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A dual channel, quality-based price competition model for the WEEE recycling market with government subsidy ☆

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ABSTRACT

It is quite common to find both formal and informal sectors for processing waste electrical and electronic equipment (WEEE) in many emerging countries. Typically, the formal channel consists of recyclers with official qualifications for disassembling WEEE while the informal channel is dominated by unregulated recyclers. We develop a quality-based price competition model for the WEEE recycling market in a dual channel environment comprising both formal and informal sectors. The equilibrium acquisition prices and effects of government subsidy in the two channels are examined under four competitive scenarios. While government subsidy can support the formal sector, our analysis shows that at a higher quality level of waste, the marginal effect of subsidy is not as promising. When the quality of waste is high but the government subsidy is not substantial, the informal sector always has a competitive advantage. To promote the healthy development of the recycling industry the government should adjust the subsidy appropriately to limit the quality of waste at a high level suitable only for refurbishing in the informal sector. Our study also shows that both the formal and informal channels prefer high quality products. However, the informal recycler always has a better acquisition price to capture a bigger market share of used products than the formal recycler at the quality level of refurbishing for both recyclers. In a quality-pricing environment, as quality increases the acquisition prices in the two channels may crossover. This indicates that neither of the two channels always have a clear price advantage at all quality levels. We will not be able to obtain this result in a uniform pricing model. As such product quality is an important factor to consider in a competitive recycling market.

1. Introduction

According to the European Commission Directive 2002/96/EC, WEEE (waste electrical and electronic equipment) means "electrical or electronic equipment, which is waste…including all components, subassemblies and consumables, which are part of the product at the time of discarding" [9]. With frequent updating and upgrading, the amount of WEEE has reached 4% growth [41] and about 40 million tons are generated each year [30]. For example, in UK around 4 million computers are discarded every year (UNEP 2010 year book [42]) and in Phnom Penh, Cambodia, the number of WEEE was forecasted to grow four times every ten years [22].

The issue of WEEE recycling continues to be a problem. The composition of WEEE differs greatly across product lines. Overall, e-products contain "ferrous and non-ferrous metals, plastics, glass, wood and plywood, printed circuit boards, concrete and ceramics, rubber and other items" [18]. Since valuable and scarce materials can be obtained, recycling WEEE can be very profitable. It is estimated that by 2014 global revenues from WEEE processing could be US$14.6 billion [49]. However, dealing with WEEE in an environmentally sound manner is quite complex and expensive, especially when handling hazardous materials. In reality, "environmental legislation continues to be poorly implemented by national governments in the European Union and often the legislation is not adequately enforced" [46]. In recent years,

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trans-boundary movement of WEEE, which refers to illegal exportation to developing countries, is quite common. Many crude recycling hotspots are reported in Asian countries, such as China, India, and Pakistan, and in some African countries, such as Ghana and Nigeria (Lundgren [18]). There are two reasons to explain this phenomenon. Firstly, it is cheaper to export to developing countries than to process WEEE in developed countries. For example, in Europe disposal of WEEE legally costs four times as much as the illegal exportation [27]. Secondly, these fast-growing economies also need large amounts of materials that could be reclaimed from recycling WEEE. Reports show that between 50% and 80% of WEEE collected is being exported from developed countries each year [18]. This aggravates the situation of WEEE recycling in developing countries.

In many developing countries there exists both informal and formal recycling sectors, with the informal one being more prevalent. Zhao et al. [52] note that Guiyu town in China may be the largest informal recycling site in the world with about 100,000 people engaged informally in recycling activities. Widmer et al. [47] report that in India, the "Cyber City" of Bangalore is threatened by a rapidly increasing amount of e-waste where the informal sector recyclers have caused serious harm to the health of the workers. According to Chi et al. [7] the informal unregulated recyclers often disassemble and dispose WEEE using crude and pollutive methods. If e-products collected are fit for reuse, collectors resell them to dealers in the secondary market. If unfit for reuse, WEEE goes to recyclers for disassembly to retrieve functional parts and valuable materials. Those recyclers, without disassembling qualification from the government, only use rudimentary processing techniques. Dangerous practices such as open burning and acid baths are common. In addition, the useless hazardous substances are directly thrown away. All of these actions greatly pollute the environment. Many governments have promulgated the recycling regulations and laws to forbid unlicensed recycling on WEEE. However, enforcement is very difficult due to the lack of detailed practical measures and standards, a gray zone the informal sector lies in, and consideration of local economic development and social welfare.

Compared with the informal sector, the formal sector is at a distinct disadvantage in disposing cost. The formal recyclers have disassembling qualification granted by the government and use approved techniques in handling WEEE appropriately. For the formal sector, the environmentally sound processing usually costs a lot more. For example, in 2005 Haier's spending on disposal measures accounts for one half of recycling costs and millions of dollars will be lost if Haier pays to compete with informal recyclers [8]. For the informal sector, environmentally sound processing is lacking and as such the disposal cost is cheaper. The non-government organization Basel Action Network (BAN) made an investigation of Guiyu town and found that local unlicensed processing is done manually and with little protection for workers or the environment. For example, the acid used by workers to retrieve gold from electronic chips is disposed off directly into the river [38]. A consequence of unprotected low-cost processing is a severe damage to the environment.

Because of high disposal cost, the formal recyclers find it difficult to provide a competitive acquisition price. In addition, the informal recyclers have strong operations flexibility and convenience. With a lack of public environmental awareness, most of the products flow to the informal sector. In general, the formal sector plays a minor role in the recycling industry. For example, in Brazil a formal recycling structure for treatment of WEEE is still in its infancy; with the WEEE recycling rate estimated by the Brazilian Electrical and Electronic Producers Association to be only 2% [3].

Although there is a cost disadvantage, the formal recycling sector still has other exclusive advantages. For one, as an industry that has an impact on public welfare, WEEE recycling cannot be done without support from the government. The government is committed to providing some incentives for the formal sector to increase recycling volume. To some degree, the subsidy will enable formal recyclers to offer a more competitive acquisition price and thus change the weak position they have been in. The question then becomes: what is the appropriate level of government incentive? The role of government subsidy is worth studying to provide managerial insights in regulating the recycling industry. For the other, due to disposing regulations, especially with respect to product security and quality assurance, remanufacturers are more willing to cooperate with the formal sector rather than informal sector. As such the formal sector has a distinct advantage over the informal recyclers by being able to sell recycled useful parts to remanufacturers.

WEEE quality is an important factor in the study of pricing structure in the recycling industry. Quality refers to the WEEE recyclable condition, which is usually measured by product integrity, usage age, and maintenance state. According to the difference in quality level of e-waste products, recyclers can utilize different disposal methods, which in turn can affect the profit margin. When collecting WEEE, the formal and informal sectors decide acquisition prices according to the WEEE quality level. In the existing literature, there are few studies focusing on price competition between the two sectors. However, an in-depth research on price competition is an invaluable foundation for setting government recycling policy on incentives. Only when the competitive dynamics of the recycling industry is clearly understood will the government be able to promote the development of the formal sector using a subsidy policy.

Overall, our motivation for studying quality-based price competition between formal and informal recycling channels which have different disposing methods, is to explore the impact of government incentives on the recycling industry. What is the effect of price competition? How does subsidy change the industry competitive environment? What level of subsidy is reasonable? Our research will attempt to answer these questions.

Earlier studies focus mainly on the recycling channel choice of a manufacturer, optimizing reverse logistics network and remanufacturing management in a single enterprise or a supply chain. However, the problem of uncoordinated competition between the two recycling channels is quite common in many developing countries and there is a lack of quantitative research on this. The objective of our study is to develop an analytical model that will provide insights to assist the government in developing regulating policy for the recycling industry. Here the policy studied is government subsidy, which is a financial incentive.

This paper is organized as follows. In the next section we provide a summary of the literature related to recycling and remanufacturing. This is followed by the development of the price competition model in two channels and four competitive scenarios. Then the results for the different scenarios are presented. Next, we carry out numerical simulations that describe the competition in a graphic way. Finally, we provide managerial insights and concluding remarks.

