Information sharing in a collectors-led closed-loop supply chain

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Abstract: This paper considers a closed-loop supply chain (CLSC) in which two collectors provide used products to a manufacturer for remanufacturing. The collectors act as the channel leader, while the manufacturer is the follower and possesses private demand forecast information. We aim to investigate the manufacturer's information sharing strategy and the effect of different information sharing strategies on the participants in the CLSC. We find that the manufacturer has an incentive to share its demand forecast information with the collectors. When the collectors' investment cost-efficiency is high, the manufacturer prefers to share its information with only one collector. Under this scenario, the collector obtains the highest expected profit in all the information sharing cases. In addition, when the investment cost-efficiency is low, the manufacturer is willing to share its information with both collectors.

Keywords: information sharing; closed-loop supply chain; waste collection; game theory

1. Introduction

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With the development of society, more and more waste electrical and electronic equipment (WEEE) is produced in the world. In WEEE, there are hundreds of chemical materials, and a lot of the materials are harmful to human health if not handled properly, such as the lead, mercury, cadmium and beryllium. Moreover, there are some valuable metals in WEEE, such as the gold, silver and titanium. These valuable metals can be extracted and bring economic value for the corporations (Wang et al. 2019). In view of the environmental hazards and economic value of the WEEE, many countries enact related legislations to encourage the WEEE collection and remanufacturing. In Europe, the legislation "WEEE Directive (Directive2003/108/EC)" states that the manufacturers should take financial responsibility for the WEEE collection. Similar legislations can also be seen in US, Japan and China (Wang et al. 2015). As a result, many manufacturers, such as Xerox, Canon, IBM and Caterpillar, build their used product collection and remanufacturing systems either by themselves or by a third party (Choi et al. 2013, Wu and Zhou 2017 and Huang and Wang 2017).

In practice, there are generally three participants in a closed-loop supply chain (CLSC): the manufacturer, the retailer and the third-party collector, and any one of them can undertake collecting used products (Savaskan et al. 2004). Traditionally, in the CLSC, the manufacturer is the channel leader which offers contracts to the collector, such as the Xerox, Apple and Toyota (Wang et al. 2015). However, in recent years, as the collector has developed, some collectors start to play a leadership role in the corresponding CLSC, such as IBM's Global Asset Recovery Services, ReCellular and SIMS Metal Management (Karakayali et al. 2007 and Choi et al. 2013). These collectors are known for the used product collection. We take the IBM as the example. Recognizing the growing importance of reverse logistics flows, IBM established the Global Asset Recovery Services (GARS) organization in late 1998, whose responsibility is to manage the dispositioning of returned items. GARS operates some 25 facilities all over the globe where returns are collected and inspected. It assesses which returned item may be remarketable, either 'as is' or after a refurbishment process. For this purpose, IBM operates nine refurbishment centers worldwide, each dedicated to a specific product range. In particular, after dismantling the returned item, the generic components may be sold on the open market and the remainder is broken down into recyclable material fractions, which are sold to external recyclers (Grenchus et al., 2001; Fleischmann et al., 2004). Thus, one can see that the existence of a CLSC with upstream collectors and downstream corporations is quite common in practice.

Another focal problem that has attracted extensive theoretical and practical attention is information asymmetry between the upstream collectors and the manufacturer in the CLSC. In reality, because of the lack of detailed sell-through data, collectors couldn't adequately observe the product demand information. By comparison, the manufacturer can more easily acquire superior demand information than can upstream collectors. For example, IBM and Hewlett-Packard routinely require their resellers to provide them with the sell-through data and make a product demand forecast to reduce risk through analyzing the data (Lee and Whang 2000). Thus, collectors may have to rely on the manufacturer for product demand information. In the CLSC, the collectors decide the collection investment, collection rate and transfer price of used products based on the product demand information. And then the manufacturer decides the product prices considering the above decisions and product demand information. Thus, product demand information has important effects on the expected profits of the manufacturer and collectors. Hence, it naturally generates the following research problems: Does the manufacturer have an incentive to share its private demand forecast information with the upstream collectors? If yes, how should it selectively share its information with the collectors? What are the information sharing preferences of the collectors? What are the effects of different information sharing arrangements on the CLSC decisions? To address these questions, in this paper, we consider a CLSC with one manufacturer and two collectors. The collectors act as the channel leader, while the manufacturer is the follower and has the private demand forecast information. The manufacturer could choose to share its demand forecast information with the collectors or not. Therefore, there are three information sharing cases in the CLSC: (1) no information sharing, (2) the manufacturer sharing information with only one collector, (3) the manufacturer sharing information with both collectors. In our paper, we focus on investigating the information sharing strategies of the manufacturer, and examining the effect of the different information sharing strategies on the CLSC.

The main contributions of this paper are presented as follows: Firstly, we consider a collectors-led CLSC structure, in which the collectors are the channel leaders which offer contracts to the manufacturer. As the collector has developed, this CLSC structure is common in practice. However, few scholars study it. Secondly, we extend the theme of information sharing in the CLSC. We examine the information sharing strategy of the manufacturer in a collectors-led CLSC. The manufacturer should not only decide whether to share its information with the collectors, but also the number of the collectors it shares with, which is a realistic and important topic. Thirdly, conventional wisdom and a lot of literature suggest that the downstream corporation should not share its information with its upstream corporations in the supply chain, because it will hurt itself but benefit the upstream corporations if it shares. However, we find that, in the collectors-led CLSC, the downstream manufacturer has an incentive to share its information. And we show the conditions under which the manufacturer should share its information with only one collector or both collectors. Our research results provide important managerial implications for the participants in the CLSC.

The rest of this paper is organized as follows: In the next section, the relevant literature is presented. In section 3, we describe the problem and make some assumptions. In section 4, we build the different information sharing models and obtain the equilibrium solutions through backward induction. In section 5, by comparing the different information sharing cases, we get the manufacturer's information sharing preference and the impact of the different information sharing strategies on the CLSC. Finally, section 6 draws a conclusion of this paper.

2. Literature review

Our work is closely related to two research streams, that is, information sharing in the supply chains and remanufacturing in CLSCs.

2.1. Information sharing in the supply chains

Information sharing in supply chains has been intensively investigated in recent years. After an excellent survey of the literature, it shows that most of the studies focus on the impacts of information sharing on the forward supply chain (Li 2002, Yue and Liu 2006, Ha and Tong 2008, Ha et al. 2011, Shang et al. 2016, Ha et al. 2017 and Zhang et al. 2018). In the latest literature, Wu et al. (2019) investigate the information sharing issues in a supply chain with multiple suppliers and two retailers. Zhang et al. (2019) study the impact of information sharing on the dual-channel supply chain and derive the conditions under which the manufacturer should give up its pricing power. Guan et al. (2020) discuss the influence of manufacturer-provided service on the information sharing issues in two competing supply chains. Lei et al. (2020) explore the issue of ex post demand information sharing in a supply chain with two suppliers and one retailer. Xing et al. (2020) investigate the information sale issue in a supply chain with one supplier and multiple manufacturers. Wang et al. (2020) explore the intermediary's information sharing strategies in an online retailing supply chain. Yu et al. (2020) study the impact of demand information sharing on the carbon emission reduction in supply chains. Wang et al. (2020) analyze the influence of information sharing on a supply chain with a contract manufacturer, and the results shows that information sharing is beneficial for original equipment manufacturer when the wholesale price is exogenous. Wang et al. (2021) study the interaction between information sharing and information leakage in a two-echelon supply chain.

The above studies mainly explore the issues of information sharing in the forward supply chain, however, few scholars explore the information sharing issues in the reverse supply chain. Recently, several researchers are aware of these issues. Zhang et al. (2014) investigate the issue of contract design in a closed-loop supply chain with asymmetric cost information. Hosoda et al. (2015) study the effect of information sharing on a closed loop supply chain with uncertain market demands and product returns. Wang et al. (2017) design a reward-penalty mechanism in a closed-loop supply chain with asymmetric information on the collection effort level. Huang and Wang (2017) explore the influence of information sharing on a closed-loop supply chain under supplier-remanufacturing and manufacturer-remanufacturing scenarios. Zhang and Xiong (2017) consider a CLSC with one manufacturer and one retailer in which both of them have demand forecast information and the manufacturer is responsible for collecting and remanufacturing. They investigate the information sharing problem under "make-to-order" and "make-to-stock" scenarios. Our paper differs from Zhang and Xiong (2017) in two aspects. One is that we consider a CLSC with two collectors and one manufacturer. The collectors collect the used products and then sell them to the manufacturer for remanufacturing. The other is that we mainly study the influence of the manufacturer's information sharing strategy on the collectors-led CLSC. Huang and Wang (2020) study the effect of information sharing and learning effect on a closed-loop supply chain with technology licensing. Wang et al. (2021) focuses on the influence of information sharing modes on the dual-channel closed-loop supply chains. Huang et al. (2021) investigate the demand information sharing value of the retailer in a dual-channel closed-loop supply chain.

