

Economic analysis of e-waste market under imperfect information

Prudence Dato

▶ **To cite this version:**

Prudence Dato. Economic analysis of e-waste market under imperfect information. 2015. halshs-01172148v2

HAL Id: halshs-01172148
https://shs.hal.science/halshs-01172148v2

Preprint submitted on 6 Aug 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Economic analysis of e-waste market under imperfect information

Prudence Dato †

- August, 2015-

Abstract

Despite international regulations that prohibit the trans-boundary movement of electronic and electric waste (e-waste), non-reusable e-waste is often illegally mixed with reusable e-waste and results in being sent to developing countries. As developing countries are not well prepared to properly manage e-waste, this illegal trade has important negative externalities, and creates 'environmental injustice'. The two main information problems on the e-waste market are imperfect monitoring and imperfect information on the so-called 'degree of purity' of the e-waste. In this paper, we use a simple bilateral North-South trade model and show that there exists an alternative e-waste market that is better than the standard e-waste market for developing countries. This alternative e-waste market is a joint trade in reusable and non-reusable e-waste. In both cases, we consider demand and supply sides, plus the equilibrium of the e-waste market to show that the alternative market that we propose is better for developing countries.

JEL classification: Q53, L51, D82, F18.

Key words: E-waste, market, imperfect information, international trade.

† Corresponding Author. (prudence.dato@univ-savoie.fr), University Savoie Mont Blanc/ IREGE (France).
I am grateful to my former advisor Prof Philippe Bontems for guiding me and to the two members of jury for my defense, Prof Stefan Ambec and Prof Catherine Bobtcheff for their helpful comments. I also thank Prof Aude Pommeret for her valuable comments.
All remaining errors are mine.

Economic analysis of e-waste market under imperfect information

- July, 2015-

Abstract

Despite international regulations that prohibit the trans-boundary movement of electronic and electric waste (e-waste), non-reusable e-waste is often illegally mixed with reusable e-waste and results in being sent to developing countries. As developing countries are not well prepared to properly manage e-waste, this illegal trade has important negative externalities, and creates 'environmental injustice'. The two main information problems on the e-waste market are imperfect monitoring and imperfect information on the so-called 'degree of purity' of the e-waste. In this paper, we use a simple bilateral North-South trade model and show that there exists an alternative e-waste market that is better than the standard e-waste market for developing countries. This alternative e-waste market is a joint trade in reusable and non-reusable e-waste. In both cases, we consider demand and supply sides, plus the equilibrium of the e-waste market to show that the alternative market that we propose is better for developing countries.

JEL classification: Q53, L51, D82, F18.

Key words: E-waste, market, imperfect information, international trade.

1. Introduction

Around the world, 48.9 million tons of electronic waste (e-waste[1]) was generated in 2012, which corresponds to 19.6 kg per capita (StEP-UN, 2013). The growth of e-waste is estimated to reach 3-5% a year, a rate that is nearly three times that of conventional waste (UNEP, 2005). A comparative advantage in terms of labour, disparities in environmental regulations together with an imperfect monitoring system favour the e-waste trade between rich and poor countries. As developing countries are not well prepared to properly manage e-waste, the illegal trade of e-waste has important negative externalities and can be seen as 'environmental injustice'. In this paper, we show that the alternative e-waste market of joint trade in both non-reusable and reusable e-waste is better for developing countries.

Stringent environmental regulations in developed countries, together with a low purchasing power of consumers in developing countries, create incentives for the e-waste trade. Within the context of the increasing growth of e-waste throughout the world and facing high disposal costs in developed countries,[2] firms in rich countries can decide to invest in green design by increasing the level of reusability of their product (Bernard, 2015). The firms in rich countries can also sell to industries that reuse e-waste (Higashida, 2012). As the monitoring system is imperfect, the latter option is often chosen. In fact, the e-waste market is regulated by a range of international regulations such as the Basel Convention, WEEE Directives,[3] the Bamako Convention, etc. If firms really are complying with international regulations, there will be no possibility that firms from rich countries could export the non-reusable parts of e-waste to less developed countries. Unfortunately, this is not the case because e-waste is often shipped back to their countries of origin by the customs officers of importing countries due to illegally traded products (Higashida, 2012). For instance, in Hong Kong between 2006 and 2008, 291 imported shipments of controlled electronic waste were returned to their countries of origin (Kojima et al., 2011). Illegal shipment occurs not only because international regulations are weak, but also because it is difficult to identify non-reusable e-waste.[4] Hence, the two main information problems that are related to the e-waste market are imperfect monitoring and imperfect information on the so-called 'degree of

[1] There is no standard definition of e-waste. The term e-waste is generally used for all types of electrical and

[2] In the 1980's, the average disposal costs for one ton of hazardous waste in Africa was between US$2.50-$50, and in industrialized countries $100- $2,000 (Kummer, 1995).

[3] Waste Electrical and Electronic Equipment (WEEE) Directives are the legislative framework within the European Union (EU) (EC regulation N° 1013/2006).

[4] For instance, it is very costly and time-consuming to check a full container of second hand televisions to ensure that they all constitute reusable e-waste.

purity'. These two problems create incentives for non-valuable e-waste to be sent to poor countries. The negative externalities due to the hazardous components of e-waste are serious because developing countries do not have the appropriate knowledge and/or tools to properly manage e-waste.

Additionally, the mix of reusable with non-reusable e-waste can be seen as an indirect subsidy. In fact, the exporting firm indirectly pays for the disposal service by lowering the price at which it sells the e-waste in developing countries. For example, the average price for all television sets exported drops from €339 to €28 when they are exported to Nigeria, Ghana or Egypt (Bernard, 2015). In this context, we ask the following questions: first, what are the factors that could explain the increase in non-reusable e-waste in developing countries; and second, does there exist any better alternative than monitoring the standard e-waste market to reduce the trade of non-reusable e-waste?

E-waste issues are less studied in economics than in environmental engineering and chemistry. To our knowledge, Sen (1962) is the earliest contributor to the literature on the international trade in used goods. He analyzes the potential gains from the international trade in used goods that is based on the movement of used machinery from high to low labour cost countries. In the same vein, Smith (1976) and Bond (1983) model the gains that may create the comparative advantage between countries. This advantage may come from disparities in environmental regulations, labour cost or waste disposal technologies. For instance, trade in waste can be seen as trade in waste disposal services (Copeland, 1991). In this context, Copeland (1991) shows that it is optimally better to allow free trade in waste products. He suggests that this free trade must be combined with internal tax policies and regulations to control for the externalities, which are related to disposal. However, he points out that this policy may suffer from compliance or enforcement issues, and therefore may result in an increase of incentives for firms to evade taxes and regulations, and to dispose of their waste illegally. Clerides (2008) shows the same results based on asymmetric quality standards that reduce trade in new goods and generate negative impacts on domestic industry.

The 'pollution haven hypothesis' (PHH) predicts that firms will relocate to jurisdictions with less stringent environmental regulations. A large body of evidence supporting the existence of PHH has been demonstrated by Baggs (2009), Kellenberg (2010), Bernard (2015), and Kinnaman & Yokoo (2011). An exception is Higashida et al. (2008) who use a gravity model, and show that the more developed a country, the more it imports

recyclable waste. Kellenberg (2010) focuses on the consumption side of pollution instead of the production side of externalities to emphasize the 'waste havens hypothesis'. For Johnstone (1998), market and policy failures may explain the adverse economic and environmental effects of an introduction of a ban on trade in hazardous waste. Later on, Lipman (2011) shows that international regulations relating to the trans-boundary movement of hazardous waste under the Basel Convention are not able to protect developing countries.

