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Socially optimal and fund-balanced advanced recycling fees and subsidies in a competitive forward and reverse supply chain

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ABSTRACT

Advanced recycling fees (ARFs) and government subsidy fees are important for curtailing the consumption of new products and encouraging recycling and disposal of end-of-life (EOL) products. We introduce a model consisting of a leader (the Environmental Protection Agency, EPA) and two groups of followers (MIS firms and recyclers) consisting of manufacturers, importers and sellers, and recyclers which compete in both consuming and recycling markets. The EPA determines the ARFs paid by the MIS firms and the fees subsidizing recyclers to maximize the social welfare in closed-loop supply chains where the MIS firms and recyclers attempt to maximize their respective profit functions. To compare with current practice, we describe a conceptual fund balance model to determine the ARF and subsidy fee on the basis of the balance between total collected ARFs and expenditure of subsidies. Using numerical examples for the laptop computer market in Taiwan, we demonstrate that our results outperform the current practice.

1. Introduction

The consequences of global pollution from improper management and disposal of obsolete electronics products known as scrap electronics (e-scrap) is a growing concern. According to a recent study by the U.S. Environmental Protection Agency (EPA), 40% of the lead in U.S. landfills is from discarded e-scrap (DFC, 2009). Another study finds that the average lifetime of a personal computer was 6 years in 1997 but 2 years in 2005 (Greenpeace, 2009); the dramatic change indicates that e-scrap is expected to reach 90 million tons in 2016, up from 40 million tons in 2011 (MarketsandMarkets.com, 2011). In Taiwan alone, about three million e-scrap products were recycled in 2010 (RFMB, 2011).

Recognizing the severity of the problem, some governments have proposed a range of solutions. For instance, the European Union's Waste Electrical and Electronic Equipment (WEEE) assigns manufacturers the responsibility for collecting, recycling and disposing of e-scrap, the Restriction of Hazardous Substances Directive (RoHS) prohibits using specific hazardous substances as raw materials to produce new products, and the Eco-Design Requirements for Energy Using Products (EuP) gives rules for eco-design to improve the environmental performance of energy-related products (European Commission, 2013).

Other governments have turned to the use of incentives and subsidies. For example, the Taiwan EPA requires the electronics products manufacturers, importers and sellers (MIS firms) to pay the e-scrap products processing fee, called an advanced recycling fee (ARF), to support recycling. In Taiwan, consumers can bring their e-scrap products to designated recyclers and receive a financial reward. To compensate recyclers for the costs of recycling and processing the e-scrap, the Taiwan EPA uses the ARF funds collected to subsidize the recyclers on the basis of the fund's balance. This ARF is similar to one enacted by California, which assigns an ARF of $8–25 on all e-scrap containing hazardous materials depending on the viewable screen size (CalRecycle, 2009). Canada and Japan have implemented similar programs (Hicks et al., 2005; HP, 2005; Lee et al., 2000). Some countries incorporate a fee structure into their take-back programs. Allcock et al. (2010) reviews the financing and infrastructure model characteristics of different countries; for example, consumers or producers now pay fees similar to ARFs in Switzerland, Norway, Netherlands, Sweden, Japan, and Australia. Shinkuma (2003) investigates the relationship between the ARF and unit price of products, whereby the sum of the ARF and unit price is equal to the marginal disposal cost, thus attaining the social optimum. Puig-Ventosa (2004) presents a "feebate" (fee + rebate) structure that allows municipalities to improve waste management performance via its adoption.

The literature has been supportive of such regulatory instruments. Foulon et al. (2002) indicate that certain regulation

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standards need to be imposed to reflect current social responsibility policies. Chen and Sheu (2009) demonstrate that proper design of environmental-regulation pricing strategies can be applied to the firms in supply chains. Fullerton and Wolverton (1997) only analyze the usefulness of taxation and subsidization, which can affect different aspects of closed-loop supply chains, e.g. development and adoption of advanced pollution abatement technology (Jung et al., 1996), waste reduction and reuse (Conrad, 1999), market structure and welfare (Cremer and Thisse, 1999), deposit-refund systems (Kulshreshtha and Sarangi, 2001), environmental quality of products (Bansal and Gangopadhyay, 2003), and policy for green design (Fullerton and Wu, 1998). Lee (2010) studies how the EPA decides the optimal number of recycling licenses in the recycling market and illustrates the impact of the number of recycling licenses on the value of social welfare, total recycling quantity, reward money, and subsidy fees. Hong and Ke (2011) present a Stackelberg-type model to determine socially optimal ARFs and subsidy fees in reverse supply chains consisting of a MIS firm and a recycler. However, the interactions and competition among independent entities in the two groups do exist in reality, a situation that is not considered in (Hong and Ke, 2011), but dramatically affects the results obtained in a single firm case.

One issue is that the global electronic industry's supply chains are gradually evolving from open-loop unidirectional flows of products – from suppliers to end users – to more complex, closed-loop, linked forward and reverse arcs (see Fleischmann et al., 2000; Shih, 2001; Guide and Harrison, 2003; Realff et al., 2004; Pishvaee et al., 2011; Pishvaee and Torabi, 2010). Forward supply chains involve the manufacturing, importing and selling processes of new products whereas reverse supply chains include the reuse, recovery and recycle operations of end-of-life (EOL) products. In the past decade, the literature has focused on designing proper forward and reverse (closed-loop) supply chains (see Fleischmann et al., 2000; Guide and Harrison, 2003; Hong et al., 2008). Other studies have developed optimization models for reverse logistics network design in industries such as carpet recycling (Realff et al., 2004) and an e-scrap reverse logistics network in the state of Georgia in the U.S. (Hong et al., 2006). Still other studies have proposed recycling models that maximize total profits and recycling rates via mathematical programming methodologies (e.g. Inderfurth et al., 2001; Stuart et al., 1999; Uzsoy and Venkatachalam, 1998; Hoshino et al., 1995; Ron and Penev, 1995; Wang and Yang, 2007).

We note that in current practice typically a government entity assigns fees based on the concept of fund balance in the majority of ARF-financed programs, i.e. the fees are simply determined based on the concept that the total fee collection equals the total expenditure on subsidies. In the current practice model described in this paper, the government entity determines the ARFs and subsidy fees on the basis of fund balance in a competitive closed-loop supply chain consisting of multiple MIS firms and recyclers.

The objective of this paper is to study the interactions and competition among MIS firms and recyclers and to compare current practice with the socially optimal ARFs and subsidy fees. Our modeling framework assumes that a government entity establishes the ARFs and subsidy fees to maximize social welfare, which we define as the sum of producer surplus, consumer surplus, tax/subsidy revenue and the environmental externality costs (Bansal and Gangopadhyay, 2003; Hong and Ke, 2011). Each associated MIS firm and recycler selects their best response to the ARF and subsidy fee after the EPA makes them public. This allows us to present a model with the government as a leader to determine the social welfare maximized ARFs and subsidy fees and MIS firms and recyclers as the followers responding to the fees. Of course, real-world MIS firms are always competing for the sales of new products, and an individual recycler's collected EOL products quantity may vary with the financial incentives offered by all recyclers. Therefore, MIS firms and recyclers compete each other within their respective groups. The proposed model in this paper differs contextually from (Hong and Ke, 2011) by refining their model to account for the interactions among the competing MIS firms and recyclers.

