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Modeling closed-loop supply chains in the electronics industry: A retailer collection application

I-Hsuan Hong [a,*,1], Jun-Sheng Yeh [b]

[a] Institute of Industrial Engineering, National Taiwan University, 1, Section 4, Roosevelt Road, Taipei 106, Taiwan
[b] Department of Industrial Engineering and Management, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan

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ABSTRACT

This paper proposes a *retailer collection* model whereby the retailer collects end-of-life products and the manufacturer cooperates with a third-party firm to handle used products, and a *non-retailer collection* model whereby a third-party firm is subcontracted by the manufacturer for collection work. While the return rate, manufacturer's profits, and channel members' total profits of the retailer collection model are not always superior to those of the non-retailer collection model, we find that the retail collection model analytically outperforms when the third-party firm is a non-profit organization for recycling and disposal.

1. Introduction

Collection, recycling and disposal procedures for used and obsolete products are important components of corporate responsibility. In an industry which seemingly produces new electronics almost daily, the volume of scrap electronics, or e-scrap, has proliferated throughout the world. For example, there are an estimated 500 million obsolete or unused computers in the United States alone, but only 10% are recycled (SVTC, 2009). Much e-scrap poses serious risks because of the hazardous substances it contains, such as lead, cadmium and mercury.

The environmental impacts of e-scrap have not gone unnoticed and governmental entities in both Europe and North America regulate disposal of electronic equipment containing toxic materials. In Europe, Waste Electrical and Electronic Equipment Directive (WEEE, 2003) and Restriction of Hazardous Substances Directive (RoHS, 2003) have been applicable for several years. In the United States, California specifies a mandatory electronic waste recycling fee of $8–$25 for certain electronic products shipped directly to the state (IWMB, 2003). In Maine all producers are responsible for electronic waste recycling (MRS, 2008). In addition, some governments also request that manufacturers selling new or replacement goods must collect the older products from customers and dispose of them appropriately. Many manufacturers even encourage customers to return brands other than their own for safe disposal or recycling. For example, in 2008 Hewlett–Packard (HP) collected 265 million pounds of used products; since 1987 the cumulative volume is more than 1435 million pounds (HP, 2008a). In 2008 Dell reported recovery for 135 million pounds of information technology equipment (Dell, 2008a). Nowadays, Dell's manufacturing operations can recycle or reuse about 95% of their waste (Dell, 2008a).

Since e-scrap and other product recycling can enhance a company's reputation and potentially attract more sales from environmentally conscious consumers, improving the efficiency of recycling programs has become a subject of interest in

* Corresponding author. Tel.: +886 2 3366 9507; fax: +886 2 2362 5856.
E-mail address: ihong@ntu.edu.tw (I.-H. Hong).
[1] The corresponding author holds a joint appointment with the Department of Mechanical Engineering, National Taiwan University.

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the literature. Several studies discuss reverse logistics management for used products. Guide and Van Wassenhove (2009) extensively review the rapidly evolving field of closed-loop supply chains covering 1996–2008. Ross and Evans (2003) and Jenkins et al. (2003) introduce the importance of choosing recycling strategies which provide positive effects on environment. Shi et al. (2011) determine the production quantities of brand-new products, the remanufactured quantities, and the acquisition prices of the used products simultaneously so as to maximize the manufacturer's total expected profit. Chen and Sheu (2009) conclude that governments should gradually raise regulation standards so that rational manufacturers will gradually improve product recyclability. Pochampally and Gupta (2003), Sarkis (2003), Hong et al. (2006), and Vlachos et al. (2007) investigate strategic issues of reverse supply chain network design or capacity planning, including the selection of the most economical products to reprocess, identifying potential facilities from a set of candidate recovery facilities, and solving facility location and capacity problems to achieve the optimum mix of logistics and quantities of goods. In addition, several studies discuss the inventory management for green components (Chung and Wee, 2008, 2010), deteriorating green products (Wee et al., 2011), short life-cycle products (Chung and Wee, 2011), and used products (Chung et al., 2008).

The global electronic industry's supply chains are gradually evolving from open-loop unidirectional flows of products – from supplier to end user – to more complex, closed-loop, linked forward and reverse arcs (see Fleischmann et al., 2000; Guide et al., 2003; Realff et al., 2004; Pishvaee et al., 2011). Some literature examines recycling or green practices in specific industries, i.e. paper (Pati et al., 2006, 2008), plastics (Arena et al., 2003; Siddique et al., 2008) and automobiles (Azevedo et al., 2011; Schultmann et al., 2006). For electronics Nagurney and Toyasaki (2005) and Hong et al. (2008) analyze the decision-making behaviors of recyclers, processors, and consumers associated with the demand markets for distinct products in a model of reverse supply chain management of e-scrap.

Subcontracting with a third-party firm such as a transportation service provider or a non-profit organization to operate recycling programs is common industry practice. For instance, GENCO, a third-party logistics company in North America, provides reverse logistics services that can decrease return processing cost-per-unit by 50% (GENCO, 2008). Other examples can be found in the personal computer industry. In Europe, Dell Corporation subcontracts to third-party firms for collecting used computer equipment and delivering it to Dell's obsolete products processing center (Dell, 2008b). Hewlett Packard contracts with a waste removal and management firm to collect e-scrap (HP, 2008b). Acer Corporation consults with a logistics company to carry out product recycling programs for the entire European region (Acer, 2008). All used products are sent to Acer's cooperating local third-party recyclers and disposed of properly.

It is important to note the existence of contract design issues between manufacturers and third-party firms. Giannoccaro and Pontrandolfo (2004) provide an exhaustive review of supply chain coordination by contract design. Taylor (2001) examines channel coordination under end-of-life returns. Krumwiede and Sheu (2002) and Meade and Sarkis (2002) show the importance of partnering with third-party logistics providers in reverse logistics processes, and Östlin et al. (2008) identify and discuss different types of closed-loop relationships for gathering worn/broken/used products for remanufacture.