One of the main recommendations in the European Topic Centre's report on Sustainable Consumption and Production (ETC/SCP)—trans-boundary shipments of waste in the European Union—is to study the choices and behaviour of waste producers/collectors. Notably, such a study could help to better understand the drivers of this trade in order to reduce their impact, and/or to adapt legislation. To our knowledge, only Bernard (2015) focuses on the strategies of e-waste producers to explore the driving forces for illegal waste trade. The analysis of the behaviour of collectors will be an important issue in this paper.

In this paper, we use a simple bilateral North-South trade model, and show that there exists an alternative better than the standard e-waste market for developing countries. This model is close to that of Bernard (2015), and considers one representative firm in the North and one representative firm in the South. Our contribution is four-fold. First, it seems more realistic to analyze collectors' behaviours than producers' behaviours, as it is through collectors that producers participate in the e-waste market. Collectors can collect e-waste mainly from households, companies or in the second-hand goods market. Second, we consider that at the moment the collectors are collecting the e-waste, they do not know which part of the waste constitutes reusable e-waste. However, after collecting the e-waste, the collector can decide to invest in sorting, and to separate the reusable waste from the non-reusable waste. Third, before exporting, the collector has incentives to mix additional non-reusable e-waste that is illegally provided by companies in charge of disposing e-waste in their country of origin, which are willing to pay for the disposal cost in the North. In the case where the collector does not invest in sorting, he participates in the standard market. The non-reusable e-waste can probably be detected as illegal by international monitoring systems and returned to the country of origin. The collector in this case has to pay a fine, and can participate in the alternative market that we propose by investing in the sorting process. The alternative e-waste market is a joint trade in reusable and non-reusable e-waste without a monitoring system.

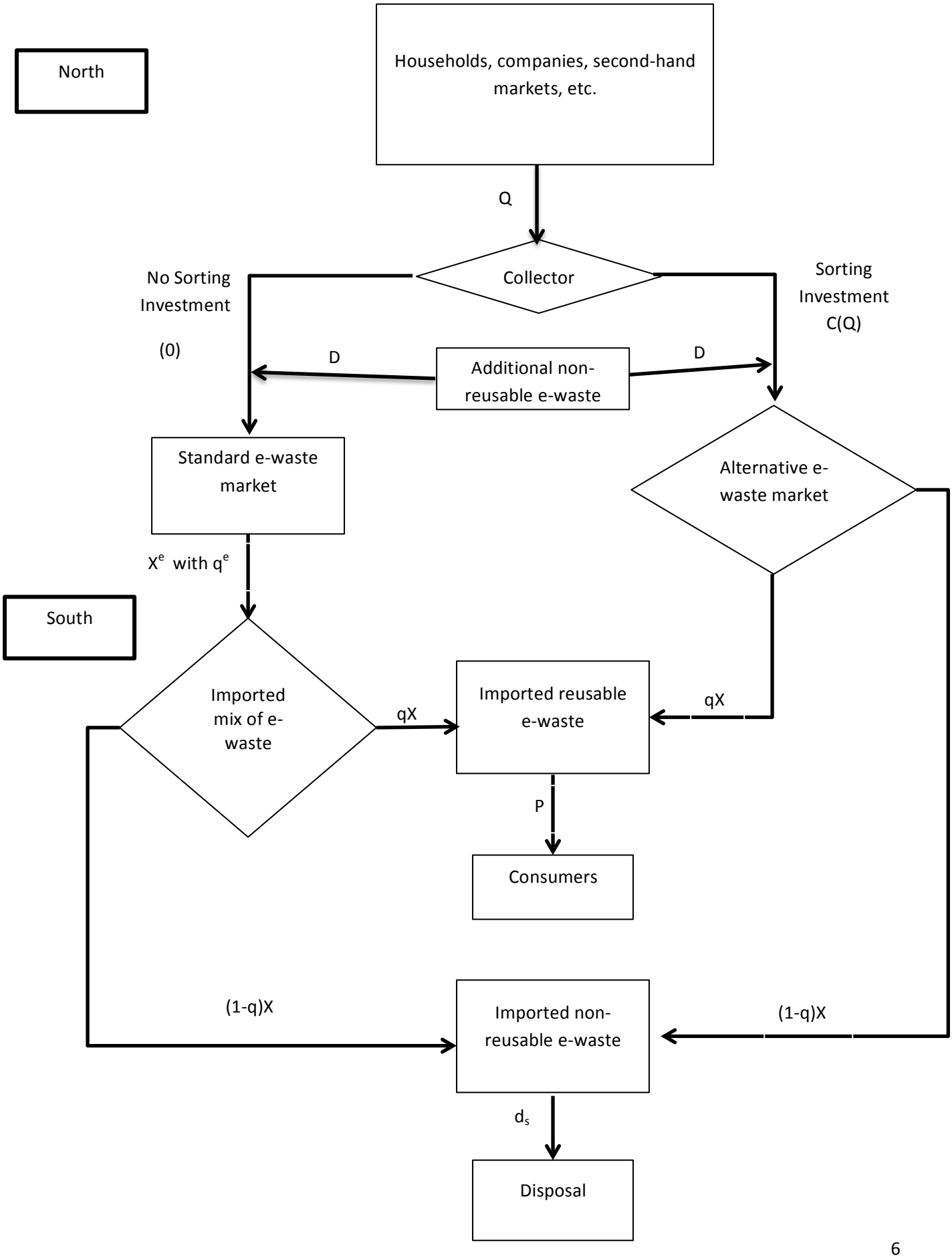
The fourth is our main finding. We show that, first, firms in the North are willing to pay to get rid of their non-reusable e-waste, while firms in the South are willing to get compensation for disposal services. This creates incentives for a trade in disposal services. Second, in the alternative market without a monitoring system, the quantity of non-valuable e-waste is lower than that in the standard market at a higher price of reusable e-waste. Thus, it can be a better option for firms in the South to adopt the alternative e-waste market, which would result in more reusable e-waste and less non-reusable e-waste, with compensation for disposal services. Third, we also show that if the standard e-waste market has to persist, only a very high marginal penalty will constrain firms in the North from mixing both types of e-waste. Another important issue is the implementation of this alternative market. Firms in developing countries need to induce firms in the North to invest in sorting, and to truthfully reveal the degree of purity. This implementation issue requires incentives theory together with information learning mechanisms that can be applied to the Principal-Agent framework. This issue is explored in Dato (2014).

The remainder of the paper is organized as follows. The model is described in Section 2. In Section 3, we analyze the case of no investment in sorting, while Section 4 is devoted to the case of investment in sorting with participation in the alternative e-waste market. We compare both cases in Section 5. The comparative statics are presented in Section 6. Finally, Section 7 concludes.

2. The model

We propose the following framework to describe the e-waste market (Fig 1). We use a simple bilateral North-South trade model and consider one representative firm in the North and one representative firm in the South. This model is close to that of Bernard (2015), who uses green design strategies to explain the increase in the illegal shipment of e-waste. She considers that the firm in the North produces the new good and manages it at the end-of-life. The firm in this case can try to increase the level of reusability of the new good by incorporating the disposal cost of the e-waste at the end-of-life, or can decide to illegally ship the e-waste. In fact, most of the firms from developed countries that are involved in e-waste markets are collectors. The exporters are not the firms that produce the new goods, hence one may consider that their strategies might be different. Also, while trading, firms in the South do not know the exact degree of purity that is defined as the part of reusable second-hand products in the import.

