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SCREENING THIRD-PARTY COLLECTORS' DOUBLE ASYMMETRIC INFORMATION IN A DUAL-CHANNEL CLOSED-LOOP SUPPLY CHAIN

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Abstract. We investigate the third-party collector's private information in a dual-channel closed-loop supply chain (DCLSC). The manufacturer sells her products through both an e-channel and retail channel and delegates the collection of waste electrical and electronic equipment (WEEE) to a third-party collector. The collector in a DCLSC has two types of private information: *i.e.*, his collection effort level and collection ability. We develop principal-agent models to help the manufacturer design an information screening contract to obtain the collector's asymmetric information. The results show that (i) an information screening contract can effectively prevent low ability collectors from misrepresenting their private information; (ii) although the increased awareness of environmental protection of consumers improves the manufacturer's expected profit, it does not affect the retailer's expected profit and the collector's expected utility; (iii) the manufacturer's expected profit enhances with the number of high ability collectors, whereas the expected utility of the high ability collector declines; (iv) the e-channel could not increase the total expected profit of the manufacturer and the retailer, but the channel transfers a part of the retailer's expected profit to the manufacturer.

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1. Introduction

According to the United Nations' Global E-waste Monitor 2020 report, a record 53.6 million metric tons (Mt) of e-waste was generated globally in 2019 and an increase of 9.2 Mt in 5 years[1]. This e-waste causes serious environmental pollution, such as water and land pollution. However, only 17.4% of e-waste was collected and recycled in 2019; therefore, high-value recyclable materials were mostly dumped or incinerated instead of being collected for processing and reuse. If waste electrical and electronic equipment (WEEE) can be collected and remanufactured effectively, this can not only cut down companies' production costs but also reduce the environmental hazards caused by WEEE. This creates major opportunities for manufacturing enterprises and collector industries to make more profit [1]. How can we combine collection and remanufacturing organically to achieve a circular economy and environmental protection based on environmental responsibility and interests?

Keywords. Dual-channel closed-loop supply chain, asymmetric information, information screening contract, WEEE.

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[1]For more details about the International Telecommunication Unions Global E-waste Monitor 2020 report, please see https://www.itu.int/en/ITUD/Environment/Pages/Spotlight/Global-Ewaste-Monitor-2020.aspx.

Many companies and numerous scholars are focusing on this problem in the closed-loop supply chain (CLSC) in the literature related to the collection and remanufacturing of WEEE [2–5].

Based on the extended producer responsibility system, manufacturing companies are responsible for the recycling and collection of their products after consumption. Today, the cooperation between the manufacturer and the collector has become the norm in the CLSC. The manufacturer takes the initiative to assume the responsibility for remanufacturing WEEE and entrusts a third-party collector to retrieve WEEE. For example, ReCellular Inc., the largest mobile phone remanufacturer in the United States, outsources its collection business to collectors [6], and AHS Device has formed extensive cooperation with Apple, Huawei, and Xiaomi. This process greatly reduces the environmental damage caused by WEEE and increases the profits of manufacturers and collectors [7, 8].

Most manufacturers have also opened e-channels. In contrast to traditional sales methods, e-channels are a popular method for manufacturers to save labor and fixed costs [9]. Many companies, such as IBM, Apple, Dell, Sony, and Lenovo, have developed their own e-channels to sell their products [10]. For example, Dell sells its product backlog through an e-channel called Dell Outlet Stores [11]. Similarly, Hewlett-Packard (HP) sells remanufactured computers through its e-channel [12]. Consumers are more inclined to use an e-channel for greater convenience and lower prices compared with offline channels. Therefore, e-channels pose a great challenge to traditional offline channels, which creates more complex problems for CLSC management. Thus, manufacturers sell their products through their e-channel and offline channels in a dual-channel closed-loop supply chain (DCLSC).

When CLSC members agree to make centralized decisions, they can always help the entire CLSC to obtain the maximum expected profit [13, 14]. In reality, however, as every node enterprise in the supply chain is an "economic man" not "social man" when making decisions, they tend to first consider maximizing their own profit instead of maximizing the overall profit of the supply chain. Profit competition between enterprises is mainly based on their private information, which is the core competitiveness of enterprises that are unwilling to freely share their information with others [15]. The private information of various enterprises is extensively studied by scholars in the CLSC literature, such as retailers' efforts to collect WEEE [16–18], manufacturers' production costs [19], and collectors' collection efforts and ability [20]. In practice, CLSC members are prone to information asymmetry because some members use their own private information to transfer other members' profits to themselves. Collectors who are commissioned to collect WEEE have access to more collection markets and operational information than the manufacturer does, especially in the collection and remanufacturing industry [17]. Collectors' collection effort and ability are core private information rarely known by the manufacturer, which makes it difficult for the manufacturer to obtain a certain amount of collection information and set an appropriate buyback price. Thus, the collector can easily cheat the manufacturer to earn more profit. Voigt and Inderfurth [21] point out that the loss of efficiency caused by information asymmetry is inevitable. Khan and Hussein [22] explore information sharing in a two-level sustainable supply chain model and find that information sharing can lead to better annual profits and lower retail prices. Therefore, how manufacturers obtain collectors' private information is an urgent problem to be solved.

Some researchers explore how to accurately obtain the collector's private information [14, 16, 20]. Although most studies focus on the CLSC, they rarely consider the impact of the manufacturer's dual sales channel on the decisions and profits of CLSC members under asymmetric information and do not perform a comparative analysis of the situation where the collector has single and dual private information. We consider that the collector has two types of private information in DCLSCs: *i.e.*, the collection effort level and collection ability. Our research specifically answers the following questions:

(i) How does the manufacturer effectively identify the third-party collector's private information?
(ii) What are the effects of an increase in the collector's asymmetric information types on DCLSC members?
(iii) How does the dual sales channel affect the profits of DCLSC members?

To solve these problems, we analyze a DCLSC model consisting of a manufacturer (she), a retailer, and a third-party collector (he). The manufacturer's new and remanufactured products are sold to her consumers through an e-channel and an offline channel. The manufacturer commissions the third-party collector to collect WEEE and repurchases it for remanufacturing. The collector's collection effort and ability are two types of private information that are difficult for the manufacturer to obtain. We help the manufacturer to design information screening contracts to screen the collector's private information to prevent him from deceiving the manufacturer and causing economic losses. Based on the types of asymmetric information, the DCLSC is divided into single asymmetric information DCLSC (SDCLSC) and double asymmetric information DCLSC (DDCLSC), where SDCLSC means that the manufacturer cannot obtain information about the collector's collection effort, while DDCLSC means that the manufacturer cannot access information about the collector's collection effort and ability.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 provides the model description, notations, and assumptions. Section 4 explores the SDCLSC and DDCLSC decision-making models. Furthermore, we compare both models to obtain managerial insights. Numerical examples are given to validate the proposition and probe the influence of other important parameters on the DCLSC in Section 5. Section 6 presents the conclusions, discusses managerial implications, and investigates possible directions for future research.

2. Literature review

Our work mainly relates to three research streams in literature. Section 2.1 reviews literature exploring the problem of selecting a collection channel in a CLSC. In Section 2.2, we discuss the relevant literature on the effect of dual sales channels on corporate profits. In Section 2.3, we discuss the identification of asymmetric information in a CLSC.

2.1. Selecting a collection channel in a CLSC

Researchers seek an optimal collection channel to enhance the efficiency of collection in a CLSC. Giovanni *et al.* [23] confirm that remanufacturers should manage their own waste collection or outsource collection to a collector. Yi *et al.* [24] explore remanufacturers' allocation of collection to retailers and third-party collectors and find that the optimal allocation strategy is determined by the reverse logistics cost coefficient. Saha *et al.* [25] analyze three collection modes in a CLSC, which include a third-party collector-led mode, a manufacturer-led mode, and a retailer-led mode. They observe that the remanufacturing rate is maximized when the used product is procured directly from the manufacturer. Chu *et al.* [26] find that a third-party collector mode serving multiple manufacturers is better than individual retailer- and manufacturer-managed modes. In a comparison of different collection channel models, Zhao *et al.* [27] reveal that the producer-led independent collection channel is the most efficient. Taleizadeh *et al.* [28] examine three models where the collection process is conducted by a manufacturer, a retailer, or a third party in a decentralized structure, and find that the expected profit of the manufacturer reaches its highest value under the retailer collection. In the above literature, the optimal collection channel is obtained under different conditions. Manufacturing enterprises have different focuses because they choose diverse collection channels to collect WEEE. In practice, some manufacturers outsource their collection operations to third-party collectors so they can focus on their own manufacturing operations. Cooperation between collectors and manufacturers is also widespread. For example, as the leading enterprises in the collection WEEE in Chain, Aibo Green cooperates with 35 large electrical and electronic product manufacturers, including Suning, JD Central, Haier, and TCL. Therefore, manufacturers entrust their collection business to third-party collectors for practical reasons.

2.2. The effect of dual sales channels on corporate profits

Many studies discuss the effects of dual sales channels on a CLSC from different perspectives. Some researchers explore the impact of dual-channel sales on the profits of CLSC members. Yan and Pei [29] show that a manufacturer with an e-channel achieves better performance than a manufacturer with a single retail channel. Tsay and Agrawal [30] find that few manufacturers discard their retail channels while some manufacturers sell their products in both retail channels and e-channels. Lu and Liu [31] study the effect of an e-channel on the manufacturer's profitability and behavior. Batarfi *et al.* [32] investigate the effect of the dual-channel strategy on the profit of the centralized supply chain. Shi *et al.* [33] show that a company's organizational structure affects its marketing decisions. Independent retail sales generate higher company profits, supply chain profits, and total consumer demand than manufacturers' direct sales. Furthermore, how to solve the conflict between the dual saless channels is also a focus of the literature. Xie *et al.* [34] explore the contract coordination problem of centralized and decentralized dual-channel CLSCs and Xie *et al.* [35] take revenue-sharing contracts into the forward channel to solve the conflict between e-channels and retail channels. Xu *et al.* [36] investigate the coordination of a supply chain composed of manufacturers and retailers that sell products through offline channels and online platforms. Wang *et al.* [37] examine the supply chain coordination and contracting issue for competitive dual sales channels in the mobile phone industry. The above literature shows that dual sales channels affect the profits of CLSC members and how to coordinate conflicts between dual sales channels. Few studies explore dual sales channels in CLSCs with asymmetric information. We discuss the situation where the manufacturer sells her products through an e-channel and an offline channel, which leads to price competition when the collector has private information, and how the market share of the e-channel influences the profits of the manufacturer, retailer, collector, and the whole CLSC.