The proposed concept of social welfare maximization provides the EPA with a different tax and subsidy instrument than the fund balance idea. Our findings highlight that a single recycler model (Hong and Ke, 2011) may distort the subsidy fee leading to an increasing welfare in the pollution cost, one parameter considered in the model, while our multiple recyclers model captures the interactions and competition among recyclers so that the relation between the social welfare and pollution cost behaves in a reasonable manner. Finally our results reveal that the fund balance idea may in fact distort the market behavior that a high reward offered by the EAP may result in a lower collected quantity of EOL products.

The remainder of this paper is organized as follows. In Section 2, we define the problem and conceptual operations in our closed-loop supply chain. Section 3 presents the model and its equilibrium outcomes followed by the fund balance model for comparative purposes. In Section 4, we conduct numerical examples and give comparative statistics to examine the difference in the performance measures between our proposed social welfare maximized model and the current practice fund balance model. We conclude in Section 5.

2. Closed-loop supply chain

The concerned closed-loop supply chain in this paper includes both forward and reverse flows, where MIS firms sell new products to consumers and recyclers collect EOL products. Fig. 1 shows the proposed model constructing a closed-loop supply chain as a system where the government as leader determines ARFs and subsidy fees, and the MIS and recyclers as followers seek to optimize their own objectives according to the government's transparent data of ARFs and subsidy fees.

There are three key elements in our supply chain system: material, cash and information flows. In general, MIS firms act as manufacturers, importers or sellers of new products to consumers. In this paper, the group of MIS firms consists of multiple independently owned firms (n firms) which sell new products to consumers, competing with one another in forward channels. After usage, consumers can bring their obsolete (EOL) products to recyclers which remanufacture or recycle and convert them into recovery materials as well as some unwanted trash. The multiple recyclers (m recyclers) are located in distinct geographic areas similar to the assumption in (Hong et al., 2006). Fig. 1 illustrates the materials, information and cash flows in our hypothetical closed-loop supply chain. Although both groups (MIS firms and recyclers) include multiple independently owned entities, we note that typically MIS firms compete within a market as shown by the dotted square in Fig. 1, whereas there may be only one recycler in a geographic area as shown by the several dotted squares. We assume this subtle difference since consumers tend to bring their EOL products to the nearest recycler to save transportation and time, and thus a clearer geographic gap can be observed in a recycling market.

We use a hypothetical EPA which determines the ARFs and subsidy fees. MIS firms pay ARFs when manufacturing, importing or selling new products in support of the EPA's implementation of recycling EOL products and to subsidize certified recyclers for their operational and recycling costs. The EPA uses the ARF funds to subsidize recyclers which may choose to compensate consumers returning EOL products with a specified amount of money to encourage (reward) recycling behaviors.

We assume that the EPA has the requisite regulatory power to act as the leader in the determination of ARFs and subsidy fees.

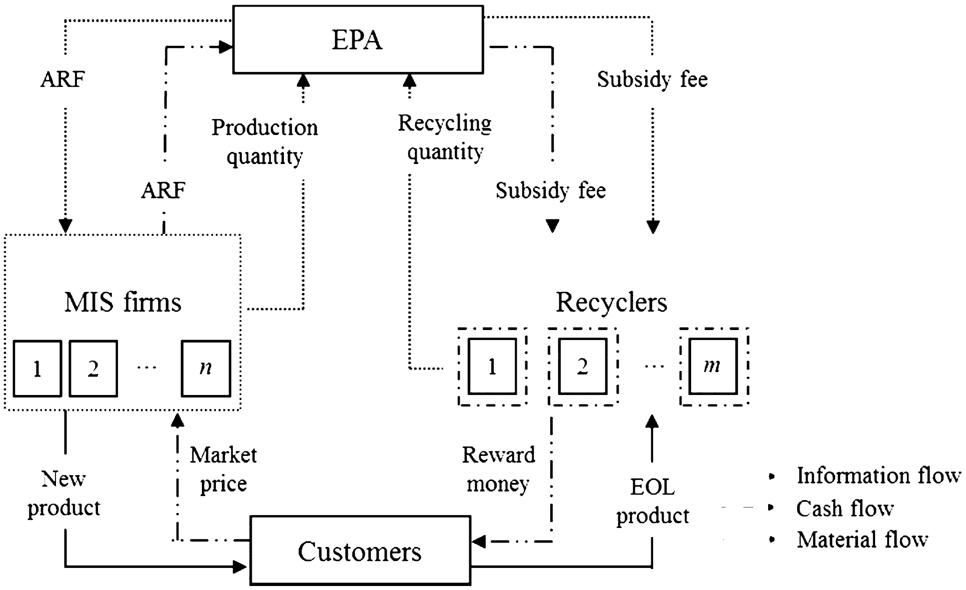

Fig. 1. The material, cash and information flows in a closed-loop supply chain.

MIS firms and recyclers therefore behave at the equilibrium status by choosing the optimal quantity and the rate of reward money for collection. In practice, the EPA can obtain MIS firms' quantitative (manufacturing, importing and selling) information. We also assume the collected quantity handled by recyclers is affected by the amount of reward money offered and that recyclers are required to update and report their quantitative data to the EPA for auditing purposes.

3. Model description

As stated, our objective is to determine the socially optimal ARFs and subsidy fees in a competitive closed-loop supply chain consisting of multiple competing MIS firms and recyclers. The social welfare maximized model is proposed in Section 3.1. To compare with current practice, we propose a conceptual model in Section 3.2, where the government simply determines the associated fees on the basis of fund balance, i.e. the total ARFs collected equal the total expenditure of subsidy fees.

3.1. The social welfare maximization model

We assume that the EPA as a unit of government maximizes social welfare and considers its two followers' potential decisions by anticipating their behavior prior to determining an optimal policy. Clearly, the followers will fashion their optimal policies according to the policy of the leader. In addition, we assume two markets exist – a consuming market where new products are sold to consumers and a recycling market where EOL products are brought to recyclers – and that competitive participants exist in both markets.

3.1.1. The model of MIS firms

We first construct the MIS model to determine the quantity of new products manufactured, imported and sold in the market given the ARF fee announced by the EPA. Let q_{x_i} denote MIS firm i's production quantity, $i = 1, 2, \ldots, n$. The total demand quantity in the market, Q_x, is the sum of MIS firms' production quantity; that is, $Q_x = \sum_{i=1}^{n} q_{x_i}$. Assume that the total demand is characterized by a commonly used linear demand function, $P_x = a - bQ_x$, where P_x is the market price, a is the intercept parameter and b is the slope parameter, $a, b > 0$. A linear form of the inverse demand function helps to obtain qualitative insights with less analytical complexity. A typical downward sloping demand function illustrates that demand declines as price rises.

