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Modeling and assessment of e-waste take-back strategies in India

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ABSTRACT

The problem of growing e-waste (also called as WEEE) quantities in developing countries have prompted governments to plan innovative control measures and to institutionalize environment friendly strategies to mitigate the threats emanating from such waste. In India, e-waste recycling has been primarily a market driven industry. Under India's newly drafted e-waste management handling rules, the producers are expected to introduce and implement EPR regimes as early as possible. The scope of implementing EPR has also been discussed in these guidelines. In this work, we make an attempt to assess different EPR take-back policies and investigate their suitability for the Indian conditions. We use an economic model to ascertain the profitability of different EPR take-back schemes. In order to sustain the higher costs of e-waste recycling, the overall profitability of the e-waste take-back scheme is vital to the success of any e-waste recycling mandate. The results from our modeling clearly show that from the viewpoint of both the consumers and the producers, an individual take-back scheme outperforms the collective take-back scheme. We also describe impacts and implications of these take-back schemes on the model parameters of interest.

1. Introduction

In the developed world, e-waste take-back legislations have been implemented through directives under the guiding principle of Extended Producer Responsibility (EPR). The EPR concept holds manufacturers responsible for the collection and environment friendly disposal of products at the end of their useful life. Take-back policy that invokes the EPR principle mandates the manufacturers to develop adequate systems for the collection and environmentally safe treatment of such products. The long term goal of EPR (Nnorom and Osibanjo, 2008) was to improve product reusability and recyclability, reduce material usage, downsize products, and incorporate Design for Environment (DfE) principles in the product design process to significantly reduce the environmental impact of products put into the market. Take-back legislation in developed economies (Atasu et al., 2012) principally follows one of two approaches: consumer pay or producer pay. The Japanese and the Californian states in particular, have chosen the consumer pay principle, where the end-user is charged an extra fee for the safe treatment of used products. Contrarily, several European countries favor the producer pay principle which holds the manufacturer responsible for environment friendly treatment of used products.

Several policies have been implemented to address the critical issue of e-waste management and, in particular, e-waste recycling. The European Union (EU) has framed two recent policies. The WEEE (Waste Electrical and Electronics Equipment) Directive (Directive 2002/96/EC, 2003) transfers the burden of recycling to the manufacturers by requiring them to take-back and recycle WEEE. Another EU initiative, the RoHS (Restriction of Hazardous Substances) Directive (Directive 2002/95/EC, 2003), restricts the use of certain hazardous materials in electrical and electronic equipment. Yet another initiative, the Basel Convention (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989), legally bans the export of hazardous waste and their disposal from developed countries to developing countries. The EU WEEE directive clearly imposes collection, recovery, and recycling targets on its member countries. It stipulates a minimum collection target of 4 kg/capita per year for all the member states. These collection and weight based recycling targets seek to reduce the amount of hazardous substances disposed to landfills and to increase the availability of recyclable materials which indirectly encourages less virgin material consumption in new products. Netherlands was the first member state to fully implement these directives through their own national legislation. Sepulveda et al. (2010) propose that the EU's WEEE Directive, which is more focused on toxic control and manual disassembly

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based recycling systems, should also aim to serve multiple and broader environmental goals like recovery of valuable materials and energy preservation. The authors justify their argument by citing latest innovations in shredding and separation technologies together with technological progress in dedicated smelting operations of valuable materials.

In 2001, Japan adopted a new legal framework (Ogushi and Kandlikar, 2007) to kick-start its own WEEE recycling system incorporating EPR and, with a view to establish a sound material-cycle society that promotes the 3R (Reduce, Reuse, Recycle) principle. Such a law was necessitated by the fact that proper treatment of e-waste would enable proper resource recovery and reduce dependence on landfill. A unique feature of the Japanese EPR law is that it is primarily based on the principle of shared responsibility wherein the responsibilities of different stakeholders are explicitly shared. For instance, according to the Home Appliance Recycling Law (HARL), retailers are mandated to collect used products, consumers are responsible for financing recycling and transportation by paying recycling fees to the retailer at the point of disposal and producers are mandated with setting-up pretreatment plants and collection networks. The above law covers four major e-waste products, namely air-conditioners, televisions, laundry machines and refrigerators. The retailers, and the municipality in some cases, are obliged to transfer the collected units to the producers' designated collection points and subsequently pass on the recycling fee to the producers. The producers are mandated to collect e-waste from their designated collection points and achieve the recovery targets set under the legislation.

Bulk and business consumers, on the other hand, could either engage the treatment of e-waste at their own expense or return to the retailer by paying the requisite recycling fees. The law for the management of e-waste from PCs (Personal Computers) from the business sector also came into effect from April, 2001 while those from the household sector came under the purview of the EPR law from October, 2003. However, for computers, the costs of recycling are borne at the point of sale, as opposed to at the point of disposal for products under HARL. Yet another law, the Small-sized Home Appliance Law was enacted on April, 2013 to cater to small electronic and electrical home appliances such as mobile phones, gaming machines, small personal computers etc. The new law, which covers about 100 items, does not require consumers to pay recycling fees. Under the new law, the concerned municipality is responsible for setting up collection centers, from where collected waste is to be sent to certified recycling companies. Further, each municipality is stipulated to design their own collection centers and identify the products to be collected.

Take-back policy requires financial instruments in the form of disposal (or recovery) fees either at the time of disposal or at the time of purchase (advance recycling fees or advance disposal fees). For instance, the Japanese model argues for both approaches: advance fees for computers, and fees at the point of disposal for home appliances. The Californian and the Taiwanese models, on the other hand, favor advance recycling fees for all products, which are typically used to fund the state controlled recycling system (Lee et al., 2010; Atasu and Van Wassenhove, 2012). Advance disposal or recovery fees have the advantage of being visible to all the stakeholders which influences better future planning at the downstream end. Additionally, fees charged at the point of disposal might lead to an indifferent disposer who, in all likelihood, might be tempted to illegally dump the used products or perpetually store them.

