has an incentive to alter the timing strategy from $(t_b, t_{pD}) = (1, 3)$ to the other possible strategy that satisfies $t_b < t_{pT}$, i.e., $(t_b, t_{pD}) = (1, 1)$, because then its profit increases from Π^L to Π^E. Hence, $(t_b, t_{pD}, t_{pT}) = (1, 3, 2)$ does not constitute the SPNE.

(vi): $(t_b, t_{pD}, t_{pT}) = (1, 3, 3)$

The collector has an incentive to alter the timing strategy from $t_{pT} = 3$ to the other possible strategy $t_{pT} = 2$ that is consistent with the constraint of $t_b < t_{pT}$, because then its profit increases from π^S to π^L. Hence, $(t_b, t_{pD}, t_{pT}) = (1, 3, 3)$ does not constitute the SPNE.

(vii): $(t_b, t_{pD}, t_{pT}) = (2, 1, 3)$

The recycling company has no incentive to change its timing strategy from $(t_b, t_{pD}) = (2, 1)$ to the other possible strategy of $(t_b, t_{pD}) = (1, 1)$, $(1, 2)$, $(1, 3)$, $(2, 2)$, or $(2, 3)$ that satisfies $t_b < t_{pT}$. This is because if the recycling company changed the strategy, its profit would decrease from Π^E to Π^S or remain unchanged. Meanwhile, the collector has no choice to change its timing strategy from $t_{pT} = 3$ because there is no other timing strategy that satisfies $t_b < t_{pT}$. Consequently, $(t_b, t_{pD}, t_{pT}) = (2, 1, 3)$ constitutes the SPNE because neither firm changes the timing strategy in this state.

(viii): $(t_b, t_{pD}, t_{pT}) = (2, 2, 3)$

The recycling company has no incentive to change its timing strategy from $(t_b, t_{pD}) = (2, 2)$ to the other possible strategy of $(t_b, t_{pD}) = (1, 1)$, $(1, 2)$, $(1, 3)$, $(2, 1)$, or $(2, 3)$ that satisfies $t_b < t_{pT}$. This is because if the recycling company changed the strategy, its profit would decrease from Π^E to Π^S or remain unchanged. Meanwhile, the collector has no choice to change its timing strategy from $t_{pT} = 3$ because there is no other timing strategy that satisfies $t_b < t_{pT}$. Consequently, $(t_b, t_{pD}, t_{pT}) = (2, 2, 3)$ constitutes the SPNE because neither firm changes the timing strategy in this state.

(iv): $(t_b, t_{pD}, t_{pT}) = (2, 3, 3)$

The recycling company has an incentive to alter the timing strategy from $(t_b, t_{pD}) = (2, 3)$ to the other possible strategy of $(t_b, t_{pD}) = (1, 1)$, $(1, 2)$, $(2, 1)$, or $(2, 2)$ that satisfies $t_b < t_{pT}$, because then its profit increases from Π^S to Π^E. Hence, $(t_b, t_{pD}, t_{pT}) = (2, 3, 3)$ does not constitute the SPNE. □

Proof of Proposition 4.

Case (I): Sequence E

First, consumers satisfying $s \in [0, (p_D-p_T)/(\theta-1)]$ return the product via the online channel and the surplus of each consumer is $p_D-\theta s$. Substituting $p_D{}^E$ in Proposition 1 into $p_D-\theta s$ gives:

$p_D-\theta s = (w-c-\Gamma)/2-\theta s.$

We integrate this with respect to s in the interval of $s \in [0, (p_D-p_T)/(\theta-1)]$ to calculate the total surplus of consumers returning via the online channel. Since Proposition 1 indicates $(p_D{}^E-p_T{}^E)/(\theta-1)=(\Delta-\Gamma)/(4(\theta-1))+(w-c-\Gamma)/(4\theta)$, the surplus is:

$$\int_0^{(\Delta-\Gamma)/(4(\theta-1))+(w-c-\Gamma)/(4\theta)} ((w-c-\Gamma)/2-\theta s)ds = \frac{((2\theta-1)(w-c-\Gamma)-\theta(w-c-\Delta))(\theta(w-c-\Delta)+(2\theta-3)(w-c-\Gamma))}{32\theta(\theta-1)^2}. \tag{A18}$$

Next, we calculate the surplus of consumers who return via the offline channel: consumers in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ return the product, and their surplus is p_T-s. We integrate this with respect to s in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ to calculate the total surplus of consumers returning via the offline channel. Using $p_T{}^E=(\theta(w-c-\Delta)+(w-c-\Gamma))/(4\theta)$ in Proposition 1, we calculate the surplus as:

$$\int_{(\Delta-\Gamma)/(4(\theta-1))+(w-c-\Gamma)/(4\theta)}^{(\theta(w-c-\Delta)+w-c-\Gamma)/(4\theta)} \left(\frac{\theta(w-c-\Delta)+w-c+\Gamma}{4\theta}-s\right)ds = \frac{(\theta(w-c-\Delta)-(w-c-\Gamma))^2}{32(\theta-1)^2}. \tag{A19}$$

Summing Eqs. (A18) and (A19), we obtain CS^E in this proposition.