Let C_{v_i} denote MIS firm i's unit production cost. In addition, MIS firms pay the ARF, denoted by t per unit of products, in support of the recycling program. The profit function of MIS firm i, denoted by $\prod_{\mathrm{MIS}_i}$, is

$$\underset{q_{x_i} \geq 0}{\mathrm{Max}} \prod_{\mathrm{MIS}_i} = (P_x - C_{v_i} - t)q_{x_i}. \tag{1}$$

By simultaneously solving the n first-order conditions of (1) from n MIS firms, it is straightforward to show that at equilibrium, MIS firm i chooses

$$q_{x_i}^* = \frac{1}{(n+1)b}\left(a - t - nC_{v_i} + \sum_{\substack{j=1 \\ j \neq i}}^{n} C_{v_j}\right), \tag{2}$$

and obtains

$$P_x^* = \frac{1}{(n+1)}\left(a + nt + \sum_{i=1}^{n} C_{v_i}\right). \tag{3}$$

We note that (2) specifies MIS firm i's optimal production quantity after it observes the level of the ARF, t, announced by the EPA. Obviously, (2) and (3) can be interpreted as MIS firm i's best responses to the EPA's decision of the ARF, t.

3.1.2. The model of recyclers

Learning the subsidy fee, recyclers determine their optimal reward money compensating consumers who return their EOL products for recycling. Let q_{c_j} be the quantity collected by recycler j, and P_{w_j} denote the rate of reward money offered by recycler j. Hong et al. (2006) demonstrate the case that recyclers usually collect EOL products in their own geographic locations although some consumers may bring their EOL products to other recyclers due to a higher reward instead of the nearest recycler. Assume a dynamic market where the collected quantity of each recycler depends on the reward money offered by all recyclers as the collected quantity function, which is characterized as

$$q_{c_j} = c_j + d_j P_{w_j} - \sum_{\substack{l=1\\ l\neq j}}^{m} k_l P_{w_l}, \tag{4}$$

where c_j and d_j denote the intercept and slope parameters of j's collected quantity function, and k_l is the decrease in the collected quantity due to a unit of increase in the reward money offered by all other recyclers. In other words, consumers' recycling behaviors are influenced by the reward money offered by the nearest recycler as well as by the reward money offered by the recyclers located elsewhere. Similar modeling to (4) appears in (Gibbons, 1992; Toyasaki et al., 2011; Majumder and Groenevelt, 2001). We note that consumers in some countries may pay recyclers collection fees for safely handling EOL products (Hong et al., 2006). In our model, the sign restriction of the reward money can be relaxed to describe the situation of negative reward money without changing the sign of concavity of the recycler's profit function. However, a further constraint imposes for nonnegative collected quantity. For simplicity, this paper only considers the nonnegative reward money.

Let r_j denote recycler j's net cost for recycling one unit of EOL products. In addition, recyclers receive a subsidy fee per unit, s, for recycling EOL products. Recycler j maximizes its profits:

$$\underset{P_{w_j}\geq 0}{\mathrm{Max}} \prod_{\mathrm{rec}_j} = (s - r_j - P_{w_j})q_{c_j}. \tag{5}$$

Denoting $A_j = 2d_j - \sum_{\substack{l=1\\ l\neq j}}^{m} \dfrac{k_l(2d_j + k_j)}{2d_l + k_l}$ to simplify our notation, by simultaneously solving the m first-order conditions of (5) from m recyclers, at equilibrium recycler j chooses

$$P^*_{w_j} = \frac{1}{A_j}\left(d_j(s - r_j) - c_j - \sum_{\substack{l=1\\ l\neq j}}^{m} \frac{k_l((d_j(s - r_j) - c_j) - (d_l(s - r_l) - c_l))}{2d_l + k_l} \right), \tag{6}$$

and obtains recycler j's collected quantity as

$$q^*_{c_j} = d_j(s - r_j) - \frac{d_j}{A_j}\left(d_j(s - r_j) - c_j - \sum_{\substack{l=1\\ l\neq j}}^{m} \frac{k_l((d_j(s - r_j) - c_j) - (d_l(s - r_l) - c_l))}{2d_l + k_l} \right).(7)$$

We also note that (6) specifies recycler j's optimal reward money after it learns the level of the subsidy fee, s, announced by the EPA. Again, (6) and (7) are recycler j's best responses to the EPA's decision of the subsidy fee, s. With the MIS's best responses to the ARF announced by the EPA, we can develop the EPA's model in the next subsection.

3.1.3. The model of the EPA

The EPA's objective is to maximize social welfare, which is the sum of the producer surplus, consumer surplus, tax/subsidy revenue, and the environmental externality cost. As mentioned, there are two markets in our proposed model: new products and EOL products. It is easy to show that the consumer surplus in the market for new products is $1/2bQ_x^2$ whereas consumer surplus in the recycling market is the difference between the announced rate of reward money and the fee level that consumers are willing to pay to recyclers. In other words, consumers are willing to recycle EOL products when the announced reward is higher than the value they expect. Hence, the consumer surplus of the recycling market is $\sum_{j=1}^{m}(P_{w_j}q_{c_j} - (1/2)d_jP_{w_j}^2)$. The producer surplus here is the sum of the profits of MIS firms, $\sum_{i=1}^{n}(P_x - C_{v_i} - t)q_{x_i}$, and the profits of recyclers, $\sum_{j=1}^{m}(s - P_{w_j} - r_j)q_{c_j}$. The EPA's total ARF collected is $t\sum_{i=1}^{n}q_{x_i}$ and its total subsidy expenditure is $s\sum_{j=1}^{m}q_{c_j}$. The environmental externality cost is the sum of the pollution cost caused by uncollected EOL products and the indirect pollution cost resulting from manufacturing/importing/selling new products. In practice, if the information about the quantity of EOL products is unavailable to the EPA, or is difficult to estimate, the quantity of current generation of new products is relatively traceable and probably can be obtained from other government agencies, e.g. the department of commerce. We characterize the EPA predefined desirable level of the return rate of EOL products by τ, $\tau > 0$. A similar model appears in (Savaskan et al., 2004; Savaskan and Van Wassenhove, 2006; Hong and Ke, 2011). The EPA predefined desirable level of the return rate of EOL products, τ, can be preset based on the quantity of new products supplied to the consuming market. Parameter τ is allowed to be greater than one since the expected returned quantity may include the quantity sold in preceding planning epochs.