The literature analytically proves a third-party collection model to be ineffective in a general closed-loop supply chain; Savaskan et al. (2004) study the structural problems of a chain with product remanufacturing where three collection options (manufacturer, retailer, and third-party) are analyzed. The retailer collection option with the manufacturer as the remanufacturer is considered best for achieving performance of profits and return rates. Nevertheless, in reality electronics manufacturers of consumer products typically are not remanufacturers, a situation which hampers the design of closed-loop supply chains as proposed in the earlier literature. In this paper we propose a *retailer collection* model whereby the retailer collects end-of-life products and the manufacturer cooperates with a third-party firm to handle used products. The proposed retailer collection model, therefore, is based upon the concept that retailers engage in collection and manufacturers cooperate with third-parties. For comparative purposes, we develop a *non-retailer collection* model whereby the manufacturer subcontracts a third-party firm for collection.

The remainder of this paper is organized as follows. Section 2 introduces a non-retailer collection model for comparative purposes and develops the closed-loop supply chain model with retailer collection. Section 3 compares the performance of the retailer collection model with the non-retailer collection model for return rate, manufacturer's profits, and total profits of channel members, conducts a sensitivity analysis, and examines the behavior of a third-party firm as a non-profit organization. Section 4 presents our conclusions and suggests future research.

2. Analysis of recycling systems

This section presents two recycling models: non-retailer collection and retailer collection. As mentioned, a manufacturer subcontracts with one third-party firm in a geographical region to engage in the collection of returned and obsolete products. We develop the non-retailer collection model described below as a benchmark case for purposes of comparison.

2.1. Notation

Let c denote the manufacturer's unit cost for manufacturing products, w the unit wholesale price, and p the unit retail price. The consumer's demand function for new products in the market is assumed as $D(p) = \phi - p$, a function of the retail price with ϕ being a positive parameter. Let τ denote the fraction of current generation product that would be returned, i.e. $0 \leqslant \tau \leqslant 1$, where τ can be interpreted as a reverse channel performance. This research assumes that the demand for new products and the quantity of returned products are in a steady state which is unaffected by time. Therefore, the quantity of return products is $(\phi - p)\tau$ without considering the time factor. In addition, let I denote the effort of collecting products in retail stores, and use $I = C_L \cdot \tau^2$ to transfer the returns to investment, where C_L is a positive scaling parameter. Similar forms have been used in effort response models in the literature (Coughlan, 1993; Savaskan et al., 2004). Let b, a positive parameter, denote the unit profit of the entity that handles or sells the treated obsolete products in both the retailer and non-retailer collection models. For comparative purposes, we deliberately assume an identical b for the manufacturer in the non-retailer collection model and the third-party firm in the retailer collection model, which implies that the manufacturer or third-party firm acts as the remanufacturer. An identical level of earning profit flowing into a recycling system for handling obsolete products leads to the assumption that b's are at the same level in the two models. In addition, a retailer or third-party firm charges consumers returning used computer hardware a unit service fee, A, which is without sign restriction. A retailer or third-party firm *charges* or *pays* for collecting recycled items if A is positive or negative respectively. In cases when recycling operations are economically viable, the profits are positive, i.e. $b + A > 0$. Let ψ denote the contract expense paid by the manufacturer to the third-party firm; ψ is a function of the return rate, τ, where $\psi = F \cdot \tau$, with F being a total expense whenever τ is equal to one. In this paper, it is reasonable to assume that F is a decision variable of the manufacturer because the manufacturer determines the contract.

2.2. Non-retailer collection model

Generally speaking, a third-party firm that cooperates with the manufacturer is usually subcontracted by the manufacturer for collection work. The conceptual model of the non-retailer collection is depicted in Fig. 1. For notational simplicity, we refer to this model as the non-retailer collection model throughout the paper.

This research assumes that the third-party firm decides the product's return rate, τ, the retailer decides the retail price, p, in the market, and the manufacturer decides the wholesale price, w. The contract is provided by the manufacturer to the third-party firm, so the contract variable, F, is a decision variable of the manufacturer. Other notations in Fig. 1 are the same as described in Section 2.1. Let Π_i^N denote the profit function for member i in the non-retailer collection model, where subscript i takes value M, R, or 3P, which denotes the manufacturer, retailer, or third-party firm. The profit functions of the manufacturer, retailer, and third-party firm are

$$\Pi_M^N = (\phi - p)(w - c) + b\tau(\phi - p) - F\tau, \tag{1}$$
$$\Pi_R^N = (\phi - p)(p - w), \tag{2}$$
$$\Pi_{3P}^N = A\tau(\phi - p) + F\tau - C_L\tau^2. \tag{3}$$

The sequence of decision-making in the non-retailer collection model is depicted in Fig. 2. After observing the unit manufacturing cost, the manufacturer determines the wholesale price, w, and the contract variable, F. Then the retailer decides the retail price, p, and the third-party firm determines the return rate, τ, simultaneously based on the wholesale price and the contract information revealed by the manufacturer.