2. Literature review

Recently, there are an increasing number of research papers focusing on reverse logistics management. Fleischmann et al. [11] present a review of mathematical models for reverse logistics. Krumwiede and Sheu [14] provide a conceptual model of reverse logistics by introducing a third party in addition to OEMs (original equipment manufacturers) and retailers. Likewise, Spicer and Johnson discuss the role of third party recyclers and compare three kinds of recycling channels – OEM take backs (manufacturers have direct responsibility), pooled take backs (several manufacturers share the responsibility), third-party take back (manufacturer subcontracts to third party for end-of-life product responsibility) [35]. Atasu et al. [2] suggest that collection cost is influenced by collection rate and volume and study how cost parameters matter in the above three channel choices. Savaskan et al. [28] compare the operation efficiency of different recycling means to provide the theoretical basis for manufacturers, while Savaskan and Wassenhove [29] add multiple retailers into the channel choice analysis. Besides research on recycling channel choice, some papers study manufacturers' remanufacturing strategy. Ferguson and Toktay [10] explore how a manufacturer deals with the competition, which is a third-party recycler engaging in refurbishing and reselling. They show that the manufacturer should recycle and dispose of used products to reduce the impact of the recycler's refurbishing work on the sale of new products. Oraiopoulos et al. [24] introduce a relicensing method for OEMs to influence the scale of the secondary market. Souza [36] examines strategic issues in OEM remanufacturing and provides a modeling framework to answer the question of whether an OEM should offer a remanufactured product. Our research differs from these papers by focusing on recycling competition between the different types of recyclers.

Several researchers discuss the effects of different pricing strategies on recycling quantity and profit when firms are involved in remanufacturing. Guide et al. [12] study the relationship between acquisition price and recycling amount, and build a pricing model to optimize profits. Bakal and Akcali [4] investigate how the acquisition price is related with the price of refurbished products to achieve a perfect yield rate. A few studies such as Vorasayan and Ryan [44] and Liang et al. [16] investigate the problem of setting prices of refurbished products and the effects on demand of new products. Shi et al. [32] incorporate uncertainties into the pricing discussion. Given a stochastic environment, the remanufacturer must decide the optimal production quantity, price of new products, and acquisition price. All the above research consider used products as homogeneous and do not provide a differential pricing strategy based on quality levels. There is some research involving different quality levels in recycling. For example, Teunter [37] considers the factor of quality distribution, but only studies the strategic management of one firm's disassembly and recovery operations. Mitra [20] focuses on two kinds of quality levels of waste products and develops a model to determine pricing that will maximize the expected revenue from the recovered products. Based on volatilities in the inventory level of recovered products, Vadde et al. [43] develop an algorithm to price recyclable components. All of these papers pay attention to recovery management on one recycling firm, not on price competition between different recycling sectors.

In the area of recycling policy and regulation, there are several related papers. For example, Bansal and Gangopadhyay [5] propose different combinations of tax and subsidy incentives and analyze their impacts on green manufacturing. They show that providing a subsidy is superior to taxing when promoting cleaner production. Liu et al. [17] show how the "old-for-new" policy on household electrical appliances can be extended into a strategy at the enterprise level. Palmer et al. [25] and Palmer and Walls [26] introduce government deposit-refund measures in providing compensation in the recycling industry. Wojanowski et al. [48] emphasize the role of consumer participation in recycling efforts and suggest that the government should make use of the deposit-refund method to encourage enterprises to collect used products. In Mitra and Webster [21], the impact of subsidy on the recycling market is explored. They point out that subsidies should also flow partly to manufacturers because compensating recyclers only will harm the manufacturer's profit. Wang and Da [45] study the effectiveness of incentive mechanism on motivating recyclers to enhance the quantity recycled. Hammond and Beullens [13] model a network of manufacturers and consumer markets in a Cournot competition with perfect information. They find that legislation that enforces minimum recovery targets on new products will encourage the development of a reverse supply chain. Atasu and Subramanian [1] compare two forms of product take-back regulations and find that the collective producer responsibility model is better in stimulating manufacturers' product design for recovery than the individual producer responsibility model. As we can see, the government's policy on recycling may be in various forms. Generally, it can be unified as an exogenous finance support, which in this paper we call subsidy. We observe that in previous studies of government subsidy, the focus is on the interaction between government and a single recycler and not between government and different types of recyclers

Due to growing environmental concerns, research on WEEE recycling in developing countries is on the rise. Zhao et al. [51] in their review of decision sciences research in China note the increasing emphasis on how to strengthen green supply chain management and develop the recycling economy. Araujo et al. [3], Chi et al. [7], Li et al. [15], Manomaivibool [19], and Sepúlveda et al. [31] are examples of research focusing on recycling WEEE in developing countries. These papers examine the recycling practices of the informal sector and provide some measures to regulate the current recycling systems. Using a system dynamics approach, Besiou et al. [6] examine the effect of scavenging on the formal WEEE recovery process and find that "a legislation incorporating scavengers into the formal waste recovery system (instead of either ignoring or prohibiting their participation) is beneficial for economic, environmental and social sustainability." Liu et al. [17] study uniform pricing when collecting used products, but do not explore quality-based pricing. In addition, their research results only show a rough trend of the effect of subsidy without providing an optimal level of subsidy.

Our work is distinguished from earlier studies as follows: (1) incorporating quality-based price competition between formal and informal recycling sectors; and (2) exploring the impact of subsidy on both formal and informal sectors and discussing the optimal level of subsidy for the entire recycling industry. In addition, the condition when the informal channel is shut down is analyzed in detail. At the same time, the formal sector's cooperation with remanufacturers and the government's setting of the quality threshold of reusing to the formal sector are also studied.

3. Model development

For WEEE, there are two common disposing methods: disassembling and refurbishing, the former refers to dismantling low-quality used products into usable materiel such as metals, and the latter refers to overhauling high-quality used products and restoring them into marketable ones. When an old product is judged to be suitable for refurbishing, disassembly work will be done first and all modules will be inspected carefully [39]. The useful modules will be mended or polished. For the useless modules, new ones will be used as replacements. Finally, all usable modules will be assembled into a product. In the recycling market, we have two kinds of recycling channels: a formal sector (hereafter referred to as channel A) and an informal sector (hereafter referred to as channel B). channel A is led by regulated recyclers with official disassembly qualification, while channel B is led by unregulated ones without disassembly qualification. Both channels collect used products and choose one of the above two disposal methods based on the product quality levels. An advantage the formal sector has is the opportunity to cooperate with remanufacturers who need functional parts for reusing. So channel A has a third disposal method, which is to extract useful parts from waste products.

As an exclusive advantage, channel A can also enjoy government subsidy. According to recycling practice in most countries, only when one product is recycled appropriately, say, dismantled into useful items, government will provide a subsidy for the recycler who engages in. So in our paper, among all three available disposing methods, only disassembling and extracting useful parts meet requirements. For refurbishing, it is kind of product reusing, rather than a general recycling concept. Therefore, in practice, refurbishing cannot get government subsidy. In our paper, subsidy is provided for channel A in unit of each acquisition quantity. The subsidy level for one recycled product is assumed to be s.

In Fig. 1, both recyclers in the formal and informal sectors sell recycled metals in the raw material market and refurbished products in the secondary market. Hereafter we use subscript $i=1,2,3$ to denote three disposing methods of refurbishing, extracting useful parts and disassembling, respectively.

The focal points in our paper are recycling competition. To make this stand out, we simplify the modeling on recyclers' sale. Corresponding to different quality levels of used products, the formal recycler selects refurbishing, extracting useful parts or disassembling, while the informal recycler chooses refurbishing or disassembling. The paper assumes that prices of recycled items or products are exogenous, because they are influenced by many environmental factors and could not be described clearly as decision variables. Since extracting useful parts is the exclusive disposing method for the formal sector, we also study the effect on the recycling competition when the price of usable pars is varied. The price of refurbished products sold in secondary market is P_1. The price of extracted useful parts in a single product sold to remanufacture is P_2. The price of raw material from disassembling is assumed to be P_3. In addition, we have the following condition: $P_1>P_2>P_3$. The variables used in our study are defined in Table 1.