Contrarily, the European WEEE directives are implemented through the manufacturer operated take-back systems (Dempsey et al., 2010; Atasu and Van Wassenhove, 2012). Yoshida and Yoshida (2010) state that the current e-waste management framework that exists in Japan not only closes the material-cycle, but is also the best system in existence that reasonably captures producer feedback through DfE (Design for Environment). As opposed to the EU take-back model, where the manufacturers' contract the recycling activity to dedicated recycling companies, the producers in Japan are directly involved in the recycling process. Uwasu et al. (2013) in their pioneering work, reported that as far as developed countries whose objective remains to achieve a certain level of waste reduction are concerned, a deferred disposal fee system will always result in the highest recycling fees. They also report that factors like demand elasticity and consumer response to recycling fees shall dictate whether the deposit-refund system incurs lower recycling fees than the advanced disposal fee system. Shinkuma (2003) attempts to model the effect of transactional cost in the deposit-refund system on household waste recycling policy vis-à-vis the relative magnitude of the price of a recycled good. The author clearly outlines that in the event where the marginal transaction cost is relatively low, the deposit-refund system outperforms other schemes regardless of the price of a recycled good.

Besides these mandated product take-backs, there also exists voluntary take-back strategies (Widmer et al., 2005) which is generally the case observed in developing countries like China and India. Here, there are no laws that mandate compliance and therefore no penalties for not meeting the EPR goals. Increased public awareness and government attention to the problems emanating from e-waste have prompted few manufacturers from developing countries to establish individual take-back schemes for specific products as a part of their corporate social responsibility and green image.

A major issue for planners in the implementation of any form of EPR is in deciding which type of producer responsibility is optimal for the producers: individual or collective. From the long term perspective of EPR, the producers favoring the individual take-back, will ideally attempt to internalize the recycling cost into the product price, which could provide the required incentive for producers to adopt better product design features to facilitate better recovery and recycling, and to avoid the inclusion of hazardous substances in the manufacturing stage. A good number of producers engage in collective systems to take advantage of the economies of scale and thus to reduce costs (Atasu et al., 2009). Such an arrangement allows producers to delegate most take-back-related activities to third-party treatment providers, but it also leaves them with very little scope and incentive to make substantive future investments to address the long term objectives of EPR.

The argument over the cost efficiency of the two schemes remains debatable and has been inconclusive till date. Producers that favor an individual scheme argue that it is an ideal platform for producers to invest in environment friendly products which, in the long run, will reap economic benefits from reduced recovery costs. In stark contrast, certain industrial alliances and some national collective systems (Atasu and Subramanian, 2012) in countries such as Sweden, Netherlands, Belgium and Norway have supported collective take-back scheme based on the argument that a collective system is the simplest and most cost-effective way to collect and recycle e-waste.

The first significant headway in e-waste legislation in India was the e-waste guidelines issued by the Ministry of Environment and Forests (MoEF), Government of India vide its letter no. 23–23/2007-HSDM dated March 12, 2008. It then formed the benchmark for the scientific handling of e-waste in an environmentally sound manner (MoEF, 2007). Following this, on May 14, 2010, MoEF issued the draft “e-waste (Management and Handling) Rules, 2010” that came into force from May 1st 2012. The rules clearly stipulate producer responsibility for the proper collection of e-waste through an appropriate take-back system on the same lines as the European EPR directive.

The newly set rules clearly put the onus of e-waste management on the manufacturers on the lines of the principle of EPR and also restrict the use of hazardous substances in e-products. The rules explicitly define the roles and responsibilities of the producer, collection centers, consumer or bulk consumers, dismantlers and recyclers. Through this enactment, manufacturers now have to design their own take-back system. The producers, as per the new guidelines, are expected to voluntarily set up collection centers or take-back systems, either individually or collectively. Currently in India, there is an established informal sector which collects and processes e-waste (Dwivedy and Mittal, 2010). However, the disposal and recycling of e-waste in the informal sector are very rudimentary so far as the recycling techniques employed and safe recycling practices are concerned, resulting in low recovery of materials (Yu et al., 2010). The process followed by these recyclers is product reuse, refurbish, conventional disposal in landfills, open burning and backyard recycling (Dixit, 2007). Most often, the discarded electronic goods finally end-up in landfills along with other municipal waste or are openly burnt releasing toxic and carcinogenic substances into the atmosphere.

To avoid this, the proposed e-waste guidelines exhort producers to explore appropriate take-back schemes so that e-waste goes to the right channel. Customers need to be given incentives to return their end-of-life (EOL) e-products back to the collection centers. This could be done by enforcing a buy-back policy. Once a product reaches the end of its useful life, the producers would buy it back from the consumers at a price higher than that of the informal sector, thereby cutting off the supply to this sector and ensuring that e-waste goes to the right channel. This added cost to the manufacturer would be offset by increasing the selling price of new products. Wang et al. (2011) conducted the first of its kind econometric study for a developing country like China to assess the principal factors that affect residents' e-waste recycling behavior. Subsequently, a similar study was also conducted in the Indian context by Dwivedy and Mittal (2013). Both the studies equivocally state that consumers in developing countries look for economic benefits for discarding their e-waste. The Chinese residents, in the likelihood of a take-back regime are reportedly seems to prefer the pay-in-advance scheme, as against the deposit-refund route favored by the Indian residents. Wath et al. (2010) argue that a visible advanced recycling fee is the most suitable financing instrument for recycling e-waste given that there exists a very well networked and effective door-to-door collection network in India with which the residents are willing to trade with their e-waste. The authors, like others, fear that a deposit-refund system would be operationally infeasible due to high transaction costs and administrative burdens associated with record keeping.