2.3. Identification of asymmetric information in the CLSC

Many researchers attempt to solve the problem of how to accurately obtain private information from supply chain members. Mukhopadhyay *et al.* [15] study the optimal contract when a retailer has private value-added cost information under a dual-channel supply chain. Partha *et al.* [38] propose several combinations of information sharing and coordination mechanisms to reduce uncertainty in the supply chain. Babichabbc [39] designs a buyback contract for a supplier who sells products through a retailer with private information on demand distribution. Zhang *et al.* [16] analyze a retailer with private information on the cost of the collection effort and find that the manufacturer is at a disadvantage under asymmetric information, whereas a retailer benefits from private information. He [40] examines the application and effectiveness of a franchise fee contract and a retail price maintenance contract in a CLSC with asymmetric information. Wu *et al.* [41] discover that two-part tariffs coordinate the supply chain under asymmetric information. Wang *et al.* [17] design an information screening contract for a manufacturer to obtain a retailer's private information in a CLSC. Ma *et al.* [42] develop an optimal contract for a supply chain, in which a manufacturer's social responsibility cost is the retailer's asymmetric information. Xie *et al.* [35] compare and analyze contract coordination under centralized and decentralized DCLSCs. Zhang *et al.* [43] consider a two-period supply chain in which a supplier sells products through a retailer with potentially private market information. Wang and Guo [19] design a contract mechanism for a supply chain consisting of a retailer and a supplier with private production costs. Sun *et al.* [44] consider whether manufacturers participate in the decision to reduce costs under asymmetric or symmetric demand information. Zhu and Yu [20] study manufacturers that use revenue-sharing contracts to screen the collector's collection ability and effort in the power battery remanufacturing CLSC system. To obtain the real private information of an assembler, Lan *et al.* [18] study a supplier contract design problem in the assembly supply chain. Most of the above studies center on a manufacturer, a retailer, or a consumer who has private information, while some scholars discuss whether the third-party collector has two types of private information: *i.e.*, the effort and ability to collect. To obtain the collector's private information, we help the manufacturer design an information screening contract. In contrast to Zhu and Yu [20], who consider a third-party collector's asymmetric information, we consider the impact of dual sales channel competition in a CLSC with asymmetric information. We summarize the main differences between our study and these studies closely related to our research questions in Table 1 to illustrate the contribution of our work to the literature.

This study provides the following contributions based on previous research. First, we compare and analyze the optimal solution for a DCLSC with single and double information asymmetry. Second, we specifically explore whether the manufacturer's information screening contract can effectively identify the collector's private

TABLE 1. Our paper *vs.* the literature.

Studies	Dual sales channel	Collection channel			Asymmetric information				Asymmetric information types
		M	R	C	M	R	C	Co	
Mukhopadhyay *et al.* [15]	✓				✓				s
Zhang *et al.* [16]			✓			✓			s
Wu *et al.* [41]						✓			s
Wang *et al.* [17]			✓			✓			s
Wang *et al.* [19]					✓				s
Zhu and Yu [20]				✓			✓		d
Sun *et al.* [44]								✓	s
Ma *et al.* [42]					✓				s
Lan *et al.* [18]						✓			s
This paper	✓			✓			✓		d

Notes. (1) M, R, C, and Co represents the manufacturer, retailer, collector, and consumers, respectively. (2) The "s" and "d" represent the types of asymmetric information in the corresponding literature as single and double asymmetric information, respectively.

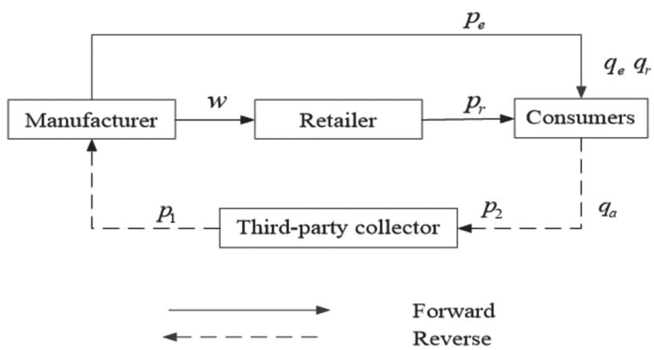

FIGURE 1. The structure of the DCLSC.

information. Finally, we investigate the influence of a dual sales channel on the profits of CLSC members with asymmetric information.

3. Model description and assumptions

In this section, we describe the structure of a DCLSC and then present some assumptions about this model as well as notations.

3.1. Model description

As shown in Figure 1, the manufacturer preferentially opts to use WEEE to produce new products [17, 45]. Products using new materials or WEEE have no difference in their quality, appearance, and function [46]. The manufacturer sells her products through two channels: an e-channel that trades goods directly to the final consumer at price and a retail channel where the manufacturer sells products at wholesale price to the retailer who sells the products to consumers at price. Depending on their preference, customers can buy the products through either the e-channel or the retail channel [47].

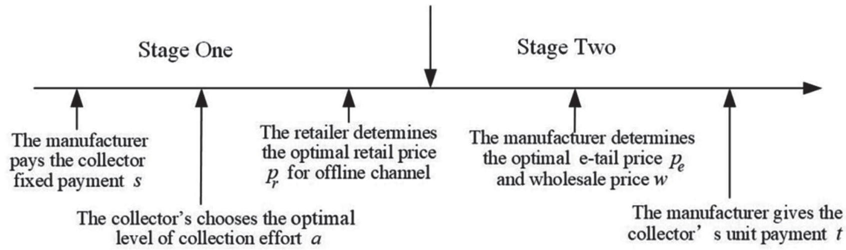

Figure 2. Decision-making order of DCLSC under information asymmetry.

The manufacturer authorizes the collector to collect WEEE, which he purchases from consumers at unit price p_2 because the use of WEEE reduces the manufacturer's production costs. The manufacturer then buys back WEEE from the collector at unit price p_1. We use $p_1 > p_2 > 0(\Delta = p_1 - p_2)$ to guarantee the collector's profitability [6], where Δ represents the collector's unit income to purchase WEEE. The collectors collection effort level and ability are private information. The quantity of WEEE collected is closely related to the collector's collection ability r and his collection effort level a. We explain some critical assumptions in Section 3.2.

3.2. Model assumptions

(i) The cost of remanufactured components c_1 is lower than the cost of new materials c_n; thus, we have $c_1 < c_n$ [26,48]. The relationship between c_1 and c_n is $c_1 = (1-\delta)c_n$, where denotes the cost-saving rate.

(ii) Analogous to Gao *et al.* [49], the market demand for the e-channel and offline channel are $q_e = \alpha\varphi - p_e + b(p_r - p_e)$ and $q_r = (1-\alpha)\varphi - p_r + b(p_e - p_r)$, respectively, where b denotes the cross-price difference sensitivity. Total market demand is $D = q_e + q_r = \varphi - p_e - p_r$.

(iii) The quantity of WEEE collected is $q_a = q_0 + \theta + ra$ [20], where q_0 represents the amount of collection when the collection effort is zero, θ indicates a market uncertainty factor with $\theta \sim (0, \sigma^2)$, r represents the collector's real collection ability, and a indicates the collector's collection effort level. In order to focus on the core issues of research, all WEEE collected will be completely used in the remanufacturing process. Similar practice has been used in literature [17,20].

(iv) The collector's collection effort cost is $c(a) = ka^2/2$ and is a marginal increment function $(c(a)' > 0, c(a)'' > 0)$, where $k(k > 0)$ is defined as a collection effort cost factor [42,44,48]. Similar to the assumption by Zhu and Yu [20], the manufacturer and the retailer aiming at maximizing profits are risk neutral and completely rational, whereas the collector is risk averse. For collectors, the disclosure of real information will affect their profits, which will lead to risk aversion.

(v) The collector's utility function is $u_{\pi_C} = -e^{\rho\pi_C}$ [20], where ρ is the degree of risk aversion ($\rho > 0, \rho = 0$ and $\rho < 0$ indicate that the collector is risk averse, risk neutral, and risk taking, respectively). The decision variables and other parameters are summarized in Table 2.

4. Model development

To increase the quantity of WEEE collected, the manufacturer designs private information screening contracts to obtain the collector's private information. We first consider the situation in which the collector's collection effort is private information. Next, we explore the case where the collector's ability and collection effort are private information. The contract designed by the manufacturer not only identifies the collector's double private information but also prevents the collector from misrepresenting his private information. The timing sequence of CLSC under information asymmetry decision making is shown in Figure 2.

TABLE 2. Notations.