In our paper, we also examine the demand information sharing in a CLSC. However, different from the above works, we consider a CLSC in which two upstream collectors collect different used products and then sell them to the downstream manufacturer for remanufacturing. The collectors are the channel leader and there is product competition. We try to examine the demand information sharing effects on this type of CLSC. To our best knowledge, none of existing literature studies this issue. Thus, our paper enriches this line of research.

2.2. Remanufacturing in CLSCs

In the recent past, remanufacturing in CLSCs has received extensive attention for the scholars. In most of existing literature, the researchers explore the related issues considering that the manufacturers act as Stackelberg leaders (Savaskan et al. 2004, Savaskan and Wassenhove 2006, Atasu et al. 2013, Huang et al. 2013, Ma et al. 2016, Wu and Zhou 2017 and Jena et al. 2018). In the latest literature, Wang et al. (2019)

consider that the manufacturer is the Stackelberg leader and investigate the government's carrot/stick mechanisms for the collection responsibility sharing in a multi-tier CLSC. Zheng et al. (2019) study the influence of different power structures on the manufacturer's encroachment strategy in a CLSC. Wang et al. (2020) explore the collusive behavior of retailers in a CLSC with one manufacturer and two competing retailers. Shi et al. (2020) discuss the integration strategy of the manufacturer in a dual-channel closed-loop supply chain. Wang et al. (2020) investigate the issue of reverse channel design in a CLSC with a dominant retailer and upstream competition. Jalali et al. (2020) propose the best configuration of complementary goods in a CLSC with one manufacturer and one retailer. Wang et al. (2020) study the effect of consumer behavior on the dual-collecting closed-loop supply chain. Wang and Wu (2020) discuss the optimal decisions on the carbon emission reduction and product collection in a CLSC with cap-and-trade regulation.

The above papers consider that the manufacturers are the Stackelberg leaders in the CLSCs. However, in practice, the manufacturers don't always have strong channel power. Recently, several scholars pay attention to the CLSCs where the collectors act as Stackelberg leaders. Choi et al. (2013) examine the impact of different channel leadership on the CLSC, and the results show that collector-led model is not the most effective model for used-product collection. Wang et al. (2015) explore the reward–penalty mechanism for the manufacturer-led and the collector-led CLSCs under various channel power structures. Wang et al. (2018) investigate the benefit of the reward-penalty mechanism in a two-period CLSC where the collector sells the used products to the manufacturer in the second period.

It can be seen from the above literature that the CLSC where the collector acts as the channel leader has attracted much attention of researchers in recent years. Our work differs from these papers in that we mainly explore the information sharing issue in the collectors-led CLSC with product competition. Specifically, we investigate the impacts of the manufacturer's information sharing choices to the collectors on the CLSC firms' operational decisions and profits.

The above sections show that our research problems presented in the Introduction are important but are not addressed in the existing literature. Table 1 describes the difference between our work and previous works. In conclusion, our work contributes to the existing literature in two main aspects. One is that we extend the previous CLSC models by considering a collectors-led CLSC with product competition. Our research results enrich the related CLSC literature. The other is that we introduce the demand information asymmetry issue into the collectors-led CLSC with competition where the manufacturer has the superior demand information. We explore the effects of different information sharing arrangement on the CLSC participants' expected profits and operational decisions.

Table 1. Differences between our work and the most related literature.

References	CLSC	Collector-led	Product competition	Demand information sharing
Wu et al. (2019)	No	No	Yes	Yes
Guan et al. (2020)	No	No	Yes	Yes
Lei et al. (2020)	No	No	Yes	Yes
Wu and Zhou (2017)	Yes	No	Yes	No
Zhang and Xiong (2017)	Yes	No	No	Yes
Huang and Wang (2017)	Yes	No	No	Yes
Wang et al. (2021)	Yes	Yes	No	Yes
Huang et al. (2021)	Yes	No	No	Yes
Choi et al. (2013)	Yes	Yes	No	No
Wang et al. (2015)	Yes	Yes	No	No
Wang et al. (2018)	Yes	Yes	No	No
This paper	Yes	Yes	Yes	Yes

3. Problem description

Consider a CLSC consisting of two collectors and a manufacturer (see Fig. 1). As in Choi et al. (2013), Wang et al. (2015) and Wang et al. (2021), we consider that the collectors have strong channel power and act as Stackelberg leaders. In the reverse supply chain, collector i ($i = 1, 2$) collects the used product i from consumers in the market. The collection rate of collector i is τ_i. In line with Savaskan et al. (2004) and Choi et al. (2013), we take a quadratic form for the investment cost of collector i. More specifically, the investment cost function is $k\tau_i^2$, where k is the scaling parameter, which captures the investment cost-efficiency. A higher k means a lower efficiency in investment since it incurs a higher cost for the same collection rate. For simplicity, we assume the unit collection cost from consumers is zero, which doesn't impact the managerial insights obtained in this paper (Wu and Zhou 2017, Shi et al. 2020). In the forward supply chain, the collector i sells the used product i to the manufacturer at a transfer price b_i for remanufacturing, and the manufacturer sells the new product i to the consumers at a retail price p_i. Consider that the unit production cost of producing a new product with used products c_r is lower than producing a new one with raw materials c_m, i.e., $c_r < c_m$. For convenience, we let $\Delta = c_m - c_r$. Δ indicates the unit saving cost of remanufacturing. Note that $\Delta > b_i$, otherwise, the manufacturer is not willing to buy the used products from the collectors. Thus, the average unit cost of a new product i is $\tau_i c_r + (1 - \tau_i)c_m = c_m - \Delta\tau_i$.

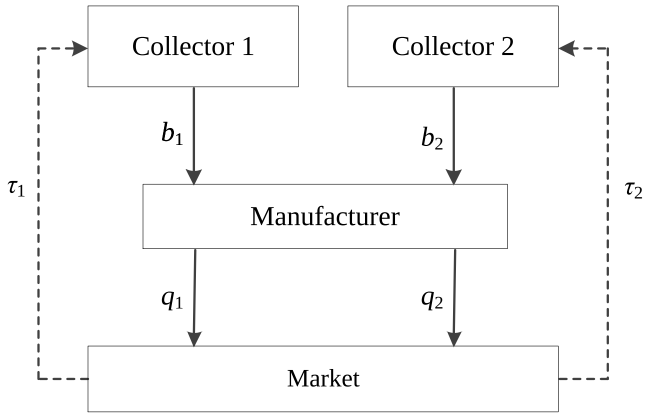

Fig. 1. The investigated CLSC structure

Following Ha et al. (2011), Wu and Zhou (2017) and Lei et al. (2020), we adopt the inverse demand function given as

$$p_i = a - q_i - \theta q_j, \quad (1)$$

where q_i is the selling quantities of product i, and $\theta \in (0, 1)$ denotes the competition intensity between the product i and the product j. a is the market base of product i. We consider that the market demand of product i is uncertain because of the changes in business conditions. Thus, in our model, a is a random variable. To capture the uncertainty, suppose $a = a_0 + e$, where a_0 is the mean demand and e is the uncertain part of the product demand. Suppose e follows a normal distribution with mean zero and variance V. In this paper, we consider that the manufacturer has the advantage to make a demand forecast with respect to the market demand a, because the manufacturer is closer to the market. The demand forecast information of the manufacturer is f, and $f = a + \varepsilon$, where ε is the error term, and follows a normal distribution with mean zero and variance S. ε and e are independent of each other. According to the research of Cyert and DeGroot (1970) and Vives (1984), we get the following information structure:

$$E(a|f) = \frac{S}{V+S}a_0 + \frac{V}{V+S}f = (1-\rho)a_0 + \rho f \equiv A, \tag{2}$$

where $\rho = V/(V+S)$, which indicates the forecast accuracy because it is negatively correlated with the variance S, and $\rho \in (0, 1)$. Furthermore, based on the above information, we can get the following equation.

$$E\left[(f - a_0)^2\right] = E\left[(e + \varepsilon)^2\right] = V + S. \tag{3}$$

The manufacturer makes a demand forecast and the forecast information is private. It can choose to share the forecast information with the collectors or not. In this paper, similar to Li 2002 and Ha et al. (2011), we assume that the shared information is true and the collectors make decisions based on the information available. We model the CLSC as a three-stage game. In the first stage, the manufacturer makes a demand forecast f and decides whether to share the forecast information with the collectors. In the second stage, collector i sets the collection rate τ_i and unit transfer price b_i of used products based on the available demand information. In the final stage, upon receiving τ_i and b_i, the manufacturer decides the selling quantities q_i of product i.

Table 2. Summary of notations.