By take-back scheme, this study refers to collection decisions while most literature in this area (Toyasaki et al., 2011) use an integrated approach between the manufacturer and the recycler to develop a framework for analyzing and optimizing take-back schemes. Since no laws exist which mandate the responsibility for the collection and recycling of the end-of-life products in India, it is too early to speculate the extended bargaining role of recyclers in the current framework. The manufacturers, though not mandated, need to or at least seem to evolve a take-back policy as expected from the latest draft guidelines. Bereft of collection and recycling targets, it becomes imperative to identify the right take-back policy from the manufacturers' point of view. Juxtaposing the experiences from the developed world will not suffice given that there exists serious shortcomings in the existing regulatory framework, and where the price sensitive Indian consumer not willing to pay for recycling the e-waste.

The purpose of this study is to report on research undertaken to model and investigate whether the current end-of-life product take-back theories and practices can be applied to developing countries like India. To this effect, the study investigates and builds upon the existing baseline European take-back schemes for WEEE recycling: Individual and Collective take-back scheme. The modeling framework proposed in this study is grounded to achieve and complement the newly set producer responsibility laws in India, and which in the near future could form the basis for legislators/regulators in determining the appropriate type of scheme to adopt.

2. Mathematical model

In this section, the framework used to represent the industrial structure, the modeling assumptions and the profit function of the manufacturer are formulated. For ease of analysis, a two-manufacturer case was investigated. Here, each manufacturer can be viewed as a single firm or a consortium of firms. The advantage of a two manufacturer industrial setting allows us to model competition that exists within the same tier of a network using stylized demand functions that are easy to handle (Toyasaki et al., 2011). In any case, a two-manufacturer industrial setting is ideal for countries like India and China where there exists only a few consortia of manufacturers. Our primary objective is to analyze the profit function of the manufacturer vis-à-vis the choice of the take-back scheme: individual or collective take-back. The model further allows us to investigate competition amongst manufacturers. Fig. 1 shows the schematic representation of both take-back schemes. In both cases, it was assumed that the manufacturers compete against each other by the market positioning of their new product prices. In the case of the individual take-back scheme, the manufacturer is responsible for institutionalizing collection networks for sourcing end-of-life (EOL) returns and allocating the same to the recyclers. The competition amongst recyclers is by nature an indirect one, which in our case is through the manufacturers.

On the other hand, in the case of the collective take-back scheme, a consortium of manufacturers sub-contract their WEEE collection activity to a third party such as a Producer Responsibility Organization (PRO) or a retailer (who sells products of both manufacturers), who in turn is responsible for collecting WEEE from the consumers and selling the same to contracted recyclers. The key points that could be ascertained from Fig. 1 are that in the individual scheme, the manufacturers are responsible for collection of EOL products from the consumers, however in the collective scheme, a third party organization collects the EOL products from the consumers and charges a fee for the same. The mathematical framework does not specifically address collection issues because the proposed take-back schemes are intended to achieve a targeted collection rate.

The objective of this study is to examine the performance measures: the manufacturer's profit and the new product selling price; since the manufacturer has the flexibility to opt either for an individual take-back or a collective take-back scheme. Henceforth, we use the superscript S to denote the take-back scheme where $S = i$ for the individual take-back scheme and $S = c$ for the collective take-back scheme. We use the subscript j, $j = 1,2$ to denote the two manufacturers. The selling price of new products for manufacturer-j in the scheme S will be denoted by p_j^s. In both the schemes, manufacturer-j sells d_j products to the consumer for a unit price of p_j. The collection is done by the manufacturer in the individual scheme and by a third party in the collective scheme who in turn charges a price of t_j from the manufacturer.

The demand model that was used is a linear model having substitution effects (Toyasaki et al., 2011). The demand (d) of manufacturer-j can be stated as

$$d_j(p_1^s, p_2^s) = \alpha_j - p_j^s + \beta p_{3-j}^s \quad j = 1, 2; \quad s = i, c \tag{1}$$

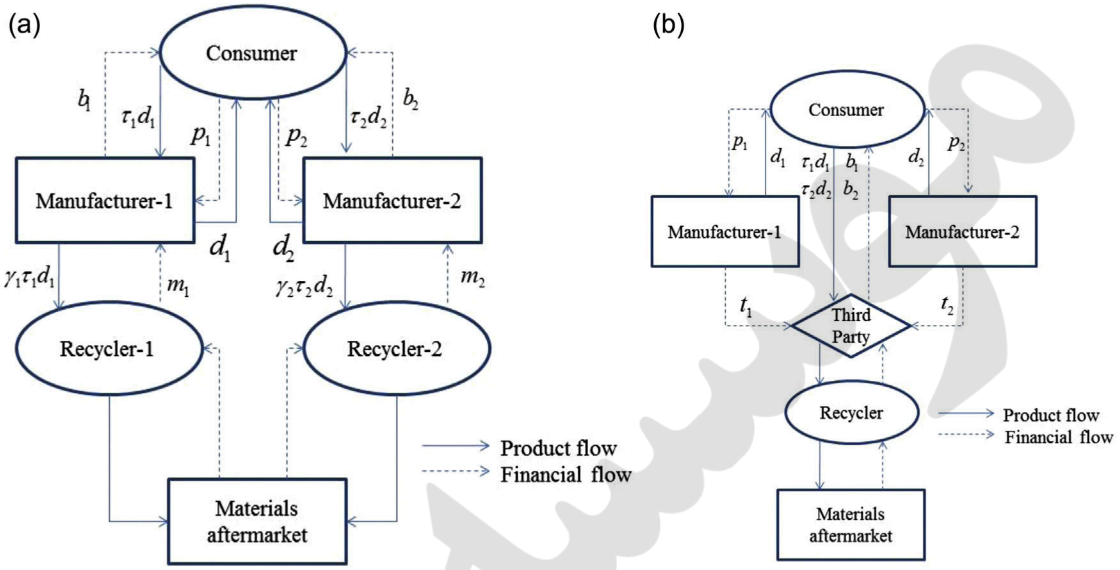

Fig. 1. Schematic representation of two take-back schemes.