Symbols	Descriptions
Decision variables	
w	Unit wholesale prices that the manufacturer sells to the retailer
p_e	Unit retail price in the e-channel
p_r	Unit retail price in the offline channel
t	Unit payment that the manufacturer pays to the collector
s	Fixed payment that the manufacturer pays to the collector
a	The collector's level of collection effort
Parameters	
c_n	Unit cost of producing a new product with raw materials
c_1	Unit cost of producing a remanufactured product with WEEE
δ	Cost-saving rate for using WEEE, $0 < \delta < 1$
α	Market share ratio of the e-channel, $0 < \alpha < 1$
b	Cross-price difference sensitivity, $0 < b < 1$
φ	Potential benchmark demand for the product in the market
q_0	Collection quantity when the collection effort is zero
θ	Market uncertainty factor
σ	Standard deviation of the market uncertainty factor
ρ	The degree of the collectors risk aversion
k	Collector's collection cost parameter, $k > 0$
v	Proportion of high collection ability collectors, $0 < v < 1$
p_1	Unit buyback price for the manufacturers purchase of WEEE from the collector
p_2	The collector's collection price
Δ	The collector's unit income to purchase WEEE
r	The collector's ability to collect WEEE
Derived function	
T	Reward to collectors in information screening contract designed by manufacturers
q_e	Market demand for the e-channel
q_r	Market demand for the offline channel
$\pi_.$	$. = M, R$ and C represents the profits of the manufacturer, retailer, and collector, respectively
π_0	Reserved utility that the collector does not participate in the screening contract
Index	
Subscript H	High-level type
Subscript L	Low-level type
Superscript $*$ and $**$	Optimal decision results for single and double private information, respectively

4.1. Single asymmetric information DCLSC model

We consider that the collector's collection ability is a constant, but the collector who has single asymmetric information on his collection effort level can decide whether the real information should be shared. In this case, the manufacturer cannot accurately observe the collector's collection effort level; therefore, the manufacturer designs an information screening contract $T = s + tq_a$ to identify the collector's collection effort level. When the manufacturer signs a contract with a collector with a given collection ability, the profits of the manufacturer and the retailer are expressed as follows:

$$\pi_M = (p_e - c_n)q_e + (w - c_n)q_r + (c_n - c_1 - p_1)(q_0 + ra + \theta) - s - t(q_0 + ra + \theta). \tag{1}$$

In equation (1), $(p_e - c_n)q_e + (w - c_n)q_r$ is the profit of selling new products online and offline, $(c_n - c_1 - p_1)(q_0 + ra + \theta)$ is the cost saved by using WEEE collected to reproduce new products, and $s + t(q_0 + ra + \theta)$ is the manufacturer's expenditure on collectors using information screening contracts.

$$\pi_R = (p_r - w)[(1-\alpha)\varphi - p_r + b(p_e - p_r)]. \tag{2}$$

The manufacturer and the retailer are risk neutral; thus, their expected profits are equal to their expected utility, and the manufacturer and the retailer expect profit to be

$$E(\pi_M) = (p_e - c_n)q_e + (w - c_n)q_r + (c_n - c_1 - p_1 - t)(q_0 + ra) - s \tag{3}$$

$$E(\pi_R) = (p_r - w)[(1-\alpha)\varphi - p_r + b(p_e - p_r)]. \tag{4}$$

The collector is risk averse; thus, his profit is expressed as

$$\pi_C = (t + \Delta)(q_0 + ra + \theta) + s - ka^2/2. \tag{5}$$

According to the certainty equivalent (CE) method, the solution yields the expected utility of the collector:

$$\mathrm{CE}(\pi_C) = (t + \Delta)(q_0 + ra) + s - ka^2/2 - \rho\sigma^2(t + \Delta)^2/2 \tag{6}$$

where $(t + \Delta)(q_0 + ra) + s - ka^2/2$ denotes the expected income of the collector and $\rho\sigma^2(t + \Delta)^2/2$ is the risk cost of the collector caused by exogenous uncertain factors. The specific proof process to obtain the collector's certainty equivalent income is in the following.

According to the collector's profit function $\pi_C = (t + \Delta)(q_0 + ra + \theta) + s - ka^2/2$ with $\theta \sim N(0, \sigma^2)$, we obtain $E(\pi_C) = (t + \Delta)(q_0 + ra) + s - ka^2/2$ and $Var(\pi_C) = (t + \Delta)^2\sigma^2$. We have $E(u_{\pi_C}) = \int_{-\infty}^{+\infty} -e^{\rho\pi_C} \frac{1}{\sqrt{2\pi Var(\pi_C)}} e^{-\frac{\{\pi_C - E(\pi_C)\}^2}{2Var(\pi_C)}} \mathrm{d}\pi_c = -e^{-\rho\left\{E(\pi_C) - \frac{\rho Var(\pi_c)}{2}\right\}}$ from the utility function $u_{\pi_C} = -e^{\rho\pi_C}$. According to the definition of the CE method, $E(u_{\pi_C}) = U(\mathrm{CE})$, *i.e.*, $-e^{-\rho(\mathrm{CE})} = -e^{-\rho\left\{E(\pi_C) - \frac{\rho Var(\pi_c)}{2}\right\}}$, and the collector's CE income $\mathrm{CE} = E(\pi_C) - \frac{\rho Var(\pi_c)}{2} = (t + \Delta)(q_0 + ra) + s - ka^2/2 - \rho\sigma^2(t + \Delta)^2/2$, because maximizing the collector's expected utility is equivalent to maximizing his CE income, it can be concluded that CE income can replace the expected utility according to the above analysis. Therefore, we refer to the collector's CE income as the expected utility in the following. We obtain the collector's expected utility: $\mathrm{CE}(\pi_C) = (t + \Delta)(q_0 + ra) + s - ka^2/2 - \rho\sigma^2(t + \Delta)^2/2$.

The objective function and constraints are given by

$$\max_{p_e, w, s, t} E(\pi_M) = (p_e - c_n)q_e + (w - c_n)q_r + (c_n - c_1 - p_1 - t)(q_0 + ra) - s \tag{7}$$

$$\text{s.t.} \begin{cases} p_r^* = \arg\max E(\pi_R) \\ a^* = \arg\max \mathrm{CE}(\pi_C) \\ \mathrm{CE}(\pi_C) \geq \pi_0. \end{cases} \tag{8}$$

For these constraints, $a^* = \arg\max \mathrm{CE}(\pi_C)$ is the incentive compatibility constraint, which indicates that the collector selects the optimal effort level in the SDCLSC. $\mathrm{CE}(\pi_C) \geq \pi_0$ is the participation constraint, which guarantees that the collectors profit is higher than that in the case without a contract.

By solving the above model utilizing the Lagrange multiplier method, we obtain the following optimal solutions:

$$p_e^* = \frac{(\alpha + b)\varphi + (1 + 2b)c_n}{2 + 4b}, \qquad w^* = \frac{(b - \alpha + 1)\varphi + (1 + 2b)c_n}{2 + 4b},$$

$$p_r^* = \frac{[(2b + 1)(b - 2\alpha + 3) - \alpha - b]\varphi + (1 + 2b)^2 c_n}{4(1 + 2b)(1 + b)}, \qquad a^* = \frac{(t^* + \Delta)r}{k},$$

$$s^* = \pi_0 + \frac{\rho\sigma^2(t^*+\Delta)^2}{2} - (t^*+\Delta)q_0 - \frac{(t^*+\Delta)^2 r^2}{2k}, \qquad t^* = \frac{(\delta c_n - p_1)r^2 - k\rho\sigma^2\Delta}{r^2 + k\rho\sigma^2}.$$

By substituting the equilibrium solutions obtained for the decision variables into the expected utility of the manufacturer, retailer, and collector, we obtain their expect utility.

$$E(\pi_M^*) = (p_e^* - c_n)q_e^* + (w^* - c_n)q_r^* + (\delta c_n - p_1 - t^*)(q_0 + ta^*) - s^*,$$
$$E(\pi_R^*) = (p_r^* - w^*)[(1-\alpha)\varphi - p_r^* + b(p_e^* - p_r^*)], \quad \text{and} \quad \mathrm{CE}(\pi_C^*) = \pi_0.$$

To avoid trivial computation processes, the solution for these optimal results is provided in Appendix A.1.

4.2. Double asymmetric information DCLSC model

In Section 4.1, we consider that the collector's collection ability is a constant. However, the collector's collection ability as determined by the technological innovation and the scale of his enterprise is another factor that affects collection quantity factor in addition to the collector's collection effort level. In this case, the manufacturer's information asymmetry usually includes two situations. Before the contract is signed, the manufacturer cannot observe the information because the collector's collection ability is private information. This is a typical "adverse selection" problem. After the contract is signed, the collector chooses his best effort level based on his own profit maximization. Information asymmetry thus reflects the "moral hazard" problem. It is therefore crucial in the DCLSC to design a contract to report the collector's true collection ability and increase his collection effort level.

We use r_i and a_{ij} to represent the collector's collection ability and collection effort level, respectively, under double information asymmetry. There are two types of collectors in the market, *i.e.*, low collection ability collectors r_L and high collection ability collectors r_H, and $r_L < r_H$. The proportion of high ability collectors is v, which is available to all participants, and the proportion of low ability collectors is $1-v$. The collection effort level a_{ij} of label i represents the collector's real information, j represents the information reported by the collector to the manufacturer, and $i \cdot j \in \{H, L\}$.

The manufacturer provides different contracts for collectors with different collection abilities to realize information screening, induce the collectors to work hard, and improve their collection effort level. The manufacturers contract $T_j(T_j = s_j + t_j q_a, j \in \{H, L\})$ is designed for the collector whose reporting ability is r_i. Different collectors sign contracts based on their true collection ability r_i and choose the corresponding level of effort after signing the contract to maximize their own profit.