Notation	Definition
a	the market base of the products
a_0	mean market demand
τ_i	collection rate of collector i, $i = 1, 2$ (decision variable)
b_i	unit transfer price of used product i decided by collector i, $i = 1, 2$ (decision variable)
q_i	selling quantity of product i (decision variable)
θ	the competition coefficient between the two products, $0 < \theta < 1$
k	investment cost coefficient
c_m	unit production cost of producing a new product with raw materials
c_r	unit production cost of producing a new product with used products
Δ	unit saving cost of remanufacturing, $\Delta > b_i$
f	manufacturer's demand forecast information
A	forecast expected value of market demand

e	uncertain part of the product demand
ε	error term of forecast
V	variance of uncertain demand
S	variance of forecast
ρ	forecasting accuracy, $\rho = V/(V+S)$ and $0 < \rho < 1$
$\pi_{ci}^{IS}(n)$	informed collector i's expected profit when information is shared with n collectors
$\pi_{ci}^{NI}(n)$	uninformed collector i's expected profit when information is shared with n collectors
$\pi_M(n)$	manufacturer's expected profit when information is shared with n collectors
$\Pi_{SC}(n)$	whole supply chain's expected profit when information is shared with n collectors

Based on the CLSC structure, we note that there are three information sharing cases: (1) manufacturer doesn't share information with the collectors, (2) manufacturer shares information with only one collector, (3) manufacturer shares information with both collectors. Next, we will investigate these three information sharing cases, and obtain the equilibrium solutions in each case by backward induction. Based on the equilibrium solutions, we will make analysis and obtain some managerial insights.

The notations used in our model are shown in Table 2.

4. Information sharing cases

In this section, we develop the three information sharing models and get the equilibrium solutions through backward induction. Similar to Savaskan et al. (2004), Choi et al. (2013) and Ha et al. (2017), to guarantee that the interior equilibrium solutions exists and $\Delta > b_i$, we assume $k_0 = \Delta^2/[8(1-\theta^2)] < k < \Delta^2/[4(1-\theta^2)] = 2k_0$, i.e., it is not too cheap or too expensive to make the investment in used products collection. In addition, $\pi_{ci}(n)$, $\pi_M(n)$ and $\Pi_{SC}(n)$ stand for the expected profits of the collector i, the manufacturer and the whole supply chain when the manufacturer shares the demand forecast information with n collectors, respectively, $n = 0, 1, 2$. The superscript *NI* represents that the manufacturer doesn't share demand forecast information with the collector, and the superscript *IS* denotes that the manufacturer shares the information with the collector.

4.1. case 1: no information sharing

In this case, the manufacturer doesn't share the demand forecast information with the collectors. As a result, the collectors only know the expected value of the market demand. Therefore, the collector i's decision function and the manufacturer's decision function can be described as follows:

$$\max_{\tau_i,b_i} E(\pi_{ci}^{NI}) = E(b_i\tau_i q_i - k\tau_i^2), \tag{4}$$

$$\max_{q_i,q_j} E(\pi_M|f)=E[(p_i - c_m+(\Delta - b_i)\tau_i)q_i+(p_j - c_m+(\Delta - b_j)\tau_j)q_j|f], \tag{5}$$

where $p_i = a - q_i - \theta q_j$ and $p_j = a - q_j - \theta q_i$.

By jointly solving the first derivative of $E(\pi_M|f)$ with respect to q_i and q_j, we get the optimal response functions of the manufacturer as follows: $q_i^{NI}=\frac{(1-\theta)A+(\Delta-b_i)\tau_i-(\Delta-b_j)\tau_j+c_m\theta-c_m}{2(1-\theta^2)}$ and $q_j^{NI}=\frac{(1-\theta)A+(\Delta-b_j)\tau_j-(\Delta-b_i)\tau_i+c_m\theta-c_m}{2(1-\theta^2)}$. Note that the collector i doesn't know the demand forecast information. Thus, collector i anticipates that the manufacturer's response functions as follows: $E(q_i^{NI})=\frac{(1-\theta)a_0+(\Delta-b_i)\tau_i-(\Delta-b_j)\tau_j+c_m\theta-c_m}{2(1-\theta^2)}$ and $E(q_j^{NI})=\frac{(1-\theta)a_0+(\Delta-b_j)\tau_j-(\Delta-b_i)\tau_i+c_m\theta-c_m}{2(1-\theta^2)}$. Substituting $E(q_i^{NI})$ and $E(q_j^{NI})$ into the collector i's decision function, we can obtain the equilibrium collection rates and transfer prices. Taking the equilibrium collection rates and transfer prices into q_i^{NI} and q_j^{NI}, then we can get the equilibrium selling quantities of product i. All the equilibrium solutions are presented in the following lemma 1. The detailed proof of lemma 1 is shown in Appendix.

Lemma 1. *In case 1, in which there is no information sharing in the CLSC, the equilibrium solutions in this case are characterized as follows*:

$$b_i^{NI}(0)=b_j^{NI}(0)=\frac{4k(1-\theta^2)}{\Delta}, \tag{6}$$

$$\tau_i^{NI}(0)=\tau_j^{NI}(0)=\frac{\Delta(a_0 - c_m)}{8k + 4k\theta - 4k\theta^2 - \Delta^2}, \tag{7}$$

$$q_i^{NI}(0)=q_j^{NI}(0)=\frac{A}{2(1+\theta)}+\frac{4a_0k\theta^2 + a_0\Delta^2 - 4c_mk\theta - 4a_0k - 4c_mk}{2(1+\theta)(8k + 4k\theta - 4k\theta^2 - \Delta^2)}. \tag{8}$$

Based on the above equilibrium decisions, we obtain the expected profits of the collector i and the manufacturer as follows:

$$\pi_{ci}^{NI}(0)=\pi_{cj}^{NI}(0)=\frac{k(8k-\Delta^2-8k\theta^2)\,(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}, \tag{9}$$

$$\pi_M(0)=\frac{8k^2(1+\theta)(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{\rho V}{2(1+\theta)}. \tag{10}$$

Thus, the expected profit of the whole supply chain is

$$\Pi_{SC}(0)=\frac{2k(a_0-c_m)^2(12k+4k\theta-8k\theta^2-\Delta^2)}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{\rho V}{2(1+\theta)}. \tag{11}$$

It shows that there are stable equilibrium solutions in this case. The selling quantities of product i and product j are increasing in the demand forecast value (A). The reason is that a larger A indicates a higher demand. The manufacturer could gain more profits through producing more products. Moreover, we find that the expected profit of the manufacturer increases with the forecast accuracy (ρ), which is consistent with our intuition that a more accurate forecast is more beneficial to the manufacturer.

4.2. case 2: sharing information with only one collector

In this case, the manufacturer shares its demand forecast information with only one collector. Because of the symmetry, without loss of generality, we assume that the manufacturer shares the information with collector i. Consequently, collector i has the demand forecast information, however, the other collector (i.e., collector j) only knows the expected value of the market demand. Thus, the collector i's, the collector j's and the manufacturer's decision functions are described as follows:

$$\max_{\tau_i,b_i} E(\pi_{ci}^{IS}|f)=E(b_i\tau_i q_i-k\tau_i^2|f), \tag{12}$$

$$\max_{\tau_j,b_j} E(\pi_{cj}^{NI})=E(b_j\tau_j q_j-k\tau_j^2), \tag{13}$$

$$\max_{q_i,q_j} E(\pi_M|f)= E[(p_i-c_m+(\Delta-b_i)\tau_i)q_i+(p_j-c_m+(\Delta-b_j)\tau_j)q_j|f],$$

where $p_i=a-q_i-\theta q_j$ and $p_j=a-q_j-\theta q_i$. Since the manufacturer has the forecast information, its response functions are the same as the response functions in case 1. Moreover, note that the collector j's optimal decisions are the same as its optimal decisions in case 1, because collector j doesn't know the demand forecast information. Substituting manufacturer's response functions and collector j's optimal decisions into collector i's decision function, we can obtain the collector i's equilibrium decisions. Subsequently, other decision variables can be solved directly. The equilibrium results are summarized in the following lemma 2.