Let E denote the unit indirect pollution cost of uncollected EOL products and let e denote the unit indirect pollution cost incurred in manufacturing/importing/selling new products. The total environmental externality cost can then be described as $E(\tau Q_x - \sum_{j=1}^{m}q_{c_j})$. Hence, the EPA optimizes the total social welfare as shown in (8).

$$\begin{aligned}\underset{t,s\geq 0}{\mathrm{Max}} \prod_{\mathrm{gov}} = {} & \sum_{i=1}^{n}(P_x - C_{v_i} - t)q_{x_i} + \sum_{j=1}^{m}(s - P_{w_j} - r_j)q_{c_j} \\ & + \frac{1}{2}bQ_x^2 + \sum_{j=1}^{m}\left(P_{w_j}q_{c_j} - \frac{1}{2}d_jP_{w_j}^2\right) \\ & + \left(t\sum_{i=1}^{n}q_{x_i} - s\sum_{j=1}^{m}q_{c_j}\right) - E\left(\tau Q_x - \sum_{j=1}^{m}q_{c_j}\right) - eQ_x \end{aligned} \tag{8}$$

The rationality assumption – the EPA anticipates that the MIS firms and recyclers will choose their best response to the announced fees of t and s – allows us to characterize the Nash equilibrium of the MIS firms and recyclers' problems which depend on the EPA's decision of the ARF, t, and subsidy fee, s, by the backward induction. Substituting (2), (3), (6), and (7) into (8), the first-order conditions return the Nash equilibrium solution of the ARF and subsidy fee, which are

$$t^* = \frac{1}{n^2}\left((n + 1)(nE\tau + ne) - na + \sum_{i=1}^{n}C_{v_i}\right), \tag{9}$$

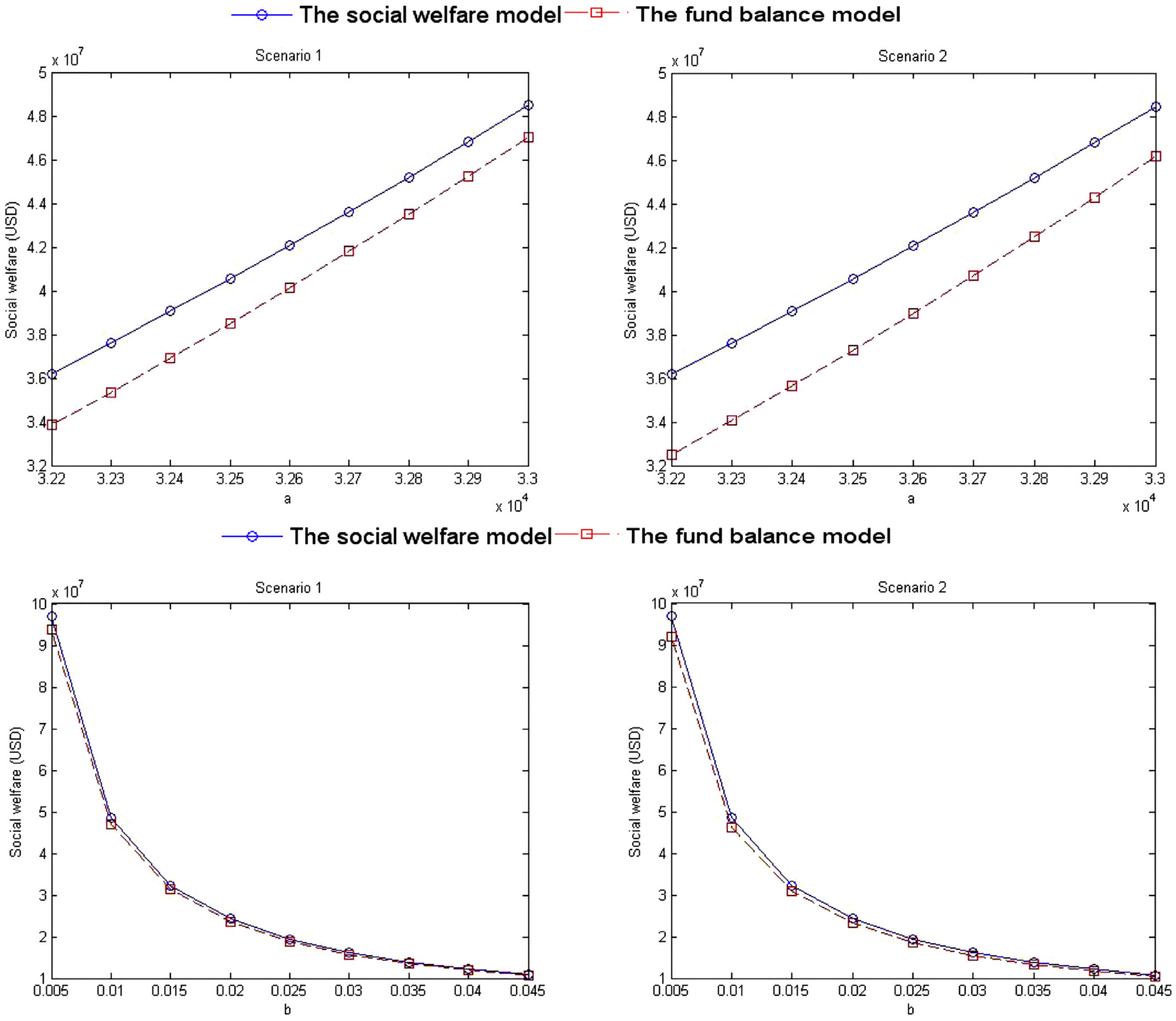

Fig. 2. Impact of *a* and *b* on the value of social welfare.

$$s^* = \frac{\sum_{j=1}^{m}\left(d_j\left(E-r_j+\left(\frac{B_j}{A_j}\right)\right)\left(r_j-E+\frac{C_j}{A_j}\right)\right)\Big)}{\sum_{j=1}^{m}\left(d_j\left(\frac{B_j}{A_j}\right)^2\right)} \tag{10}$$

where $B_j = d_j - \sum_{\substack{l=1 \\ l \neq j}}^{m} \frac{k_l(d_j-d_l)}{2d_l+k_l}$ and $C_j = d_j r_j + c_j + \sum_{\substack{l=1 \\ l \neq j}}^{m} \frac{k_l(-d_j r_j - c_j + d_l r_l + c_l)}{2d_l+k_l}$.

To maximize social welfare, the EPA determines the rate of ARF, *t*, and subsidy fee, *s*, as noted in (9) and (10). After observing the ARF and the subsidy, the decisions of MIS firms and recyclers can be obtained by substitution of *t* and *s* in (2), (3), (6) and (7). MIS firms and recyclers behave at the equilibrium status by choosing the optimal production quantity in the market and optimal reward money for individuals who bring EOL products to recyclers. Hence, the ARF and subsidy fees determined by our approach achieve the maximum of the social welfare at the equilibrium status, while MIS firms and recyclers gain the maximum self-profit.