The expected profits of the manufacturer and the retailer are expressed as follows:

$$\begin{aligned} E(\pi_M) = {} & (p_e - c_n)q_e + (w - c_n)q_r + v[(c_n - c_1 - p_1 - t_H)(q_0 + r_H a_H H) - s_H] \\ & + (1-v)[(c_n - c_1 - p_1 - t_L)(q_0 + r_L a_L L) - s_L] \end{aligned} \tag{9}$$

$$E(\pi_R) = (p_r - w)[(1-\alpha)\varphi - p_r + b(p_e - p_r)]. \tag{10}$$

Similarly, we obtain the collector's profit function and expected utility separately as follows:

$$\pi_{Cij} = (t_j + \Delta)(q_0 + r_i a_{ij} + \theta) + s_j - k a_{ij}^2/2 \tag{11}$$

$$\mathrm{CE}(\pi_{Cij}) = (t_j + \Delta)(q_0 + r_i a_{ij}) + s_j - k a_{ij}^2/2 - \rho\sigma^2(t_j + \Delta)^2/2. \tag{12}$$

Finally, is specifically expressed from equations (13) to (16).

$$\mathrm{CE}(\pi_{CHH}) = (\Delta + t_H)(q_0 + r_H a_{HH}) + s_H - k a_{HH}^2/2 - \rho\sigma^2(t_H + \Delta)^2/2 \tag{13}$$

$$\mathrm{CE}(\pi_{CHL}) = (\Delta + t_L)(q_0 + r_H a_{HL}) + s_L - k a_{HL}^2/2 - \rho\sigma^2(t_L + \Delta)^2/2 \tag{14}$$

$$\mathrm{CE}(\pi_{CLH}) = (\Delta + t_H)(q_0 + r_L a_{LH}) + s_H - k a_{LH}^2/2 - \rho\sigma^2(t_H + \Delta)^2/2 \tag{15}$$

$$\mathrm{CE}(\pi_{CLL}) = (\Delta + t_L)(q_0 + r_L a_{LL}) + s_L - k a_{LL}^2/2 - \rho\sigma^2(t_L + \Delta)^2/2. \tag{16}$$

The manufacturer's objective function and constraints are expressed as follows:

$$\max_{p_e,w,s_L,t_L,s_H,t_H} E(\pi_M) = (p_e - c_n)q_e + (w - c_n)q_r + v[(\delta c_n - p_1 - t_H)(q_0 + r_H a_{HH}) - s_H] + (1-v)[(\delta c_n - p_1 - t_L)(q_0 + r_L a_{LL}) - s_L] \tag{17}$$

$$\text{s.t.} \begin{cases} p_r^{**} = \arg\max E(\pi_R) \\ a_{HH}^{**} = \arg\max \mathrm{CE}(\pi_{CHH}) \\ a_{LL}^{**} = \arg\max \mathrm{CE}(\pi_{CLL}) \\ \mathrm{CE}(\pi_{CHH}) \geq \mathrm{CE}(\pi_{CHL}) \\ \mathrm{CE}(\pi_{CLL}) \geq \mathrm{CE}(\pi_{CLH}) \\ \mathrm{CE}(\pi_{CHH}) \geq \pi_0 \\ \mathrm{CE}(\pi_{CLL}) \geq \pi_0. \end{cases} \tag{18}$$

where $\mathrm{CE}(\pi_{CHH}) \geq \mathrm{CE}(\pi_{CHL})$ and $\mathrm{CE}(\pi_{CLL}) \geq \mathrm{CE}(\pi_{CLH})$ are the incentive compatibility constraints, which enable the collector to select choose the appropriate information screening contract. $\mathrm{CE}(\pi_{CHH}) \geq \pi_0$ and $\mathrm{CE}(\pi_{CLL}) \geq \pi_0$ are the participation constraints that guarantee the collector's profit is higher than that in the case without a contract. We obtain the following optimal results by solving the above model utilizing the Lagrange multiplier method:

$$p_e{}^{**} = \frac{(a+b)\varphi + (1+2b)c_n}{2+4b}, \quad p_r^{**} = \frac{[(2b+1)(b-2\alpha+3)-\alpha-b]\varphi + (1+2b)^2 c_n}{4(1+2b)(1+b)},$$

$$w^{**} = \frac{(b-\alpha+1)\varphi + (1+2b)c_n}{2+4b}, \quad s_L^{**} = \pi_0 + \frac{\rho\sigma^2(t_L^{**}+\Delta)^2}{2} - \frac{(t_L^{**}+\Delta)^2 r_L^2}{2k} - (t_L^{**}+\Delta)q_0,$$

$$s_H^{**} = s_L^{**} + (t_L^{**} - t_H^{**})q_0 + \frac{\left(k\rho\sigma^2 - r_H^2\right)\left[(t_H^{**}+\Delta)^2 - (t_L^{**}+\Delta)^2\right]}{2k},$$

$$t_H^{**} = \frac{(\delta c_n - p_1)r_H^2 - k\rho\sigma^2\Delta}{r_H^2 + k\rho\sigma^2}, \quad t_L^{**} = \frac{(1-v)(\delta c_n - p_1)r_L^2 + v\Delta(r_L^2 - r_H^2) - (1-v)k\rho\sigma^2\Delta}{(1-v)(r_L^2 + k\rho\sigma^2) + v(r_H^2 - r_L^2)},$$

$$a_{HH}^{**} = (t_H^{**}+\Delta)r_H/k, \quad a_{HL}^{**} = (t_L^{**}+\Delta)r_H/k, \quad a_{LH}^{**} = (t_H^{**}+\Delta)r_L/k, \quad a_{LL}^{**} = (t_L^{**}+\Delta)r_L/k.$$

By substituting the equilibrium solutions obtained for the decision variables into the expected utility for the manufacturer, retailer, and collector, we obtain

$$E\left(\pi_M^{**}\right) = (p_e^{**} - c_n)q_e^{**} + (w^{**} - c_n)q_r^{**} + v[(\delta c_n - p_1 - t_H^{**})(q_0 + r_H a_{HH}^{**}) - s_H^{**}] + (1-v)[(\delta c_n - p_1 - t_L^{**})(q_0 + r_L a_{LL}^{**}) - s_L^{**}],$$

$$E(\pi_R^{**}) = (p_r^{**} - w^{**})[(1-\alpha)\varphi - p_r^{**} + b(p_e^{**} - p_r^{**})],$$

$$\mathrm{CE}(\pi_{CHH}^{**}) = \mathrm{CE}(\pi_{CHL}^{**}) = \pi_0 + (t_L^{**}+\Delta)^2\left(r_H^2 - r_L^2\right)/2k$$

$$\mathrm{CE}(\pi_{CLH}^{**}) = \pi_0 - (t_L^{**} + t_H^{**} + 2\Delta)(t_H^{**} - t_L^{**})\left(r_H^2 - r_L^2\right)/2k, \ \mathrm{CE}(\pi_{CLL}^{**}) = \pi_0.$$

The solution for the optimal results is given in Appendix A.2.

4.3. Analysis of SDCLSC and DDCLSC models

We obtain the optimal results by solving the SDCLSC and DDCLSC models. Next, we analyze the impact of asymmetric information and the sensitivity of market parameters by comparing these two models.

Proposition 4.1. *$a^* = a_{HH}^{**}$, $t^* = t_H^{**}$, $a^* > a_{LL}^{**}$, and $t^* > t_L^{**}$.*

Proposition 4.1 reveals that the collection effort level and unit payment of the high ability collector are unchanged in the two cases; however, the collection effort level and unit payment of the low ability collector decline. If single asymmetric information becomes double asymmetric information, the manufacturer reduces the unit payment for the low ability collector, and the collection quantity decreases with the low ability collector's collection effort level. The manufacturer cannot accurately obtain the collector's private information because of the information barrier between the manufacturer and the collector. Therefore, the manufacturer can only give the corresponding unit payment according to the collector's collection effort level as determined in the collector's signed contract to avoid losing profit.

Proposition 4.2. $\mathrm{CE}(\pi^{**}_{CLH}) < \mathrm{CE}(\pi^{*}_{C}) = \mathrm{CE}(\pi^{**}_{CLL}) = \pi_0 < \mathrm{CE}(\pi^{**}_{CHH}) = \mathrm{CE}(\pi^{**}_{CHL})$.

From Proposition 4.2, the expected utility of the low ability collector is unchanged, but that of the high ability collector increases from single asymmetric information to double asymmetric information. In addition, the low ability collector with double information asymmetry obtains less than the retained utility if he lies to the manufacturer about his collection ability. It can be seen from Proposition 4.1 that the manufacturer pays a lower unit payment to the collector. The expected utility of the high ability collector has nothing to do with whether the collector misrepresents his private information.

From a practical point of view, there is no need for the high ability collector to lie about his private information because he can compete with the low ability collector in the collection market. Therefore, the information screening contract can effectively identify the private information of both the low and high ability collectors and allow the low ability collector to truthfully report his private information to the manufacturer in the market.

Proposition 4.3. (i) $\frac{\partial t^*}{\partial q_0} = 0$, $\frac{\partial t^{**}_H}{\partial q_0} = \frac{\partial t^{**}_L}{\partial q_0} = 0$, $\frac{\partial s^*}{\partial q_0} < 0$, $\frac{\partial s^{**}_L}{\partial q_0} < 0$, *and* $\frac{\partial s^{**}_H}{\partial q_0} < 0$;

(ii) $\frac{\partial \mathrm{CE}(\pi^*_C)}{\partial q_0} = \frac{\partial \mathrm{CE}(\pi^{**}_{CHH})}{\partial q_0} = \frac{\partial \mathrm{CE}(\pi^{**}_{CLL})}{\partial q_0} = 0$, *and* $\frac{\partial E(\pi^*_M)}{\partial q_0} = \frac{\partial E(\pi^{**}_M)}{\partial q_0} > 0$.

Proposition 4.3 demonstrates that under single and double information asymmetry, the unit payment does not depend on consumers' environmental awareness, but the fixed payment decreases as their environmental awareness increases. Consumers' awareness of environmental protection constantly improves and the quantity of collection for which consumers are willing to provide their used electronic products for free also increases. However, the manufacturer does not increase the collector's unit payment. The price of products is determined by their value in the law of value; therefore, the value of used electronic products is unaffected by consumers' environmental awareness. Thus, the type of information asymmetry and consumers environmental awareness do not affect the unit payment. The manufacturer does not have to increase her fixed payment to the collector to increase the total quantity of WEEE collected. In contrast, the manufacturer reduces her fixed payments to save on expenditure, thereby increasing her expected profit. In addition, the collector's expected utility and the retailer's expected profit have nothing to do with consumers' environmental awareness, and the manufacturer's expected profit increases.

Proposition 4.4. $\partial t^{**}_H/\partial v = 0$, $\partial \mathrm{CE}(\pi^{**}_{CHH})/\partial v < 0$, $\partial t^{**}_L/\partial v < 0$, *and* $\partial \mathrm{CE}(\pi^{**}_{CLL})/\partial v = 0$.

From Proposition 4.4, the unit payment of the high ability collector never changes with the proportion of high ability collectors, the high ability collector's expected utility decreases. However, the unit payment of the low ability collector decreases with the proportion of high ability collectors; the low ability collector's expected utility never changes. As the number of high ability collector's increases, low ability collectors occupy less market share. Although the manufacturer does not raise the high ability collector's unit payment, the manufacturer's total payment to the collectors increase with the number of high ability collectors, thereby reducing the low ability collector's unit payment. According to Proposition 4.2, as long as the low ability collector truthfully reports his collection ability and effort to the manufacturer, he still obtains the reserved utility.