where, α_j is the market share of manufacturer j and β is the cross elasticity of demand. It was also assumed that the products sold by competing manufacturers are comparable substitutes, so$\beta > 0$, and that the concerned manufacturer's own-price effect will be stronger than the cross-price effect, implying $\beta < 1$. Only EOL reverse flows of products for potential recycling have been considered here. The fraction of total products of manufacturer *j* collected at the end of the period is denoted by $\tau_j, j = 1{,}2, 0 < \tau_j \le 1$. The buy-back price is denoted as b_j^s. In the case of collective take-back, the manufacturer pays a certain fee (t) per collected unit to the third party contracted for EOL product collection, which can be expressed as a certain fraction over the buy-back rate $t = \frac{b}{v}, \quad 0 < v < 1$. In both schemes, the buy-back price is taken to be a certain fraction (k) of the selling price of a new product, $b = kp$, $0 < k < 1$. Therefore, we have $t = \frac{k}{v}p$. Since the per-unit fee paid by the manufacturer to the third-party should be lesser than the selling price of a new product, i.e. $t < p$, we have $\frac{k}{v} < 1$. For ease of comparison, the unit cost of production for each manufacturer is assumed to be *c* in both the schemes. Note that this *c* is different from the superscript *c*. In the collective scheme, we let m_j denote the cost per unit the recycler pays to obtain the collected items from the manufacturer *j*. Note that unlike Europe, in India the recycler would buy the collected items. Here, the recycler is assumed to buy a certain fraction (γ) of the collected items from the manufacturer and $0 < \gamma \le 1$. Additionally, the government sets a penalty that the manufacturer would have to incur in case they do not meet the set collection target. Thus, this penalty will be some function (say *f*) of the collection rate τ_j which is subtracted from the profit function of manufacturer *j*. Since the penalty is designed to decrease with the increase in collection, *f* is assumed to be a decreasing function of τ_j.

Manufacturer *j's* optimization problem for the individual take-back scheme can be expressed as

$$\max_{p_j} \pi_j^i = (\alpha - p_j + \beta p_{3-j})(p_j - c) - b_j \tau_j (\alpha - p_j + \beta p_{3-j}) + \gamma m_j \tau_j (\alpha - p_j + \beta p_{3-j}) - f(\tau_j) \tag{2}$$

Eq. (2) thus gives the *jth* manufacturer's profit function taking into account a unit selling price (p_j), the unit production cost (c), cost incurred in the collection of used products from the consumers, the revenue earned from selling collected EOL products to the recycler and the associated penalties resulting from not fulfilling the mandated collection targets. Introducing $b_j = kp_j$ into the manufacturer 1's profit function results in:

$$\pi_1^i = (\alpha - p_1 + \beta p_2)(p_1 - c - \tau_1 k p_1 + \tau_1 \gamma m_1) - f(\tau_1) \tag{3}$$

For the collective take-back scheme (superscript *c*), manufacturer *j's* optimization problem is analogous to the individual scheme except that the manufacturer does not physically transact any EOL collection or management cost, while contracting the same to a PRO for a unit price of t_j resulting in

$$\pi_j^c = (\alpha - p_j + \beta p_{3-j})(p_j - c) - \tau_j t_j (\alpha - p_j + \beta p_{3-j}) - f(\tau_j) \tag{4}$$

Eq. (4) thus gives the *jth* manufacturer's profit function taking into account a unit selling price (p_j), unit production cost (c), collection costs borne by the manufacturer which is paid to the PRO with whom the manufacturer has an exclusive contract for the collection and disposal of products put into the market by him and the associated penalties resulting from not fulfilling the mandated collection targets. Introducing $b_j = kp_j$ and $t_j = b_j/v$ into manufacturer 1's profit function results in:

$$\pi_1^c = (\alpha - p_j + \beta p_2)(p_1(1 + \frac{k\tau_1}{v}) - c) - f(\tau_1) \tag{5}$$

Here the PRO is responsible for collecting used products from the consumer, while the inability to meet the collection targets is penalized on the manufacturer.

2.1. Equilibrium prices

In this section, the reaction functions of the manufacturers for both take-back schemes are derived and the Nash equilibrium prices are computed from the derived profit functions. For the individual take-back scheme, the reaction functions are derived by differentiating Eq. (3).

$$\frac{\partial \pi_1^i}{\partial p_1} = (\alpha - p_1 + \beta p_2)(1 - k\tau_1) - (p_1(1 - k\tau_1) - c + \tau_1 \gamma m_1) = 0 \tag{6}$$

Solving Eq. (6) results in $2p_1 = \alpha + \beta p_2 + \frac{c - \tau_2 \gamma m_1}{1 - k\tau_1}$ which gives the reaction function of manufacturer 1 as

$$p_1^{i*}(p_2) = 1/2 \left[\alpha + \beta p_2 + \frac{c - \tau_1 \gamma m_1}{1 - k\tau_1} \right] \tag{7}$$

Table 1
Partial derivatives of the performance measures.