3.2. The fund balance model

Let t' denote the ARF charged by the EPA and s' denote the fee subsidized by the EPA under the policy of fund balance. MIS firms and recyclers face the same decision problem, as proposed in Section 3.1, after observing the EPA's announcement of the ARF and subsidy fee. Recalling that under current practice the EPA determines the rates on the basis of fund balance, the total ARFs will be equal to the total subsidy expenditure

$$t'Q'^{*}_{x} = s'Q'^{*}_{c} \tag{11}$$

where the total collected quantity is $Q'^{*}_{c} = \sum_{j=1}^{m} q'^{*}_{cj}$. To have a fair basis for comparison, let the EPA collect the identical total ARFs under the two different policies, thus

$$t'Q'^{*}_{x} = t^{*}Q^{*}_{x}. \tag{12}$$

Combining (11) and (12) gives two equations for two unknowns, allowing us to analytically obtain the corresponding ARF, *t*', and subsidy fee, *s*', under the policy of fund balance. Obviously the ARFs under both policies of social welfare maximization and fund

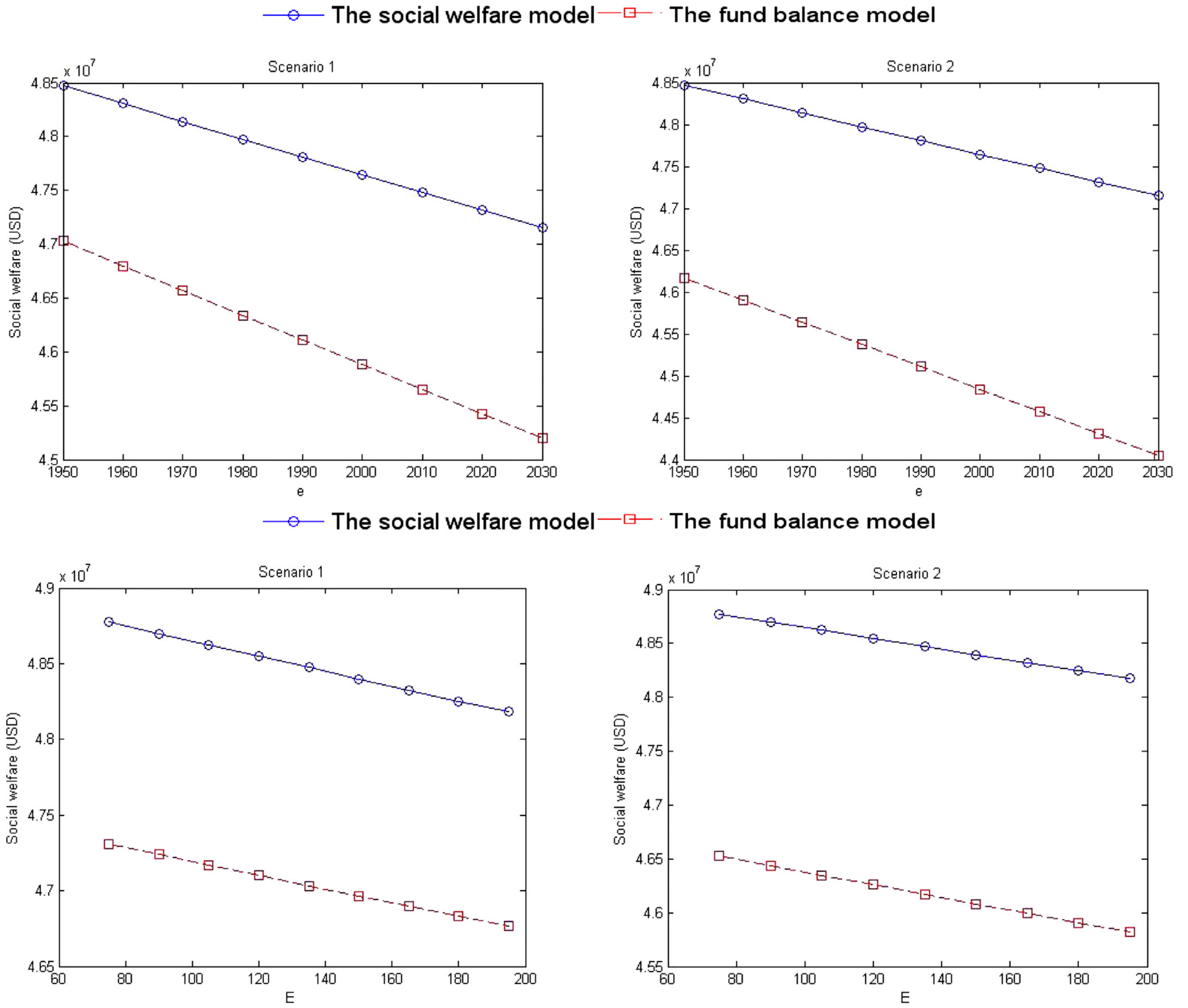

Fig. 3. Impact of *e* and *E* on the value of social welfare.

balance are identical as shown (9) due to the same amount of the total ARFs.

Denoting $D = \frac{\left(-\sum_{i=1}^{n} C_{v_i} - ne - nE\tau + na\right)\left(\sum_{i=1}^{n} C_{v_i} - na + n(n+1)(e+E\tau)\right)}{n^3 b}$, $F_j = d_j \sum_{\substack{l=1\\ l\neq j}}^{m} \frac{k_l(d_j + d_l + k_j)}{2d_l + k_l}$, and $G_j = d_j \sum_{\substack{l=1\\ l\neq j}}^{m} \frac{k_l(d_j r_j + d_l r_l - c_j + c_l + r_j k_j)}{2d_l + k_l}$ to simplify our notation, (11) can be rewritten as

$$\left(\sum_{j=1}^{m} \frac{d_j^2 - F_j}{A_j}\right) s'^2 + \left(\sum_{j=1}^{m} \frac{-d_j^2 r_j + d_j c_j + G_j}{A_j}\right) s' - D = 0, \qquad (13)$$

which simply is a quadratic equation in one variable, s'. We assume a non-negative discriminant of the quadratic polynomial in (13) to ensure the feasibility. Assumption 1 follows from the condition.

Assumption 1.

$$\left(\sum_{j=1}^{m} \frac{-d_j^2 r_j + d_j c_j + G_j}{A_j}\right)^2 + 4\left(\sum_{j=1}^{m} \frac{d_j^2 - F_j}{A_j}\right) D \geq 0.$$

Recall that this paper only focuses on the case of nonnegative subsidy fees (i.e. $s' \geq 0$). Solving the roots of (13) and denoting $H = \sum_{j=1}^{m} \frac{-d_j^2 r_j + d_j c_j + G_j}{A_j}$ to simplify our notation, we obtain the subsidy fee per unit

$$s' = \frac{-H + \sqrt{H^2 + 4\left(\sum_{j=1}^{m} \frac{d_j^2 - F_j}{A_j}\right) D}}{2\left(\sum_{j=1}^{m} \frac{d_j^2 - F_j}{A_j}\right)}. \qquad (14)$$

After observing the ARF and subsidy fee obtained in the fund balance model, the decisions of MIS firms and recyclers can be obtained by substitution of t' and s' in (2), (3), (6) and (7).