Lemma 2. *In case 2, in which the manufacturer shares its demand forecast information with only one collector, the equilibrium decisions of the supply chain participants are shown as follows*:

$$b_i^{IS}(1)= \frac{4k(1-\theta^2)}{\Delta}, \tag{14}$$

$$b_j^{NI}(1)=\frac{4k(1-\theta^2)}{\Delta}, \tag{15}$$

$$\tau_i^{IS}(1)=\frac{\Delta(-4a_0k\theta^3-a_0\Delta^2\theta+8c_mk\theta^2+\Delta^2c_m+4a_0k\theta-8c_mk)}{(8k-8k\theta^2-\Delta^2)\,(8k+4k\theta-4k\theta^2-\Delta^2)}+F(A), \tag{16}$$

$$\tau_j^{NI}(1)=\frac{\Delta(a_0-c_m)}{8k+4k\theta-4k\theta^2-\Delta^2}, \tag{17}$$

$$q_i^{IS}(1)=\frac{2k(8c_mk\theta^2+\Delta^2c_m+4a_0k\theta-4a_0k\theta^3-a_0\Delta^2\theta-8c_mk)}{(8k-8k\theta^2-\Delta^2)\,(8k+4k\theta-4k\theta^2-\Delta^2)}+J(A), \tag{18}$$

$$q_j^{NI}(1)= \frac{a_0(48k^2\theta^2+12\Delta^2k-32k^2-16k^2\theta^4-8\Delta^2k\theta^2-\Delta^4)}{2(8k-8k\theta^2-\Delta^2)\,(8k+4k\theta-4k\theta^2-\Delta^2)}$$

$$+\frac{c_m(32k^2\theta^2+4\Delta^2k-32k^2)}{2(8k-8k\theta^2-\Delta^2)\,(8k+4k\theta-4k\theta^2-\Delta^2)}+I(A), \tag{19}$$

where $F(A)=A(1-\theta)\Delta/(8k-8k\theta^2-\Delta^2)$, $J(A)=2A(1-\theta)k/(8k-8k\theta^2-\Delta^2)$ and $I(A)=A(8k-4k\theta-4k\theta^2-\Delta^2)/(16k-16k\theta^2-8\Delta^2)$.

Then, we can obtain the collector i's, the collector j's and the manufacturer's expected profits as follows:

$$\pi_{ci}^{IS}(1)=\frac{k(8k-\Delta^2-8k\theta^2)\,(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{k(1-\theta)^2\rho V}{8k-8k\theta^2-\Delta^2}, \tag{20}$$

$$\pi_{cj}^{NI}(1)=\frac{k(8k-\Delta^2-8k\theta^2)\,(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}, \tag{21}$$

$$\pi_M(1)=\frac{(48k^2\theta^4+16\Delta^2k\theta^2+32k^2\theta^3+\Delta^4-128k^2\theta^2-16\Delta^2k-32k^2\theta+80k^2)\rho V}{4\,(8k-8k\theta^2-\Delta^2)^2}$$

$$+\frac{8k^2(1+\theta)(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}. \quad (22)$$

Thus, the expected profit of the whole supply chain can be given by

$$\Pi_{SC}(1)=\pi_{ci}^{IS}(1)+\pi_{cj}^{NI}(1)+\pi_M(1). \quad (23)$$

In this case, the collector i obtains the demand forecast information. Based on the above equilibrium solutions, we observe that the collection rate of collector i is increasing in the demand forecast value (A). The reason behind this result is that when it shows that the market demand is high, the collector can collect more used products by raising the collection rate. However, it is interesting to find that the transfer price of product i is irrelevant to the demand forecast, even if the collector i have the demand forecast information. The expected profit of the collector i increases with the forecast accuracy (ρ). This is because an increase in forecast accuracy could let the collector i make its decisions more precisely.

4.3. case 3: sharing information with both collectors

In this case, the manufacturer shares its demand forecast information with both collectors. As a result, both collectors know the information. Hence, each collector's and the manufacturer's decision functions are given by

$$\max_{\tau_i,b_i} E(\pi_{ci}^{IS}|f) = E(b_i\tau_i q_i - k\tau_i^2|f), \quad (24)$$

$$\max_{q_i,q_j} E(\pi_M|f)= E[(p_i-c_m+(\Delta-b_i)\tau_i)q_i+(p_j-c_m+(\Delta-b_j)\tau_j)q_j|f],$$

where $p_i = a - q_i - \theta q_j$ and $p_j = a - q_j - \theta q_i$. Similarly, through employing backward induction, the equilibrium solutions in this case are shown in lemma 3.

Lemma 3. *In case 3, in which the manufacturer shares its forecast information with both collectors, the equilibrium solutions are presented as follows*:

$$b_i^{IS}(2)= b_j^{IS}(2) = \frac{4k(1-\theta^2)}{\Delta}, \quad (25)$$

$$\tau_i^{IS}(2)=\tau_j^{IS}(2)=\frac{\Delta(A-c_m)}{8k+4k\theta-4k\theta^2-\Delta^2}, \quad (26)$$

$$q_i^{IS}(2)=q_j^{IS}(2)=\frac{2k(A-c_m)}{8k+4k\theta-4k\theta^2-\Delta^2}. \quad (27)$$

Accordingly, the expected profits of the collectors and the manufacturer are

$$\pi_{ci}^{IS}(2)=\pi_{cj}^{IS}(2)=\frac{k(8k-\Delta^2-8k\theta^2)\,(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{k(8k-\Delta^2-8k\theta^2)\rho V}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}, \quad (28)$$

$$\pi_M(2)=\frac{8k^2(1+\theta)(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{8k^2(1+\theta)\rho V}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}. \quad (29)$$

The expected profit of the whole supply chain is

$$\Pi_{SC}(2)=\pi_{ci}^{IS}(2)+\pi_{cj}^{NI}(2)+\pi_M(2). \quad (30)$$

We can find that the collection rates and the selling quantities are increasing in the demand forecast value (A), which means that the collectors and the manufacturer adjust their decisions based on the demand forecast. Nevertheless, the collectors don't adjust the transfer prices of used products, which is an interesting finding. We also observe that a higher forecast accuracy (ρ) can bring more profits of the supply chain participants. This can be understood that a higher accurate forecast allows the supply chain members to make better decisions to maximize their profits.

5. Comparison and analysis

In this section, we compare the equilibrium solutions in the three information sharing cases to gain the information sharing preferences of the supply chain players. The outcomes are shown in Proposition 1-6. Proofs of all propositions are given in Appendix.

Proposition 1. *The transfer prices in the three information sharing cases are the same, i.e.,* $b_i^{NI}(0)=b_j^{NI}(0)=b_i^{IS}(1)=b_j^{NI}(1)=b_i^{IS}(2)=b_j^{IS}(2)=4k(1-\theta^2)/\Delta$.

From Proposition 1, it is interesting to find that the transfer prices of collectors are always the same in various information sharing cases. It implies that the information sharing strategies of the manufacturer have no impact on the transfer prices of the used products. From the expression, we can see that the transfer prices are increasing in the investment cost coefficient k, and are decreasing in the product competition coefficient θ and unit saving cost of remanufacturing Δ. It shows that the stable transfer prices are the balance point between the investment costs and the saving costs, given the product competition. This finding provides an important enlightenment for the practitioner. For example, Universal Recycling Technologies and Electronic Recyclers International, Inc. are Samsung's main recycling partners. These two collectors collect used products of Samsung and then sell them to Samsung for recycling (Tian et al. 2019). In this case, Universal Recycling Technologies and Electronic Recyclers International, Inc. should set a stable transfer price for the used products no matter the demand information sharing scenarios.

Proposition 1 immediately implies that for different demand information sharing scenarios, the transfer price of used products set by the collectors is stable. This proposition will help the collectors make proper investment decision on the collection of used products.

Proposition 2. *If* $A > a_0$, *the collection rates in the three information sharing cases are related as* $\tau_i^{IS}(1)>\tau_i^{IS}(2)=\tau_j^{IS}(2)>\tau_i^{NI}(0)=\tau_j^{NI}(0)=\tau_j^{NI}(1)$;

Proposition 2 indicates that the collection rates of the two kinds of products are the same in case 1 and case 3 because of the symmetry. Furthermore, the collection rate of product j in case 2 is equal to the collection rates in case 1, and the collection rates are the lowest. This is because the collectors don't have the demand forecast information in these cases. When the collectors obtain the information that the forecast demand is higher than the mean demand, Proposition 2 shows that the collection rate of product i in case 2 is the highest. The reason is that in this case, the collector i have the demand forecast information, but the collector j don't have the information. As a result, based on the information advantage, the collector i improves its collection rate greatly to gain more profits. For example, ReCellular and IBM subcontract their collection activities to many third-party collectors separately (Li et al. 2021; Grenchus et al. 2001). In practice, the manufacturer has the advantage over the collectors that it owns the product demand information, such as IBM (Lee and Whang 2000). This proposition indicates that if the demand forecast information is positive, the collector would increase its collection rate when obtaining the information from IBM.

Proposition 2 implies that if the manufacturer's demand forecast information is positive, sharing the positive information with collectors could increase collection rate. Thus, from the perspective of environmental protection, the government should encourage the manufacturer to share its demand forecast information with the collectors if the forecast information is positive.

Proposition 3. *If* $A > a_0$*, the retail prices and selling quantities in the three information sharing cases are related as follows:*

(i) $p_i^{NI}(0)=p_j^{NI}(0)=p_j^{NI}(1)>p_i^{IS}(2)=p_j^{IS}(2)>p_i^{IS}(1)$;

(ii) $q_i^{IS}(1)>q_i^{IS}(2)=q_j^{IS}(2)>q_i^{NI}(0)=q_j^{NI}(0)>q_j^{NI}(1)$.