Figure 1: Conceptual Framework



This degree of purity determines their decision to trade and the quantity of e-waste that they are willing to trade. In the North, the level of illegal e-waste they are willing to mix with the reusable e-waste depends on the monitoring system, which is headed by national authorities through the inspection of export (or import) materials. It is then important to account for the issue of imperfect information to analyze the e-waste market.

The exporter in the North is, in general, a collector. He collects a quantity Q of e-waste in the home country through many means. He can collect e-waste from the company that has to renew their materials, from households, from the second-hand goods market in his home country, etc. In order to collect and export e-waste, it costs $C_N(\alpha,Q)$ for the firm in the North. The cost function is increasing in the quantity of e-waste Q that is collected, and the marginal cost is high when the part of reusable α is high. The cost function is convex in the level of export, and the marginal cost is increasing in the degree of purity α. After collecting e-waste, the firm can decide to invest in sorting and to separate the reusable part αQ from the non-reusable part $(1-\alpha)Q$. This investment costs C(Q). If the collector decides not to invest in sorting, he will not be able to know the degree of purity α.

Before exporting, the firm has incentives to mix additional non-reusable e-waste D, that is illegally provided by companies in charge of disposing e-waste in their home country. These companies are willing to pay for the disposal cost in the North d_N. In the case where the collector does not invest in sorting, he supplies the quantity of e-waste X in the standard market. The quantity X is the sum of the quantity of collected e-waste Q and the additional non-reusable e-waste D. Then, both types of e-waste are mixed and sold to the firm in the South at the price P^e. The non-reusable part in the export is $(1-q) = [(1-\alpha)Q + D]/X$, with q the degree of purity of export.[5] The non-reusable e-waste $(1-q)X$ has probability σ to be detected as illegal by the international monitoring system and returned to the home country. The firm in this case has to pay a fine F(q,X) which is increasing in the non-reusable part. On the contrary, we propose an alternative e-waste market that we define as a joint trade in reusable and non-reusable e-waste without a monitoring system. This alternative e-waste market holds if and only if the collector decides to invest in sorting. If he does so, he is able to separate the two types of e-waste and supply to the alternative e-waste market. The reusable part αQ is sold at a price P_1, and the non-reusable part $(1-\alpha)Q + D$ is sold at a price P_0 and he bears a sorting cost C(Q).

[5] Note that the degree of purity of the export is different from that of the collected e-waste because of the additional e-waste D.

The firm in the South under imperfect information pays P^e to the firm in the North for both types of second-hand goods. It costs Cs(q,X) for the firm in the South to import and transform—even partially—the second-hand goods. The cost function is increasing in the quantity of import and the marginal cost is low when the reusable part is high. The cost function is convex in the level of import and the marginal cost is decreasing in the degree of purity. The firm in the North gains P for reselling the reusable part in the South and bears d_s as the disposal cost that is related to the non-reusable part. However, the quantity of the non-reusable e-waste that ends up in the South depends on the international monitoring system. In fact, at the moment the firm in the North decides to mix illegal and legal second-hand goods, the firm in the North does not know for certain whether the export will be inspected or not. In the case of the alternative e-waste market, the firm will pay P_1 and P_0 for reusable and non-reusable e-waste respectively.

Benefits and costs of the bilateral North-South trade model are summarized in Table 1. We use this framework to analyze the standard and the alternative markets of e-waste. First, we focus on the standard e-waste market that corresponds to the imperfect information on the degree of purity from the importer side. In this case, the firm in the North does not invest in sorting and supplies a mixed type of e-waste. Second, we analyze the case of perfect information on the degree of purity and on the monitoring system. This corresponds to the alternative e-waste market that we propose. The collector in the North invests in sorting, and supplies in a joint market of reusable and non-reusable e-waste, while the firm in the South demands the same joint market of reusable and non-reusable e-waste. We assume a joint trade of both types of e-waste to highlight the possibility of legally trading non-reusable e-waste, instead of illegally mixing it. Due to the comparative advantage in terms of labour, it may be optimal to treat e-waste in developing countries. A transfer of appropriate technologies that could help developing countries to properly dispose of e-waste could follow this joint market.

	Firms in North (Supply)		*Firms in South (Demand)*	
	Benefit	*Cost*	*Benefit*	*Cost*
Profit/ (NSI)	$P^e\alpha Q + P^e(1-\sigma)\left[(1-\alpha)Q + D\right] + d_N D$	$C_N(\alpha, Q) + \sigma F(Q, D)$	PqX	$\left[q + (1-\sigma)(1-q)\right]P^e X +$ $C_S(q, X) + d_S(1-\sigma)(1-q)X$
Profit/ (SI)	$P_1\alpha Q + P_0\left[\ (1-\alpha)Q + D\ \right] + d_N D$	$C_N(\alpha, Q) + C(Q)$	PX_1	$P_1X_1 + P_0X_0 + C_S(X_1) + d_S X_0$

Table1: Benefits and costs of the bilateral North-South model.

3. No sorting investment

We focus on the standard market that corresponds to the case of no investment in sorting. We study the market equilibrium that is given by demand and supply of e-waste. Π_N^{NSI} and Π_S^{NSI} denote the profit without investment in sorting for the collector in the North and that of the firm in the South, respectively. Both supply and demand are obtained by maximizing the two profits. We assume that firms and collectors are price takers in this model, in that they do not influence prices. In fact, many firms in the South are interested in e-waste as second-hand goods. In this way, several collectors in developed countries also have an incentive to get rid of their e-waste in order to avoid facing costly e-waste disposal.

3.1. Supply (Collector in the North)

The Collector in the North solves the following programme:

$$\max_{Q,D} \Pi_N^{NSI} = P^e \alpha Q + P^e (1-\sigma)\left[(1-\alpha)Q + D\right] - C_N(\alpha, Q) + d_N D - \sigma F(Q,D) \quad \text{(S.1)}$$

(S.1) states that the collector optimally chooses the quantity of e-waste that he collects and the additional non-reusable e-waste that is mixed in order to get a maximum benefit net of expected costs.

The first and second order conditions with respect to Q and D are given respectively by:

$$\frac{\partial \Pi_N^{NSI}}{\partial Q} = P^e\left[\alpha + (1-\sigma)(1-\alpha)\right] - \frac{\partial C_N(\alpha,Q)}{\partial Q} - \sigma \frac{\partial F(Q,D)}{\partial Q} = 0 \quad \text{(S.2)}$$

$$\frac{\partial \Pi_N^{NSI}}{\partial D} = P^e(1-\sigma) - \sigma \frac{\partial F(Q,D)}{\partial D} + d_N = 0 \quad \text{(S.3)}$$

$$\frac{\partial^2 \Pi_N^{NSI}}{\partial Q^2} = -\frac{\partial^2 C_N(\alpha,Q)}{\partial Q^2} - \sigma \frac{\partial^2 F(Q,D)}{\partial Q^2} \prec 0 \quad \text{(S.4)}$$

$$\frac{\partial^2 \Pi_N{}^{NSI}}{\partial D^2} = -\sigma \frac{\partial^2 F(Q,D)}{\partial D^2} \prec 0 \quad \text{(S.5)}$$

(S.2) and (S.3) are arbitrage conditions. The collector is indifferent between the expected additional gain from selling one additional unit of the collected e-waste or that of the additional non-reusable e-waste, and the expected additional costs. (S.4) and (S.5) are second

order conditions that ensure that the profit is maximal at the optimum levels of the collected e-waste and of the additional non-reusable e-waste. Due to the properties of C_N and of F(Q,D), (S.4) and (S.5) ensure that the profit function is concave in Q and D. Then, the first order conditions (FOC)—with respect to Q and D—lead to an optimum level of the collected e-waste $Q^*(P^e)$, and the optimal level of additional non-reusable e-waste $D^*(P^e)$. Hence the supply can be deduced as: $S_e = S(P^e) = Q^*(P^e) + D^*(P^e)$.