In practice, the manufacturer, the first mover in the decision timeline, has sufficient bargaining power to act as a Stackelberg leader. This provides the justification for examining another performance measure, the manufacturer's profit, since the manufacturer may opt to choose retailer collection or non-retailer collection depending on its profit. When making decisions, the manufacturer considers the retailer's and the third-party firm's best responses to its decisions. The retailer and the third-party firm making decisions after observing the manufacturer's decision are the followers. We solve this two-stage sequential game by using backward induction moving from the second stage, retailer and third-party firm's decisions, to

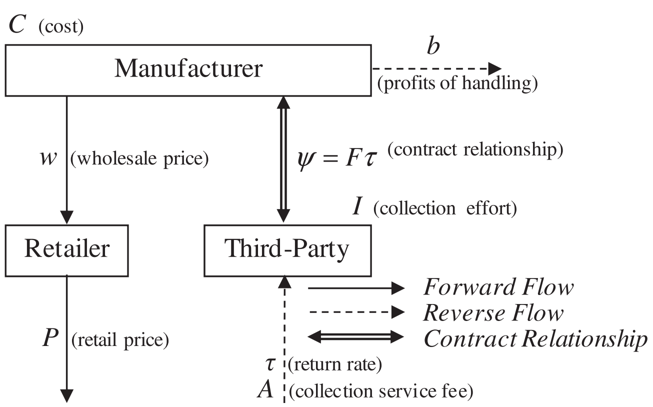

Fig. 1. Electronics industry recycling: non-retailer collection model.

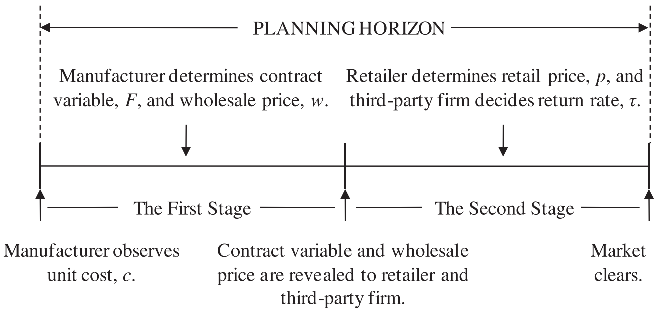

Fig. 2. Decision timeline: non-retailer collection model.

manufacturer's decision problem in the first stage. Throughout this paper, *stage* refers to the sequence of decision-making and *step* to the computational ordering.

2.2.1. Step 1. The retailer's decision in the second stage

The retailer maximizes its profits from selling new products as shown in (4).

$$\operatorname*{Max}_{p} \Pi_R^N = (\phi - p)(p - w). \tag{4}$$

Because $\frac{d^2\Pi_R^N}{dp^2} = -2 < 0, \Pi_R^N$ is concave in p. Then (4) is maximized when first-order conditions hold. From the first-order conditions, the retailer sets the retail price as

$$p^* = \frac{\phi + w}{2}. \tag{5}$$

2.2.2. Step 2. The third-party firm's decision in the second stage

The profits of the third-party firm are the revenue incurred from those recycling services and the contract minus the collection effort as shown in (6).

$$\operatorname*{Max}_{\tau} \Pi_{3P}^N = A\tau(\phi - p^*) + F\tau - C_L\tau^2. \tag{6}$$

From the second-order conditions, we have $\frac{d^2\Pi_{3P}^N}{d\tau^2} = -2C_L < 0$. Then Π_{3P}^N is concave in τ whenever $C_L > 0$, so (6) is maximized when the first-order conditions hold. Using the first-order conditions to derive the best response to the return rate gives

$$\tau = \frac{A(\phi - p^*)}{2C_L} + \frac{F}{2C_L}. \tag{7}$$

For any value of p, the third-party firm determines the return rate as above. In the second stage, the retailer or the third-party firm solves its problem simultaneously. Then we substitute (5), the optimal retail price, into (7) to obtain the optimal return rate as

$$\tau^* = \frac{A(\phi - w)}{4C_L} + \frac{F}{2C_L}. \tag{8}$$

The profit function of third-party firm, Π_{3P}^N, is concave in τ. In order to ensure that the optimal return rate, τ^*, is bounded between zero and one, we impose the condition of $\frac{\partial\Pi_{3P}^N}{\partial\tau}|_{\tau=1} < 0$ on τ. Assumption 1 follows from this condition.

Assumption 1. The parameter, C_L, defined in the collection effort is assumed to be sufficiently large such that $\tau^* < 1$, i.e. $16C_L > (b + A)^2 + (\phi + c)(b + A)$.

2.2.3. Step 3. The manufacturer's decision in the first stage

The manufacturer solves the problem to maximize its total profit, which is the sum of the revenue from selling new and recycled products minus the cost of the contract relationship with the third-party firm.

$$\operatorname*{Max}_{w,F} \Pi_M^N = (\phi - p^*)(w - c) + b\tau^*(\phi - p^*) - F\tau^*. \tag{9}$$

In making the decision, the manufacturer considers the retailer's and the third-party firm's best responses. Substituting (5) and (8) into the manufacturer's profit function, the manufacturer's profit in the non-retailer collection model is

$$\underset{w,F}{\text{Max}}\, \Pi_M^N = \frac{(\phi - w)(w - c)}{2} + \frac{b(\phi - w)}{2}\left[\frac{A(\phi - w)}{4C_L} + \frac{F}{2C_L}\right] - F\left[\frac{A(\phi - w)}{4C_L} + \frac{F}{2C_L}\right]. \tag{10}$$