Proposition 3 (i) shows that the retail price of product j in case 2 is equal to the retail prices of products in case 1, and the retail prices are the highest. This is because the collectors don't have the demand forecast information and the unit production costs are the same in these cases. When the collectors obtain the information that the forecast demand is higher than the mean demand, it shows that the product i's retail price in case 2 is the lowest on account of the lowest unit production cost. Because of the retail prices shown in Proposition 3 (i), Proposition 3 (ii) indicates that the selling quantity of product i in case 2 is the highest, followed by the selling quantities in case 3, and then the selling quantities in case 1. Interestingly, Proposition 3 (ii) suggests that the selling quantity of product j in case 2 is not the same as the selling quantities in case 1, even if their retail prices are the same (see Proposition 3 (i)). The reason behind this result is that the retail price of product i is lower than the retail price of product j in case 2. So the product i steals the selling quantity of product j in this case. We also take IBM as an example. IBM possesses private demand forecast information. When IBM shares the positive forecast information with a collector and the collector has the information advantage, the corresponding retail price of products would be low, thereby resulting in high sales quantities. It occurs because with high cost saving from remanufacturing, as the collection rate increases, the manufacturer's unit production cost decreases.

The implication of Proposition 3 is that if the manufacturer's demand forecast information is positive, sharing the information with the collector could decrease the retail price of products and be beneficial to consumers. Accordingly, the sales quantity of products would increase for the corporations.

Proposition 4. *The expected profits of the collectors in the three information sharing cases are related as* $\pi_{ci}^{IS}(1)>\pi_{ci}^{IS}(2)=\pi_{cj}^{IS}(2)>\pi_{ci}^{NI}(0)=\pi_{cj}^{NI}(0)=\pi_{cj}^{NI}(1)$.

Proposition 4 shows that because of the symmetry, the expected profits of the two collectors are the same in case 1 and case 3. Specifically, the expected profit of collector j in case 2 is the same as the expected profits of the collectors in case 1, and the expected profits are the lowest. This is because the collectors don't have the demand forecast information in these cases, which highlights the importance of demand forecast information. Accordingly, based on the information advantage, the collector i in case 2 gets the largest expected profit through its low production cost and high selling quantity. In practice, a manufacturer currently mostly contracts with more than one third-party collector. For example, Universal Recycling Technologies and Electronic Recyclers International, Inc. are Samsung's two collection partners (Tian et al. 2019). This proposition indicates that if a collector obtains the demand forecast information from Samsung, it could obtain more profits due to the information advantage.

The implication of Proposition 4 is that no matter the manufacturer's demand forecast information is positive or negative, if the collector has the information and owns the information advantage, its profit could increase. Thus, the collector should try to obtain the demand forecast information of the manufacturer by some means.

Actually, Proposition 4 presents the collectors' information sharing preference across the three information sharing cases. Next, we explore the manufacturer's information sharing preference, and the result is shown in the following proposition.

Proposition 5. *By comparing the manufacturer's expected profits in the three information sharing cases, we find that there exists a threshold* k_1 *such that:*

(1) *If* $k_0 < k < k_1$*, then* $\pi_M(1) > \pi_M(2) > \pi_M(0)$*;*

(2) *If* $k = k_1$*, then* $\pi_M(1) = \pi_M(2) > \pi_M(0)$*;*

(3) *If* $k_1 < k < 2k_0$*, then* $\pi_M(2) > \pi_M(1) > \pi_M(0)$*;*

where k_1 *is the solution for* $64(3\theta^2 - 4\theta - 12)(1-\theta^2)^2 k^3 + 16\Delta^2(1-\theta^2)(2-\theta)(8+7\theta)k^2 + 4\Delta^2(1+\theta)(5\theta - 7)\,k + \Delta^6 = 0$ *in the interval* $(k_0, 2k_0)$*, which exists and is unique.*

Proposition 5 indicates that collectors' investment cost-efficiency is a very important factor that affects the profit relationship of the manufacturer under the three information sharing scenarios. More specifically, if collectors' investment cost-efficiency is high, the manufacturer prefers to share its demand forecast information with only one collector. Assuming that the manufacturer shares information only with the collector i, under this scenario, the manufacturer can gain more profits from the product i. However, if collectors' investment cost-efficiency is low, the manufacturer is willing to share its information with both collectors. It shows that complete information sharing can make the manufacturer gain the largest profit through setting the proper prices for the products in this scenario. In reality, if third-party collectors provide used products for the manufacturer and the manufacturer owns private demand forecast information, such as IBM, Samsung and ReCellular. This proposition provides important insights for these manufacturers that collectors' investment cost-efficiency plays an important role in their information sharing decisions.

The enlightenment of this proposition for the manufacturer is that the collector's investment cost-efficiency is an important factor that affects its information sharing decisions. Specifically, the manufacturer should share its demand forecast information with only one collector if the collectors' investment cost-efficiency is high. Otherwise, the manufacturer should share its demand information with both collectors.

6. Numerical analysis

In this section, we provide some numerical examples and make sensitivity analyses to obtain more managerial insights. Specifically, we explore the impacts of the manufacturer's demand forecast value (A) and forecast accuracy (ρ), and the market demand uncertainty (V) on the CLSC members' decisions and expected profits. Referring to Huang and Wang (2017), we set the parameters as follows: $a_0 = 25$, $c_m = 10$, $c_r = 4$, $\theta = 0.8$, $k = 20$. The analysis results are summarized in Figs. 2-8.

6.1. Effect of demand forecast value (A)

From Proposition 1, we note that the transfer price of used products in the three information sharing cases are unrelated to the demand forecast value (A). Hence, we investigate the influence of the demand forecast value (A) on the collector 1's collection rate, selling quantity and retail price of product 1 due to the symmetry. We change the value of A from 20 to 30 and the results are presented in Figs. 2, 3 and 4. Fig. 2 shows that the demand forecast value has no impact on the collection rate of the collector 1 under no information sharing scenario because of the absence of demand forecast information. However, when the collector has the forecast information, its collection rate increases with the forecast value. The reason may be that the collector anticipates that it could collect more used products and obtain more profits with the increase of the demand forecast value. In addition, from Fig. 2, we find that if $A > a_0 = 25$, then $\tau_1^{IS}(1)>\tau_1^{IS}(2)>\tau_1^{NI}(0)$, and if $A < a_0 = 25$, then $\tau_1^{IS}(1)<\tau_1^{IS}(2)<\tau_1^{NI}(0)$, which is consistent with Proposition 2.

Fig. 3 presents that the retail price of product 1 in all information sharing cases is increasing in the demand forecast value (A). The intuition behind the result is that as the demand forecast value increases, the manufacturer aims to obtain more profits by increasing the retail price of product 1. Interestingly, from Fig. 4, it shows that the selling quantity of product 1 in all information sharing cases is also increasing in the demand forecast value (A). The reason behind this phenomenon is that though the retail price increases, the increment of selling quantity because of the increased demand exceeds the decrement because of the increased retail price.