Case (II): Sequence S

Consumers satisfying $s \in [0, (p_D-p_T)/(\theta-1)]$ return the product via the online channel and the surplus of each consumer is $p_D-\theta s$. Substituting $p_D{}^S$ in Proposition 1 into $p_D-\theta s$ gives:

$$p_D-\theta s=((8\theta+3)(w-c-\Gamma)-2\theta(w-c-\Delta))/(2(8\theta+1))-\theta s.$$

We integrate this with respect to s in the interval of $s \in [0, (p_D-p_T)/(\theta-1)]$ to calculate the total surplus of consumers returning via the online channel. Because Proposition 1 indicates $(p_D{}^S-p_T{}^S)/(\theta-1)=((8\theta^2-\theta-1)(w-c-\Gamma)-6\theta^2(w-c-\Delta))/(2\theta(\theta-1)(8\theta+1))$, the surplus is:

$$\int_0^{\left((8\theta^2-\theta-1)(w-c-\Gamma)-6\theta^2(w-c-\Delta)\right)/(2\theta(\theta-1)(8\theta+1))} \left(\frac{(8\theta+3)(w-c-\Gamma)-2\theta(w-c-\Delta)}{2(8\theta+1)}-\theta s\right)ds = \frac{\left((8\theta^2-\theta-1)(w-c-\Gamma)-6\theta^2(w-c-\Delta)\right)\left(2\theta(2+\theta)(w-c-\Delta)+(w-c-\Gamma)\left(8\theta^2-9\theta-5\right)\right)}{8\theta(\theta-1)^2(8\theta+1)^2}. \tag{A20}$$

Next, we calculate the surplus of consumers who return via the offline channel: consumers in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ return the product, and their surplus is p_T-s. We integrate this with respect to s in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ to calculate the total surplus of consumers returning via the offline channel. Using $p_T{}^S=(\theta(w-c-\Delta)+(w-c-\Gamma))/(4\theta)-(\theta(w-c-\Delta)-(w-c-\Gamma))/(4\theta(8\theta+1))$ in Proposition 1, we calculate the surplus as:

$$\int_{\left((8\theta^2-\theta-1)(w-c-\Gamma)-6\theta^2(w-c-\Delta)\right)/(2\theta(\theta-1)(8\theta+1))}^{\left((4\theta+1)(w-c-\Gamma)+4\theta^2(w-c-\Delta)\right)/(2\theta(8\theta+1))} \left(\frac{(4\theta+1)(w-c-\Gamma)+4\theta^2(w-c-\Delta)}{2\theta(8\theta+1)}-s\right)ds = \frac{(2\theta+1)^2(\theta(w-c-\Delta)-(w-c-\Gamma))^2}{2(\theta-1)^2(8\theta+1)^2}. \tag{A21}$$

Summing Eqs. (A20) and (A21), we obtain CS^S in this proposition.

Case (III): Sequence L

First, consumers satisfying $s \in [0, (p_D-p_T)/(\theta-1)]$ return the product via the online channel and the surplus of each consumer is $p_D-\theta s$. Substituting $p_D{}^L$ in Proposition 1 into $p_D-\theta s$ gives:

$$p_D-\theta s=\frac{\theta((8\theta-3)(w-c-\Gamma)-(2\theta-1)(w-c-\Delta))}{2\left(8\theta^2-5\theta+1\right)}-\theta s.$$

We integrate this with respect to s in the interval $s \in [0, (p_D-p_T)/(\theta-1)]$ to calculate the total surplus of consumers returning via the online channel. Because Proposition 1 indicates $(p_D{}^L-p_T{}^L)/(\theta-1)=((8\theta^2-7\theta+1)(w-c-\Gamma)-(2\theta-1)(3\theta-1)(w-c-\Delta))/(2(\theta-1)(8\theta^2-5\theta+1))$, the surplus is:

$$\int_0^{\frac{\left(8\theta^2-7\theta+1\right)(w-c-\Gamma)-(2\theta-1)(3\theta-1)(w-c-\Delta)}{2(\theta-1)\left(8\theta^2-5\theta+1\right)}} \left(\frac{\theta((8\theta-3)(w-c-\Gamma)-(2\theta-1)(w-c-\Delta))}{2\left(8\theta^2-5\theta+1\right)}-\theta s\right)ds = \theta\left(\left(8\theta^2-15\theta+5\right)(w-c-\Gamma)+\left(2\theta^2+\theta-1\right)(w-c-\Delta)\right) \times \left(\left(8\theta^2-7\theta+1\right)(w-c-\Gamma)-\left(6\theta^2-5\theta+1\right) \times(w-c-\Delta)\right)/\left(8(\theta-1)^2\left(8\theta^2-5\theta+1\right)^2\right). \tag{A22}$$