To ensure Π_M^N is concave in w and F, the Hessian Matrix of (10), $\begin{bmatrix} -1 + \frac{bA}{4C_L} & \frac{-(b-A)}{4C_L} \\ \frac{-(b-A)}{4C_L} & \frac{-1}{C_L} \end{bmatrix}$, must be negative semi-definite. Then it should satisfy the conditions $-1 + \frac{bA}{C_L} < 0$, $\frac{-1}{C_L} < 0$ and $16C_L > (b + A)^2$. Note that $C_L > 0$, then $\frac{-1}{C_L} < 0$ is trivially satisfied. According to Assumption 1, $16C_L > (b + A)^2 + (\phi + c)(b + A)$, and the condition, $(b + A)(\phi + c) > 0$, one can easily verify that $16C_L > (b + A)^2$, and it also implies $-1 + \frac{bA}{C_L} < 0$. Hence, the manufacturer's profit function, Π_M^N, is concave in w and F, so (10) is maximized when the first-order conditions hold. The partial derivative of Π_M^N with respect to w and F is

$$\frac{d\Pi_M^N}{dw} = \frac{\phi - w}{2} - \frac{w - c}{2} - \frac{(b - A)F}{4C_L} - \frac{bA(\phi - w)}{4C_L}, \tag{11}$$

$$\frac{d\Pi_M^N}{dF} = \frac{(b - A)(\phi - w)}{4C_L} - \frac{F}{C_L}. \tag{12}$$

From the first-order conditions, the manufacturer decides the wholesale price w and the contract variable F as

$$w^* = \phi - \frac{2C_L(\phi - c) + F^*(b - A)}{4C_L - bA}, \tag{13}$$

and

$$F^* = \frac{(b - A)(\phi - w^*)}{4}. \tag{14}$$

Solving the two equations for two unknown variables, the final results of w and F which simultaneously satisfy the first-order conditions are

$$w^* = \phi - \frac{8C_L(\phi - c)}{16C_L - (b + A)^2}, \tag{15}$$

$$F^* = \frac{2C_L(\phi - c)(b - A)}{16C_L - (b + A)^2}. \tag{16}$$

Substituting the optimal wholesale price w^* and the contact variable F^* in (10), the manufacturer's profits are given by

$$\Pi_M^{*N} = \frac{2C_L(\phi - c)^2}{16C_L - (b + A)^2}. \tag{17}$$

The optimal unit retail price and return rate can be obtained by substituting w^* and F^* into (5) and (8).

This study also evaluates the total profits of the non-retailer collection model by summing the profits of the manufacturer, the retailer, and the third-party firm. However, as mentioned, a third-party collection model has been proven ineffective in the design of a closed-loop supply chain (Savaskan et al., 2004). In the next subsection, we integrate the concept that manufacturers may take advantage of the existing retail channel for collection in our proposed model.

2.3. Retailer collection model

According to Savaskan et al. (2004), a closed-loop supply chain with a retailer engaging in collection produces the best return rate, manufacturer's profits, and total profits of channel members but, as noted, an electronics consumer products manufacturer typically does not play a role in remanufacturing due to the industry's outsourcing business model. This section presents a proposed model where the retailer collects used products while charging a service fee and the manufacturer cooperates with a third-party firm for further handling of the collected items. The proposed model provides a remedy for cases where retailers are incapable of properly handling obsolete e-scrap. For notational simplicity, this research refers to this model as the retailer collection model depicted in Fig. 3.

Let r denote the unit revenue for the retailer from selling a unit of the used products to the third-party firm. Assume that the retailer's profits from collecting used products are positive so the condition, $r + A > 0$, holds. Again, the profit function for member i is denoted by Π_i, where subscript i takes value M, R, or $3P$, which denotes the manufacturer, the retailer, or the third-party firm. The profit functions are

$$\Pi_M = (\phi - p)(w - c) - F\tau, \tag{18}$$

$$\Pi_R = (\phi - p)(p - w) + \tau(r + A)(\phi - p) - C_L\tau^2, \tag{19}$$

$$\Pi_{3P} = \tau(b - r)(\phi - p) + F\tau. \tag{20}$$

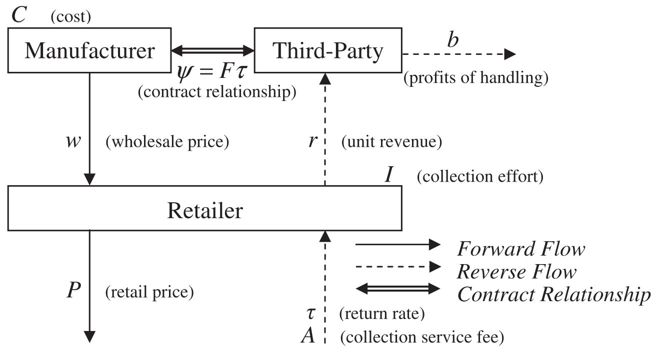

Fig. 3. Electronics industry recycling: retailer collection model.

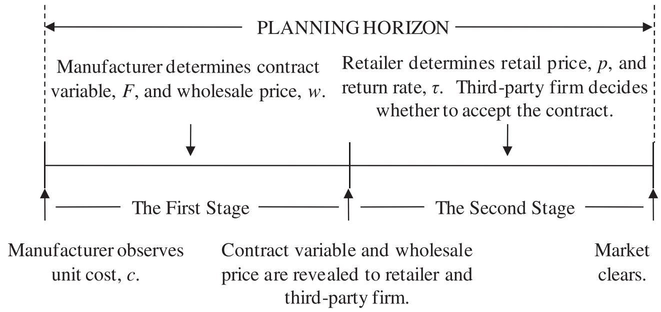

Fig. 4. Decision timeline of the retailer collection model.

The associated players' sequence of decision-making in the retailer collection model is depicted in Fig. 4. After observing the unit manufacturing cost, the manufacturer determines the wholesale price, w, and the contract variable, F. Then the retailer decides the retail price, p, and the third-party firm determines the return rate, τ, simultaneously based on the wholesale price and the contract information revealed by the manufacturer.

Acting as the first mover, the manufacturer considers the retailer's and the third-party firm's best responses when making decisions. The followers, the retailer and the third-party firm, make decisions after observing the manufacturer's decision. This research applies backward induction to studying this sequential two-stage model moving from the retailer's and the third-party firm's decision problems in the second stage to the manufacturer's decision problem in the first stage.