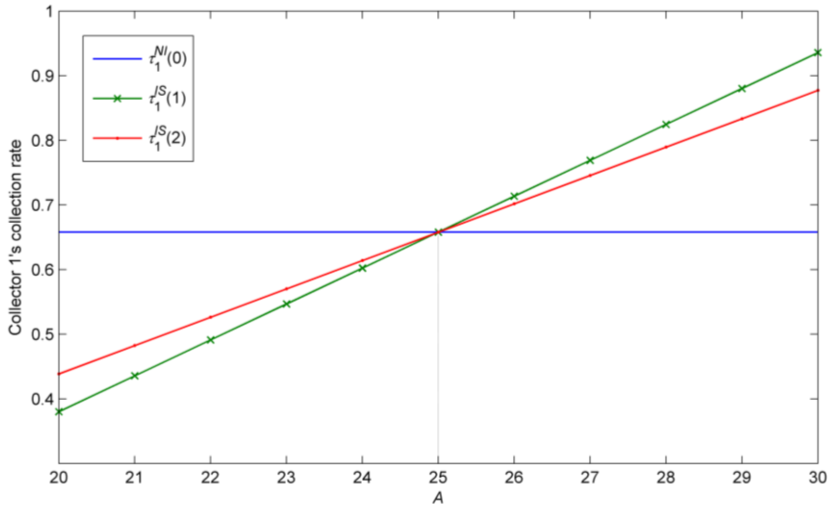

Fig. 2. Impact of the demand forecast value on the collector 1's collection rate

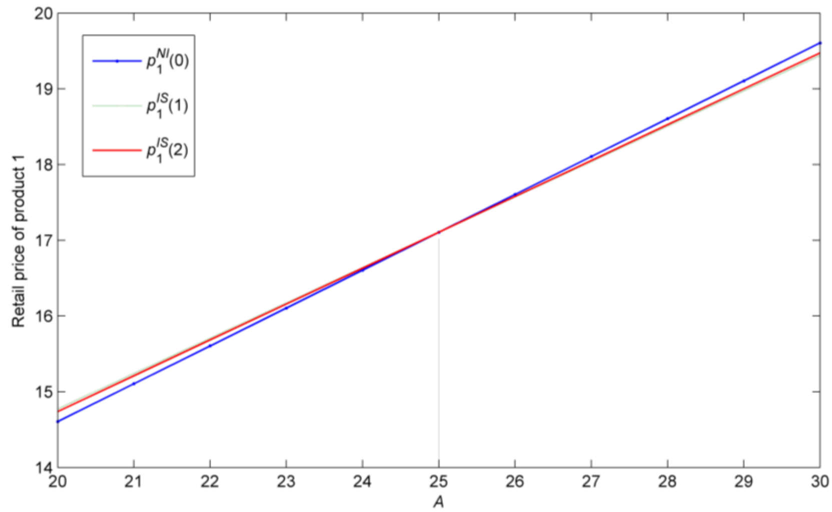

Fig. 3. Impact of the demand forecast value on the retail price of product 1

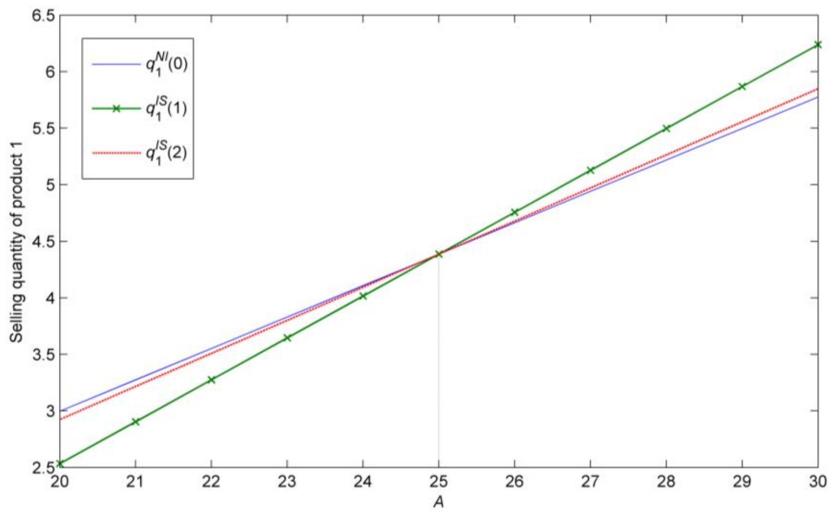

Fig. 4. Impact of the demand forecast value on the selling quantity of product 1

6.2. Effect of demand forecast accuracy (ρ)

We change the value of ρ from 0 to 1 under $V = 5$ and the results are presented in Fig. 5 and 6. Fig. 5 shows that due to the lack of demand forecast information, the manufacturer's demand forecast accuracy has no impact on the expected profit of the collector 1 in no information sharing case. However, once the collector 1 owns the forecast information of the manufacturer, its expected profit increases with the manufacturer's forecast accuracy, which is intuitive. Furthermore, it is interesting to find that the impact of the forecast accuracy on the collector 1's expected profit in case 2 is greater than the impact on the collector 1's expected profit in case 3. This finding indicates that the collector has motivation to stimulate the manufacturer to improve its forecast accuracy. Fig. 6 shows that the manufacturer's demand forecast accuracy has a positive effect on its expected profit, which is intuitive. Interestingly, it is observed that with the increase of the forecast accuracy, the manufacturer's expected profit in case 2 increases at almost the same speed as in case 3, which is higher than the speed in case 1.

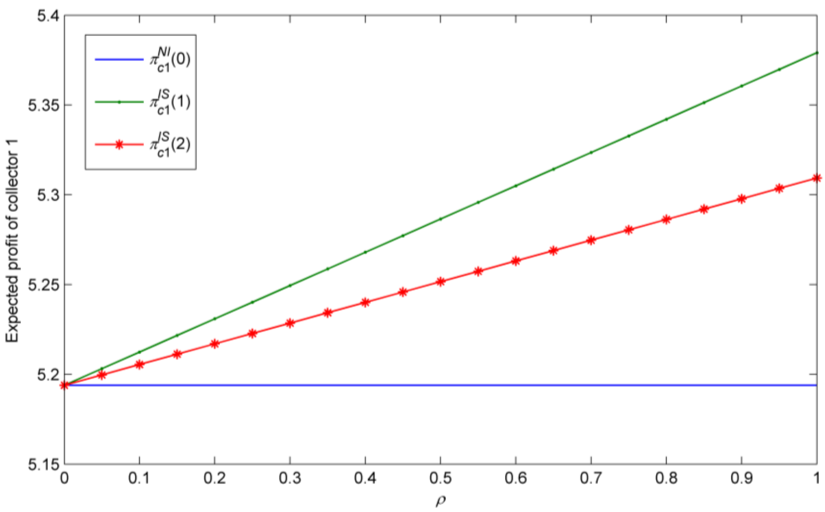

Fig. 5. Impact of the demand forecast accuracy on the expected profit of collector 1

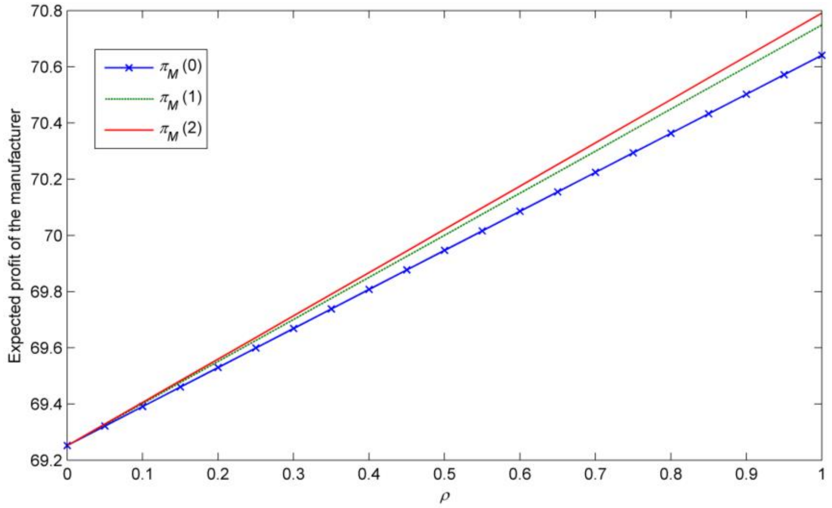

Fig. 6. Impact of the demand forecast accuracy on the expected profit of the manufacturer

6.3. Effect of market demand uncertainty (V)

We vary the value of V in the range from 5 to 10 under $\rho = 5$ and the effects are shown in Figs. 7 and 8. Fig. 7 shows that under no information sharing case, the product demand uncertainty has no impact on the collector 1's expected profit. This is because collector 1 makes its decisions under no demand forecast information. However, from Figs. 7 and 8, it shows that when the collector 1 and the manufacturer have the demand forecast information, their expected profits are increasing in the demand uncertainty. This finding reflects the value of demand forecast information when the product demand is highly uncertain in the market. In addition, it is observed that with the increase of the demand uncertainty, the collector 1's expected profit in case 2 increases at a higher speed than in case 3 (refer Fig. 7) and the manufacturer's expected profit increases at almost the same speed under the three information sharing cases (refer Fig. 8). These observations present the importance of owning demand forecast information for the collector 1 and the manufacturer under different information sharing cases.