3.2. Demand side (Firm in the South)

The programme that solves the firm in the South is the following:

$$\max_X \Pi_S^{NSI}(q,X) = PqX - P^e qX - (1-\sigma)(1-q)P^e X - C_S(q,X) - d_S(1-\sigma)(1-q)X \quad \text{(D.1)}$$

As the firm in the South could not identify Q and D, it faces the whole package of e-waste. (S.1) states that the firm in the South optimally chooses the quantity of the mixed e-waste that provides a maximum expected benefit net of expected costs.

The first and second order conditions with respect to X are given respectively by:

$$\frac{\partial \Pi_S^{NSI}}{\partial X} = Pq - d_S(1-\sigma)(1-q) - P^e\left[q + (1-\sigma)(1-q)\right] - \frac{\partial C_S(q,X)}{\partial X} = 0 \quad \text{(D.2)}$$

$$\frac{\partial^2 \Pi_S^{NSI}}{\partial X^2} = -\frac{\partial^2 C_S(q,X)}{\partial X^2} \prec 0 \quad \text{(D.3)}$$

(D.2) is also an arbitrage condition, and (D.3) ensures that the profit is maximal at the optimal level of X. Then, we can deduce the demand function as $D_e = X(P^e)$.

3.3. Market equilibrium

By equalizing demand and supply ($D_e = S_e$), we get the equilibrium level of trade X*. Using X*, we can calculate D* = X* - Q* and (1-q) = [(1-α)Q* + D*]/X*.

From (S.2)-(D.2) and (S.3)-(D.2), we get the following equilibrium conditions:

$$Pq - (1-q)(1-\sigma)d_S - \frac{\partial C_S(q,X)}{\partial X} = \frac{q + (1-\sigma)(1-q)}{\alpha + (1-\sigma)(1-\alpha)} * \left[\frac{\partial C_N(\alpha,Q)}{\partial Q} + \sigma \frac{\partial F(Q,D)}{\partial Q}\right] \quad \text{(E.1)}$$

and

$$(E.2) \qquad Pq-(1-q)(1-\sigma)d_S-\frac{\partial C_S(q,X)}{\partial X}=\frac{q+(1-\sigma)(1-q)}{1-\sigma}*\left[d_N+\sigma\frac{\partial F(Q,D)}{\partial D}\right].$$

Both equilibrium conditions (E.1) and (E.2) state that the resale price in the South of one unit of the e-waste trade should be equal to the marginal costs (costs in the North and in the South, penalty from inspection) related to the trade, and the disposal costs that are adjusted by the probability of inspection and the degree of purity. The equilibrium conditions incorporate all of the parameters that are related to both sides of the e-waste trade and to the inspection. The effect of each parameter on the equilibrium price is not obvious. We perform comparative statistics in Section 6 on the above equilibrium conditions to deduce their effects.

4. Sorting investment

The sorting investment allows the collector to participate in the joint trade of the non-reusable and reusable e-waste markets. As before, we study the market equilibrium, and both supply and demand are obtained by maximizing the profit of each firm. Π_N^{SI} and Π_S^{SI} are defined as the profit with investment in sorting by the collector in the North and the firm in the South, respectively.

4.1. Supply (Collector in the North)

The programme to be solved by the firm in the North is the following:

$$(S.6) \qquad \max_{Q,D}\Pi_N^{SI}=P_1\alpha Q+P_0\left[\ (1-\alpha)Q+D\ \right]-C_N(\alpha,Q)-C(Q)+d_ND$$

By denoting $X_1=\alpha Q$ and $X_0=(1-\alpha)Q+D$, the quantity of the reusable e-waste and that of the non-reusable e-waste respectively is:

$$\max_{X_0,X_1}\Pi_N^{SI}=P_1X_1+P_0X_0-C_N(\alpha,Q)-C(Q)+d_ND$$
$$Subject\quad to\quad X_1=\alpha Q\quad and\quad X_0=(1-\alpha)Q+D$$

Implicitly, the collector chooses the quantity of reusable e-waste and that of non-reusable e-waste that provides maximal profit on the joint e-waste market.

The first order conditions are given by:

(S.7) $$\frac{\partial \Pi_N^{SI}}{\partial X_1} = P_1 - \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{\partial Q}{\partial X_1} - \frac{\partial C(Q)}{\partial Q} * \frac{\partial Q}{\partial X_1} + d_N * \frac{\partial D}{\partial X_1} = 0$$

(S.8) $$\frac{\partial \Pi_N^{SI}}{\partial X_0} = P_0 - \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{\partial Q}{\partial X_0} - \frac{\partial C(Q)}{\partial Q} * \frac{\partial Q}{\partial X_0} + d_N * \frac{\partial D}{\partial X_0} = 0$$

With $\frac{\partial Q}{\partial X_1} = \frac{1}{\alpha}$; $\frac{\partial D}{\partial X_1} = 0$; $\frac{\partial Q}{\partial X_0} = \frac{1}{1-\alpha}$ and $\frac{\partial D}{\partial X_0} = 1$.

(S.7) and (S.8) become respectively:

(S.9) $$P_1 = \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{1}{\alpha} + \frac{\partial C(Q)}{\partial Q} * \frac{1}{\alpha}$$

(S.10) $$P_0 + d_N = \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{1}{1-\alpha} + \frac{\partial C(Q)}{\partial Q} * \frac{1}{1-\alpha} = 0$$

(S.9) and (S.10) are arbitrage conditions with respect to the quantity of the reusable e-waste and to the non-reusable e-waste respectively. With Q*, we deduce $S_1 = S_1(P_1)$ and $S_0 = S_0(P_0)$, being the supply in the reusable e-waste and in the non-reusable e-waste, respectively.

We claim on the supply side the following:

Proposition 1: *In the case of sorting investment, the price of non-reusable e-waste should be 'negative'; the firm in the North should pay to get rid of its non-reusable e-waste.*

- ***Proof of Proposition 1***:

(S.9) is the well-known result of perfect competition. The price of the reusable e-waste is equal to its marginal cost. We can easily deduce the implicit supply function of the reusable e-waste as $S_1 = S_1(P_1)$. This is indeed a supply function because:

$$\frac{\partial P_1}{\partial X_1} = \frac{1}{\alpha^2}\left[\frac{\partial^2 C_N(\alpha,Q)}{\partial Q^2} + \frac{\partial^2 C(\mathrm{Q})}{\partial Q^2} \right] \succ 0.$$

Note that the price of reusable e-waste that is paid by firms in the South P_1 is higher than the one in the North. If this condition does not hold, then firms in the North will prefer to sell in the home country and then the reusable e-waste market will break down. In general, the price of the reusable e-waste is low in the North due to the fact that consumers in the North have less interest in obsolete equipment.