2.3.1. Step 1. The retailer's decision in the second stage

The retailer maximizes its profit function, Π_R, which is the profit from selling new products and recycling units minus the collection effort as shown in (21).

$$\underset{p,\tau}{\text{Max}}\, \Pi_R = (\phi - p)(p - w) + \tau(r + A)(\phi - p) - C_L\tau^2. \tag{21}$$

From the first-order conditions, p^* and τ^* are

$$p^* = \frac{\phi + w - \tau^*(r + A)}{2}, \text{and} \tag{22}$$

$$\tau^* = \frac{(\phi - p^*)(r + A)}{2C_L}. \tag{23}$$

Solving the two equations of (22) and (23) for two unknown variables, we obtain the optimal retail price p^* and return rate τ^* as

$$p^* = \phi - \frac{2C_L(\phi - w)}{4C_L - (r + A)^2}, \tag{24}$$

$$\tau^* = \frac{(\phi - w)(r + A)}{4C_L - (r + A)^2}. \tag{25}$$

Intuitively, the return rate, τ, must be less than one. To ensure this, we assume that the retailer's profit function is downward-sloping at $\tau = 1$, i.e. $\frac{\partial \Pi_R}{\partial \tau}|_{\tau=1} < 0$ so that the optimal return rate is located within the area below one. Assumption 2 follows from this condition.

Assumption 2. Parameter C_L defined in the collection effort is assumed to be sufficiently large such that $\tau^* < 1$, i.e. which means $C_L > \frac{(r+A)^2+(r+A)(\phi-w)}{4}$.

To ensure that Π_R is concave in p and τ, the Hessian Matrix of Π_R, $\begin{bmatrix} -2 & -r-A \\ -r-A & -2C_L \end{bmatrix}$, must be negative semi-definite, i.e. $-2C_L < 0$ and $C_L > \frac{(r+A)^2}{4}$. Note that C_L is positive, so $-2C_L < 0$. From Assumption 2, $C_L > \frac{(r+A)^2+(r+A)(\phi-w)}{4}$, and then it follows that $C_L > \frac{(r+A)^2}{4}$. Hence, the retailer's profit function is concave in p and τ, and then (21) is maximized when the first-order conditions hold.

2.3.2. Step 2. The third-party firm's decision in the second stage

The third-party's profit function, shown in (26) includes the profits from those obsolete products plus the revenue from the contract.

$$\Pi_{3P} = \tau^*(b-r)(\phi-p^*) + F\tau^*. \tag{26}$$

In (26) all of these notations in the profit function are given parameters for the third-party firm. In other words, there is no decision variable in this step. Instead of maximizing its profits, the third-party firm must decide whether to accept the manufacturer's contract. The third-party firm would accept the contract when its profits are nonnegative, i.e. $\Pi_{3P} \geqslant 0$. Hence, there is a constraint, as shown in (27) about the contract variable F for any value of p to ensure that the third-party firm has a nonnegative profit

$$F \geqslant -(b-r)(\phi-p^*). \tag{27}$$

In the second stage, the third-party firm and the retailer make decisions simultaneously. Substituting (24) into (27), the constraint of the contract variable is

$$F \geqslant -\frac{2C_L(\phi-w)(b-r)}{4C_L-(r+A)^2}. \tag{28}$$

Constraint (28) shows that there exists a lower bound of F which is the decision variable of the manufacturer. It implies that the contract must be incentivized enough for the third-party firm to accept it. From (28) the lower bound of F is positive whenever $r > b$, meaning that if the unit cost of the obsolete products is higher than the unit revenue, the manufacturer pays the third-party firm to help it assume responsibility for the recycling processes. On the contrary, if the third-party firm can receive positive profits from those used products, it has incentives to join this closed-loop supply chain collection program absent any payment from the manufacturer.

2.3.3. Step 3. The manufacturer's decision in the first stage

The manufacturer decides the wholesale price, w, and the contract, F, to maximize its profits from selling the new products minus the cost of contract as

$$\underset{w,F}{\text{Max}}\, \Pi_M = (\phi-p^*)(w-c) - F\tau^*. \tag{29}$$

When making the decision, the manufacturer considers the retailer's and the third-party firm's best responses. Substituting (24) and (25) into this profit function, the manufacturer's profit is

$$\underset{w,F}{\text{Max}}\, \Pi_M = \frac{2C_L(\phi-w)(w-c)}{4C_L-(r+A)^2} - \frac{F(\phi-w)(r+A)}{4C_L-(r+A)^2}. \tag{30}$$

Lemma 1. *The profit of the manufacturer is maximized when F reaches the lower bound.*

The proofs of this and the following propositions and observations are given in Appendix A. Lemma 1 simplifies the manufacturer's problem as a single-variable problem. Substituting the lower bound of the contact variable, $\underline{F}$, into (30), the manufacturer's profit can be further simplified as

$$\underset{w}{\text{Max}}\, \Pi_M = \frac{2C_L(\phi-w)(w-c)}{4C_L-(r+A)^2} + \frac{2C_L(\phi-w)^2(b-r)(r+A)}{[4C_L-(r+A)^2]^2}. \tag{31}$$

From the first-order conditions, the optimal wholesale price is

$$w^* = \phi - \frac{(\phi-c)[4C_L-(r+A)^2]}{8C_L-2(r+A)(b+A)}. \tag{32}$$

The second-order condition, $\frac{d^2\Pi_M}{dw^2} < 0$, holds whenever $4C_L \geqslant (r+A)^2 + (r+A)(b-r)$. Substituting (32) into the constraint of Assumption 2, $C_L > \frac{(r+A)^2+(r+A)(\phi-w)}{4}$, yields $4C_L > (r+A)^2 + (r+A)(b-r) + \frac{(r+A)(\phi-c)}{2}$. Because the two terms, $(r+A)$ and $(\phi$