Proposition 4.5. *If* $1/2 < \alpha < 1 - c_n/\varphi$, *we have* $\frac{\partial p^*_e}{\partial \alpha} = \frac{\partial p^{**}_e}{\partial \alpha} > 0$, $\frac{\partial q^*_e}{\partial \alpha} = \frac{\partial q^{**}_e}{\partial \alpha} > 0$, $\frac{\partial w^*}{\partial \alpha} = \frac{\partial w^{**}}{\partial \alpha} < 0$, $\frac{\partial p^*_r}{\partial \alpha} = \frac{\partial p^{**}_r}{\partial \alpha} < 0$, *and* $\frac{\partial q^*_r}{\partial \alpha} = \frac{\partial q^{**}_r}{\partial \alpha} < 0$.

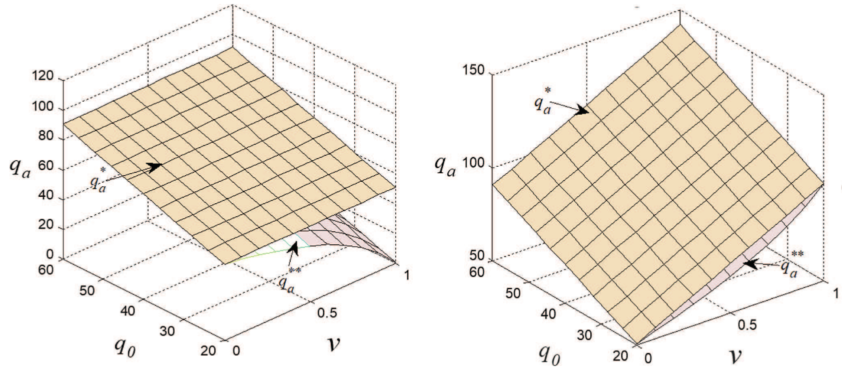

FIGURE 3. Low ability collector's collection quantity (*left*) and total collection quantity (*right*) *vs.* q_0 and v.

From Proposition 4.5, the manufacturer's e-channel prices and sales volumes increase to varying degrees as the market share of the e-channel increases, but the offline channel's wholesale prices and retail prices decline. To maintain a balance between the manufacturer's e-channel and retail channel, she must lower her wholesale prices to stimulate retailers to wholesale more of her products. Simultaneously, the retailer lowers its retail prices to attract more consumers to the offline channel. However, offline channel sales are still declining, which hurts the retailer's profits.

The above conclusion is valid if the market share of the e-channel is $1/2 < \alpha < 1 - c_n/\varphi$. Most of the manufacturer's profit comes from her offline channel and the retailer also obtains a larger profit if α is less than 0.5. The manufacturer's profit reaches its maximum value if α is greater than $1 - c_n/\varphi$. Meanwhile, the retailer's profit is 0, which does not match reality. Therefore, α will not be greater than $1 - c_n/\varphi$.

All proofs are given in Appendices A.3–A.7.

5. Numerical examples

To get a clearer presentation of the above propositions and deepen the obtained management insights, we further explore the DCLSC model using numerical simulation. Based on examining several companies in combination with actual situations [34, 43], we have $\delta = 0.55$, $\varphi = 250$, $\pi_0 = 400$, $q_0 = 30$, $k = 3$, $\rho = 3$, $\sigma = 3$, $b = 0.3$, $\alpha = 0.65$, $r_H = 8$, $r_L = 5$, $c_n = 50$, $p_1 = 20$, $p_2 = 18$, $\Delta = p_1 - p_2 = 2$, and $v \in (0, 1)$.

As depicted from Figure 3, the low ability collector's collection quantity and total collection quantity increase with consumers' environmental awareness under the SDCLSC and DDCLSC. The low ability collector's collection quantity is unchanged with the increasing proportion of high ability collectors under the SDCLSC. But, the low ability collector's collection quantity is decreasing with the proportion of high ability collectors under the SDCLSC. The low ability collector's collection quantity and total collection quantity increase with the proportion of high ability collectors under the SDCLSC and DDCLSC. Meanwhile, the total quantity of collection increases with the proportion of high ability collectors and consumers' environmental awareness. However, the total quantity of collection decreases with the type of asymmetric information. Double information asymmetry is worse than single information asymmetry for collecting WEEE. In summary, increased information asymmetry decreases the overall recycling amount, which is not conducive to recycling resources. The increase in the proportion of high ability collectors also discourages the low ability collector's enthusiasm. Thus, the manufacturer must take measures to screen the asymmetric information of other CLSC members to promote the collection and reuse of her used electronic products and reduce the waste of resources.

The manufacturer's expected profit obviously increases with the proportion of high ability collector's under double information asymmetry (Fig. 4). The high ability collector's expected utility decreases, which is always

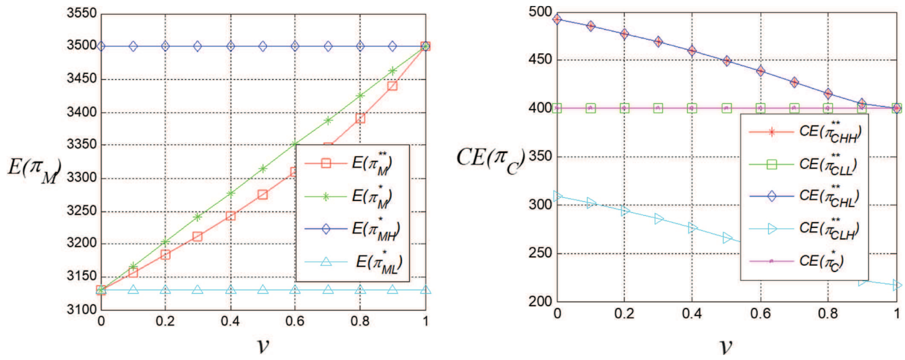

FIGURE 4. Expected profit for the manufacturer (*left*) and expected utility collector (*right*) *vs.* v.

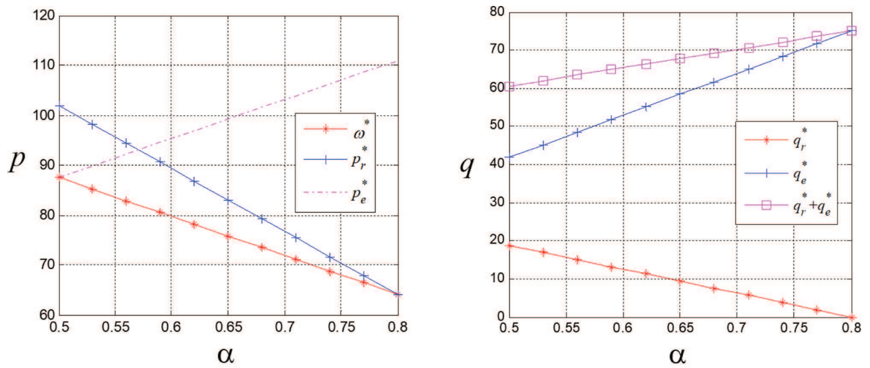

FIGURE 5. Price (*left*) and sales volume (*right*) *vs.* α.

higher than under single information asymmetry. The type of information asymmetry indicates that the higher the collection ability of collectors in the market, the smaller their competitive advantage and profit. Simultaneously, the low ability collector only obtains the retained utility. In single information asymmetry, the expected profit of the manufacturer who signs a contract with the high ability collector is higher than for a contract with the low ability collector. If the proportion of high ability collectors is the same under single and double information asymmetry, the manufacturer gains less expected profit under double information asymmetry and the collector's expected utility remains unchanged. This is the same result as Proposition 4.2. The high ability collector can obtain the same profit by truthfully reporting and misreporting private information under double information asymmetry. However, the rewards for pretending to have high ability collector are significantly lower than truthful reporting for the low ability collector. Therefore, the designed contract can effectively distinguish the collector's private information, *i.e.*, collectors with any collection ability cannot lie about their private information.

As shown in Figure 5, the increase in α causes the manufacturer to raise her e-channel price, while the wholesale and retail prices decrease. This trend is mainly because the manufacturer increases her e-channel price accordingly to obtain more profit; nevertheless, the manufacturer's offline channel must attract consumers because of the increased demand from potential e-channel customers. Therefore, the retail price declines, which is a way for retailers to increase their competitive power. In addition, we know that the increasing α reduces the offline channel's sales volume and improves the e-channel's sales volume. More importantly, the total volume of sales increases with α, when $1/2 < \alpha < 1 - c_n/\varphi$. The establishment of an e-channel increases the total amount of sales.

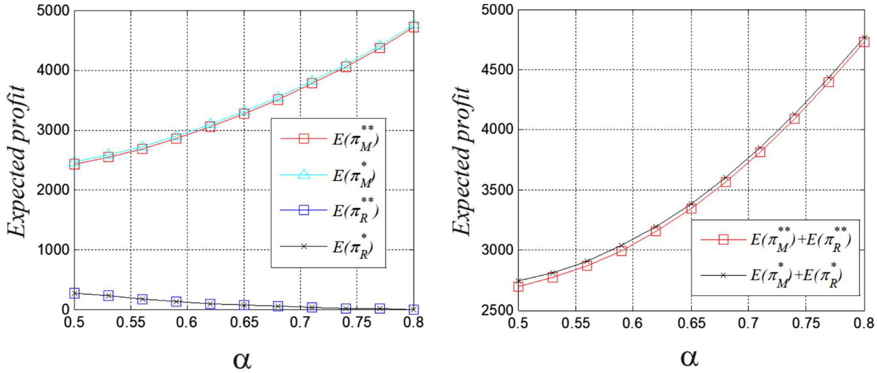

FIGURE 6. Expected profit for the manufacturer and retailer *vs.* α.