We assume that both recyclers are able to assess the quality level when collecting used products. Here we define the quality level as a value evaluation on future disposing method and earning. It refers to the WEEE recyclable condition, which is usually measured by product integrity, usage age, and maintenance state. In general, products at higher quality levels are refurbished, while those at lower levels are extracted or disassembled. We use θ as the quality of used products, which is normally assumed to have a uniform distribution on [0,1]. Based on the quality levels of collected products, when recyclers choose to refurbish a product, the disposal cost differs substantially with regards to quality. When the quality level of old products is low, it is more likely that old modules will be replaced with new ones. Because the cost of purchasing new modules is usually higher than that of repairing, a higher quality level typically translates to a lower refurbishing process cost. In describing the refurbishing cost function, we use the Spence job market signaling model for reference [33,34]. In Spence signaling model, the cost of improving education level is a reciprocal function of employees' productive capabilities. In our paper, the relationship between refurbishing cost and quality level is also negatively related and can be similarly expressed in a reciprocal form. To simplify the model analysis and at the same time keep the basic results unchanged, we use a reciprocal of quality level to express the refurbishing cost function. Then the refurbishing costs for formal and informal recyclers are shown as C_{1A}/θ and C_{1B}/θ, respectively. Ideally, when the quality level θ equals to 1, the refurbishing costs will be C_{1A} and C_{1B}. Similarly, when extracting useful parts, the cost for formal recycler

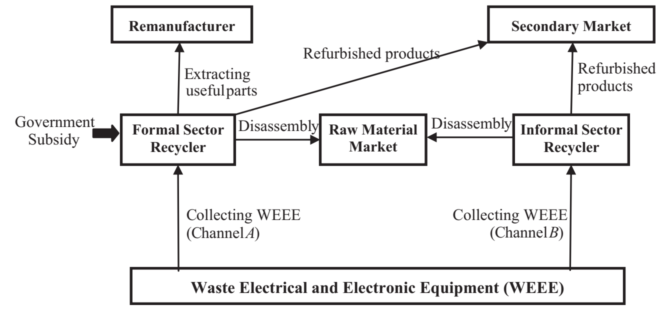

Fig. 1. WEEE flows in formal and informal sectors.

is set to be C_{2A}/θ. When disassembling a waste product, useful raw materials are extracted. This disassembling process is often not affected by the quality of the used product. So the disassembly costs for the two recyclers are C_{3A} and C_{3B}. Because the formal recycler needs to invest in environmental-friendly disposal technology and provide quality assurance and warranty, the formal sector has a higher disposing cost than informal sector. As such we have $C_{1A}>C_{1B}>C_{2A}>C_{3A}>C_{3B}$.

Based on the quality information of collected used products, recyclers decide the acquisition prices, $p_A=f(\theta)$, $p_B=g(\theta)$, which are continuous functions of quality level. Acquisition quantity is assumed to be a linear function of acquisition price, which has been used by Savaskan et al. [28] and Savaskan and Wassenhove [29]. Following these previous studies and considering that price is a major factor for product acquisition in developing countries, we set up the acquisition quantities q_A and q_B, using the equations below.

$$q_A=q+ap_A-bp_B \tag{1}$$

$$q_{\boldsymbol{B}}=q+ap_B-bp_A \tag{2}$$

Here, p_A and p_B are the acquisition prices for formal and informal sectors. q is acquisition quantity when acquisition price is equal to 0. a is recycler's self-price sensitivity on acquisition quantity and b is cross-price sensitivity on acquisition quantity. This kind of demand function is wildly used in the literature, such as Tsay and Agrawal [40], Yao and Liu [50], Mukhopadhyay et al. [23].

In reality, besides the price factor, acquisition quantities can also be affected by many exogenous factors, which can cause the acquisition quantities to be uncertain. The variance of uncertainty can be associated with the quality of old products, or independent of the quality. In either situation, from the viewpoint of expected profits, the influence of uncertainty is a decrease or an increase in the final acquisition quantity, which will affect the total profit. After taking a derivative of expected profit with respect to acquisition price, the first-order-condition involves an additional constant when introducing uncertainty. So uncertainty is independent of pricing decision and will not influence the basic results of our model.

4. Model solution

Besides providing supporting policy, the government also supervises the recycling behaviors in the formal sector, which has official disassembly qualification. According to our observation on recycling practice, the extracted useful parts must meet the minimum quality requirements set by the government. However, for the unregulated informal sector, there is a lack of supervisory control. To reflect this point, we add a parameter τ^* to represent quality threshold of reusing WEEE, which means that products beyond this quality level can be extracted for useful parts or

Table 1
Definition of parameters and variables.

Description	Parameters and variables	
Quality of used products	θ	
Acquisition quantity when acquisition price is equal to 0	q	
Price sensitivity on acquisition quantity	a	
Cross-price sensitivity on acquisition quantity	b	
Price of refurbished products in secondary market	P_1	
Price of extracted useful parts in a single product	P_2	
Price of raw material extracted from disassembling used products	P_3	
	Channel *A*	**Channel *B***
Total profit of the recycler	π_A	π_B
Acquisition price of WEEE	P_A	P_B
Acquisition quantity of WEEE	q_A	q_B
Government subsidy for disassembly (refurbishing not included)	s	None
Refurbishing cost (when $\theta=1$)	C_{1A}	C_{1B}
Cost of extracting useful parts (when $\theta=1$)	C_{2A}	None
Cost of recycling raw material	C_{3A}	C_{3B}
Minimum quality point for refurbishing	τ_A	τ_B
Quality threshold of reusing WEEE, products beyond this quality point can be extracted for useful parts or refurbished	τ^*	None

refurbished. This quality threshold of reusing is mandatory for the formal sector, but not for the informal sector. Therefore, recyclers in the formal sector only extract useful parts from products above the lowest quality point τ^*.

The formal sector has three disposal choices on collected products. The profit margins associated with each are shown below:

(1) For refurbished products the profit margin obtained is $\pi_{1A}=P_1-C_{1A}/\theta-p_A$.
(2) For the extraction of useful parts, the profit margin is $\pi_{2A}=P_2+s-C_{2A}/\theta-p_A$.
(3) For disassembling used products, the profit margin is $\pi_{3A}=P_3-C_{3A}+s-p_A$.

We assume τ_A to be a demarcation point of quality between refurbishing and extracting useful parts in channel *A*.

τ_A is a decision variable for the formal sector and its value is dependent on the comparison between two profit margins of refurbishing and extracting useful parts. When two margins have no difference, we obtain the demarcation point of quality τ_A. For products with quality level $\theta \geq \tau_A$, refurbishing will be chosen; for products with $\tau^* \leq \theta < \tau_A$, the formal recycler will extract useful parts from them; and for products with $\theta < \tau^*$, disassembling will be carried out. Clearly, the possible minimum value for τ_A is τ^*.

When $\pi_{1A}=\pi_{2A}$, the condition $P_1-P_2-s=(C_{1A}-C_{2A})/\theta$ should be met. Because $\theta \in [0,1]$ and $\tau_A \in [0,1]$, then if $s > P_1-P_2-(C_{1A}-C_{2A})$, we have $\tau_A=1$, otherwise $\tau_A=max[(C_{1A}-C_{2A})/(P_1-P_2-s),\tau^*]$.

The informal sector has two disposal choices on collected products. If refurbishing, the profit margin obtained is $\pi_{1B}=P_1-C_{1B}/\theta-p_B$; if disassembling, the profit margin is $\pi_{3B}=P_3-C_{3B}-p_B$. We assume τ_B to be a demarcation point of quality between refurbishing and disassembling in channel *B*.

τ_B is a decision variable for informal sector and its value depends on the comparison between two profit margins of refurbishing and disassembling. When two margins have no difference, we obtain the demarcation point of quality τ_B. For products with quality level $\theta \geq \tau_B$, refurbishing will be chosen; for products with $\theta < \tau_B$, disassembling will be done. When $\pi_{1B}=\pi_{3B}$, the condition $P_1-C_{1B}/\theta=P_3-C_{3B}$ holds and we get $\tau_B=C_{1B}/(P_1-P_3+C_{3B})$.

τ_A and τ_B are the boundaries between different disposing methods and could be derived after comparing the different profit margins. When the price of recycled items or products changes, τ_A and τ_B will need to be recalculated. Later, we will show the effect of changes of P_2 on τ_A.

The profit function of formal recycler in channel *A* is π_A, which is comprised of three parts. The first part is the profit obtained from refurbishing $\int_{\tau_A}^{1}(P_1-(C_{1A}/\theta)-p_A)q_A d\theta$, and the second is from extracting useful parts $\int_{\tau^*}^{\tau_A}(P_2+s-(C_{2A}/\theta)-p_A)q_A d\theta$, and the third is from disassembling $\int_0^{\tau^*}(P_3-C_{3A}+s-p_A)q_A d\theta$. To sum up, we get the profit function of formal recycler π_A.

$$\pi_A=\int_0^{\tau^*}(P_3-C_{3A}+s-p_A)(q+ap_A-bp_B)d\theta + \int_{\tau^*}^{\tau_A}\left(P_2+s-\frac{C_{2A}}{\theta}-p_A\right)(q+ap_A-bp_B)d\theta + \int_{\tau_A}^{1}\left(P_1-\frac{C_{1A}}{\theta}-p_A\right)(q+ap_A-bp_B)d\theta. \quad (3)$$

The profit function of the informal recycler in channel *B* is π_B, which includes two parts. The first part is the profit obtained from refurbishing $\int_{\tau_B}^{1}(P_1-(C_{1B}/\theta)-p_B)q_B d\theta$, and the second is from disassembling $\int_0^{\tau_B}(P_3-C_{3B}-p_B)q_B d\theta$. In total, the profit of informal recycler is as follows.

$$\pi_B=\int_0^{\tau_B}(P_3-C_{3B}-p_B)(q+ap_B-bp_A)d\theta + \int_{\tau_B}^{1}\left(P_1-\frac{C_{1B}}{\theta}-p_B\right)(q+ap_B-bp_A)d\theta. \quad (4)$$

In addition to the two demarcation points of quality, τ_A and τ_B, we have acquisition price decision variables of p_A and p_B. Next we derive π_A and π_B with respect to p_A and p_B according to derivative rules for implicit functions. There are three different quality levels when $\theta \in [0,1]$, which we need to derive piecewise.