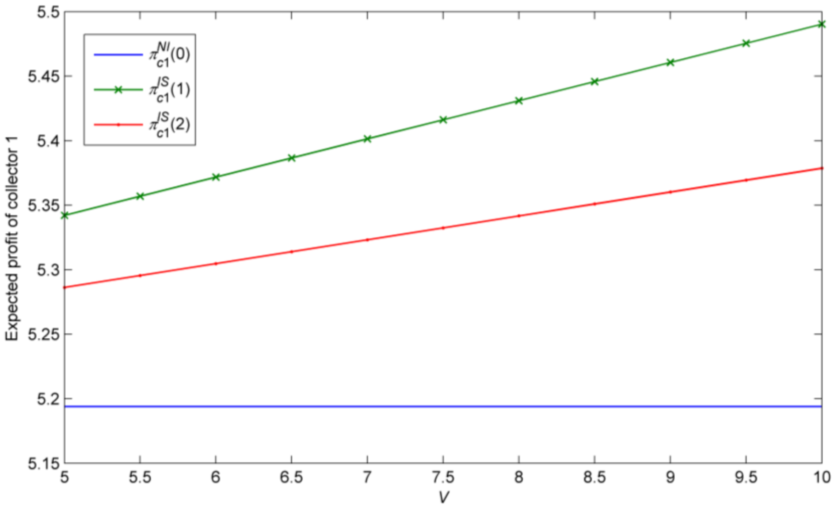

Fig. 7. Impact of the demand uncertainty on the expected profit of collector 1

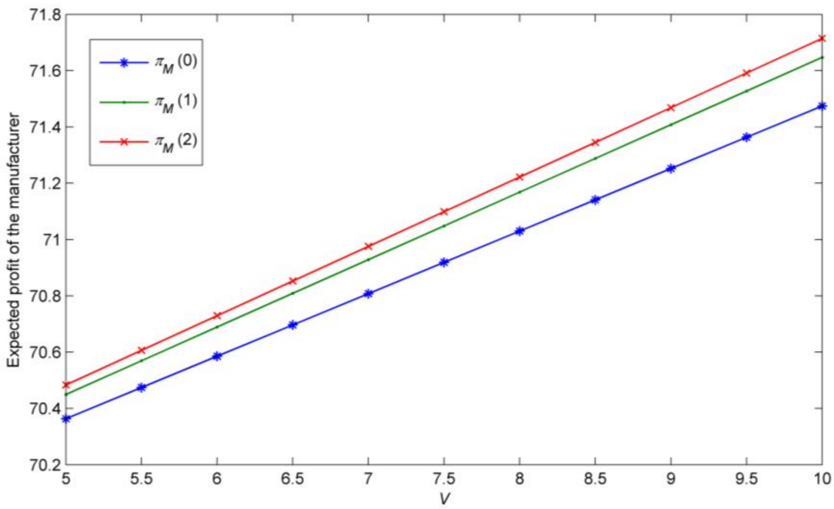

Fig. 8. Impact of the demand uncertainty on the expected profit of the manufacturer

7. Concluding remarks

In this paper, we consider a collectors-led CLSC with one manufacturer and two collectors. The collectors act as the Stackelberg leaders, while the manufacturer is the follower and has private demand forecast information. Hence, there are three information sharing strategies for the manufacturer: (1) no information sharing, (2) sharing information with only one collector, (3) sharing information with both collectors. We focus on studying the information sharing preference of the manufacturer and the effect of the different information sharing strategies on the CLSC.

Our research results show that the collectors' investment cost-efficiency plays an important role in the information sharing strategy of the manufacturer. When the investment cost-efficiency is high, the manufacturer prefers to share its demand forecast information with only one collector. However, when the investment cost-efficiency is low, the manufacturer is willing to share its information with both collectors. In addition, interestingly, we find that the transfer prices of the used products in the three information sharing cases are always the same. And the transfer prices are increasing in the investment cost coefficient, but decreasing in the product competition coefficient and unit saving cost of remanufacturing. When the collectors obtain the information that the forecast demand is higher than the mean demand, product i's collection rate and selling quantity in case 2 is the highest, and its retail price is the lowest. Finally, the collector i in case 2 gets the largest expected profit.

There are also several limitations of this paper, which can be possible research directions in the future. Firstly, we assume that the quality of the new and remanufactured products is the same, and consumers cannot distinguish between new and remanufactured products. In practice, some remanufactured products don't reach the quality standards of new products. Thus, future research could consider the scenarios with differentiated remanufactured products. In addition, we consider that the shared information is true. In reality, the manufacturer may share false demand forecast information with the collectors for the sake of self-interest. Hence, the scenarios with false information can be considered in the future. Finally, we make an assumption that the participants in the CLSC are risk-neutral when the product demand is uncertain. However, the participants may be risk-averse toward the uncertain product demand in practice. Therefore, one can consider this scenario and explore the interaction effect between risk aversion and information sharing on the CLSC in the future.

Acknowledgements

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Appendix

Proof of Lemma 1

We employ backward induction to obtain the equilibrium solutions. Taking the first and second partial derivatives of $E(\pi_M|f)$ with respect to q_i and q_j, we get

$$\frac{\partial E(\pi_M|f)}{\partial q_i} = A + (\Delta - b_i)\tau_i - 2q_i - 2q_j\theta - c_m,$$

$$\frac{\partial E(\pi_M|f)}{\partial q_j} = A + (\Delta - b_j)\tau_j - 2q_j - 2q_i\theta - c_m,$$

$$\frac{\partial^2 E(\pi_M|f)}{\partial q_i^2} = \frac{\partial^2 E(\pi_M|f)}{\partial q_j^2} = -2<0,\ \frac{\partial^2 E(\pi_M|f)}{\partial q_i \partial q_j} = \frac{\partial^2 E(\pi_M|f)}{\partial q_j \partial q_i} = -2\theta<0.$$

Thus, the Hessian matrix is

$$H = \begin{pmatrix} -2 & -2\theta \\ -2\theta & -2 \end{pmatrix}.$$

Since $|H| = 4(1-\theta^2)>0$, it shows that $E(\pi_M|f)$ is joint concave in q_i and q_j. Let $\partial E(\pi_M|f)/\partial q_i = \partial E(\pi_M|f)/\partial q_j = 0$. We gain the manufacturer's response functions as follows:

$$q_i^{NI} = \left[(1-\theta)A + (\Delta - b_i)\tau_i - (\Delta - b_j)\tau_j + c_m\theta - c_m\right]/[2(1-\theta^2)],$$

$$q_j^{NI} = \left[(1-\theta)A + (\Delta - b_j)\tau_j - (\Delta - b_i)\tau_i + c_m\theta - c_m\right]/[2(1-\theta^2)].$$

Note that collector i doesn't know the demand forecast information. Hence, collector i anticipates that the manufacturer's response functions are

$$E(q_i^{NI}) = \left[(1-\theta)a_0 + (\Delta - b_i)\tau_i - (\Delta - b_j)\tau_j + c_m\theta - c_m\right]/[2(1-\theta^2)],$$

$$E(q_j^{NI}) = \left[(1-\theta)a_0 + (\Delta - b_j)\tau_j - (\Delta - b_i)\tau_i + c_m\theta - c_m\right]/[2(1-\theta^2)].$$

Substituting $E(q_i^{NI})$ and $E(q_j^{NI})$ into collector i's decision function, we get collector i's expected profit function as follow:

$$\max_{\tau_i,b_i} E(\pi_{ci}^{NI})$$

$$= \frac{a_0(1-\theta)b_i\tau_i + \tau_i(b_i(b_j\tau_j\theta + c_m\theta - c_m + \Delta\tau_i - b_i\tau_i - \Delta\tau_j\theta) + 2k\tau_i\theta^2 - 2k\tau_i)}{2(1-\theta^2)}.$$

Similarly, it is easy to verify that $E(\pi_{ci}^{NI})$ is joint concave in τ_i and b_i. Let $\partial E(\pi_{ci}^{NI})/\partial\tau_i = \partial E(\pi_{ci}^{NI})/\partial b_i = \partial E(\pi_{cj}^{NI})/\partial\tau_j = \partial E(\pi_{cj}^{NI})/\partial b_j = 0$. We obtain the equilibrium decisions of collector i as follows:

$$b_i^{NI}(0)=b_j^{NI}(0)=\frac{4k(1-\theta^2)}{\Delta},$$

$$\tau_i^{NI}(0)=\tau_j^{NI}(0)=\frac{\Delta(a_0-c_m)}{8k+4k\theta-4k\theta^2-\Delta^2}.$$

Substituting $b_i^{NI}(0)$, $b_j^{NI}(0)$, $\tau_i^{NI}(0)$, and $\tau_j^{NI}(0)$ into q_i^{NI} and q_j^{NI}, we can gain the equilibrium decisions of the manufacturer as follows:

$$q_i^{NI}(0)=q_j^{NI}(0)=\frac{A}{2(1+\theta)}+\frac{4a_0k\theta^2+a_0\Delta^2-4c_mk\theta-4a_0k-4c_mk}{2(1+\theta)(8k+4k\theta-4k\theta^2-\Delta^2)}.$$

Taking $b_i^{NI}(0)$, $b_j^{NI}(0)$, $\tau_i^{NI}(0)$, $\tau_j^{NI}(0)$, $q_i^{NI}(0)$ and $q_j^{NI}(0)$ into collectors' and manufacturer's decision functions, we can obtain their expected profits as follows:

$$\pi_{ci}^{NI}(0)=\pi_{cj}^{NI}(0)=\frac{k(8k-\Delta^2-8k\theta^2)(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2},$$

$$\pi_M(0)=\frac{8k^2(1+\theta)(a_0-c_m)^2}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{\rho V}{2(1+\theta)}.$$

Thus, the expected profit of the whole supply chain is

$$\Pi_{SC}(0)=2\pi_{ci}^{NI}(0)+\pi_M(0)=\frac{2k(a_0-c_m)^2(12k+4k\theta-8k\theta^2-\Delta^2)}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}+\frac{\rho V}{2(1+\theta)}.$$

The proofs of Lemma 2 and Lemma 3 are similar. So, we omit them.