Figure 6 shows that the retailer's expected profit is unaffected by the type of information asymmetry, *i.e.*, the manufacturer's expected profit decreases with the type of information asymmetry. The manufacturer's expected profit simultaneously increases with α. Thus, the manufacturer must open an e-channel to obtain more expected profit. The retailer's expected profit decreases with α. When $\alpha = 0.8$, the retailer's expected profit is 0. The increased expected profit from the manufacturer's e-channel sacrifices the retailer's profit; thus, the e-channel does not boost the total profit for the manufacturer and the retailer. The e-channel does not change the total expected profit for all CLSC members because it only increases the manufacturer's expected profit. However, the offline channel allows people to quickly buy goods and provides an intuitive experience of the appearance, quality, and price of goods, which is still indispensable for people compared with the e-channel. Therefore, the retail industry is still vibrant in today's rapid development of the Internet of Things. According to the "Report on Chinas Home Appliances Market in the First Half of 2021," China's home appliance consumption will further migrate online. The contribution rate of manufacturer e-channels for home appliance reached 53.65% in the first half of 2021, which means that α was about 0.54.

6. Conclusions and managerial implications

This paper investigates a DCLSC, in which the manufacturer sells products through both an e-channel and an offline channel and delegates the collection of WEEE to a third-party collector with private information on his collection effort level and ability. Therefore, we design an information screening contract for the manufacturer to obtain this private information. Optimal decision-making results using the principal-agent theory are obtained by solving both models. The conclusions and managerial implications are as follows.

6.1. Conclusions

(i) The information screening contract effectively allows the manufacturer to obtain the collector's private information, which can prevent low ability collectors from misrepresenting their private information.

(ii) Asymmetric information has a negative effect on DCLSC stakeholders. The collection quantity decreases with the type of information asymmetry. Moreover, the low ability collector's expected utility and the manufacturer's expected profit are reduced if the collector's ability is private information. The high ability collector gains much expected utility from double information asymmetry. The retailer's expected profit is irrelevant to the collector's private information.

(iii) Enhancing consumers' environmental awareness can improve the quantity of collection and simultaneously boost the manufacturer's expected profit. The manufacturer's expected profit increases with the proportion of high ability collectors in the collection market, but the high ability collector's expected utility decreases.

The expected utility of the low ability collector who misrepresents his private information is lower than the reserved utility.

(iv) The e-channel increases total sales and leads to the decline of the offline channel. The increasing proportion of sales from the e-channel promotes market demand and raises the e-channel price, but curtails the offline channel's market demand. Overall, the total sales of the two channels increase. However, the manufacturer's e-channel does not change the total expected utility of all CLSC members because it only increases the manufacturer's expected profit.

6.2. Managerial insights

Some managerial insights for DCLSC enterprises are provided based on the above conclusions.

For manufacturers, enhancing their consumers' environmental awareness can boost their profits. Manufacturing enterprises may imperceptibly improve their consumers' environmental awareness by promoting recycling for environmental protection on their product packaging and describing consumers' active recycling practices in the advertising of their products. Manufacturers who obtain their partners' private information through designing an information screening contract also increase their profit. However, firms' private information is the core element of their competitiveness. If the information screening contract of manufacturers cannot obtain their partners' private information effectively, manufacturers can design other incentive mechanisms to encourage enterprises with core competitive information to share their private information. This may improve the profit of the whole CLSC. Furthermore, manufacturers may expand their e-channel market share to obtain more profit.

For retailers, the e-channel of manufacturers reduces their profit and recycling WEEE cannot bring profit to retailers. Retailers only boost their profit by improving their sales through their offline channel. Therefore, retailers can use their own advantages to provide their customers with better product experience and after-sales service to compete with manufacturers to obtain more profit, which will raise the retailer's costs. However, retailers do not lose too much profit by increasing the price of products properly because some customers consider factors such as time cost and then choose to purchase products from offline stores.

For collectors, hiding their private information can improve their profit. It is unnecessary for high ability collectors to lie about their private information when they accept the manufacturer's information screening contract, which will not bring extra income to high ability collectors. Low ability collectors obtain more profit only when they share their real private information. Low ability collectors thus should improve their collection ability through technological innovation, the introduction of advanced production lines, and management optimization. Otherwise, they will exit the market.

6.3. Further research directions

Several possible extensions are available for future research. The fierce competition between collectors regarding the quantity of WEEE collected is not considered in our two models; thus, we could consider a CLSC that consists of a manufacturer, a retailer, and multiple collectors in competition for future research. Dual collection channels and dual sales channels in CLSCs with multidimensional asymmetric information is another research direction that deserves to be explored.

Appendix A.

A.1. Solving the optimal solution for the SDCLSC model

Based on equation (6), we assume that $\partial \mathrm{CE}(\pi_C)/\partial a = (t+\Delta)r - ka = 0$, so we have

$$a^* = (t+\Delta)r/k. \tag{A.1}$$

Similarly, we take a partial derivative of equation (4) with respect to p_r. As $\partial \mathrm{CE}(\pi_R)/\partial p_r = (1-\alpha)\varphi - 2(1+b)p_r + bp_e + (1+b)w = 0$, we obtain

$$p_r^* = \frac{(1-\alpha)\varphi + bp_e + (1+b)w}{2(1+b)}. \tag{A.2}$$

Next, we substitute equations (A.1) and (A.2) into equation (3) and obtain the following formula:

$$E(\pi_M) = (p_e - c_n)\left[\alpha\varphi - (1+b)p_e + \frac{(1-\alpha)b\varphi + b^2 p_e + (1+b)bw}{2(1+b)}\right] + (w - c_n)[(1-\alpha)\varphi + bp_e - (1+b)w]/2 + (\delta c_n - p_1 - t)\left[q_0 + (t+\Delta)r^2/k\right] - s. \tag{A.3}$$

The manufacturer follows her own interests and there is no need to pay more to the collector. Therefore, in the best case, the participation constraint $\mathrm{CE}(\pi_C^*) = \pi_0$ holds according to the Kuhn–Tucker (K-T) condition. The fixed payment s is realized through a one-time payment and does not affect the marginal revenue of the CLSC. Therefore, the manufacturer's problem is to formulate unit payment t to encourage the collector to choose an optimal level of effort. At present, the fixed payment is

$$s^* = \pi_0 + \rho\sigma^2(t+\Delta)^2/2 - (t+\Delta)q_0 - (t+\Delta)^2 r^2/2k. \tag{A.4}$$

By substituting equation (A.4) into equation (A.3), we get

$$E(\pi_M) = (p_e - c_n)\left[\alpha\varphi - (1+b)p_e + \frac{(1-\alpha)b\varphi + b^2 p_e + (1+b)bw}{2(1+b)}\right] + (w - c_n)[(1-\alpha)\varphi + bp_e - (1+b)w]/2 + (\delta c_n - p_1 - t) \times \left[q_0 + (t+\Delta)r^2/k\right] - \left[\pi_0 + \rho\sigma^2(t+\Delta)^2/2 - (t+\Delta)q_0 - (t+\Delta)^2 r^2/2k\right]. \tag{A.5}$$

Taking a partial derivative of equation (A.5) with respect to t, p_e, w, we respectively obtain

$$\partial\mathrm{CE}(\pi_M)/\partial t = -\left[q_0 + (t+\Delta)r^2/k\right] + (\delta c_n - p_1 - t)r^2/k - \rho\sigma^2(t+\Delta) + \left[q_0 + (t+\Delta)r^2/k\right] \tag{A.6}$$

$$\frac{\partial\mathrm{CE}(\pi_M)}{\partial p_e} = \frac{(2\alpha + b + \alpha b)\varphi}{2(1+b)} + bw - \frac{2+4b+b^2}{1+b}p_e + \frac{2+3b}{2(1+b)}c_n \tag{A.7}$$

$$\frac{\partial\mathrm{CE}(\pi_M)}{\partial w} = c_n/2 + (1-\alpha)\varphi/2 + bp_e - (1+b)w. \tag{A.8}$$

The Hessian matrix of $E(\pi_M)_{(p_e,w,t)}$ is $H = \begin{bmatrix} -\frac{2+4b+b^2}{1+b} & b & 0 \\ b & -(1+b) & 0 \\ 0 & 0 & -(\frac{r^2}{k} + \rho\sigma^2) \end{bmatrix}$. We use the d_l $(l = 1,2,3)$ represents the order master of this matrix. We have $d_l = -\frac{2+4b+b^2}{1+b} < 0$, $d_2 = 2 + 4b > 0$, and $d_3 = -(2 + 4b)(\frac{r^2}{k} + \rho\sigma^2)$. They satisfy the negative definite conditions of the Hessian matrix.

As $\partial\mathrm{CE}(\pi_M)/\partial t = 0$, $\partial\mathrm{CE}(\pi_M)/\partial p_e = 0$, and $\partial\mathrm{CE}(\pi_M)/\partial w = 0$, by solving these equations, we get equations (A.9)–(A.11).

$$t^* = \frac{(\delta c_n - p_1)r^2 - k\rho\sigma^2\Delta}{r^2 + k\rho\sigma^2} \tag{A.9}$$

$$p_e^* = \frac{(\alpha+b)\varphi + (1+2b)c_n}{2+4b} \tag{A.10}$$

$$w^* = \frac{(b-\alpha+1)\varphi + (1+2b)c_n}{2+4b}. \tag{A.11}$$

By substituting equations (A.9), (A.10), and (A.11) into equations (A.1), (A.2), and (A.4), we get the following optimal solution:

$$a^* = (t^* + \Delta)r/k, \tag{A.12}$$

$$p_r^* = \frac{[(2b+1)(b-2\alpha+3) - \alpha - b]\varphi + (1+2b)^2 c_n}{4(1+2b)(1+b)} \tag{A.13}$$

$$s^{*}=\pi_{0}+\rho\sigma^{2}(t^{*}+\Delta)^{2}/2-(t^{*}+\Delta)q_{0}-(t^{*}+\Delta)^{2}r^{2}/2k. \tag{A.14}$$