When $\theta \in [0,\tau^*]$, derive $\int_0^{\tau^*}(P_3-C_{3A}+s-p_A)(q+ap_A-bp_B)d\theta$ in terms of p_A. Because we do not consider the correlation between acquisition quantities on different quality levels, which means that each quality is independent, the optimization work can be done in each quality level. Since it is a form of definite integral, we derive $(P_3-C_{3A}+s-p_A)(q+ap_A-bp_B)|_{\theta \in [0,\tau^*]}$ with respect to p_A, and then we can obtain the first-order condition

$$2ap_A-bp_B=a(P_3-C_{3A}+s)-q \quad (5)$$

When $\theta \in [\tau^*,\tau_A]$, derive $\int_{\tau^*}^{\tau_A}(P_2+s-(C_{2A}/\theta)-p_A)(q+ap_A-bp_B)d\theta$ in terms of p_A. The first-order condition is obtained.

$$2ap_A-bp_B=a\left(P_2+s-\frac{C_{2A}}{\theta}\right)-q \quad (6)$$

When $\theta \in [\tau_A, 1]$, derive $\int_{\tau_A}^{1} (P_1 - (C_{1A}/\theta) - p_A)(q + ap_A - bp_B)d\theta$ in terms of p_A. The first-order condition is as follows:

$$2ap_A - bp_B = a\left(P_1 - \frac{C_{1A}}{\theta}\right) - q \tag{7}$$

Similarly, we derive π_B in terms of p_B piecewise. The first-order conditions are as follows:

When $\theta \in [0, \tau_B], 2ap_B - bp_A = a(P_3 - C_{3B}) - q$ (8)

When $\theta \in [\tau_B, 1], 2ap_B - bp_A = a\left(P_1 - \frac{C_{1B}}{\theta}\right) - q$ (9)

The above first-order conditions are the best response functions for pricing used products with different quality levels.

Based on the relative changes of τ^* and s, we have four competitive scenarios as shown in Fig. 2. These settings reflect many common situations in practice. If $\tau^* > \tau_B$, we have scenario S_H. As the subsidy (s) increases we have three additional scenarios: S_{L1} ($\tau_A < \tau_B$), S_{L2} ($1 > \tau_A > \tau_B$), S_{L3} ($\tau_A = 1$), respectively.

For scenario S_H, $\tau_B < \tau^* \le \tau_A$, there are four quality levels to solve, which are $[0, \tau_B]$, $[\tau_B, \tau^*]$, $[\tau^*, \tau_A]$ and $[\tau_A, 1]$. Combining the response functions of two recyclers and simultaneously solving the equations will give the acquisition price functions of quality. Tables 2 and 3 show the acquisition prices and quantities at different quality levels.

5. Scenario analysis

5.1. Scenario S_H

In this competitive scenario, $\tau_B < \tau^* \le \tau_A$, and the minimum quality point for refurbishing in channel B is less than the quality threshold of reusing set by the government. This means that the informal recycler has a high refurbishing ratio. For those used products with relatively low quality, channel B will still try to sell them in the secondary market after refurbishing, regardless of the quality assurance guidelines.

We have the following findings for Scenario S_H:

(1) For $\theta \in [0, \tau_B], \partial p_A/\partial\theta = \partial p_B/\partial\theta = 0$; for $\theta \in [\tau_B, \tau^*], \partial p_A/\partial\theta < \partial p_B/\partial\theta$; for $\theta \in [\tau^*, \tau_A]$, $\partial p_A/\partial\theta < \partial p_B/\partial\theta$; for $\theta \in [\tau_A, 1], \partial p_A/\partial\theta > \partial p_B/\partial\theta$.

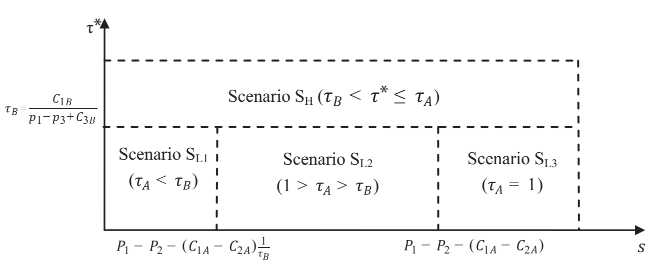

Fig. 2. Four competitive scenarios.

At the disassembly quality level, the acquisition price is not impacted by quality. However, at other levels, the higher the quality of used products, the faster the acquisition price will advance. Initially, the growth speed of the acquisition price is higher in channel B. However at the quality level for refurbishing, the acquisition prices in channel A exceeds channel B.

(2) As the subsidy increases, the acquisition prices in both channels go up. The acquisition quantity increases in channel A but drops in channel B. The quantity of collected used products rises.

(3) Except at the disassembly quality level, the total collected quantity increases as the quality level rises. However, for each channel the situation is influenced by cost factors such as:
When $\theta \in [\tau_B, \tau^*]$, $\partial q_A/\partial\theta < 0, \partial q_B/\partial\theta > 0$;
When $\theta \in [\tau^*, \tau_A]$, $\partial q_B/\partial\theta > 0$. If $C_{2A}/C_{1B} > ab/(2a^2 - b^2)$, then $\partial q_A/\partial\theta > 0$, otherwise $\partial q_A/\partial\theta < 0$.
When $\theta \in [\tau_A, 1]$, $\partial q_A/\partial\theta > 0$. If $C_{1B}/C_{1A} > ab/(2a^2 - b^2)$, then $\partial q_B/\partial\theta > 0$, otherwise $\partial q_B/\partial\theta < 0$.

(4) The acquisition price is influenced directly by the subsidy level. At low-quality levels, the higher the subsidy, the more likely it is that channel A will have a higher acquisition price than channel B. However at the refurbishing quality level, channel B's acquisition price is always higher than channel A. At the quality level beyond τ_B, $\partial(p_A - p_B)/\partial\theta = -(aC_{1B}/(2a+b)\theta^2) < 0$, the higher the quality, the more likely it is that channel B has a higher acquisition price than channel A even if the subsidy is quite high. We also observe that as the subsidy changes, neither of the two channels will always have a higher acquisition price at all quality levels.
When $\theta \in [0, \tau_B]$, let $\hat{s} = C_{3A} - C_{3B}$, if $s > \hat{s}$, then $p_A > p_B$.
When $\theta \in [\tau_B, \tau^*]$, let $\hat{s}_1 = -(C_{1B}/\tau^*) + P_1 - P_3 + C_{3A}$, if $s > \hat{s}_1$, then $p_A > p_B$.
When $\theta \in [\tau^*, \tau_A]$, let $\hat{s}_2 = P_1 - P_2 - ((C_{1B} - C_{2A})/\tau^*)$, if $s > \hat{s}_2$,
then for $\theta \in (\tau^*, ((C_{1B} - C_{2A})/(P_1 - P_2 - s))$, $p_A > p_B$.

From the above results, we note that both channels prefer high-quality products. At the refurbishing quality level for both recyclers, channel A is more sensitive to high quality than channel B. The formal recycler strives to raise acquisition price, which can be seen from its higher increase rate in price at the highest quality level. However, channel B always has a more attractive acquisition price due to its cost advantage.

To some degree, government subsidy can promote the development of channel A and weaken the competitiveness of channel B. With an increasing quality level, the marginal effect of subsidy on competition is weakening. When the subsidy is not sufficiently high, it is difficult for channel A to win more market share, which also shows a dependency of channel A on the subsidy level.

At different quality levels, the change in acquisition quantity as subsidy increases is not consistent since it can be greatly influenced by other cost factors. At the refurbishing quality level for both recyclers, channel A is willing to recycle more high-quality products, while channel B begins to weigh the relative value of recycling. If channel

Table 2
Acquisition prices and changes in quality for scenario S_H.