Par	Individual take-back scheme		Collective take-back scheme		Difference (individual-collective)	
	Price	Profit	Price	Profit	Price	Profit
α	+	+	+	+	0	+
β	+	+	+	+	–	+
c	+	–	+	–	–	–
τ_1		+	+	–	–	+
τ_2		–	+	+	–	–
v	NA	NA	–	+	NA	NA
k	+	–	+	–	+	+
m_1	–	+	NA	NA	NA	NA
m_2	–	+	NA	NA	NA	NA
γ	–	+	NA	NA	NA	NA

Eq. (7) states that for a given manufacturer 2's price (p_2^i), the manufacturer 1 reacts by selecting price $p_1^{i*}(p2)$.

Similarly, setting ${}^{\partial\pi_2^i}\!/\!{}_{\partial p_2} = 0$, the reaction function of manufacturer 2 was found to be

$$p_2^{i*}(p_1) = 1/2\left[\alpha + \beta p_1 + \frac{c - \tau_2\gamma m_2}{1 - k\tau_2}\right] \tag{8}$$

Solving these expressions simultaneously for Nash equilibrium, the optimal prices are found to be $2p_1^{i*} = \left(\alpha + \frac{c-\tau_1\gamma m_1}{1-k\tau_1}\right) + \frac{\beta}{2}\left(\alpha + \beta p_1 + \frac{c-\tau_2\gamma m_2}{1-k\tau_2}\right)$ which on further simplification results in

$$p_1^{i*} = \left[(2+\beta)\alpha + 2\left(\frac{c - \tau_1\gamma m_1}{1 - k\tau_1}\right) + \beta\left(\frac{c - \tau_2\gamma m_2}{1 - k\tau_2}\right)\right]\frac{1}{(4-\beta^2)} \tag{9}$$

and

$$p_2^{i*} = \left[(2+\beta)\alpha + 2\left(\frac{c - \tau_2\gamma m_2}{1 - k\tau_2}\right) + \beta\left(\frac{c - \tau_1\gamma m_1}{1 - k\tau_1}\right)\right]\frac{1}{(4-\beta^2)} \tag{10}$$

For the collective take-back scheme, the reaction functions are derived in the same way from $\frac{\partial\pi_1^c}{\partial p_1} = (\alpha - p_1 + \beta p_2)\left(1 - \frac{k\tau_1}{v}\right) - \left(p_1\left(1 - \frac{k\tau_1}{v}\right) - c\right) = 0$ and ${}^{\partial\pi_2^c}\!/\!{}_{\partial p_2} = 0$, which on solving gives the reaction functions of manufacturer 1 and 2 as

$$p_1^{c*}(p_2) = 1/2\left[\alpha + \beta p_2 + \frac{c}{1 - \frac{k\tau_1}{v}}\right] \tag{11}$$

$$p_2^{c*}(p_1) = 1/2\left[\alpha + \beta p_1 + \frac{c}{1 - \frac{k\tau_2}{v}}\right] \tag{12}$$

Solving these optimal prices simultaneously for Nash equilibrium results in $2p_1^{*} = \left(\alpha + \frac{c}{1-\frac{k\tau_1}{v}}\right) + \frac{\beta}{2}\left(\alpha + \beta p_1 + \frac{c}{1-\frac{k\tau_2}{v}}\right)$ which on simplification results in

$$p_1^{c*} = \left[(2+\beta)\alpha + \frac{2c}{1 - \frac{k\tau_1}{v}} + \frac{\beta c}{1 - \frac{k\tau_2}{v}}\right]\frac{1}{(4-\beta^2)} \tag{13}$$

and

$$p_2^{c*} = \left[(2+\beta)\alpha + \frac{2c}{1 - \frac{k\tau_2}{v}} + \frac{\beta c}{1 - \frac{k\tau_1}{v}}\right]\frac{1}{(4-\beta^2)} \tag{14}$$

3. Analysis

Next an attempt is made to study how the equilibrium price and the manufacturer profit vary with respect to variation in the different variables, for both the schemes. Since our principal motivation is to compare the two schemes, it can be assumed that the market share of both the manufacturers is the same. i.e. $\alpha_1 = \alpha_2 = \alpha$. It was also assumed that all EOL products collected, in both schemes, are given to recycler i.e. $\gamma = 1$. Further, we note the following guidelines for analyzing the mathematical model:

A1:$c > m_1$,m_2 always holds, indicating that the collection cost (m_j) is always a fraction of the unit production cost, c.

A2:$c - \gamma m_j \geq 0$ and $c - \gamma m_j \tau_j > 0$ follows from $0 < \gamma \leq 1$, $0 < \tau \leq 1$ and A1.

A3: The sign of $ck - \gamma m_j$ varies with the choice of k.

A4: $1 - \tau_j k > 0$ holds true always since $0 < \tau_j \leq 1$ and $0 < k < 1$.

A5: The expressions $4 - \beta^2 > 0$ and $1 - \beta > 0$ are always true since $0 < \beta < 1$.

A6: For the purpose of numerical simulation, the values of the variables were chosen to be $\alpha = 65{,}000$ (fixed), $c = 60{,}000$ (fixed), $0.2 \leq \beta \leq 0.8$, $\gamma = 1$, $0.05 \leq k \leq 0.2$, $0.8 \leq v \leq 0.95$, $8000 \leq (m_1, m_2) \leq 12{,}000$, $0.2 \leq (\tau_1, \tau_2) \leq 0.6$.

A7: $1 - \frac{k\tau_j}{v} > 0$. As previously mentioned, $\frac{k}{v} < 1$. Using $\tau_j < 1$ we get $\frac{k\tau_j}{v} < 1$.