By substituting equations (A.9), (A.14) into equations (3), (4), and (6), we obtain the expected profits for the manufacturer, retailer, and the expected utility collector

$$E(\pi_{M}^{*})=(p_{e}^{*}-c_{n})q_{e}^{*}+(w^{*}-c_{n})q_{r}^{*}+(\delta c_{n}-p_{1}-t^{*})(q_{0}+ta^{*})-s^{*} \tag{A.15}$$

$$E(\pi_{R}^{*})=(p_{r}^{*}-w^{*})[(1-\alpha)\varphi-p_{r}^{*}+b(p_{e}^{*}-p_{r}^{*})]. \tag{A.16}$$

$$\mathrm{CE}(\pi_{C}^{*})=\pi_{0}. \tag{A.17}$$

A.2. Solving the optimal solution for the DDCLSC model

According to equations (13)–(16), the collector's optimal collection effort level is obtained with the first-order optimal conditions. We assume that

$$\partial\mathrm{CE}(\pi_{CHH})/\partial a_{HH}=(\Delta+t_{H})r_{H}-ka_{HH}=0 \tag{A.18}$$

$$\partial\mathrm{CE}(\pi_{CHL})/\partial a_{HL}=(\Delta+t_{L})r_{H}-ka_{HL}=0 \tag{A.19}$$

$$\partial\mathrm{CE}(\pi_{CLH})/\partial a_{LH}=(\Delta+t_{H})r_{L}-ka_{LH}=0 \tag{A.20}$$

$$\partial\mathrm{CE}(\pi_{CLL})/\partial a_{LL}=(\Delta+t_{L})r_{L}-ka_{LL}=0. \tag{A.21}$$

Next, we can further obtained the following:

$$a_{HH}^{**}=(t_{H}+\Delta)r_{H}/k \tag{A.22}$$

$$a_{HL}^{**}=(t_{L}+\Delta)r_{H}/k \tag{A.23}$$

$$a_{LH}^{**}=(t_{H}+\Delta)r_{L}/k \tag{A.24}$$

$$a_{LL}^{**}=(t_{L}+\Delta)r_{L}/k. \tag{A.25}$$

According to equation (10), calculating the first-order partial derivatives with respect to p_r, as well as making it equal to 0, we obtain the following:

$$p_{r}^{**}=\frac{(1-\alpha)\varphi+bp_{e}+(1+b)w}{2(1+b)}\cdot \tag{A.26}$$

Next, we substitute equations (A.22)–(A.26) into equation (9) and obtain the following formulas:

$$\begin{aligned}E(\pi_{M})=(p_{e}-c_{n})&\left[\alpha\varphi-(1+b)p_{e}+\frac{(1-\alpha)b\varphi+b^{2}p_{e}+(1+b)bw}{2(1+b)}\right]+(w-c_{n})/2\\&\times[(1-\alpha)\varphi+bp_{e}-(1+b)w]+v\{(\delta c_{n}-p_{1}-t_{H})[q_{0}+(t_{H}+\Delta)r_{H}^{2}/k]-s_{H}\}\\&+(1-v)\{(\delta c_{n}-p_{1}-t_{L})[q_{0}+(t_{H}+\Delta)r_{H}^{2}/k]-s_{H}\}\end{aligned} \tag{A.27}$$

s.t.

$$\begin{aligned}&(t_{H}+\Delta)q_{0}+s_{H}+(t_{H}+\Delta)^{2}r_{H}^{2}/2k-\rho\sigma^{2}(t_{H}+\Delta)^{2}/2\\&\quad\geq(t_{L}+\Delta)q_{0}+s_{L}+(t_{L}+\Delta)^{2}r_{L}^{2}/2k-\rho\sigma^{2}(t_{L}+\Delta)^{2}/2\end{aligned} \tag{A.28}$$

$$\begin{aligned}&(t_{L}+\Delta)q_{0}+s_{L}+(t_{L}+\Delta)^{2}r_{L}^{2}/2k-\rho\sigma^{2}(t_{L}+\Delta)^{2}/2\\&\quad\geq(t_{H}+\Delta)q_{0}+s_{H}+(t_{H}+\Delta)^{2}r_{L}^{2}/2k-\rho\sigma^{2}(t_{H}+\Delta)^{2}/2\end{aligned} \tag{A.29}$$

$$(t_{H}+\Delta)q_{0}+s_{H}+(t_{H}+\Delta)^{2}r_{H}^{2}/2k-\rho\sigma^{2}(t_{H}+\Delta)^{2}/2\geq\pi_{0} \tag{A.30}$$

$$(t_{L}+\Delta)q_{0}+s_{L}+(t_{L}+\Delta)^{2}r_{L}^{2}/2k-\rho\sigma^{2}(t_{L}+\Delta)^{2}/2\geq\pi_{0}. \tag{A.31}$$

According to equations (A.28) and (A.31), we have

$$(t_{H}+\Delta)q_{0}+s_{H}+(t_{H}+\Delta)^{2}r_{H}^{2}/2k-\rho\sigma^{2}(t_{H}+\Delta)^{2}/2$$

$$
\begin{aligned}
&\geq (t_L+\Delta)q_0 + s_L + (t_L+\Delta)^2 r_H^2/2k - \rho\sigma^2(t_L+\Delta)^2/2\\
&(t_L+\Delta)q_0 + s_L + (t_L+\Delta)^2 r_L^2/2k - \rho\sigma^2(t_L+\Delta)^2/2\\
&\quad + (t_L+\Delta)^2\left(r_H^2 - r_L^2\right)/2k \geq \pi_0 + (t_L+\Delta)^2\left(r_H^2 - r_L^2\right)/2k.
\end{aligned}
$$

Therefore, equation (A.30) may be omitted. Next, we apply the Lagrange multiplier method to solve the information screening contract parameters. The relative Lagrange multiplier of equations (A.28), (A.29), and (A.31) are denoted by λ, μ and γ, respectively. We obtain the following Kuhn–Tucker (K-T) optimal conditions:

$$\frac{\partial L}{\partial p_e} = \frac{(2\alpha + b + \alpha b)\varphi}{2(1+b)} + bw - \frac{2+4b+b^2}{1+b}p_e + \frac{2+3b}{2(1+b)}c_n = 0 \tag{A.32}$$

$$\partial L/\partial w = c_n/2 + (1-\alpha)\varphi/2 + bp_e - (1+b)w = 0 \tag{A.33}$$

$$\partial L/\partial s_H = -v + \lambda - \mu = 0 \tag{A.34}$$

$$\partial L/\partial s_L = -(1-v) - \lambda + \mu + \gamma = 0 \tag{A.35}$$

$$
\begin{aligned}
\partial L/\partial t_H = {}& v\left\{-\left[q_0 + (t_H+\delta)r_H^2/k\right] + (\delta c_n - p_1 - t_H)r_H^2/k\right\}\\
&+ \lambda\left[q_0 + (t_H+\Delta)r_H^2/k - \rho\sigma^2(t_H+\delta)\right] + \mu\left[-q_0 - (t_H+\Delta)r_L^2/k + \rho\sigma^2(t_H+\delta)\right] = 0
\end{aligned} \tag{A.36}
$$

$$
\begin{aligned}
\partial L/\partial t_L = {}& (1-v)\left\{-\left(\left[q_0 + (t_L+\delta)r_L^2/k\right]\right) + (\delta c_n - p_1 - t_L)r_L^2/k\right\}\\
&- \lambda\left[q_0 + (t_L+\Delta)r_H^2/k - \rho\sigma^2(t_L+\delta)\right] + \mu\left[q_0 + (t_L+\Delta)r_L^2/k - \rho\sigma^2(t_L+\delta)\right]\\
&+ \gamma\left[q_0 + (t_L+\Delta)r_L^2/k - \rho\sigma^2(t_L+\delta)\right] = 0.
\end{aligned} \tag{A.37}
$$

From equations (A.34) and (A.35), we know that $\gamma = 1$ and $\lambda = v + \mu > 0$. Furthermore, we obtain $\mu = 0$. (Disproof: we assume that $\mu > 0$, and according to the K-T condition, the inequality constraint equation (A.29) is equal to 0. Similarly, the inequality constraints, equations (A.28) and (A.31), are also equal to 0, and we have $s_H = s_L$ and $t_H = t_L$. The high and low ability collectors choose the same information screening contract. The manufacturer's profit decreases and the high ability collector is dissatisfied with this matter because the supply chain cannot be balanced. Therefore, the assumption $\mu > 0$ is not tenable and we obtain $\mu = 0$.)

Giving that $\gamma = 1 > 0$, we take the equal sign of equation (A.31) and obtain $\mathrm{CE}(\pi_{CLL}^{**}) = \pi_0$. Based on the value of λ, μ, γ, and equations (A.32)–(A.37), we have

$${p_e}^{**} = \frac{(a+b)\varphi + (1+2b)c_n}{2+4b} \tag{A.38}$$

$$w^{**} = \frac{(b-\alpha+1)\varphi + (1+2b)c_n}{2+4b} \tag{A.39}$$

$$t_H^{**} = \frac{(\delta c_n - p_1)r_H^2 - k\rho\sigma^2\Delta}{r_H^2 + k\rho\sigma^2} \tag{A.40}$$

$$t_L^{**} = \frac{(1-v)(\delta c_n - p_1)r_L^2 + v\Delta(r_L^2 - r_H^2) - (1-v)k\rho\sigma^2\Delta}{(1-v)(r_L^2 + k\rho\sigma^2) + v(r_H^2 - r_L^2)} \tag{A.41}$$

$$s_L^{**} = \pi_0 + \frac{\rho\sigma^2(t_L^{**}+\Delta)^2}{2} - \frac{(t_L^{**}+\Delta)^2 r_L^2}{2k} - (t_L^{**}+\Delta)q_0 \tag{A.42}$$

$$s_H^{**} = s_L^{**} + (t_L^{**} - t_H^{**})q_0 + \frac{\left(k\rho\sigma^2 - r_H^2\right)\left[(t_H^{**}+\Delta)^2 - (t_L^{**}+\Delta)^2\right]}{2k}. \tag{A.43}$$