(S.10) states that the marginal price of the non-reusable e-waste should be equal to the marginal cost, net of the payment received from additional non-reusable e-waste (d_N). Likewise, we can deduce the implicit supply function of the non-reusable e-waste as S_0 $=S_0(P_0)$ and $\frac{\partial P_0}{\partial X_0} = \frac{1}{1-\alpha} * \left[\frac{\partial^2 C_N(\alpha,Q)}{\partial Q^2} + \frac{\partial^2 C(Q)}{\partial Q^2} \right] \succ 0$. First, we assume that it is cheaper to get non-reusable e-waste than reusable e-waste because the former has less economic value. It means that the Right Hand Side (RHS) of equation (S.10) is very small. As environmental regulations are stringent in the North, d_N is assumed to be high. Then, to have the equality in equation (S.10), the Left Hand Side (LHS) must also be small, and hence P_0 must be negative. In this case, firms in the North are willing to pay firms in the South in order to dispose of the non-reusable e-waste. Note that their willingness to pay must not exceed the disposal cost they have to pay in their home country. Otherwise, it is better to dispose of it locally, and this will break down the non-reusable e-waste market that is a part of the alternative e-waste market. Likewise, this is not the general case.■

4.2. Demand side (Firm in the South)

(D.4) $$\max_{X_0, X_1} \Pi_S^{SI} = PX_1 - P_1X_1 - P_0X_0 - C_S(X_1) - d_SX_0$$

The first order conditions with respect to X_0 and X_1 are given respectively by:

(D.5) $$\frac{\partial \Pi_S^{SI}}{\partial X_0} = -P_0 - d_S \begin{cases} = 0 \text{ if } P_0 \prec 0 \\ \prec 0 \text{ otherwise} \end{cases}$$

(D.6) $$\frac{\partial \Pi_S^{SI}}{\partial X_1} = P - P_1 - \frac{\partial C_S(X_1)}{\partial X_1} = 0$$

We claim on the demand side, the following:

Proposition 2: *In the case of sorting investment, the price of the non-reusable e-waste should be 'negative'; the firm in the South is willing to get compensation for disposal services.*

- ***Proof of Proposition 2***:

From (D.6) we get that:

(D.7) $$P = \frac{\partial C_S(1, X_1)}{\partial X_1} + P_1$$

This result is a perfect competition condition stating that the price must be equal to the marginal cost. The marginal cost has two components: the price of one unit of reusable e-waste that is paid to the firm in the North and the marginal cost related to the repairing efforts. For a given price P in the South, we can deduce a demand function for the reusable e-waste as $D^1 = D^1(P^1)$. We can check that D^1 is indeed a demand function. The derivative of (D.4) with respect to X is given by $\frac{\partial P_1}{\partial X_1} = -\frac{\partial^2 C_S(1, X_1)}{\partial X_1^2} < 0$. The demand of reusable e-waste exists as long as the resale price P of the reusable e-waste in the South is higher than the price P_1 that is paid to the firm in the North.

(D.5) leads to $-P_0 - d_S \begin{cases} = 0 \text{ if } P_0 \prec 0 \\ \prec 0 \text{ otherwise} \end{cases}$.

In order to have an optimum demand of the non-reusable e-waste (X_0), the condition (D.5) should be equal to zero. This means that the price of the non-reusable e-waste P_0 should be negative. Hence, the necessary condition for firms in the South to trade in the presence of non-reusable e-waste is to be compensated. We can also deduce an implicit demand function $D^0 = D^0(P_0)$. The compensating price P_0 should at least be equal to the disposal cost in the South in order for firms there to trade. ■

4.3. Market equilibrium

By equalizing demand and supply ($D_0=S_0$ and $D_1=S_1$), we get in equilibrium the levels of trade X_0^* and X_1^*.

From (S.9)-(D.6) and (S.10)-(D.5), we get the following equilibrium conditions:

(E.3) $$P = \frac{1}{\alpha} * \left[\frac{\partial C(\mathrm{Q})}{\partial Q} + \frac{\partial C_N(\alpha, \mathrm{Q})}{\partial Q} \right] + \frac{\partial C_S(1, X_1)}{\partial X_1}$$

and

(E.4) $$d_N - d_S = \frac{1}{1-\alpha} * \left[\frac{\partial C(\mathrm{Q})}{\partial Q} + \frac{\partial C_N(\alpha, \mathrm{Q})}{\partial Q} \right].$$

(E.3) states that the resale price of the reusable e-waste in the South should be equal to its marginal cost. The marginal cost is related to both firms in the North and in the South and to the sorting investment. From (E.4), we can deduce that at the equilibrium, the difference in environmental regulations (disposal cost) positively depends on the sum of the marginal sorting cost and the marginal cost of collecting in the North. The marginal sorting cost and the marginal cost of collecting in the North are assumed to be positive so that the disposal cost in the North is always higher than that in the South.

5. No sorting investment vs sorting investment

In this section, we compare results between the standard e-waste market and the alternative e-waste market at the levels of supply and demand.

5.1. Supply side

In the supply side, we claim the following:

Proposition 3: *Imperfect information on the degree of purity without monitoring leads to a price of e-waste that lies between P_0 and P_1.*

Corollary 1*: Imperfect information on the degree of purity without monitoring leads to less supply of the reusable e-waste and more supply of the non-reusable e-waste.*

Proposition 4: *In the case of imperfect information on the degree of purity with perfect monitoring, only high marginal penalties can make the standard e-waste market less attractive.*

- ***Proof of Proposition 3***:

Using (S.2) and (S.3), we can derive the implicit supply function $S^e=X(P^e)$. It can be shown that $S^e=X(P^e)$ is indeed a supply function using the following condition:

$$\frac{\partial Pe}{\partial X}=\frac{\partial Pe}{\partial Q}+\frac{\partial Pe}{\partial D} \text{ with X= Q+D}$$

$$=\frac{\sigma}{1-\sigma}*\frac{\partial^2 F(\mathrm{Q},\mathrm{D})}{\partial D^2}+\frac{1}{\left[\alpha+(1-\sigma)(1-\alpha)\right]}*\left[\frac{\partial^2 C_N(\alpha,Q)}{\partial Q^2}+\sigma\frac{\partial^2 F(\mathrm{Q},\mathrm{D})}{\partial Q^2}\right]\succ 0$$

In order to compare P_e, P_1 and P_0, we will consider two cases ($\sigma=0$ in the case of no monitoring, and $\sigma=1$ in the case of full monitoring). By assumption, the price that holds in the standard market is positive for the market to exist. Proposition 1 shows that the price of the non-reusable e-waste should be negative. This allows us to only compare the price in the standard market to the price of reusable e-waste in the alternative market.

* ***No monitoring ($\sigma=0$)***

Using (S.2) and replacing $\sigma=0$, we get the following equations:

$$P^e = \frac{\partial C_N(\alpha,Q)}{\partial Q} \text{ and } P_1 = \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{1}{\alpha} + \frac{\partial C(Q)}{\partial Q} * \frac{1}{\alpha}.$$

As α is lower than one, we can conclude that without the monitoring system, the price of the reusable e-waste in the alternative market is higher than the price in the standard market, because firms in the South will anticipate this and mix both types of e-waste. ■

- ***Proof of Corollary 1***

By using the properties of supply function, we can easily deduce that without monitoring, the supply in the reusable e-waste in the standard market is less than that of the alternative market. In fact, the price of the reusable e-waste in the alternative market is more attractive for the firm in the North. In the same way, the price of the non-reusable e-waste is less attractive in the alternative market and induces less supply of the non-reusable e-waste. ■

- ***Proof of Proposition 4***:

The full monitoring corresponds to the case of $\sigma=1$.