θ	p_A	p_B
$[0, \tau_B]$	$\frac{2a^2(P_3 - C_{3A} + s) + ab(P_3 - C_{3B}) - (2a+b)q}{4a^2 - b^2}$.	$\frac{ab(P_3 - C_{3A} + s) + 2a^2(P_3 - C_{3B}) - (2a+b)q}{4a^2 - b^2}$.
$[\tau_B, \tau^*]$	$\frac{2a^2(P_3 - C_{3A} + s) + ab\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$	$\frac{ab(P_3 - C_{3A} + s) + 2a^2\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$
$[\tau^*, \tau_A]$	$\frac{2a^2\left(P_2 + s - \frac{C_{2A}}{\theta}\right) + ab\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$	$\frac{ab\left(P_2 + s - \frac{C_{2A}}{\theta}\right) + 2a^2\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$
$[\tau_A, 1]$	$\frac{2a^2\left(P_1 - \frac{C_{1A}}{\theta}\right) + ab\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$	$\frac{ab\left(P_1 - \frac{C_{1A}}{\theta}\right) + 2a^2\left(P_1 - \frac{C_{1B}}{\theta}\right) - (2a+b)q}{4a^2 - b^2}$

Table 3
Acquisition quantities of formal and informal recyclers for scenario S_H.

	$q_A - q$	$q_B - q$
$[0, \tau_B]$	$\dfrac{a\left(2a^2-b^2\right)(P_3-C_{3A}+s)-a^2b(P_3-C_{3B}) + (b-a)(2a+b)q}{4a^2-b^2}.$	$\dfrac{-a^2b(P_3-C_{3A}+s)+a\left(2a^2-b^2\right)(P_3-C_{3B}) + (b-a)(2a+b)q}{4a^2-b^2}.$
$[\tau_B, \tau^*]$	$\dfrac{a\left(2a^2-b^2\right)(P_3-C_{3A}+s)-a^2b\left(P_1-\frac{C_{1B}}{\theta}\right) + (b-a)(2a+b)q}{4a^2-b^2}.$	$\dfrac{-a^2b(P_3-C_{3A}+s)+a\left(2a^2-b^2\right)\left(P_1-\frac{C_{1B}}{\theta}\right) + (b-a)(2a+b)q}{4a^2-b^2}.$
$[\tau^*, \tau_A]$	$\dfrac{a\left(2a^2-b^2\right)\left(P_2+s-\frac{C_{2A}}{\theta}\right)-a^2b\left(P_1-\frac{C_{1B}}{\theta}\right) + (b-a)(2a+b)q}{4a^2-b^2}.$	$\dfrac{\left(2a^2-b^2-ab\right)aP_1-\frac{\left[C_{1B}\left(2a^3-ab^2\right)-a^2bC_{1A}\right]1}{\theta} + (b-a)(2a+b)q}{4a^2-b^2}.$
$[\tau_A, 1]$	$\dfrac{\left(2a^2-b^2-ab\right)aP_1-\frac{\left[C_{1A}\left(2a^3-ab^2\right)-a^2bC_{1B}\right]1}{\theta} + (b-a)(2a+b)q}{4a^2-b^2}$	$\dfrac{\left(2a^2-b^2-ab\right)aP_1-\frac{\left[C_{1B}\left(2a^3-ab^2\right)-a^2bC_{1A}\right]1}{\theta} + (b-a)(2a+b)q}{4a^2-b^2}.$

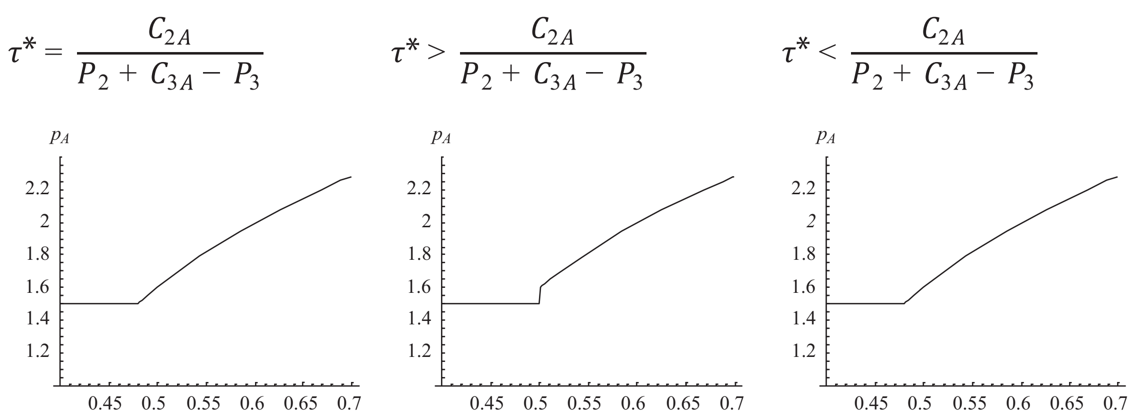

Fig. 3. Effect of τ^* on acquisition price and quantity.

A's cost is relatively high, it will prefer high-quality products. We conclude that when both recyclers engage in refurbishing work, the higher the quality level, the more products channel *A* will collect and refurbish. However, there is no clear situation for channel *B*, which may refurbish more low-quality products.

This competitive scenario is quite common in practice, and the booming secondary market provides channel *B* with a nice selling platform. Due to the high economic profit in refurbishing and lack of government supervision, channel *B* can refurbish an excessively high proportion of used products even if the quality level is low. As such it is necessary for the government to assist the formal sector by providing subsidies to slow down the growth of the informal channel.

5.2. Scenario S_{L1}

In this competitive scenario, $\tau_A < \tau_B < 1$, the minimum quality point for refurbishing in channel *B* is higher than that in channel *A*. This indicates that channel *B* has a smaller refurbishing proportion than channel *A* because the unit profit from disassembly is relatively high for channel *B*.

The results in Scenario S_{L1} are similar to those in scenario S_H, except at the quality level$\theta \in [\tau_A, \tau_B]$, in which channel *A* does refurbishing work while channel *B* disassembles used products. At this quality level, we have $p_A < p_B, q_A < q_B$, $\partial q_A/\partial\theta > 0$, $\partial q_B/\partial\theta < 0, \partial(q_A+q_B)/\partial\theta > 0$. Since the refurbishing profit is highly related to quality, channel *A* would prefer to collect more better-quality products. However, at a certain quality level, channel *B* will always have a higher acquisition price and quantity than channel *A*, given the fact that channel *B* only does disassembly work which is not dependent on quality. This sounds counterintuitive because channel *B* should have set a lower acquisition price to reduce its own cost, at least at the high quality level. In reality, channel *B* will raise the acquisition price to win more market share and restrict channel *A* to a small acquisition amount. This situation will definitely lead to a dilemma of "being hungry" for the formal recycler. Currently, this situation is very common in developing countries where the government subsidy is quite low and the formal recycler is stifled in its quest to expand acquisition quantity.

5.3. Scenario S_{L2}

In this competitive scenario, $\tau^* < \tau_B < \tau_A < 1$, the minimum quality point for refurbishing in channel *B* is lower than that in channel *A*. This means that channel *B* has a higher refurbishing proportion than channel *A*. The results in Scenario S_{L2} are similar to those in scenario S_H, except at the quality level $\theta \in (\tau^*, \tau_B)$, where channel *A* extracts useful parts while channel *B* does disassembly work. At this quality level, we have the following results:

(1) The acquisition prices in the two channels are directly influenced by the size of the subsidy. If the subsidy is very high, then $p_A > p_B$; if the subsidy is very low, then $p_A < p_B$. To be more specific, let $\hat{s}_1 = C_{2A}(P_1 - P_3 + C_{3B})/C_{1B} – P_2 + P_3 - C_{3B}$, $\hat{s}_2 = C_{2A}/k - P_2 + P_3 - C_{3B}$.
If $s < \hat{s}_1$, then $p_A < p_B$. If $s > \hat{s}_2$, then $p_A > p_B$. If $\hat{s}_2 > s > \hat{s}_1$, then for $\theta \in ((C_{2A}/P_2 + s - P_3 + C_{3B}), \tau_B)$, $p_A > p_B$.
At the same time, when $\partial(p_A - p_B)/\partial\theta = (aC_{2A}/(2a+b)\theta^2) > 0$ and the subsidy is relatively high, an increase in the quality level will result in channel A having a higher acquisition price than channel B.
(2) $\partial q_A/\partial\theta > 0$, $\partial q_B/\partial\theta < 0$, $\partial(q_A + q_B)/\partial\theta > 0$. As quality rises, the acquisition quantity increases in channel A and decreases in channel B, and the total quantity goes up.

This is different from the previous result because channel A prefers high-quality products for extracting useful parts while channel B does disassembly anyway, regardless of the product quality, and chooses to collect more low-quality products. We conclude that when channel B's profitability is not affected by the quality level, there is a greater chance that channel A is very competitive at high quality levels. The extra disposing method, extracting useful parts, helps channel A to expand acquisition quantity and improve its profitability. In practice, channel B's profitability lacks structural diversity. Therefore, channel A should develop more business models such as cooperating with remanufacturers and retailers in a closed-loop supply chain to enhance its competitive position.