3.1. Sensitivity analysis

To investigate how key operating variables and market conditions affect product prices and manufacturer profits under the two take-back schemes, the sensitivity of the investigated parameters towards the equilibrium prices and profits are derived and are presented in Table 1. Here, the sign '+' and '–' represent increase and decrease in the equilibrium, given a marginal increase in the parameters. The variables that do not arise in a particular scheme are denoted by 'NA' indicating "Not Applicable". Prices for collective and individual scheme have all been proofed, while the rest which could not be analytically tractable, have been determined numerically.

The table below shows the partial derivatives of manufacturer 1's equilibrium prices and profits with respect to different parameters. (A1) to (A5) and (A7) are used in computing the derivatives.

Proof: A: For Individual take-back scheme

$$\frac{\partial p_1^{*i}}{\partial\alpha} = \frac{1}{2-\beta} > 0 \quad (\text{A5})$$

$$\frac{\partial p_1^{*i}}{\partial\beta} = \frac{1}{(4-\beta^2)^2}\left[(4-\beta^2)\left(\alpha + \frac{c - \gamma m_2\tau_2}{1 - \tau_2 k}\right) + 2\beta\left(\frac{2(c - \gamma m_1\tau_1)}{1 - \tau_1 k} + \alpha(2+\beta) + \frac{\beta(c - \gamma m_2\tau_2)}{1 - \tau_2 k}\right)\right] > 0 \quad (\text{A2;}\quad \text{A4})$$

$$\frac{\partial p_1^{*i}}{\partial c} = \frac{1}{4-\beta^2}\left(\frac{2}{1-\tau_1 k} + \frac{\beta}{1-\tau_2 k}\right) > 0 \quad (\text{A4;}\quad \text{A5})$$

$$\frac{\partial p_1^{*i}}{\partial\tau_1} = \frac{2(ck - \gamma m_1)}{(4-\beta)^2(1-\tau_1 k)^2} > \text{ or } < 0 \quad (\text{A3})$$

$$\frac{\partial p_1^{*i}}{\partial \tau_2} = \frac{\beta(ck-\gamma m_2)}{(4-\beta)^2(1-\tau_2 k)^2} > \text{ or } < 0 \quad (A3)$$

$$\frac{\partial p_1^{*i}}{\partial k} = \frac{-1}{(4-\beta^2)}\left(\frac{2\tau_1(c-\gamma m_1\tau_1)}{(1-\tau_1 k)^2} + \frac{\beta\tau_2(c-\gamma m_2\tau_2)}{(1-\tau_2 k)^2}\right)$$
$$> 0 \quad (A2; \quad A4; \quad A5)$$

$$\frac{\partial p_1^{*i}}{\partial \gamma} = \frac{-1}{(4-\beta^2)}\left[\frac{2\tau_1 m_1}{(1-\tau_1 k)} + \frac{\beta\tau_2 m_2}{(1-\tau_2 k)}\right] < 0 \quad (A4; \quad A5)$$

$$\frac{\partial p_1^{*i}}{\partial m_1} = \frac{-1}{(4-\beta^2)}\left[\frac{2\tau_1\gamma}{(1-\tau_1 k)}\right] < 0 \quad (A4; \quad A5)$$

$$\frac{\partial p_1^{*i}}{\partial m_2} = \frac{-1}{(4-\beta^2)}\left[\frac{\beta\tau_2\gamma}{(1-\tau_2 k)}\right] < 0 \quad (A4; \quad A5)$$

B: For collective take-back scheme

$$\frac{\partial p_1^{*c}}{\partial \alpha} = \frac{1}{2-\beta} > 0 \quad (A5)$$

$$\frac{\partial p_1^{*i}}{\partial \beta} = \frac{1}{(4-\beta^2)^2}\left[(4-\beta^2)\left\{\alpha + \frac{c}{1-k\tau_2/\nu}\right\} + 2\beta\left\{(2+\beta)\alpha + \frac{2c}{1-k\tau_1/\nu} + \alpha + \frac{\beta c}{1-k\tau_2/\nu}\right\}\right]$$
$$> 0 \quad (A5; \quad A7)$$

$$\frac{\partial p_1^{*c}}{\partial c} = \frac{1}{(4-\beta^2)}\left(\frac{2}{1-k\tau_1/\nu} + \frac{\beta}{1-k\tau_2/\nu}\right) > 0 \quad (A5; \quad A7)$$

$$\frac{\partial p_1^{*c}}{\partial \tau_1} = \frac{2c}{(4-\beta^2)(1-k\tau_1/\nu)^2}\left(\frac{k}{\nu}\right) > 0 \quad (A5; \quad A7)$$

$$\frac{\partial p_1^{*c}}{\partial \tau_2} = \frac{\beta c}{(4-\beta^2)(1-k\tau_2/\nu)^2}\left(\frac{k}{\nu}\right) > 0 \quad (A5; \quad A7)$$

$$\frac{\partial p_1^{*c}}{\partial \nu} = \frac{-ck}{(4-\beta^2)\nu^2}\left\{\frac{2\tau_1}{(1-k\tau_1/\nu)^2} + \frac{\beta\tau_2}{(1-k\tau_2/\nu)^2}\right\} < 0 \quad (A5; \quad A7)$$

$$\frac{\partial p_1^{*c}}{\partial k} = \frac{c}{(4-\beta^2)\nu}\left\{\frac{2\tau_1}{(1-k\tau_1/\nu)^2} + \frac{\beta\tau_2}{(1-k\tau_2/\nu)^2}\right\} > 0 \quad (A5; \quad A7)$$

It is clear that any increase in the market size α shifts the demand upwards, which allows the manufacturers to increase prices and recover more profits in both the schemes. Further, with the increase in production cost, the equilibrium prices will increase while the equilibrium profit shall decrease. Similarly, when the degree of substitutability factor, β, for products increases, the demand curve shifts up, allowing the manufacturers to charge higher prices and therefore generate more profits.