By substituting equations (A.38)–(A.43) into equations (A.22)–(A.26), we obtain the optimal solution:

$$a_{HH}^{**} = (t_H^{**}+\Delta)r_H/k \tag{A.44}$$

$$a_{HL}^{**} = (t_L^{**}+\Delta)r_H/k \tag{A.45}$$

$$a_{LH}^{**} = (t_H^{**}+\Delta)r_L/k \tag{A.46}$$

$$a_{LL}^{**} = (t_L^{**} + \Delta)r_L/k \tag{A.47}$$

$$p_r^{**} = \frac{[(2b+1)(b-2\alpha+3)-\alpha-b]\varphi + (1+2b)^2 c_n}{4(1+2b)(1+b)}. \tag{A.48}$$

By substituting equations (A.38)–(A.48) into equations (9), (10) and equations (13)–(16), we obtain the expected profits for the manufacturer, retailer, and the expected utility collector

$$\begin{aligned} E(\pi_M^{**}) &= (p_e^{**} - c_n)q_e^{**} + (w^{**} - c_n)q_r^{**} + v[(\delta c_n - p_1 - t_H^{**})(q_0 + r_H a_{HH}^{**}) - s_H^{**}] \\ &\quad + (1-v)[(\delta c_n - p_1 - t_L^{**})(q_0 + r_L a_{LL}^{**}) - s_L^{**}] \end{aligned} \tag{A.49}$$

$$E(\pi_R^{**}) = (p_r^{**} - w^{**})[(1-\alpha)\varphi - p_r^{**} + b(p_e^{**} - p_r^{**})] \tag{A.50}$$

$$\mathrm{CE}(\pi_{CHH}^{**}) = \mathrm{CE}(\pi_{CHL}^{**}) = \pi_0 + (t_L^{**} + \Delta)^2 (r_H^2 - r_L^2)/2k \tag{A.51}$$

$$\mathrm{CE}(\pi_{CLH}^{**}) = \pi_0 - (t_L^{**} + t_H^{**} + 2\Delta)(t_H^{**} - t_L^{**})(r_H^2 - r_L^2)/2k \tag{A.52}$$

$$\mathrm{CE}(\pi_{CLL}^{**}) = \pi_0. \tag{A.53}$$

A.3. Proof of Proposition 4.1

Proof. We have $t^* - t_L^{**} = \frac{v(r_H^2 - r_L^2)[(\delta c_n - p_1)r^2 - k\rho\sigma^2\Delta] + k\rho\sigma^2\Delta(1-v)(r_L^2 + r^2)}{[(1-v)(r_L^2 + k\rho\sigma^2) + v(r_H^2 - r_L^2)](r^2 + k\rho\sigma^2)}$ according to equations (A.9) and (A.41). Due to $0 < v < 1$, $r_H > r_L$, and $(\delta c_n - p_1)r^2 > k\rho\sigma^2\Delta$, and we obtain $t^* > t_L^{**}$.

Based on $a^* = (t^* + \Delta)r/k$ and $a_{LL}^{**} = (t_L^{**} + \Delta)r_L/k$, we have $a^* > a_{LL}^{**}$. Furthermore, as $t_H^{**} = \frac{(\delta c_n - p_1)r_H^2 - k\rho\sigma^2\Delta}{r_H^2 + k\rho\sigma^2}$ and $r = r_H$, we obtain $t^* = t_H^{**}$. According to $a^* = (t^* + \Delta)r/k$ and $a_{HH}^{**} = (t_H^{**} + \Delta)r_H/k$, we obtain $a^* = a_{HH}^{**}$. □

A.4. Proof of Proposition 4.2

Proof. According to $\mathrm{CE}(\pi_C^*) = \pi_0$ and $\mathrm{CE}(\pi_{CLL}^{**}) = \pi_0$, we know that $\mathrm{CE}(\pi_C^*) = \mathrm{CE}(\pi_{CLL}^{**}) = \pi_0$. Based on $\mathrm{CE}(\pi_{CHH}^{**}) = \pi_0 + (t_L^{**} + \Delta)^2(r_H^2 - r_L^2)/2k$, we have $\mathrm{CE}(\pi_C^*) < \mathrm{CE}(\pi_{CHH}^{**})$. In addition, we have $\mathrm{CE}(\pi_{CHH}^{**}) = \mathrm{CE}(\pi_{CHL}^{**})$.

Moreover, we have $\mathrm{CE}(\pi_{CLL}^{**}) - \mathrm{CE}(\pi_{CLH}^{**}) = (t_L^{**} + t_H^{**} + 2\Delta)(t_H^{**} - t_L^{**})(r_H^2 - r_L^2)/2k$ according to equations (A.53) and (A.52). Because of $t^* = t_H^{**}$ and $t^* > t_L^{**}$, we have $t_H^{**} > t_L^{**}$, *i.e.*, $\mathrm{CE}(\pi_{CLL}^{**}) > \mathrm{CE}(\pi_{CLH}^{**})$. □

A.5. Proof of Proposition 4.3

Proof. Taking the partial derivative of equations (A.4) and (A.9) with respect to q_0, we have $\partial s^*/\partial q_0 = -(t^* + \Delta) < 0$ and $\partial t^*/\partial q_0 = 0$, respectively.

From equations (A.31) and (A.32), we know that $\partial t_H^{**}/\partial q_0 = \partial t_L^{**}/\partial q_0 = 0$. Similarly, from equations (A.33) and (A.34), we obtain $\partial s_L^{**}/\partial q_0 = -(t_L^{**} + \Delta) < 0$ and $\partial s_H^{**}/\partial q_0 = -(t_H^{**} + \Delta) < 0$.

According to $\mathrm{CE}(\pi_C^*) = \pi_0$, $\mathrm{CE}(\pi_{CHH}^{**}) = \pi_0 + (t_L^{**} + \Delta)^2(r_H^2 - r_L^2)/2k$, and $\mathrm{CE}(\pi_{CLL}^{**}) = \pi_0$, we know that $\partial\mathrm{CE}(\pi_C)^*/\partial q_0 = \partial\mathrm{CE}(\pi_{CHH}^{**})/\partial q_0 = \partial\mathrm{CE}(\pi_{CLL}^{**})/\partial q_0 = 0$.

From $E(\pi_M^*) = (p_e^* - c_n)q_e^* + (w^* - c_n)q_r^* + (\delta c_n - p_1 - t^*)(q_0 + ta^*) - s^*$, we obtain $\partial\mathrm{CE}(\pi_M^*)/\partial q_0 = (\delta c_n - p_1 - t^*) - \partial s^*/\partial q_0 = \delta c_n - p_1 + \Delta$. From assumption (4), we obtain $\partial\mathrm{CE}(\pi_M)^*/\partial q_0 > 0$. Furthermore, based on $E(\pi_M^{**}) = (p_e^{**} - c_n)q_e^{**} + (w^{**} - c_n)q_r^{**} + v[(\delta c_n - p_1 - t_H^{**})(q_0 + r_H a_{HH}^{**}) - s_H^{**} + (1-v)[(\delta c_n - p_1 - t_L^{**})(q_0 + r_L a_{LL}^{**}) - s_L^{**}]$, we have $\partial\mathrm{CE}(\pi_M^{**})/\partial q_0 = \delta c_n - p_1 + \Delta > 0$. □

A.6. Proof of Proposition 4.4

Proof. Taking the partial derivative of equations (A.30) and (A.31) with respect to v, we obtain $(\partial t_H^{**})/\partial v = 0$ and $(\partial t_L^{**})/\partial v = -\frac{r_L^2(r_H^2 - r_L^2)(\Delta + \delta c_n - p_1)}{[(1-v)(r_L^2 + k\rho\sigma^2) + v(r_H^2 - r_L^2)]^2}$, respectively.

Based on $\mathrm{CE}(\pi_{CHH}^{**}) = \mathrm{CE}(\pi_{CHL}^{**}) = \pi_0 + (t_L^{**} + \Delta)^2(r_H^2 - r_L^2)/2k$, $\mathrm{CE}(\pi_{CLL}^{**}) = \pi_0$, and the above analysis results, we have and $\partial\mathrm{CE}(\pi_{CLL}^{**})/\partial v = 0$. □

A.7. Proof of Proposition 4.5

Proof. According to the assumption in Section 2.2, we know that the price must be satisfied with $p_e^* - w^* = \frac{(2\alpha-1)\varphi}{2+4b} > 0$ and $p_r^* - w^* = \frac{(1+2b)[(1-\alpha)\varphi - c_n]}{2(1+b)(2+4b)} > 0$. Therefore, α must satisfy $1/2 < \alpha < 1 - c_n/\varphi$. Due to $p_e^* = p_e{}^{**} = \frac{(a+b)\varphi+(1+2b)c_n}{2+4b}$, $w^* = w^{**} = \frac{(b-\alpha+1)\varphi+(1+2b)c_n}{2+4b}$, $p_r^* = p_r^{**} = \frac{[(2b+1)(b-2\alpha+3)-\alpha-b]\varphi+(1+2b)^2 c_n}{4(1+2b)(1+b)}$, $q_r^{**} = \frac{(1-\alpha)\varphi - c_n}{4}$, and $q_e^{**} = \frac{(2\alpha+\alpha b+b)\varphi-(2+3b)c_n}{4(1+b)}$.

We take the partial derivative of the above equations with respect to α, and we have $\frac{\partial p_e^*}{\partial\alpha} = \frac{\partial p_e^{**}}{\partial\alpha} = \frac{\varphi}{2+4b} > 0$, $\frac{\partial w^*}{\partial\alpha} = \frac{\partial w^{**}}{\partial\alpha} = \frac{-\varphi}{2+4b} < 0$, $\frac{\partial p_r^*}{\partial\alpha} = \frac{\partial p_r^{**}}{\partial\alpha} = \frac{-(4b+3)\varphi}{4(1+2b)(1+b)} < 0$, $\frac{\partial q_e^*}{\partial\alpha} = \frac{\partial q_e^{**}}{\partial\alpha} = \frac{(4b+3)\varphi}{4(1+2b)(1+b)} > 0$, and $\frac{\partial q_r^*}{\partial\alpha} = \frac{\partial q_r^{**}}{\partial\alpha} = \frac{-\varphi}{4} < 0$, respectively. □

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