5.4. Scenario S_{L3}

When the subsidy is higher than $P_1 - P_2 - (C_{1A} - C_{2A})$, the scenario S_{L2} evolves into scenario S_{L3}, that is $\tau^* < \tau_B < \tau_A = 1$, so channel A does not engage in refurbishing work. Comparing the two channels at three quality levels $[0, \tau^*], (\tau^*, \tau_B)$ and $[\tau_B, 1]$, we have:

(1) At the quality level of disassembly for the two channels, $\theta \in [0, \tau^*]$, $p_A > p_B$; at the high quality level $[\tau_B, 1]$, let $\hat{s}_1 = P_1 - P_2 - ((C_{1B} - C_{2A})(P_1 - P_3 + C_{3B})/C_{1B})$, $\hat{s}_2 = P_1 - P_2 - C_{1B} + C_{2A}$. If $s < \hat{s}_1$, then $p_A < p_B$. If $s > \hat{s}_2$, then $p_A > p_B$. If $\hat{s}_2 > s > \hat{s}_1$, then for $\theta \in (\tau_B, (C_{1B} - C_{2A})/(P_1 - P_2 - s))$, $p_A > p_B$.
(2) When $\theta \in (\tau^*, \tau_B)$, $\partial q_A/\partial\theta > 0$, $\partial q_B/\partial\theta < 0$, $\partial(q_A + q_B)/\partial\theta > 0$; When $\theta \in [\tau_B, 1]$, $\partial q_B/\partial\theta > 0$, $\partial(q_A + q_B)/\partial\theta > 0$, if $C_{2A}/C_{1B} > ab/(2a^2 - b^2)$, then $\partial q_A/\partial\theta > 0$, otherwise $\partial q_A/\partial\theta < 0$.

Due to the large subsidy, channel A can provide a higher acquisition price than channel B at the quality level of disassembly. But at higher quality levels, channel B refurbishes used products and prefers to raise acquisition price to win more market share. Channel A collects more used products than channel B only if the subsidy is beyond $P_1 - P_2 - C_{1B} + C_{2A}$.

When channel A extracts useful parts and channel B disassembles products, channel A prefers high-quality products while channel B does not. When channel B turns to refurbishing products, it is more inclined to collect high-quality products, while channel A begins to weigh the relative cost. If the cost of extracting useful parts is higher, channel A collects more high-quality products in order to improve profitability. This is to compensate for the heavy disposal cost and to restrict the acquisition amount of channel B.

5.5. Single channel scenario

When the subsidy becomes too high, channel B drops out of the recycling market, and only channel A is left. Similar to the dual-channel scenario, the acquisition quantity is a linear function of acquisition price, $q_A = q + a\,p_A$. The profit function of the formal recycler is,

$$\pi_A = \int_0^{\tau^*} (p_3 - C_{3A} + s - p_A)(q + a\,p_A)\,d\theta + \int_{\tau^*}^{\tau_A} \left(p_2 - \frac{C_{2A}}{\theta} + s - p_A\right)(q + a\,p_A)\,d\theta + \int_{\tau_B}^{1} \left(p_1 - \frac{C_{1A}}{\theta} - p_A\right)(q + a\,p_A)\,d\theta. \quad (10)$$

At the quality level of disassembly, $p_A = ((p_3 - C_{3A} + s)/2) - (q/2a)$; at the quality level of extracting useful parts, $p_A = ((p_2 - (C_{2A}/\theta) + S)/2) - (q/2a)$; at the quality level of refurbishing, $p_A = ((p_1 - (C_{1A}/\theta) + S)/2) - (q/2a)$.

In the single channel scenario, $\partial p_A/\partial s = 1/2$, while in the dual-channel scenario, $\partial p_A/\partial s = 2a^2/(4a^2 - b^2) > 1/2$. This shows that through price transmission, the formal recycler passes one half of subsidy to consumers in the single channel, while more than one half is passed in the dual-channel scenario. Therefore, when the subsidy is so large that there is only channel A, the role subsidy plays begins to change and channel A will make use of the subsidy to increase its own profit. It can be seen that the existence of channel B is not always a bad thing, and without competition from channel B, the effects of subsidy on total acquisition quantity will tell a different story.

Next we discuss the effects of quality threshold of reusing τ^*, government subsidy s and cooperation with remanufacturer on the two recyclers.

6. Parameter discussion

6.1. Effects of different quality threshold of reusing

We find when $\tau^* = C_{2A}/(P_2 + C_{3A} - P_3)$, the relationship between acquisition price and quality of used products is $\theta = \tau^*$. When $\tau^* > C_{2A}/(P_2 + C_{3A} - P_3)$, the acquisition price jumps upwards at the quality point $\theta \to \tau^{*+}$. When $\tau^* < C_{2A}/(P_2 + C_{3A} - P_3)$, the acquisition price is unaffected, which is similar to the situation when $\tau^* = C_{2A}/(P_2 + C_{3A} - P_3)$. The results of the simulation are shown in Fig. 3.

When the quality threshold of reusing set by the government equals the standard implemented by the formal recycler, we have $\tau^* = C_{2A}/(P_2 + C_{3A} - P_3)$, and the firm can price accordingly to obtain the optimal profit. When the quality threshold of reusing is set at a value higher than $C_{2A}/(P_2 + C_{3A} - P_3)$, the informal recycler is hardly affected because of the lack of effective government control. However the formal recycler, who has to strictly adhere to government regulations, begins to disassemble used products, which would originally have been extracted to obtain useful parts. As such a price discontinuity occurs and the acquisition quantity at this quality level decreases, which eventually impedes the development of channel A. When the quality threshold of reusing is small (lower than $C_{2A}/(P_2 + C_{3A} - P_3)$), the formal recycler just ignores the quality limitation and behaves normally $\tau^* = C_{2A}/(P_2 + C_{3A} - P_3)$. As a result, the policy stifles channel A, but encourages the growth of channel B, which often has a lower minimum quality point of refurbishing. Therefore, the government should not aim too high in setting a quality threshold of reusing in promoting the healthy growth of the formal recycling industry.

The range of quality levels for refurbishing in channel A is $[0,\ max[C_{2A}/(P_2+C_{3A}-P_3), \tau^*]]$, which only affects the competitive scenario the two channels are in and does not change the basic results in all scenarios.

6.2. Discussion on optimal government subsidy

The effects of different subsidies on channel B vary greatly. When the subsidy is low, channel B engages in disassembling and refurbishing. With the growth in subsidy, channel B will gradually give up disassembly work, then refurbishing low quality products, followed by refurbishing high quality products, and finally refurbishing work at all quality levels. We analyze the situation where channel B will stop recycling products at a certain quality point. The scenario S_H is examined closely although the basic conclusions for the other scenarios are similar.

In the competitive scenario S_H, $\tau_B<\tau^*\le\tau_A$, the minimum quality point of refurbishing is lower than the quality threshold of reusing set by the government. Due to a lack of environmental-friendly disposal methods, channel B's disassembly work should be strictly forbidden but unfortunately there is a lack of enforcement. Channel B is lacking in standardized renovation technology and security assurance in refurbished products, so the refurbishing proportion in channel B will need to be controlled appropriately. Here we assume that the minimum quality point of refurbishing to be at least θ^* (where $\theta^*>\tau^*$).

(1) At the quality level $\theta\in(0,\tau_B)$, define $s^{(1)}=((2a+b)q+\left(za^2-b^2\right)(p_3-C_{3B})/ab)-p_3+C_{3A}$. When $s\ge s^{(1)}$, $q_B=0$, channel B no longer disassembles the products at the quality level θ.
(2) At the quality level $\theta\in(\tau_B,\tau^*)$, define $s^{(2)}(\theta)=((2a+b)q+(za^2-b^2)(p_1-(C_{1B}/\theta))/ab)-p_3+C_{3A}$. When $s\ge s^{(2)}$, $q_B=0$.
(3) At the quality level $\theta\in(\tau^*,\tau_A)$, define $s^{(3)}(\theta)=((2a+b)q+\left(za^2-b^2\right)(p_1-(C_{1B}/\theta))/ab)-p_2+(C_{2B}/\theta)$, when $s\ge s^{(3)}$, $q_B=0$. We have $s^{(3)}(\theta)>(p_1-p_2)-(C_{1A}-C_{2A})$ when θ is relatively high. As such channel A has stopped refurbishing work long before the disappearance of channel B.
(4) At the quality level $\theta\in(\tau_A,1)$, if channel A still refurbishes products, there is no possibility for channel B to stop refurbishing.