$-\,c$), are positive, the second-order condition, $\frac{d^2\Pi_M}{dw^2} < 0$, holds. Hence, the profit function of the manufacturer is concave in w so (31) is maximized when the first-order conditions hold. Finally, the manufacturer's profit is given by

$$\Pi_M^* = \frac{C_L(\phi - c)^2}{8C_L - 2(r + A)(b + A)}. \tag{33}$$

The optimal return rate can be found by the substitution of w^*, giving

$$\tau^* = \frac{(r + A)(\phi - c)}{8C_L - 2(r + A)(b + A)} = \frac{(\phi - c)}{\frac{8C_L}{(r+A)} - 2(b + A)}. \tag{34}$$

From (33) and (34), the optimal return rate, τ^*, and the profits of the manufacturer, Π_M, positively relate to r. This leads to the result that the manufacturer desires a high return rate.

Proposition 1. *The manufacturer wants to provide the third-party firm with a contract that will induce the retailer to increase the return rate.*

3. Comparison of the models

This section summarizes the optimal decision variables and profit functions determined by each channel member in the two closed-loop supply chain models for comparative purposes, and conducts a sensitivity analysis to investigate how the changes in parameters affect the return rate and manufacturer's profit in the retailer collection and non-retailer collection models. We then study a case whereby a third-party firm in the retailer collection model is a non-profit organization that considers the fund balance between unit cost and unit revenue instead of the profit-maximization objective.

3.1. Performance comparison

A rational channel member would like to maximize its profits, but a channel structure designer, for example, the government, may focus on the return rate and total profits of a closed-loop supply chain. Based on the results summarized in Table 1, some interesting observations can be made about performance.

Observation 1. The optimal return rate in the retailer collection model, τ^*, is greater than the optimal return rate in the non-retailer collection model, τ^{N*}, whenever the condition $32C_L(r + A) - 16C_L(b + A) + 2(r + A)(b + A)^2 > 0$ holds.

Observation 2. The optimal profits of the manufacturer in the retailer collection model are greater than the profits in the non-retailer collection, i.e. $\Pi_M > \Pi_M^N$, whenever the condition $4(r + A) > (b + A)$ holds.

3.2. Numerical investigation

This research undertakes numerical studies that examine the return rates and manufacturer's profits by adjusting parameters C_L, A, r, and b. We first study how the collection effort parameter, C_L, would affect the return rate and the manufacturer's profits. In particular, unless explicitly mentioned, we give the parameters shown in Table 2, where C_L^N denotes the collection effort parameter in the non-retailer collection model. We investigate the ratios of the return rate and the manufacturer's profits in the retailer collection model to the performance measures in the non-retailer collection model. The value of col-

Table 1
Analytical results of the two models.

	Non-retailer collection model	Retailer collection model
Total profits	$\frac{3C_L(\phi-c)^2}{16C_L-(b+A)^2} + \frac{2C_L(\phi-c)^2(b+A)^2}{[16C_L-(b+A)^2]^2}$	$\frac{3C_L(\phi-c)^2}{16C_L-4(r+A)(b+A)} + \frac{4C_L(\phi-c)^2(b-r)(r+A)}{[16C_L-4(r+A)(b+A)]^2}$
Profits of manufacturer	$\frac{2C_L(\phi-c)^2}{16C_L-(b+A)^2}$	$\frac{2C_L(\phi-c)^2}{16C_L-4(r+A)(b+A)}$
Profits of retailer	$\frac{16C_L^2(\phi-c)^2}{[16C_L-(b+A)^2]^2}$	$\frac{4C_L(\phi-c)^2[4C_L-(r+A)^2]}{[16C_L-4(r+A)(b+A)]^2}$
Profits of third-party firm	$\frac{C_L(\phi-c)^2(b+A)^2}{[16C_L-(b+A)^2]^2}$	0
Retail price	$\phi - \frac{4C_L(\phi-c)}{16C_L-(b+A)^2}$	$\phi - \frac{4C_L(\phi-c)}{16C_L-4(r+A)(b+A)}$
Wholesale price	$\phi - \frac{8C_L(\phi-c)}{16C_L-(b+A)^2}$	$\phi - \frac{2(\phi-c)[4C_L-(r+A)^2]}{16C_L-4(r+A)(b+A)}$
Return rate	$\frac{(\phi-c)(b+A)}{16C_L-(b+A)^2}$	$\frac{2(\phi-c)(r+A)}{16C_L-4(r+A)(b+A)}$
Contract variable	$\frac{2C_L(\phi-c)(b-A)}{16C_L-(b+A)^2}$	$-\frac{4C_L(\phi-c)(b-r)}{16C_L-4(r+A)(b+A)}$

Table 2
Parameters in sensitivity analysis of C_L.

C_L^N	ϕ	c	A	b	r
200	40	10	5	15	15

lection effort parameter, C_L, in the retailer collection model varies from 180 to 580, which is 0.9–2.9 times of C_L^N, while C_L^N remains the same in the non-retailer collection model. The results are given in Fig. 5.

In Fig. 5, a ratio greater than one indicates that the performance measure in the retailer collection model is higher than in the non-retailer collection model. The collection effort, $I = C_L \cdot \tau^2$, is the cost paid by the associated party that engages in collection. An increase in C_L implies that it is more costly to increase the return rate in the reverse channel. As the collection effort in the retailer collection model, C_L, increases, both the return rate and the manufacturer's profits in the retailer collection model decrease. The retailer collection model shows that the manufacturer's profits remain superior over the non-retailer collection model within the examined range of C_L/C_L^N.