3.2. Numerical analysis results

The sensitive analysis discussed in previous section was simulated through numerical experiments. The data used in our numerical experiments have been obtained from the investigation carried out by Toyasaki et al. (2011). In all the cases that are investigated numerically, each parameter in question was varied within their prescribed range while keeping the others fixed at their baseline values given in A6. For the case when $k \geq m_1\gamma/c$, as the collection rate (τ_1) increases, the equilibrium price (p_1^*) offered by manufacturer 1 will increase in the individual collection scheme, and the same trend can be consistently observed for the assumed data in the collective scheme. In the same way, for the stated data, increase in the collection cost (from increase in the value of k) results directly in the increase in the equilibrium prices and a drop in the profits to the manufacturer. The manufacturer who opts for the individual scheme, sells the collected used products to the recycling market, therefore allowing the possibility of reducing the new product prices in the future, which in the long run would result in improving profit margins from increased economics of scale, which our numerical study conclusively proves. The expressions for difference in equilibrium prices and profits for individual versus collective scheme are not tractable analytically, therefore are examined numerically. The results that are obtained from the numerical runs are consistent.

Fig. 2 shows the variation of difference in equilibrium price for manufacturer 1 between individual and collective take-back schemes. The graphs are plotted for three different values of k (0.05, 0.1, 0.15). From Fig. 2, it was observed that as the degree of substitutability of products (β) increases, the absolute difference in equilibrium prices increases. In general, it can be observed that the equilibrium prices for new products are always higher for the collective case. As the market competition increases, the price difference between the collective and individual cases further increases. With an increase in the buy-back cost (through an increase in k), the absolute difference in equilibrium values further increases. This implies that an increase in the buy-back price has a greater impact on the prices in the collective case.

Fig. 3 shows the difference in equilibrium profit between the two schemes for manufacturer 1, plotted against the cross elasticity of demand (β), for three different values of k (0.05, 0.1, 0.15) with all other variables having standard values. From Fig. 3, it was observed that as the degree of substitutability of products (β) increases, the difference in equilibrium profits increase steadily upto a particular value $\beta \approx 0.7$, after which there is a decline. As the cross elasticity of demand increases, the demand for products of competing manufacturers is affected by not only their own price, but also by the price quoted by the competitors. This translates to higher profits in the individual collection scheme up to $\beta \approx 0.7$, following

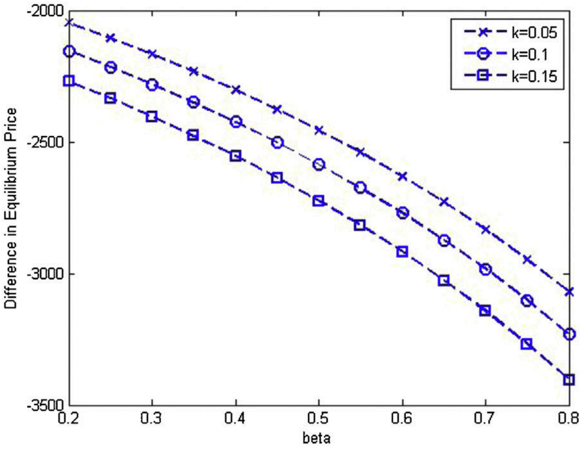

Fig. 2. Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs β.

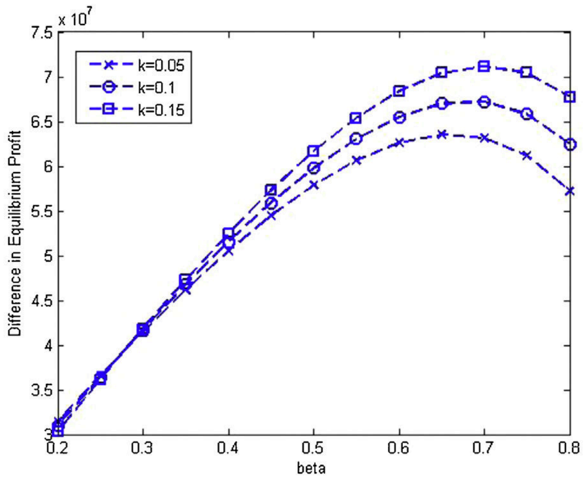

Fig. 3. Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs β.

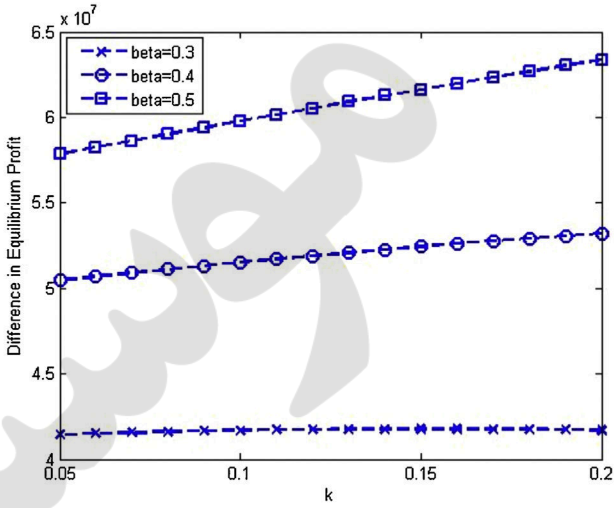

Fig. 5. Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs k.