To conclude: i) channel B will stop disassembly work when $s\ge s^{(1)}$; ii) channel B will stop refurbishing products with a quality lower than the quality threshold of reusing, $s\ge s^{(2)}|_{\theta=\tau^*}$; iii) channel B will only refurbish products at the quality level $\theta\in\left(\theta^*,1\right)$ when $s\ge s^{(3)}|_{\theta=\theta^*}$; iv) channel B will stop disassembling completely when $s\ge s^{(3)}|_{\theta=1}$. At the same time the secondary

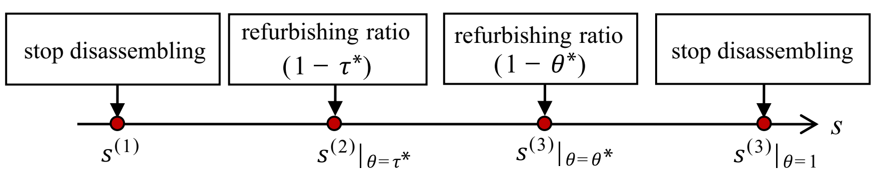

Fig. 4. Types of disposal methods in channel B at different subsidy levels.

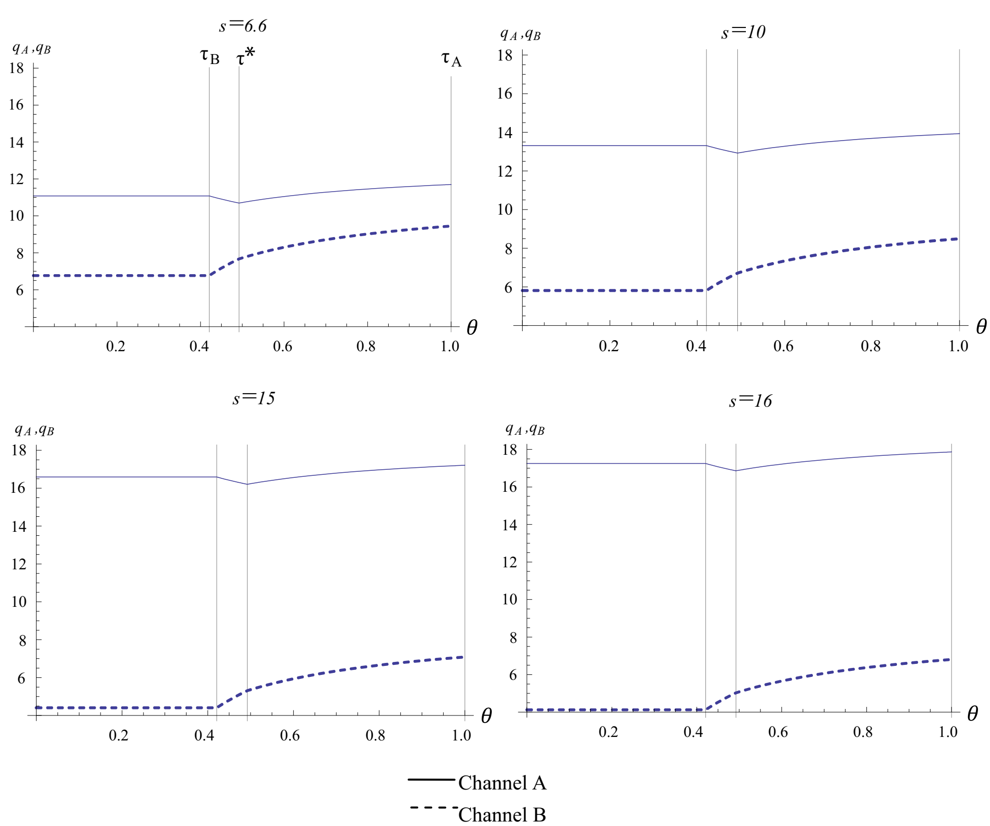

Fig. 5. Changes in acquisition quantity at different subsidy levels.

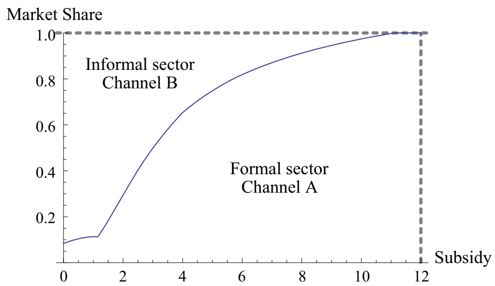

Fig. 6. Market share of the formal and informal sectors as government subsidy increases.

market disappears. Fig. 4 shows the diagrammatic drawing of the above changing process.

The numerical analysis in Fig. 5 shows the change of acquisition quantities in the two channels as the subsidy level rises. From this it is clear that the effect of marginal subsidy becomes weaker when the subsidy level is high. The subsidy paid by the government to make channel B go away is extremely high. Fig. 6 presents the changes of market share in the two sectors. It is obvious that when subsidy goes up, the market share of the formal sector begins to gradually increase. Only when the subsidy is very high, the market share of the informal sector drops down to zero. Therefore, the government should strike a balance between support for the formal sector and the social effects of the informal sector and secondary market, because to some degree the existence of the informal sector can help solve the problem of employment and the secondary market can play an important role in meeting social needs in second-hand products and improving social welfare. It is not wise to stifle the development of the informal sector completely. A subsidy level which makes channel B refurbish only high-quality products can be an optimal one.

6.3. *Effects of cooperating with the remanufacturer on recycling*

In the recycling process, the remanufacturer purchases the extracted useful parts and the price of extracted parts exerts significant influence on pricing and profitability of channel A.

We get the following:

$$\frac{\partial p_A}{\partial P_2}=\frac{2a^2}{4a^2-b^2},\frac{\partial p_B}{\partial P_2}=\frac{ab}{4a^2-b^2},\frac{\partial q_A}{\partial P_2}=\frac{a\left(2a^2-b^2\right)}{4a^2-b^2},\frac{\partial q_B}{\partial P_2}=\frac{-a^2b}{4a^2-b^2},\frac{\partial(q_A+q_B)}{\partial P_2}=\frac{2a^2+ab}{4a^2-b^2}.$$

On one hand, the change of the price P_2 of extracted useful parts only affects the unit profit of channel A at the quality level of extracting useful parts $\theta\in\left(\tau^*,\theta_A^*\right)$ rather than at other quality levels. The role of P_2 is similar to that of government subsidy at some specific quality level. On the other hand, when the price of extracted useful parts P_2 goes up, the minimum quality point of refurbishing τ_A becomes higher due to $\tau_A=(C_{1A}-C_{2A})/(P_1-P_2-s)$. This implies the acquisition quantity for extracting useful parts increases in channel A but the total collection amount drops down in channel B because used products at more quality levels are affected. When the subsidy is very low, P_2 has a more obvious impact on recycling competition such as the change from scenario S_{L1} to scenario S_{L2}.

Therefore, besides obtaining cheaper useful parts to reduce the manufacturing cost, the remanufacturer is also an important factor in supporting the development of the formal sector. In the win-win model, cooperation in recycling between firms should be encouraged greatly to improve the self-sufficient ability of the recycling industry.

7. Numerical simulation

We use numerical simulation to show the recycling competition and effects of subsidy in a more graphic way. In Fig. 7, the simulation results are presented. Here $a=1.5$, $b=1$, $p_1=11, p_2=6$, $p_3=2$, $C_{1A}=6$, $C_{1B}=4$, $C_{2A}=3.2$, $C_{3A}=2.5$, $C_{3B}=0.5$.

When there is no subsidy ($s=0$), the acquisition price is always higher in channel B than that in channel A which only collects a small amount of high-quality products to refurbish. When subsidy rises to $s=1$ (about 40% of the disassembly cost of channel A in this simulation), the acquisition price and quantity increase obviously in channel A, but they are still below that in channel B. This phenomenon is quite common in developing countries currently. Although the government has provided some subsidy, the acquisition prices at all quality levels are always higher in the informal sector. This indicates that the formal sector is still at a competitive disadvantage. In addition, we notice that in the quality level $\theta\in(\tau_B,\tau^*)$, as quality ascends, the acquisition quantity rises in channel B but drops in channel A, this is because channel A does not prefer high-quality products for disassembly.

When subsidy rises to $s=2.2$ (about 88% of disassembly cost of channel A in this simulation), $\tau_A=1$, channel A quits from the secondary market and is able to provide higher prices than channel B only at the disassembly quality level. It is clear that in the secondary market without competition from channel A, it becomes more difficult to slow down the acquisition quantity of channel B which has become monopolistic. In addition, we observe that there is a price crossover in the quality-based pricing environment. This shows that, as the subsidy changes, neither of the two channels will always have a higher acquisition price at all quality levels. This is consistent with recycling practice and explains why our model works well in reflecting reality.