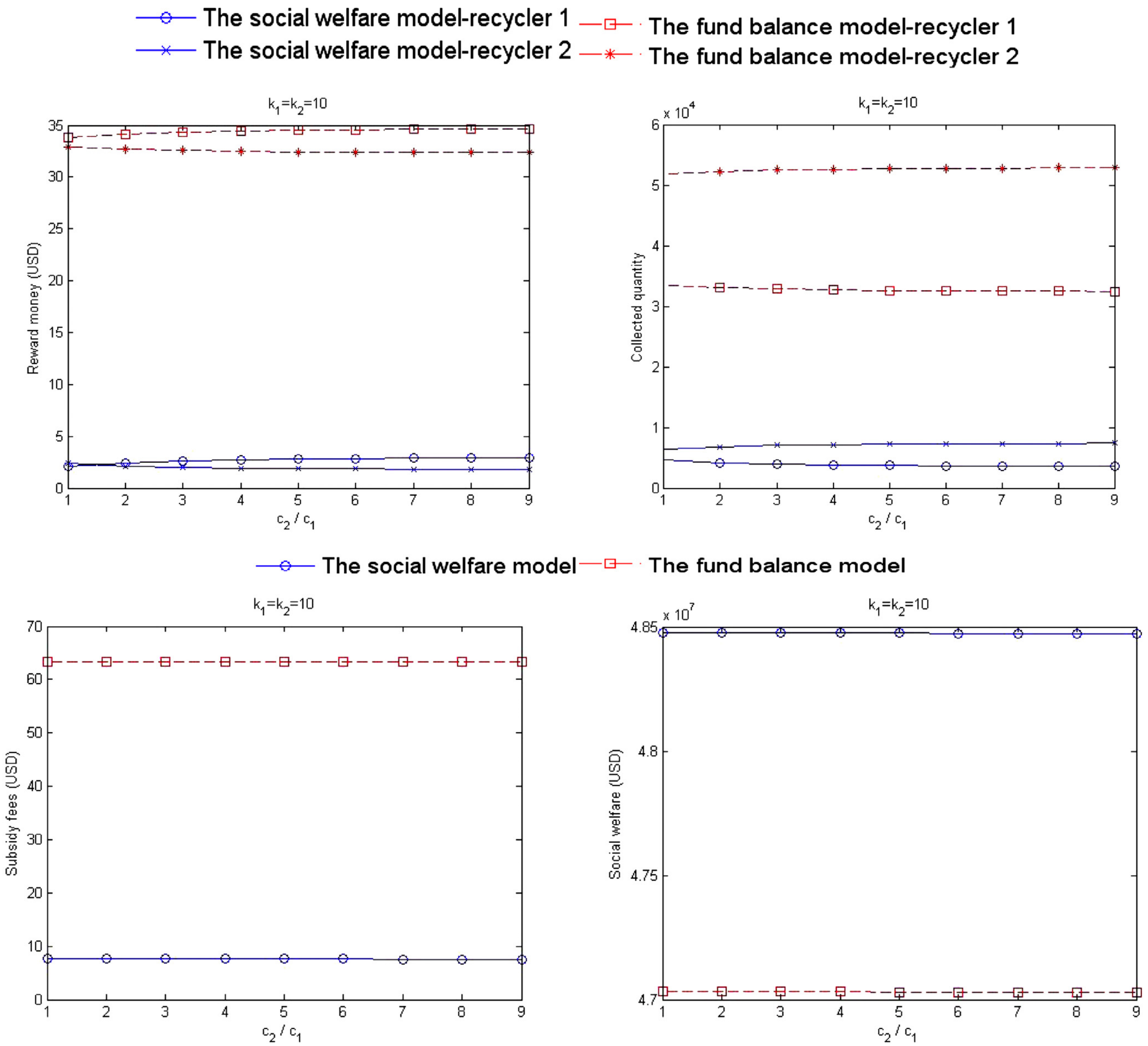

Fig. 4. Impact of c_2/c_1 on reward money, collected quantity, subsidy fees and the value of social welfare.

4. Numerical analysis

This section provides a set of numerical experiments to illustrate the use of the proposed model to determine the ARFs and subsidy fees in a real-world e-scrap (laptop computers) closed-loop supply chain and to investigate the behavior of the ARFs and subsidy fees with different parameter settings. The numerical data used mainly follow the case study data in (Hong and Ke, 2011) to which readers can refer for the detailed estimates of the model parameters. We note that the data only apply to our numerical analysis and will differ for different geographical regions, products and/or times.

4.1. Dataset

We consider the two markets for laptop computers in Taiwan and assume that there are three MIS firms and two recyclers. The inverse demand function in the market for new products is $P_x = 33{,}000 - 0.01Q_x$ (Hong et al., 2007), and the hypothetical collected quantity functions in the recycling market are $q_{c_1} = 1400 + 40P_{w_1} - \sum_{l=1,\, l \neq 1}^{2} k_l P_{w_l}$ for recycler 1 and $q_{c_2} = 4200 + 60P_{w_2} - \sum_{l=1,\, l \neq 2}^{2} k_l P_{w_l}$ for recycler 2 where the sum of the base collected quantities of zero reward money in recyclers 1 (1400) and 2 (4200) is identical to the base collected quantity of zero reward money (5600) in the case study in (Hong and Ke, 2011). The sensitivities of the collected quantity with respect to the reward money (40 and 60) are deliberately set slightly lower than used in (Hong and Ke, 2011), since the reward money offered by other recyclers may reduce the sensitivity due to competition. We assume that the production cost per unit of new laptop computers for the three MIS firms is 25,000/26,000/27,000 New Taiwan Dollar (NTD) (approximately 835/868/902 USD), which is a similar number to the production cost estimated in (Hong and Ke, 2011). According to (Li, 2005), production costs have increased by around 5–10% due to the launch of WEEE and RoHS. Thus, we estimate the unit indirect pollution