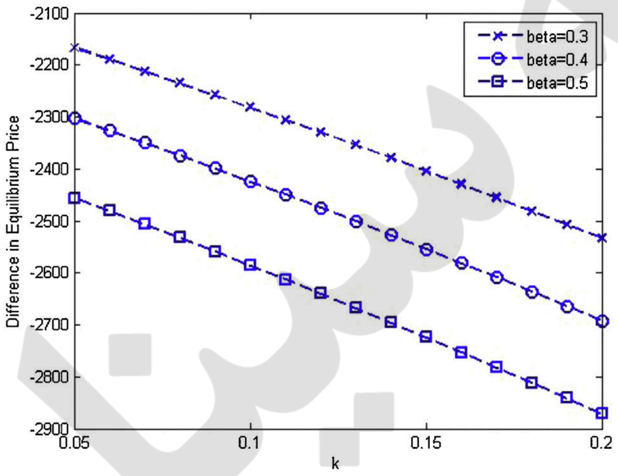

Fig. 4. Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs k.

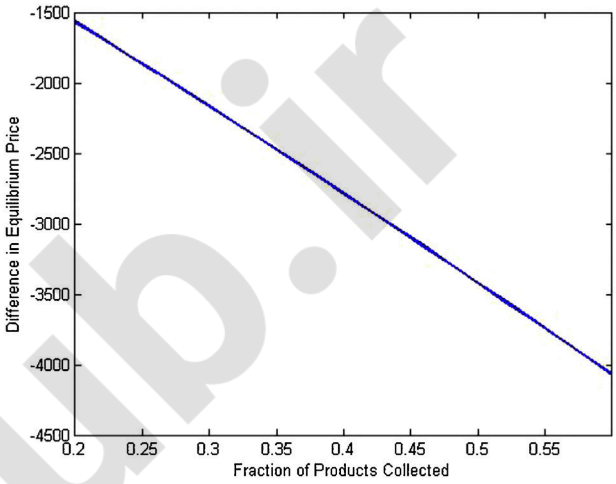

Fig. 6. Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs τ.

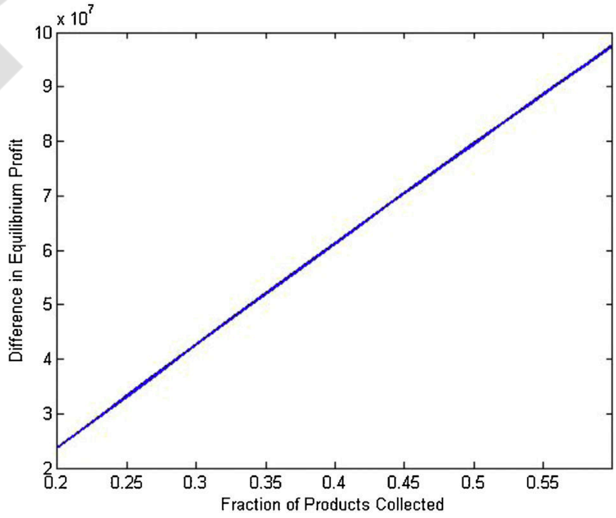

Fig. 7. Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs τ.

which, a decline is observed on account of cross-price effect. Also observed is the fact that the difference in equilibrium profits are more pronounced when the buy-back prices increase.

The plot for difference in equilibrium prices and equilibrium profits for different values of buy-back price fraction k are shown in Figs. 4 and 5, respectively. From Fig. 4, it was observed that the price difference, once again, consistently remains negative, demonstrating clearly that new product prices in the collective take-back scheme are always higher than those observed in the individual take-back scheme. There was a steady increase in the absolute price difference with an increase in the buy-back price. Contrarily, with the increase in buy-back price, the profit difference (Fig. 5) increases only marginally. However, the profit difference consistently remains positive, for all values of k, reinforcing the fact that the profits are comparably higher in the individual collection scheme over the collective scheme.

The equilibrium price and profit of manufacturer 1 have been plotted against the fraction of products collected of manufacturer 1 (τ_1), with all other variables having standard values in Fig. 6 and Fig. 7, respectively.

It was also observed from the plots that as the fraction of products collected by manufacturer 1 increases, the absolute values of both the price and profit difference increase. Here too, for the given data range, the prices are always higher in the collective scheme and profits are higher in the individual collection scheme.

4. Conclusions

For a peculiar nature of market for recycling in India, where consumers expect economic benefits while disposing e-waste, the EPR model practiced in the developed countries is likely to fail because it imposes cost to consumers. The objective of this research undertaken was to gain insight into the impact of such market conditions into an EPR model. Here an analytical framework was proposed and analyzed to compare two different modes of collection of EOL products. The analysis reveals key insights which have significant ramification for policymaking in the future, especially in deciding which take-back practice is best suited to the Indian scenario. Results showcase a win-win scenario for both the consumers and the manufacturers. The equilibrium price is always higher in the collective case, and the equilibrium profit is always higher in the individual case. Higher product prices translate to lower demand, lowering the profit margins for manufacturers that favor collective take-back scheme. Thus, the individual case is a win-win situation (with respect to consumers and manufacturers). Since the work deals only with take-back schemes vis-a-vis the interaction between the consumer and manufacturer, the effect of costs incurred by the manufacturer during the interaction with the recyclers was not analyzed. In the collective case, due to different makes of products, the collected products need to be segregated before they can be recycled. This added cost is not present in the individual case. These results principally contradict the findings of several authors who have attempted to model different take-back schemes in the context of developed countries, but their focus was on allocation of collected end-of-life products to recyclers and does not go into the details of the respective take-back schemes. Another notable difference is that the proposed model explicitly incorporated the idea of making a payment to the consumers in the process of collecting used products from them, which is a reality in the Indian context.

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