Proof of Proposition 1

The outcome of Proposition 1 is obvious.

Proof of Proposition 2

If $A > a_0$, we compare the equilibrium collection rate in the three information sharing cases and gain the following:

$$\tau_i^{NI}(0) - \tau_i^{IS}(1) = -\frac{\Delta(1-\theta)(A-a_0)}{8k-8k\theta^2-\Delta^2} < 0,$$

$$\tau_i^{NI}(0) - \tau_j^{NI}(1) = 0,$$

$$\tau_i^{NI}(0) - \tau_i^{IS}(2) = -\frac{\Delta(A-a_0)}{8k+4k\theta-4k\theta^2-\Delta^2} < 0,$$

$$\tau_i^{IS}(1) - \tau_j^{NI}(1) = \frac{\Delta(1-\theta)(A-a_0)}{8k-8k\theta^2-\Delta^2} > 0,$$

$$\tau_i^{IS}(1) - \tau_i^{IS}(2) = -\frac{\Delta\theta(4k-4k\theta^2-\Delta^2)(A-a_0)}{(8k-8k\theta^2-\Delta^2)(8k+4k\theta-4k\theta^2-\Delta^2)} > 0,$$

$$\tau_j^{NI}(1) - \tau_i^{IS}(2) = -\frac{\Delta(A-a_0)}{8k+4k\theta-4k\theta^2-\Delta^2} < 0.$$

We can derive that $\tau_i^{IS}(1)>\tau_i^{IS}(2)=\tau_j^{IS}(2)>\tau_i^{NI}(0)=\tau_j^{NI}(0)=\tau_j^{NI}(1)$.

Proof of Proposition 3

Similar to the Proof of Proposition 2, if $A > a_0$, by comparing the equilibrium selling quantities in the three information sharing cases, we can get the following:

$$q_i^{NI}(0) - q_i^{IS}(1) = \frac{(4k-4k\theta^2-\Delta^2)(A-a_0)}{2(1+\theta)(8k-8k\theta^2-\Delta^2)} < 0,$$

$$q_i^{NI}(0) - q_j^{NI}(1) = -\frac{\theta(4k-4k\theta^2-\Delta^2)(A-a_0)}{2(1+\theta)(8k-8k\theta^2-\Delta^2)} > 0,$$

$$q_i^{NI}(0) - q_i^{IS}(2) = \frac{(4k-4k\theta^2-\Delta^2)(A-a_0)}{2(1+\theta)(8k+4k\theta-4k\theta^2-\Delta^2)} < 0,$$

$$q_i^{IS}(1) - q_j^{NI}(1) = -\frac{(4k-4k\theta^2-\Delta^2)(A-a_0)}{2(8k-8k\theta^2-\Delta^2)} > 0,$$

$$q_i^{IS}(1) - q_i^{IS}(2) = -\frac{2k\theta(4k-4k\theta^2-\Delta^2)(A-a_0)}{(8k-8k\theta^2-\Delta^2)(8k+4k\theta-4k\theta^2-\Delta^2)} > 0,$$

$$q_j^{NI}(1) - q_i^{IS}(2) = \frac{(8k-4k\theta^2-\Delta^2)(4k-4k\theta^2-\Delta^2)(A-a_0)}{2(8k-8k\theta^2-\Delta^2)(8k+4k\theta-4k\theta^2-\Delta^2)} < 0.$$

We can derive that $q_i^{IS}(1)>q_i^{IS}(2)=q_j^{IS}(2)>q_i^{NI}(0)=q_j^{NI}(0)>q_j^{NI}(1)$. Similarly, we can derive that $p_i^{NI}(0)=p_j^{NI}(0)=p_j^{NI}(1)>p_i^{IS}(2)=p_j^{IS}(2)>p_i^{IS}(1)$.

Proof of Proposition 4

Similarly, we compare the expected profits of the collectors in the three information sharing cases and gain the following:

$$\pi_{ci}^{NI}(0)-\pi_{ci}^{IS}(1)=-\frac{k\,(1-\theta)^2\rho V}{8k-8k\theta^2-\Delta^2}<0,$$

$$\pi_{ci}^{NI}(0)-\pi_{cj}^{NI}(1)=0,$$

$$\pi_{ci}^{NI}(0)-\pi_{ci}^{IS}(2)=-\frac{k(8k-8k\theta^2-\Delta^2)\rho V}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}<0,$$

$$\pi_{ci}^{IS}(1)-\pi_{cj}^{NI}(1)=\frac{k\,(1-\theta)^2\rho V}{8k-8k\theta^2-\Delta^2}>0,$$

$$\pi_{ci}^{IS}(1)-\pi_{ci}^{IS}(2)=-\frac{k\theta(4k-4k\theta^2-\Delta^2)[(4-4\theta^2)(4-\theta)k-\Delta^2(2-\theta)]\rho V}{(8k-8k\theta^2-\Delta^2)(8k+4k\theta-4k\theta^2-\Delta^2)^2}>0,$$

$$\pi_{cj}^{NI}(1)-\pi_{ci}^{IS}(2)=-\frac{k(8k-8k\theta^2-\Delta^2)\rho V}{(8k+4k\theta-4k\theta^2-\Delta^2)^2}<0.$$

We can derive that $\pi_{ci}^{IS}(1)>\pi_{ci}^{IS}(2)=\pi_{cj}^{IS}(2)>\pi_{ci}^{NI}(0)=\pi_{cj}^{NI}(0)=\pi_{cj}^{NI}(1)$.

Proof of Proposition 5

By comparing the expected profits of the manufacturer in the three information sharing cases, we obtain the following:

$$\pi_M(1)-\pi_M(0)=\frac{(1-\theta)(4k\theta^2+\Delta^2-4k)(12k-12k\theta^2-\Delta^2)\rho V}{4(1+\theta)(8k-8k\theta^2-\Delta^2)^2}>0,$$

$$\pi_M(2)-\pi_M(0)=\frac{(4k\theta^2+\Delta^2-4k)(12k+8k\theta-4k\theta^2-\Delta^2)\rho V}{2(1+\theta)(8k+4k\theta-4k\theta^2-\Delta^2)^2}>0,$$

$$\pi_M(2)-\pi_M(1)=\frac{(4k-4k\theta^2-\Delta^2)\,L(k)\rho V}{4(8k-8k\theta^2-\Delta^2)^2(8k+4k\theta-4k\theta^2-\Delta^2)^2},$$

where $L(k)=64(3\theta^2-4\theta-12)(1-\theta^2)^2k^3+16\Delta^2(1-\theta^2)(2-\theta)(8+7\theta)k^2+4\Delta^2(1+\theta)(5\theta-7)\,k+\Delta^6$. It shows that $\pi_M(1)>\pi_M(0)$ and $\pi_M(2)>\pi_M(0)$. Furthermore, Taking the first derivative of $L(k)$ with respect to k, we can get $\frac{dL(k)}{dk}=192(3\theta^2-4\theta-12)(1-\theta^2)^2k^2+32\Delta^2(1-\theta^2)(2-\theta)(8+7\theta)k+4\Delta^2(1+\theta)(5\theta-7)$. Let $\frac{dL(k)}{dk}=$

0 . We can derive two roots $k_2 = \frac{(16+6\theta-7\theta^2-\sqrt{4\theta^4-6\theta^3+31\theta^2+36\theta+4})}{12(12+16\theta+\theta^2-3\theta^3)(1-\theta)}$ and $k_3 = \frac{(16+6\theta-7\theta^2+\sqrt{4\theta^4-6\theta^3+31\theta^2+36\theta+4})}{12(12+16\theta+\theta^2-3\theta^3)(1-\theta)}$. It can be easily verified that $k_2 < k_0$ and $k_0 < k_3 < 2k_0$. Since the graph of $\frac{dL(k)}{dk}$ is a downward parabola, $L(k)$ is increasing in k in the interval (k_0 , k_3) and decreasing in k in the interval (k_3 , $2k_0$). Note that $L(k_0)=\frac{\Delta^6\theta^2}{8(1-\theta^2)} > 0$ and $L(2k_0)= -\frac{2\Delta^6}{1-\theta^2} < 0$. Therefore, there exists a k_1 in the interval $(k_0, 2k_0)$ that $L(k_1)=0$, and k_1 is unique. Then, we can derive that $L(k)>0$ in the interval (k_0, k_1) and $L(k)<0$ in the interval $(k_1, 2k_0)$. Consequently, we can obtain that $\pi_M(1)>\pi_M(2)>\pi_M(0)$ if $k \in (k_0, k_1)$, $\pi_M(1)=\pi_M(2)>\pi_M(0)$ if $k = k_1$, and $\pi_M(2) > \pi_M(1)>\pi_M(0)$ if $k \in (k_1, 2k_0)$.

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