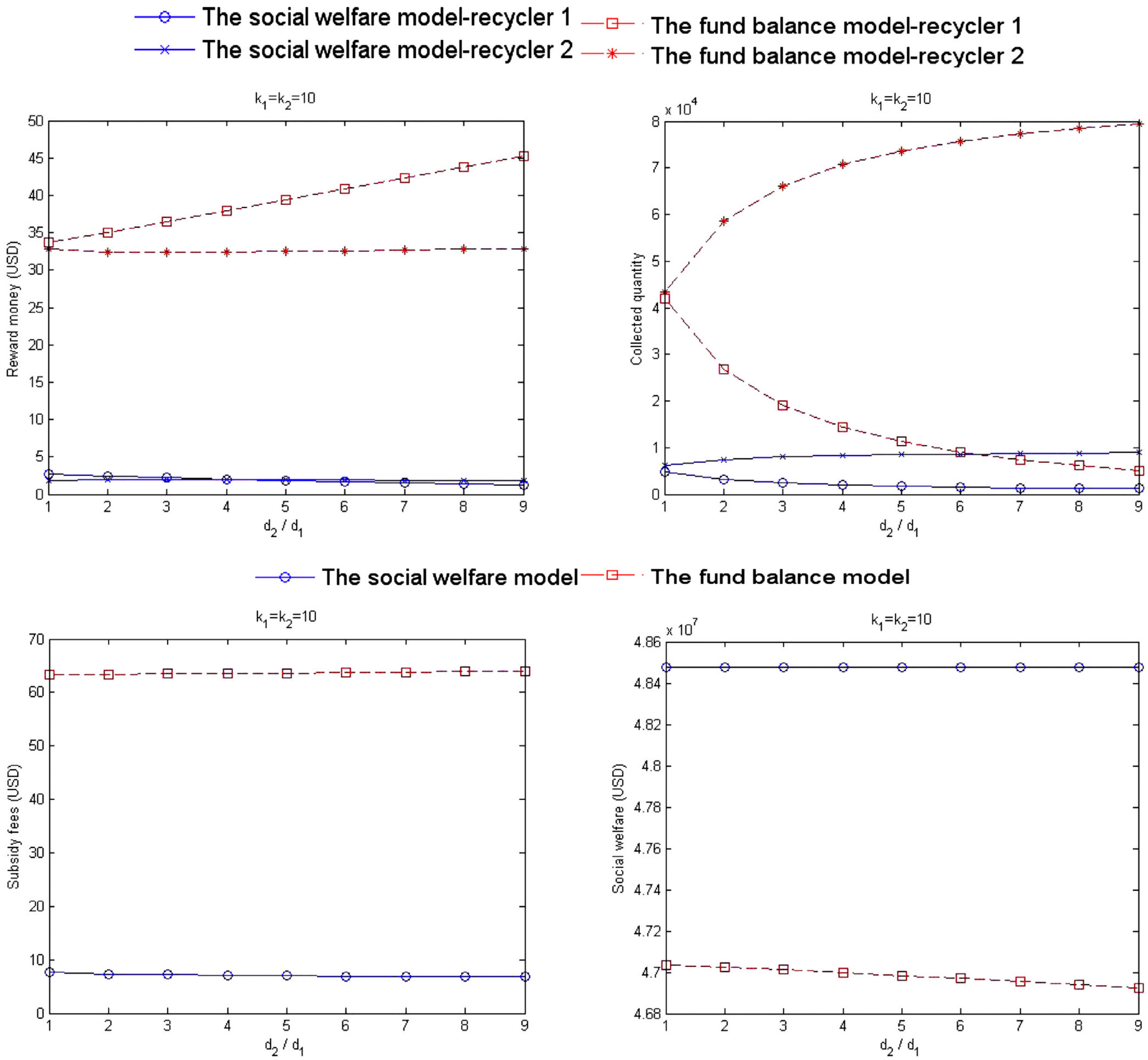

Fig. 5. Impact of d_2/d_1 on reward money, collected quantity, subsidy fees and the value of social welfare.

cost, e, as the average increase (7.5%) in the three MIS firms' average production costs due to WEEE and RoHS ($e = 1950$, approximately 65 USD). In (Wen, 2006), the total cost of recycling one unit of laptop computers is approximately estimated as 135 NTD (4.5 USD), which we assume to be the unit pollution of uncollected e-scrap products ($E = 135$). We estimate the ballpark figure of the net cost for recycling one unit of laptop computers as 50 NTD (1.67 USD) ($r_1 = r_2 = 50$), a rounding-down number of the value of recovered components of laptop computers estimated in (Wen, 2006). The EPA predefined desirable level of the return rate of e-scrap products is $\tau = 0.3183$ (EPA Taiwan, 2010). Due to data unavailability of k_l $l = 1, 2$ (the impact of the reward money offered by other recyclers on the collected quantity), we conducted a sensitivity analysis of k_l where Scenario 1 ($k_1 = k_2 = 10$) represents the relatively low influence of one recycler's reward money on the collected quantity of the other competing recycler, and Scenario 2 ($k_1 = k_2 = 20$) corresponds to a relatively high influence of one recycling firm's reward money on the other recycler's collected quantity.

4.2. Results

We study how the characteristics of the consuming market affect the value of social welfare, where the parameters, a and b, in the inverse demand function can be interpreted as the choke-off price (a) and the sensitivity of price with respect to the quantity demanded (b) in the consuming market. The choke-off price (a) is the lowest price at which there is no demand, and the sensitivity of price with respect to the quantity demanded (b) is the decrease in price per unit of an extra unit of quantity demanded. Second, we study how the unit indirect pollution cost incurred in producing new products (e) and the unit pollution cost of uncollected e-scrap (E) affect the value of social welfare. The value of social welfare in both models can be determined by substituting all realized variables into (8). Obviously, the value of social welfare in the social welfare maximization model outperforms the welfare value in the fund balance model in both scenarios as shown by Figs. 2 and 3. We summarize the major observations as follows:

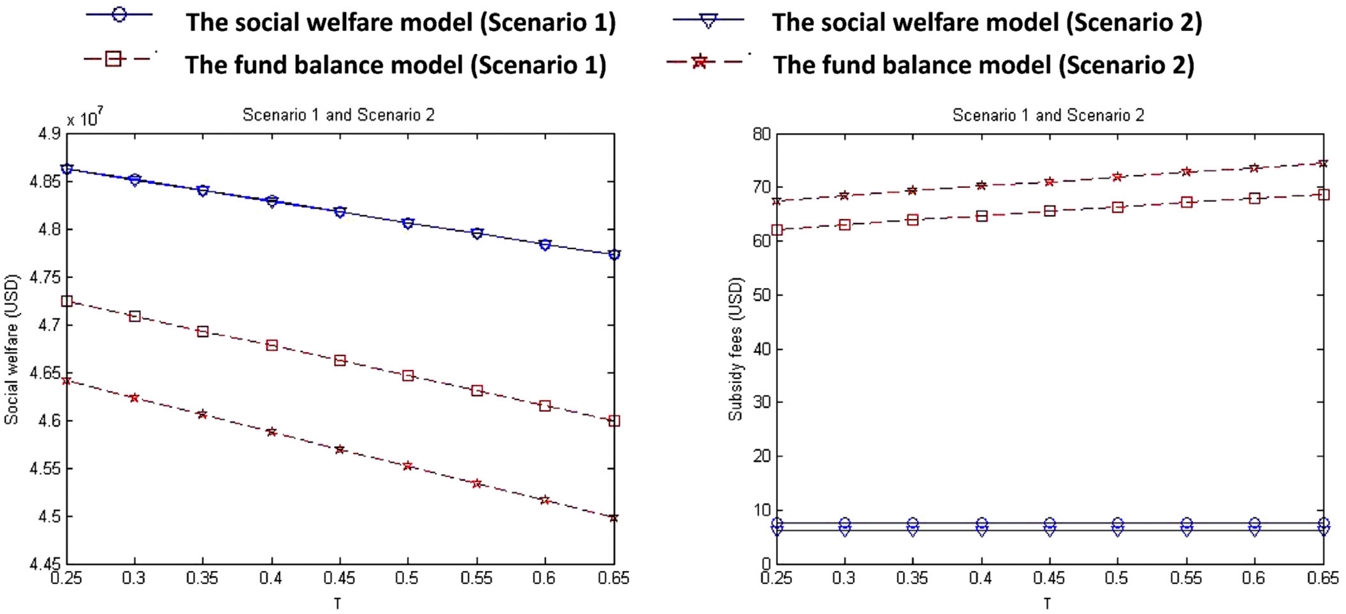

Fig. 6. Impact of τ on subsidy fees and the value of social welfare.