* ***Full monitoring $\sigma=1$***

Likewise, replacing $\sigma=1$ into (S.2) leads to:

$$P^e = \frac{1}{\alpha} * \frac{\partial C_N(\alpha,Q)}{\partial Q} + \frac{1}{\alpha} * \frac{\partial F}{\partial Q} \text{ and } P_1 = \frac{\partial C_N(\alpha,Q)}{\partial Q} * \frac{1}{\alpha} + \frac{\partial C(Q)}{\partial Q} * \frac{1}{\alpha}.$$

We can deduce the difference:

$$P^e - P_1 = \frac{1}{\alpha} * \left(\frac{\partial F}{\partial Q} - \frac{\partial C(Q)}{\partial Q}\right).$$

Depending on the difference between the marginal penalty and the marginal sorting cost, the price of the reusable e-waste in the alternative market can be higher or less than the price of e-waste in the standard market. If the marginal penalty is high, then firms in the North will have incentives to invest in sorting and to avoid mixing both types. As the alternative e-waste market will be full of suppliers, the consequence is that the price of reusable e-waste in the alternative market lowers. Therefore, the price of e-waste in the standard market increases because of the full monitoring and the high penalty. However, it makes the standard market less attractive. On contrary, if the marginal penalty is low, the collectors will not invest in sorting and will mix both types which will lower the price of e-waste in the standard market and make it more attractive. We conclude that even with a perfect monitoring system, only a high marginal penalty can induce firms in the North to avoid mixing both types of e-waste. ■

5.2. Demand side

We claim the following:

Proposition 5: *Under imperfect information, the price of e-waste in the standard e-waste market lies between P_0 and P_1.*

Corollary 2: *Under imperfect information on the degree of purity, demand for the non-reusable e-waste is less and demand for the reusable e-waste is high in the standard e-waste market.*

- ***Proof of Proposition 5***:

As before, we can compare the price of e-waste in the standard market to the price of reusable e-waste in the alternative market.

By using (D.2) and (D.6), we have:

$$P^e - P_1 = -\frac{(P+d_S)(1-\sigma)(1-q)+\sigma(1-q)\dfrac{\partial C_S}{\partial X}}{\left[q+(1-\sigma)(1-q)\right]} \prec 0 \text{ with } q \leq 1;\ \sigma \leq 1$$

We conclude that whatever the condition is of the monitoring system, the firm in the South has a high willingness to pay for reusable e-waste in the alternative market than e-waste in the standard market. As the price of the non-reusable e-waste is negative (Proposition 2), we deduce that the price of e-waste in the standard e-waste market lies between P_0 and P_1. ■

- ***Proof of Corollary 2***

As the firm in the South has a high willingness to pay for the reusable e-waste in the alternative market than e-waste in the standard market, it will prefer more reusable e-waste. Hence, demand in the non-reusable e-waste must be less, and demand in reusable e-waste must be high. ■

6. Comparative statics on market equilibrium conditions

In this section, we identify the effect of disposal costs, the difference in environmental regulations, the resale price of e-waste in the South, and the effect of the monitoring system on the equilibrium quantity and price in the alternative and standard e-waste markets.

Proposition 6:

We claim the following:

Table 2: Comparative statics[6]

	dX_1	dX_0	dX	dP_1	dP_0	dP_e
dP	+	0	+	+	0	+
dds	0	-	-	0	-	-
dd_N	0	+	+	0	-	-
$d(d_N-d_S)$	0	+	+	0	+/-	+/-
$d\sigma$	0	0	+/-	0	0	+

See the proof of Proposition 6 in Appendix I.

In the alternative e-waste market and according to Proposition 6, the level of trade in valuable e-waste (reusable) depends only on the resale price in the South. In fact, the main purpose of importing e-waste in developing countries is for re-use. Then, as long as the resale price is high in the South, the level of trade in reusable e-waste will increase at a high price. Disposal costs in the North and those in the South do not have any impact on either the price

[6] dY is the differential of Y.

or the level of trade in reusable e-waste. The fact that disposal costs essentially target non-reusable e-waste may explain this. In fact, it is quite the reverse, as disposal costs have effects (positive or negative) on non-reusable e-waste. A stringent environmental regulation in the South will result in less trade in non-reusable e-waste, while a stringent environmental policy in the North leads to more trade in the non-reusable e-waste. This fact can explain the existence of 'Pollution Havens Hypothesis'. Firms in the North may decide to escape the high disposal costs from their home country and ship the non-reusable e-waste to the South at a lower disposal cost. However, in the case where the South increases the disposal cost, shipping is no longer profitable for firms in the North. Therefore, the level of trade in the non-reusable e-waste reduces. Additionally, the difference between environmental regulation in the North and the South has a positive effect on the trade of non-reusable e-waste. As long as the disposal cost is lower in South, it will be attractive for firms in the North to ship the non-reusable e-waste. However, the difference in regulation has an undetermined qualitative effect (positive or negative) on the price of the non-reusable e-waste. Unsurprisingly, the difference affects neither the level of trade in the reusable e-waste nor its price.

In the standard market, parameters have joint effects[7] on the level of trade relative to the alternative e-waste market. The monitoring has a positive impact on the price of the e-waste, and an undetermined effect on the level of trade in e-waste. This is surprising, because the monitoring is targeted to reduce the trade in e-waste. But, as the level of trade has two components (reusable and non-reusable e-waste), a high price will induce less non-reusable and more reusable e-waste. Hence, the level of trade will decrease or increase, depending on the difference between the decreasing rate in non-reusable e-waste and the increasing rate in reusable e-waste.

7. Conclusion

In this paper, we use a simple bilateral North-South trade model and show that there exists an alternative better than the standard e-waste market for developing countries. We propose an economic analysis of a standard e-waste market that we compare with an alternative market of a joint trade in reusable and non-reusable e-waste. We then show that firms in the North are willing to pay to get rid of their non-reusable e-waste while firms in the South are willing to get compensation for disposal services. Moreover, in the alternative market without a monitoring system, the quantity of non-valuable e-waste is lower than that of the standard

[7] It is a combination of effects on both non-reusable and reusable e-waste.

market at a higher price of reusable e-waste. Then, it can be a better option for firms in the South to adopt the alternative e-waste market, which results in more reusable e-waste and less non-reusable e-waste with compensation for disposal services. We also show that only a very high marginal penalty can constrain firms in the North from mixing both types of e-waste. Thus, it should be better to allow a legal e-waste trade together with an enforcement of an appropriate technology transfer for sustainable e-waste recycling technologies in developing countries, such as for pyrometallurgical methods and de-gassing CFC/HCFC.