This section also numerically examines how the collection service fee, A, and the unit payment from the third-party firm to the retailer in the retailer collection model, r, jointly affect the performance measures. In particular, unless explicitly mentioned, we give the parameters as shown in Table 3. We vary the collection service fee, A, from five to zero and the payment from the third-party firm to the retailer, r, from −5 to 50.

Fig. 6 demonstrates the regions of A and r values for which the return rate and manufacturer's profits differ between the models. The retailer collection model performs better than the non-retailer collection model as r and A both increase probably because in the retailer collection model the retailer has greater incentives to collect obsolete products with a higher service fee or a higher unit payment from the third-party firm. On the other hand, if r and A are low, the retailer collection model may not produce the desired outcomes for return rate and manufacturer's profits.

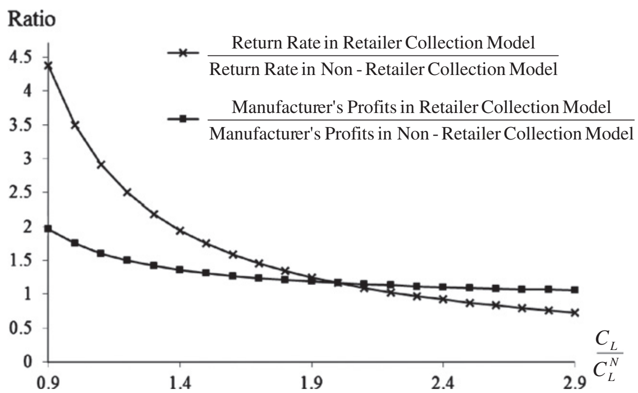

Fig. 5. Return rate and manufacturer's profits as functions of C_L.

Table 3
Parameters in sensitivity analysis of r and A.

C_L	ϕ	c	b
500	40	10	15

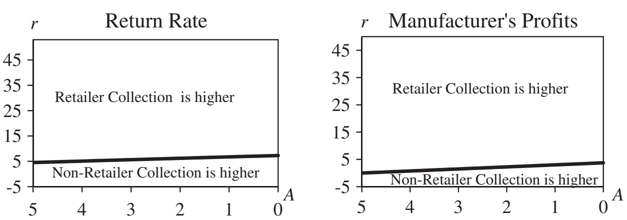

Fig. 6. Effect of r and A on return rate and manufacturer's profits.

Table 4
Parameters in sensitivity analysis of r and b.

C_L	ϕ	c	A
500	40	10	5

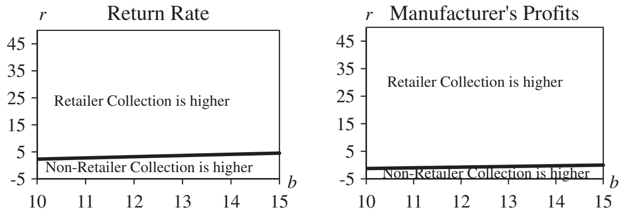

Fig. 7. Effect of r and b on return rate and manufacturer's profits.

This section numerically studies how the unit revenue, b, and cost, r, of handling returned products would jointly affect the performance measures in the models. Again, unless explicitly mentioned we give the parameters as shown in Table 4. We vary b from 10 to 15 and r from −5 to 50.

Fig. 7 demonstrates the regions of b and r values for which the return rate and manufacturer's profits differ between the models. The retailer collection model outperforms the non-retailer collection model in most of b and r investigated in this paper.

3.3. A special case: non-profit third-party

Some non-governmental organizations (NGOs) collect and dispose of used and obsolete products. For instance, in Switzerland in 2007, four non-profit organizations manage the financing, collection, transportation, and control systems for the electronics industry (Khetriwal et al., 2009). In addition, an empirical study (Kumar and Malegeant, 2006) indicates that a strategic alliance between a manufacturer and a non-profit organization in the collection process of a closed-loop supply chain is a beneficial strategy for the manufacturer. Typically, it is reasonable to assume that NGOs are non-profit organizations and third-party firms may be acting as non-profit organizations such as in the Swiss case. Hence, a third-party firm would not seek profit-maximization, but instead considers a fund balance between the revenue and cost incurred in recycling operations. Under this framework, optimal return rate, manufacturer's profits, and total profits in the retailer collection model can be obtained by substituting $r = b$ into the results of the retailer collection model in Table 1, which gives

$$\tau = \frac{2(\phi - c)(b + A)}{16C_L - 4(b + A)^2},$$

$$\Pi_M = \frac{2C_L(\phi - c)}{16C_L - 4(b + A)^2},$$

$$\Pi_T = \frac{3C_L(\phi - c)^2}{16C_L - 4(b + A)^2}.$$

Proposition 2. *When a third-party firm is acting as a non-profit organization,*

(i) *The* return rate in the retailer collection model is higher than that in the non-retailer collection model.
(ii) *The* retailer collection model outperforms the non-retailer collection model with respect to the manufacturer's profits.
(iii) *The* retailer collection model outperforms the non-retailer collection model with respect to the total profits of channel members.

The implication of Proposition 2 is that if a third-party firm is acting as a non-profit organization, the proposed retailer collection model outperforms the non-retailer collection model with respect to the return rate, manufacturer's profits and total profits. This analytical result concurs with the empirical study of (Kumar and Malegeant, 2006) and provides a useful policy implication: society (or government) has greater incentives to encourage non-profit organizations to engage in recycling operations, which ultimately enhances the benefits of all channel members in a closed-loop supply chain.