Next, we calculate the surplus of consumers who return via the offline channel: consumers in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ return the product, and their surplus is p_T-s. We integrate this with respect to s in the interval $s \in [(p_D-p_T)/(\theta-1), p_T]$ to calculate the total surplus of consumers returning via the offline channel. Using $p_T{}^L=((2\theta-1)^2(w-c-\Delta)+(4\theta-1)(w-c-\Gamma))/(2(8\theta^2-5\theta+1))$ in Proposition 1, we calculate the surplus as:

$$\int_{\frac{\left(8\theta^2-7\theta+1\right)(w-c-\Gamma)-(2\theta-1)(3\theta-1)(w-c-\Delta)}{2(\theta-1)\left(8\theta^2-5\theta+1\right)}}^{\frac{(2\theta-1)^2(w-c-\Delta)+(4\theta-1)(w-c-\Gamma)}{2\left(8\theta^2-5\theta+1\right)}} \left(\frac{(2\theta-1)^2(w-c-\Delta)+(4\theta-1)(w-c-\Gamma)}{2\left(8\theta^2-5\theta+1\right)}-s\right)ds = \frac{\theta^2(2\theta-1)^2(w-c-\Gamma-\theta(w-c-\Delta))^2}{2(\theta-1)^2\left(8\theta^2-5\theta+1\right)^2}. \tag{A23}$$

Summing Eqs. (A22) and (A23), we obtain CS^L in this proposition. □

Proof of Proposition 5. Using the results in Proposition 4, we calculate CS^E-CS^S as follows.

$$CS^E-CS^S=(\theta(w-c-\Delta)-(w-c-\Gamma))((128\theta^2-48\theta-17)(w-c-\Gamma) -\theta(64\theta-1)(w-c-\Delta))/(32\theta(\theta-1)(8\theta+1)^2)$$

First, the assumption of Inequality (5) ensures that $\theta(w-c-\Delta) > w-c-\Gamma$ is satisfied. Thus, $CS^E-CS^S > 0$ holds as long as $w-c-\Gamma > \theta(64\theta-1)(w-c-\Delta)/(128\theta^2-48\theta-17)$. The assumption of Inequality (5) indicates $w-c-\Gamma > (6\theta^2/(8\theta^2-\theta-1))(w-c-\Delta)$ holds. $(6\theta^2/(8\theta^2-\theta-1))(w-c-\Delta)-(\theta(64\theta-1)(w-c-\Delta)/(128\theta^2-48\theta-17))=0$ holds only when $\theta \to 1$ within the defined domain of $\theta > 1$. Moreover, substituting any θ satisfying $\theta > 1$ into this expression yields a positive value. Consequently, $w-c-\Gamma > (6\theta^2/(8\theta^2-\theta-1))(w-c-\Delta) > \theta(64\theta-1)(w-c-\Delta)/(128\theta^2-48\theta-17)$ always holds, indicating that $CS^E > CS^S$ holds.

Next, Proposition 4 suggests that $CS^S - CS^L$ is:

$$CS^S - CS^L = (\theta(w-c-\Delta)-(w-c-\Gamma))(\theta(w-c-\Delta)(512\theta^5-512\theta^4 + 416\theta^3-196\theta^2+31\theta+1)-(640\theta^4-440\theta^3+30\theta^2+27\theta-5) \times (w-c-\Gamma))/(8\theta(\theta-1)(8\theta+1)^2(8\theta^2-5\theta+1)^2).$$

The assumption of Inequality (5) indicates that $\theta(w-c-\Delta) > w-c-\Gamma$. Next, $-(640\theta^4-440\theta^3+30\theta^2+27\theta-5)$, which is the coefficient on $w-c-\Gamma$, is always negative. Hence, $\theta(w-c-\Delta)(512\theta^5-512\theta^4+416\theta^3-196\theta^2+31\theta+1)-(640\theta^4-440\theta^3+30\theta^2+27\theta-5)(w-c-\Gamma)$ is minimized with respect to $w-c-\Gamma$ when $w-c-\Gamma$ is the upper limit assumed in Inequality (5), i.e., $w-c-\Gamma \to \theta(w-c-\Delta)$. Inserting $w-c-\Gamma = \theta(w-c-\Delta)$ into $\theta(w-c-\Delta)(512\theta^5-512\theta^4+416\theta^3-196\theta^2+31\theta+1)-(640\theta^4-440\theta^3+30\theta^2+27\theta-5)(w-c-\Gamma)$ yields $2\theta(\theta-1)(4\theta-3)(8\theta+1)(8\theta^2-5\theta+1)(w-c-\Delta)$. Because this expression is always positive in the range of $\theta > 1$, $CS^S > CS^L$ always holds. □

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