Another important issue is the implementation of this alternative market. Firms in developing countries need to induce firms in the North to invest in sorting and to truthfully reveal the degree of purity. This implementation issue requires incentives theory together with information gathering theory applied to the Principal-Agent framework, which is explored in Dato (2014). For the sake of simplicity, we neglect in this model factors such as the existence of new products in the South, importing firms for the purpose of recycling, market power to firms in the North, production process in North, etc. However, our model is still valid. In fact, in the South, the majority of new products do not last, and even if the price is low, consumers may doubt the quality and prefer second-hand products. The existence of new products may not alter the main results in this paper. The model is also still valid in the case where the e-waste is imported for the purpose of recycling, but then the behaviour of firms in the South may change. This model needs to be empirically tested, and can be extended to empirically estimate the elasticity of e-waste demand and supply by using real data from the e-waste market. It could also help to identify the quantitative effects of taxes through the price, the monitoring system, and disposal costs on the demand, supply and the trade in e-waste. Experimental methods can also be useful to understand the strategic behaviour of collectors in the North and of firms in the South.

8. Selected References

1. Baggs, J., (2009) 'International trade in hazardous waste.' Review of International Economics 17, 1-16.
2. Bernard, S., (2015) 'North–south trade in reusable goods: Green design meets illegal shipments of waste.' *Journal of Environmental Economics and Management* 69: 22-35.
3. Bond, E. W. (1983) 'Trade in used equipment with heterogeneous firms.' The Journal of Political Economy 91, 688.705
4. Clerides, S. (2008) 'Gains from trade in used goods: Evidence from automobiles.' Journal of International Economics 76, 322.336

5. Copeland, B. R., (1991) 'International trade in waste products in the presence of illegal disposal.' Journal of Environmental Economics and Management 20, 143-162.

6. Dato, P. (2014) 'Inducing sorting investment and implementation of an alternative e-waste market under imperfect information'. FAERE Working Paper, 2014.13.

7. Grubel, H. G. (1980) 'International trade in used cars and problems of economic development' World Development, 8(10), 781-788.

8. Harford, J. D., (1978) 'Firm behavior under imperfectly enforceable pollution standards and taxes.' Journal of Environmental Economics and Management 5, 26-43.

9. Higashida K. (2012) 'Trade in Secondhand Goods, Monitoring of Illegal Trade, and Import Quotas on Legal Trade.' Discussion Paper Series 90, School of Economics, Kwansei Gakuin University.

10. Higashida, K. and Managi, S., (2008) 'The determinants of trade in recyclable wastes, the structure of recycling sector and the effects of trade restrictions', mimeo.

11. Johnstone, N. (1998). The implications of the Basel Convention for developing countries: the case of trade in non-ferrous metal-bearing waste. Resources, conservation and recycling, 23(1), 1-28.'

12. Kellenberg, D. (2010) 'Consumer waste, backhauling, and pollution havens.' Journal of Applied Economics 13, 283-304.

13. Kinnaman, T., and H. Yokoo (2011) 'The environmental consequences of global reuse.' American Economic Review 101, 71-76.

14. Kojima M., A. Yoshida, Sasaki S., and C. Sungwoo (2011) 'Trans-boundary Movement of Hazardous Waste: Lessons from uncovered cases.' Kojima and Michida ed., Economic Integration and Recycling in Asia: An Interim Report, Chosakenkyu Hokokusho, Institute of Developing Economies.

15. Krueger J. (1998) 'Prior Informed Consent and the Basel Convention: The Hazards of What Isn't Known' The Journal of Environment Development 7; 115.

16. Kummer K. (1995) 'International Management of Hazardous Wastes.' Clarendon Press Oxford.

17. Kummer, K. (1999). International Management of Hazardous Wastes: The Basel Convention and Related Legal Rules. Oxford University Press on Demand.

18. Lepawsky, J. and Mcnabb, C. (2009) 'Mapping international flows of electronic waste.' The Canadian Geographer.

19. Lipman Z. (2011) 'Trade in Hazardous Waste: Environmental Justice Versus Economic Growth' Working papers, Environmental Justice and Legal Process, Macquarie University, Australia.

20. Marbury H. R. (1995) 'Global Environmental Racism' Journal of Transnational Law, 251-293.

21. Sen, A. K. (1962) 'On the usefulness of used machines.' Review of economic .and statistics 44 : 346-348.

22. Smith, M. A. M. (1976) 'International theory in Vintage Models' review of economic studies 43: 99-113.

23. StEP-UN (2013), E-waste world map, online country level data.

24. UNEP (2005) 'E-waste, the hidden side of IT equipment's manufacturing and use' report, Environmental Alert Bulletin.

9. Appendix I

Proof of proposition 6:

The proof is divided into three cases. The first two cases are related to the alternative e-waste market while the last case concerns the standard e-waste market.

Case 1: *The reusable e-waste in the alternative e-waste market.*

We use the supply $X_1 = S_1(P_1)$ and the demand $X_1 = D_1(P_1, P)$ of the reusable e-waste to get the following system.

$$\begin{cases} X_1 - S_1(P_1) = 0 \\ X_1 - D_1(P_1, \mathrm{P}) = 0 \end{cases}$$

- *The effect of the disposal costs and the degree of monitoring.*

$$\frac{dX_1}{dd_N} = \frac{dX_1}{dd_S} = \frac{dX_1}{dd_N - dd_S} = \frac{dX_1}{d\sigma} = 0,$$ as X_1 is not a function of d_N, d_S and σ.

Likewise,

$$\frac{dP_1}{dd_N} = \frac{dP_1}{dd_S} = \frac{dP_1}{dd_N - dd_S} = \frac{dP_1}{d\sigma} = 0,$$ as P_1 is not a function of d_N, d_S and σ.

- *The effect of the resale price: (dX_1/dP and dP_1/dP)*

By taking the derivative of the system with respect to P, we get:

$$\begin{cases} \frac{dX_1}{dP} - \frac{\partial S_1}{\partial P_1} * \frac{dP_1}{dP} = 0 \\ \frac{dX_1}{dP} - \frac{\partial D_1}{\partial P_1} * \frac{dP_1}{dP} - \frac{dD_1}{dP} = 0 \end{cases}$$

and in matrix term:

$$\begin{pmatrix} 1 & -\frac{\partial S_1}{\partial P_1} \\ 1 & -\frac{\partial D_1}{\partial P_1} \end{pmatrix} * \begin{pmatrix} \frac{dX_1}{dP} \\ \frac{dP_1}{dP} \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{dD_1}{dP} \end{pmatrix}$$

We can then calculate the Jacobian determinant as:

$$\left|J\right| = \begin{vmatrix} 1 & -\dfrac{\partial S_1}{\partial P_1} \\ 1 & -\dfrac{\partial D_1}{\partial P_1} \end{vmatrix} = -\frac{\partial D_1}{\partial P_1} + \frac{\partial S_1}{\partial P_1} \succ 0$$

From the Jacobian determinant, we can deduce:

$$\frac{dX_1}{dP} = \frac{\begin{vmatrix} 0 & -\dfrac{\partial S_1}{\partial P_1} \\ \dfrac{dD_1}{dP} & -\dfrac{\partial D_1}{\partial P_1} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{\partial S_1}{\partial P_1} * \dfrac{dD_1}{dP}}{\left|J\right|} \succ 0 \text{ with } \frac{dD_1}{dP} \succ 0 \text{ and } \frac{\partial S_1}{\partial P_1} \succ 0$$

and

$$\frac{dP_1}{dP} = \frac{\begin{vmatrix} 1 & 0 \\ 1 & \dfrac{\partial D_1}{\partial P} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{dD_1}{dP}}{\left|J\right|} \succ 0$$

Case 2**:** *The non-reusable e-waste in the alternative e-waste market*

We also use the supply $X_0 = S_0(P_0)$ and the demand $X_0 = D_0(P_0, P)$ of the non-reusable e-waste to get the following system.