As subsidy continues to rise, channel A becomes more competitive. When subsidy rises to $s=5$ (about twice the disassembly cost of channel A), channel A has captured a high market share, however the competing advantage is still not very obvious at very high-quality levels. This shows that the higher the quality level, the weaker is the effect of subsidy on recycling. The government must consider the trade-offs between heavy subsidy and social effects of the secondary market such as improved employment opportunities and availability of affordable used products. Blindly raising subsidy to crack down on the informal sector can strangle the positive contributions of the secondary market.

The equilibrium profits are also compared in the two channels, with results shown in Fig. 8. Before the threshold $s=2.2$, $\tau_A<1$, which means that subsidy is not very attractive and channel A does refurbishing work, and the profit in channel B is always higher than that in channel A. After the threshold $s=2.2$, $\tau_A=1$, which means that subsidy is so high that channel A gives up refurbishing work. Then as subsidy grows, channel A's profit goes up while the profit in channel B decreases. Beyond the point $s=3.64$ (in our numerical simulation, about 1.5 times the disassembly cost of channel A), the profit in channel A is higher. Therefore, only when government subsidy is sufficiently high, the cost disadvantages the formal channel has would be alleviated and its profit may exceed the informal channel.

8. Conclusions

Sustainability is an important issue in supply chain management and handling waste electrical and electronic equipment (WEEE) is very critical, especially in emerging countries where the formal recycling sector is not well developed. Our study has examined the recycling of WEEE in a dual channel environment,

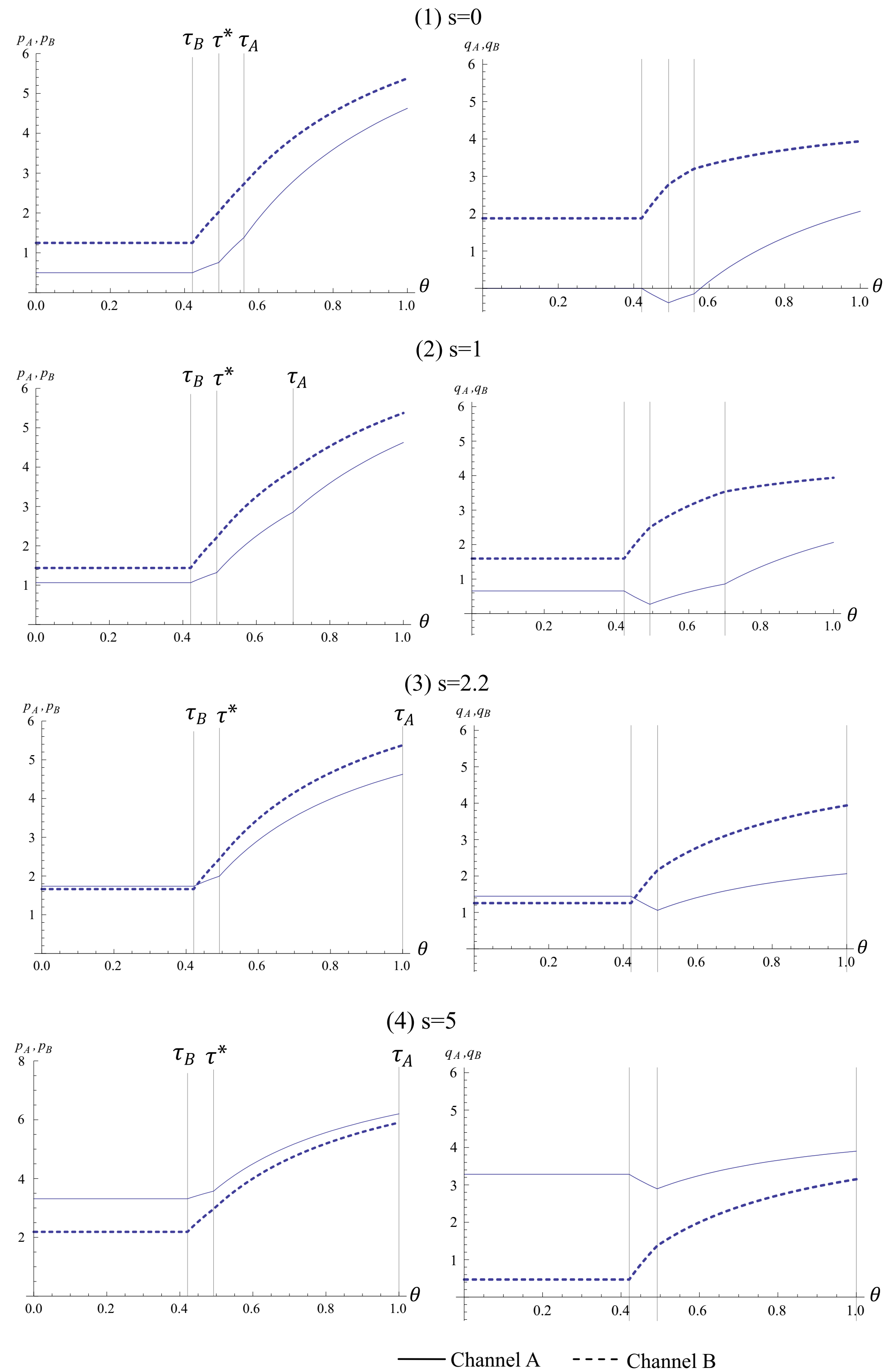

Fig. 7. Variation of acquisition prices and quantities at four subsidy levels.

which is a critical part of supply chain management. Two policy decisions from the government that can help regulate the WEEE recycling industry are: 1) the level of subsidy provided by the government to formal recyclers, and 2) the appropriate quality threshold of reusing. We have developed a quality-based price competition model for the WEEE recycling market for the dual channel environment to analyze the industry dynamics and assist the government in making decisions on WEEE recycling policies. Our research finds that government subsidy can help promote the development of the formal sector but there are caveats. At a higher quality level of waste, the marginal effect of subsidy is not as strong. When we do not have a substantial government subsidy and the quality of waste is high, the informal sector always has a competitive edge. The government can provide appropriate subsidy to limit the quality of collected products at a sufficiently high level suitable only for refurbishing in the informal sector. At the same time, the government should balance support for the formal sector and the social effects of the informal sector and secondary

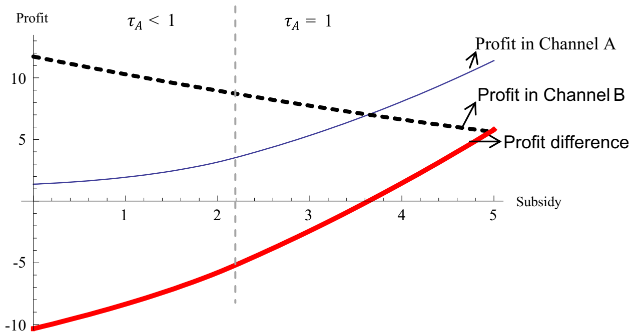

Fig. 8. Equilibrium profits comparison in two channels

market. Blindly raising the subsidy to stifle the informal sector is not a logical decision. In developing countries, the informal sector can help reduce unemployment and the secondary market plays an important role in meeting social needs in second-hand products and improving social welfare to some extent in a developing country.

In the quality-based pricing environment, the acquisition prices in the two channels may crossover as quality increases, which mean it is possible that neither of the two channels always offers a higher acquisition price at all quality levels. The result, which cannot be obtained in a uniform pricing model, is consistent with recycling practice and shows that product quality is too important a factor in recycling competition to be ignored. When government subsidy is not sufficiently high and the informal sector is very competitive, the informal recycler only refurbishes very high quality products, but will still raise the acquisition price at the disassembly quality level. This sounds counterintuitive because the informal sector recycler should have set a lower acquisition price to reduce its own costs, at least at the high quality level. In reality, these informal recyclers will likely raise the acquisition price to win more market share and restrict the formal sector to a small acquisition amount. This will lead to the dilemma of "being hungry" for the formal recycler.

The quality threshold of reusing should not be set too high by the government; otherwise it will deteriorate recycling competition because the threshold exerts great influence on the formal sector rather than the informal sector. Besides obtaining cheaper useful parts to reduce the manufacturing cost, the remanufacturer is also an important factor in supporting the development of the formal sector. In the win-win model, cooperation in recycling between firms should be encouraged greatly to improve the self-sufficient ability of the recycling industry. The conclusions reached here can provide insights for the government in making decisions on WEEE recycling policies to regulate and promote the healthy development of the recycling industry.

Our paper can be extended in several directions such as introducing penalty risks imposed on the informal sector. In depicting acquisition quantity, only the factor of acquisition price is involved, and future study can consider collecting convenience and heterogeneous consumers. In future studies, we can consider the pricing issue of recycled items or products. We believe our paper has contributed towards the understanding of recycling competition and quality-based pricing in a dual-channel WEEE recycling market.

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