4. Conclusions and future research

An efficient and effective channel design for closed-loop supply chains can reduce the costs of recycling operations and enhance the benefits of channel members, regulatory bodies, and the market. This paper describes the current recycling practice in the global electronics industry, where the manufacturer subcontracts to a third-party firm for collection of used products. However, the literature indicates that a third-party firm collection model may not be an efficient way to perform collection for a general industry. The manufacturer may take advantage of the existing retail channel to help collect e-scrap from customers. This research develops a retailer collection model where the retailer collects used products and the manufacturer contracts with a third-party firm to further handle the e-scrap. In the proposed retailer collection model, the manufacturer's contract incents the retailer to increase the return rate of e-scrap.

By using the non-retailer collection model to establish benchmarks, we show that the retailer collection model's performance is superior to the non-retailer collection model under some conditions. We also consider that the third-party firm in the retailer collection model is a non-profit organization where the unit cost is equal to the unit revenue. In this case, the retailer collection model is superior with respect to the return rate, the manufacturer's profits, and the total profits of all channel members in a closed-loop supply chain.

The contributions of this paper to the literature are twofold: (i) the proposed retailer collection model captures the reality that electronics manufacturers of consumer products typically are not remanufacturers, a situation which hampers the design of closed-loop supply chains proposed in the earlier literature, and (ii) if a third-party firm acts as a non-profit organization, the proposed retailer collection model outperforms the non-retailer collection model for the return rate, manufacturer's profits and total profits, an analytic result which concurs with earlier empirical studies.

Three extensions to our modeling framework are worth investigation. First, since we use a simple linear contract with used products' return rate as our contractual relationship between the manufacturer and the third-party firm, other contracts, i.e. revenue sharing and incentive mechanism, might give additional insights. Second the case whereby competition may occur when both retailers and third-party firms in a recycling channel collect e-scrap merits study. Third, since in practice a manufacturer will likely face multiple retailers and third-party firms, this issue also requires more study.

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Appendix A

Proof of Lemma 1. Let $\underline{F}$ denote the lower bound of F. Assume that there exists a $F' = \underline{F} + \varepsilon$ where $\varepsilon > 0$, such that the profits of the manufacturer are maximized, i.e. $\Pi_M(F') > \Pi_M(\underline{F})$, where $\Pi_M(\cdot)$ is the manufacturer's profits that is a function of the contract variable. Then we have an inequality, $-\frac{(\phi-w)(r+A)}{4C_L-(r+A)^2}\varepsilon > 0$. Assumptions 2 and the condition, $(\phi - w) > 0$, contradict this inequality. Hence, the manufacturer's profits are maximized while the contract variable, F, reaches its lower bound. □

Proof of Proposition 1. From Lemma 1, the optimal contract variable, F, which reaches its lower bound, $\frac{C_L(\phi-c)(r-b)}{4C_L-(r+A)(b+A)}$, is a function of r. Moreover, the optimal return rate, $\tau^* = \frac{(r+A)(\phi-c)}{8C_L-2(r+A)(b+A)}$, is also a function of r. The manufacturer could control r indirectly by offering the third-party firm an appropriate contract so that it can affect the retailer's decision, the return rate, τ. Furthermore, the profits of the manufacturer, Π_M, positively relate to the return rate, τ. To maximize its profits, the manufacturer would determine an appropriate contract to induce the retailer to increase the return rate, τ. □

Proof of Observation 1. The condition, $32C_L(r+A) - 16C_L(b+A) + 2(r+A)(b+A)^2 > 0$, can be written as $r > \frac{8C_L(b+A)}{16C_L+(b+A)^2} - A$. Note that in the retailer collection model, the retailer's profits from collecting obsolete products are $\tau \cdot (r+A)(\phi - p)$. In the non-retailer collection model, the third-party firm earns $A \cdot \tau(\phi - p) + F \cdot \tau$ from returned products. In the retailer collection model, the retailer's profits from collection work would be increased when the third-party firm provides more payment to the retailer for the returned products. Therefore, the retailer would determine the return rate which is higher than the return rate in the non-retailer collection model when r is large enough. More specifically, $r > \frac{8C_L(b+A)}{16C_L+(b+A)^2} - A$. □

Proof of Observation 2. From Table 1, we observe that the manufacturer's profits in the retailer collection model increase with r. The manufacturer's profits in the retailer collection model would be greater than in the non-retailer collection model whenever $r > \frac{b+A}{4} - A$. In the retailer collection model, when the retailer's unit revenue from returned products, r, increases, it gives the retailer incentives to increase the quantity of recycled products. The quantity of recycled products, $\tau \cdot (\phi - p)$, positively relates to the return rate and the market demand for new products. The manufacturer's profits also positively relate to the market demand. Then in the retailer collection model, the manufacturer can earn more profits with more recycled products as r increases. Therefore, when r is large enough, i.e. $r > \frac{b+A}{4} - A$, the manufacturer's profits in the retailer collection model would be higher than its profits in the non-retailer collection model. □

Proof of Proposition 2. (i) As $r = b$, the condition, $32C_L(r + A) - 16C_L(b + A) + 2(r + A)(b + A)^2 > 0$, in Observation 1 can be rewritten as $16C_L + 2(b + A)^2 > 0$. It is trivial to show that $16C_L + 2(b + A)^2$ is greater than zero because C_L and $(b + A)^2$ are both positive and it completes the proof.(ii) Because the condition in Observation 2, $4(r + A) > (b + A)$, holds whenever r is equal to b, this trivially follows.(iii) We compute the difference in total profits difference between the models. The total profits in the retailer collection model are greater than the profits in the non-retailer collection model when the condition $112C_L - (b + A)^2 > 0$ holds. From Assumption 2, $4C_L - (b + A)^2 > 0$ whenever $r = b$, so the condition, $112C_L - (b + A)^2 > 0$, holds and it completes the proof. □

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