(i) The numerical analysis behaves in a positive relationship between the social welfare and a, but a negative relationship between the social welfare and b, e and E.

An increase in a results in an increase in the value of the social welfare for both models in both scenarios. This indicates a positive relationship between social welfare and the choke-off price, a. However, since both models in both scenarios show that social welfare decreases as the value of the sensitivity of price with respect to the quantity demanded, b, or pollution cost (e or E) increases, it implies a negative relationship. An increase in the value of e or E implies an increase in the environmental externality cost, i.e. the EPA would increase the ARF to restrain the production of new products so that the profits of MIS firms decrease. Furthermore, the EPA would choose to increase the subsidy fee to reduce the amount of uncollected EOL products. The trend between the social welfare and a, b, e is similar to how they behave in the single recycler case study (see Hong and Ke, 2011), but the relation between the social welfare and E is in direct contrast to the results in (Hong and Ke, 2011). This finding highlights that a single recycler model may distort the subsidy fee leading to an increasing welfare in E, while our multiple recyclers model captures the interactions among recyclers so that the relation between the social welfare and E behaves in a reasonable manner.

(ii) The social welfare difference decreases in a, increases in e, but it does not show a significant difference in b.

The difference in the value of social welfare between the two models decreases in both scenarios as the value of a increases; however, the value of the social welfare between the two models does not show a significant gap in both scenarios as the value of b increases. This implies that the EPA may pay more attention to the best way to determine the associated fees when the value of the choke-off price, a, is at a low level, since the fund balance model may give a relatively poor performance when a is low. The difference in the value of social welfare between the models increases as the value of e increases. Similarly, the EPA may pay more attention to the determination of the associated fees when the value of e is at a relatively high level since the fund balance model may return a worse result at a relatively high value of e.

(iii) The social welfare of the fund balance model with a large influence of one recycler's reward money on the collected quantity of the other competing recycler (Scenario 2) is smaller than that with a small influence (Scenario 1).

The value of social welfare of the fund balance model in Scenario 2 is smaller than in Scenario 1 as shown in Figs. 2 and 3. This implies that the concept of the fund balance to determine the associated fees may produce a worse outcome in Scenario 2 which corresponds to the relatively large influence of a recycler's reward money on the collected quantity of its competitor.

Next, we study how the market intercept parameter and slope parameter of the recycling market affect the interested metrics of reward money, collected quantity, subsidy fee and the value of social welfare. First, we investigate the intercept parameters, c_1 and c_2, which we interpret as the base collected quantity of zero reward money for recyclers 1 and 2. To this end, we fix the sum of c_1 and c_2 due to a fair comparison, and vary the ratio of c_2 to c_1. A large ratio will indicate a large base collected quantity for recycler 2 as both recyclers adopt zero reward money. Then we examine how the interested metrics change as the slope parameters change. The slope parameters, d_1 and d_2, can be explained as the sensitivity of the collected quantity with respect to the reward money offered by recyclers 1 and 2. Again, we fix the sum of d_1 and d_2 due to a fair comparison, and vary the ratio of d_2 to d_1. A large ratio of d_2/d_1 implies that recycler 2's collected quantity is more sensitive to the reward money offered by itself. Our numerical experiments show that the two scenarios ($k_1 = k_2 = 10$ and $k_1 = k_2 = 20$) behave similarly; therefore, we only demonstrate the results of Scenario 1 ($k_1 = k_2 = 10$) for simplicity. Figs. 4 and 5 show the results.

Figs. 4 and 5 detail how the interactions, which are not considered in (Hong and Ke, 2011) between two competing recyclers, affect the reward money, collected quantity, subsidy fees and social welfare. Roughly speaking, the reward money, collected quantities, subsidy fees and social welfare remain at the same levels as the ratio of c_2/c_1 increases. However, the reward money of recycler 1 in the fund balance model significantly increases as d_2/d_1 increases, accompanying the drop in the collected quantity of recycler 1 in the fund balance model (see Fig. 5). This trend demonstrates an unreasonable situation that a high reward results in a low collected quantity in the fund balance model, and alerts the EPA that the fund balance idea may actually distort market behavior such that a high reward results in a lower collected quantity. We find that the social welfare maximization model seems robust under considered situations.

Another interesting sensitivity analysis is how the EPA's predefined desirable level of the return rate of EOL products, τ, affects subsidy fees and the value of social welfare. In Fig. 6, Scenarios 1 and 2 represent a relatively low or high influence of one recycler's reward money on the collected quantity of the other competing recycler. The value of social welfare decreases as the EPA's predefined desirable level of the return rate of EOL products increases. The analysis also shows relatively stable subsidy fees as the EPA's predefined desirable level of the return rate of EOL products varies.

5. Conclusions

Concern about proper management and recycling of EOL products motivates the EPA to impose ARFs on MIS firms to restrain excessive production of new products and produce environmentally friendly products; on the other hand the EPA compensates recyclers for the costs along with recycling and processing EOL products to encourage and support its recycling programs.

This paper presents a model where the EPA as leader determines the level of the ARFs and subsidy fees to maximize social welfare and multiple MIS firms and recyclers as followers are free to choose the optimal production quantity of new products and the optimal reward money after learning the level of fees announced by the EPA. We consider the impact of individual entities' behaviors in both groups of followers on the determination of ARFs and subsidy fees in order to compare the interactions and competition.

Current practice is that an EPA determines the level of ARFs and subsidy fees on the basis of fund balance, i.e. the EPA simply "makes" the total amount of ARFs equal the total expenditure on subsidy fees. Although it is an intuitive observation, our results demonstrate that the proposed social welfare maximization model may generate a significant improvement in the value of social welfare. In some of the numerical examples studied, the concept of the fund balance may even lead to a worse outcome when a relatively large influence of a recycler's reward money on the competing recycler's collected quantity occurs. It suggests that there is another social welfare perspective available for EPAs when considering appropriate fee determination mechanisms.

This paper makes three important contributions to the literature: (i) the proposed concept of social welfare maximization provides the EPA with a different tax/subsidy instrument that behaves as a socially optimum status, (ii) quantifying the possible relationship between reward money and collected quantities demonstrates a market distortion in the current practice of the fund balance model, and (iii) the trend of the reward money and collected quantity alerts the EPA that the fund balance idea may in fact distort market behavior such that a high reward results in a lower collected quantity.

We restrict our focus to the comparison of the two strategies that the EPA may adopt: social welfare maximized or fund balance. For a fair comparison, we require that the two models behave under the condition that the EPA has collected the identical total amount of ARFs. However, a synthesis of the two concepts may be considered; that is, the EPA maximizes the social welfare subject to a balance between total collected ARFs and subsidy expenditures. In addition, a mechanism design to incentivize MIS firms to disclose the information of externality costs generated by production would avoid the current difficulty of unavailability of data when estimating externality. We note that both of the extensions, to consider the synthesis and to incentivize MIS firms, will require further refinement of our proposed models. In addition, the issue of the number of recyclers is an important research question, since the EPA would like to determine an optimal level of the number of recycler licenses to be issued.

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