$$\begin{cases} X_0 - S_0(P_0, \mathrm{d}_N) = 0 \\ X_0 - D_0(P_0, \mathrm{d}_S) = 0 \end{cases}$$

- *The effect of the degree of monitoring and the resale price.*

As neither the quantity of the non-reusable e-waste nor its price is a function of P and σ, we get no effect as follows.

$$\frac{dX_0}{dP} = \frac{dX_0}{d\sigma} = 0 \quad \text{and} \quad \frac{dP_0}{dP} = \frac{dP_0}{d\sigma} = 0 \quad .$$

- *The effect of the disposal cost d_S in the South.*

Taking the derivative of the system with respect to d_S, we get:

$$\begin{cases} \dfrac{dX_0}{dd_S} - \dfrac{\partial S_0}{\partial P_0} * \dfrac{dP_0}{dd_S} = 0 \\ \dfrac{dX_0}{dd_S} - \dfrac{\partial D_0}{\partial P_0} * \dfrac{dP_0}{dd_S} - \dfrac{dD_0}{dd_S} = 0 \end{cases}$$

In matrix form we have:

$$\begin{pmatrix} 1 & -\dfrac{\partial S_0}{\partial P_0} \\ 1 & -\dfrac{\partial D_0}{\partial P_0} \end{pmatrix} * \begin{pmatrix} \dfrac{dX_0}{dd_S} \\ \dfrac{dP_0}{dd_S} \end{pmatrix} = \begin{pmatrix} 0 \\ \dfrac{dD_0}{dd_S} \end{pmatrix}$$

and $\left|J\right| = \begin{vmatrix} 1 & -\dfrac{\partial S_0}{\partial P_0} \\ 1 & -\dfrac{\partial D_0}{\partial P_0} \end{vmatrix} = -\dfrac{\partial D_0}{\partial P_0} + \dfrac{\partial S_0}{\partial P_0} \succ 0$

Then we deduce:

$$\frac{dX_0}{dd_S} = \frac{\begin{vmatrix} 0 & -\dfrac{\partial S_0}{\partial P_0} \\ \dfrac{dD_0}{dd_S} & -\dfrac{\partial D_0}{\partial P_0} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{\partial S_0}{\partial P_0} * \dfrac{dD_0}{dd_S}}{\left|J\right|} \prec 0 \text{ with } \frac{dD_0}{dd_S} \prec 0 \text{ and } \frac{\partial S_0}{\partial P_0} \succ 0$$

and

$$\frac{dP_0}{dd_S} = \frac{\begin{vmatrix} 1 & 0 \\ 1 & \dfrac{dD_0}{dd_S} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{dD_0}{dd_S}}{\left|J\right|} \prec 0$$

- *The effect of the disposal cost d_N in the North.*

The derivative of the system with respect to d_N gives:

$$\begin{cases} \dfrac{dX_0}{dd_N} - \dfrac{\partial S_0}{\partial P_0} * \dfrac{dP_0}{dd_N} - \dfrac{dS_0}{dd_N} = 0 \\ \dfrac{dX_0}{dd_N} - \dfrac{\partial D_0}{\partial P_0} * \dfrac{dP_0}{dd_N} = 0 \end{cases}$$

In matrix form we have:

$$\begin{pmatrix} 1 & -\frac{\partial S_0}{\partial P_0} \\ 1 & -\frac{\partial D_0}{\partial P_0} \end{pmatrix} * \begin{pmatrix} \frac{dX_0}{dd_N} \\ \frac{dP_0}{dd_N} \end{pmatrix} = \begin{pmatrix} \frac{dS_0}{dd_N} \\ 0 \end{pmatrix} \text{ and } |J| = \begin{vmatrix} 1 & -\frac{\partial S_0}{\partial P_0} \\ 1 & -\frac{\partial D_0}{\partial P_0} \end{vmatrix} = -\frac{\partial D_0}{\partial P_0} + \frac{\partial S_0}{\partial P_0} \succ 0$$

We deduce that:

$$\frac{dX_0}{dd_N} = \frac{\begin{vmatrix} \frac{dS_0}{dd_N} & -\frac{\partial S_0}{\partial P_0} \\ 0 & -\frac{\partial D_0}{\partial P_0} \end{vmatrix}}{|J|} = \frac{-\frac{dS_0}{dd_N} * \frac{\partial D_0}{\partial P_0}}{|J|} \succ 0 \text{ with } \frac{dS_0}{dd_N} \succ 0 \text{ and } \frac{\partial D_0}{\partial P_0} \prec 0$$

and

$$\frac{dP_0}{dd_N} = \frac{\begin{vmatrix} 1 & \frac{dS_0}{dd_N} \\ 1 & 0 \end{vmatrix}}{|J|} = \frac{-\frac{dS_0}{dd_N}}{|J|} \prec 0$$

- *The effect of the difference in the disposal costs between the North and the South (*d_N-d_S=b)

The effect on the quantity of the non-reusable e-waste is calculated as follows.

$$\frac{dX_0}{db} = \frac{dX_0}{dd_S} * \frac{\partial d_S}{\partial b} + \frac{dX_0}{dd_N} * \frac{\partial d_N}{\partial b} = -\frac{dX_0}{dd_S} + \frac{dX_0}{dd_N}$$

$$= -\frac{\frac{\partial S_0}{\partial P_0} * \frac{dD_0}{dd_S}}{|J|} - \frac{\frac{dS_0}{dd_N} * \frac{\partial D_0}{\partial P_0}}{|J|} \succ 0$$

We also determine the effect on the price of the non-reusable e-waste.

$$\frac{dP_0}{db} = \frac{dP_0}{dd_S} * \frac{\partial d_S}{\partial b} + \frac{dP_0}{dd_N} * \frac{\partial d_N}{\partial b} = -\frac{dP_0}{dd_S} + \frac{dP_0}{dd_N} \begin{cases} \succ 0 \text{ if } \frac{dP_0}{dd_N} \succ \frac{dP_0}{dd_S} \\ \prec 0 \text{ otherwise} \end{cases}$$

Case 3**:** *The standard e-waste market*

In the case of a standard e-waste market, we consider the supply $X= S_e(P_e,dN,\sigma)$ and the demand $X=D_e(P_e,P, d_S,\sigma)$ of e-waste that leads to the following system.

$$\begin{cases} X_e - S_e(P_e,\mathrm{d}_N,\sigma) = 0 \\ X_e - D_e(P_e,\mathrm{P},\sigma,\mathrm{d}_S) = 0 \end{cases}$$

- *The effect of the resale price P*

$$\begin{cases} \dfrac{dX_e}{dP} - \dfrac{\partial S_e}{\partial P_e} * \dfrac{dP_e}{dP} = 0 \\ \dfrac{dX_e}{dP} - \dfrac{\partial D_e}{\partial P_e} * \dfrac{dP_e}{dP} - \dfrac{dD_e}{dP} = 0 \end{cases}$$

In matrix form:

$$\begin{pmatrix} 1 & -\dfrac{\partial S_e}{\partial P_e} \\ 1 & -\dfrac{\partial D_e}{\partial P_e} \end{pmatrix} * \begin{pmatrix} \dfrac{dX_e}{dP} \\ \dfrac{dP_e}{dP} \end{pmatrix} = \begin{pmatrix} 0 \\ \dfrac{dD_e}{dP} \end{pmatrix} \text{ and } \left|J\right| = \begin{vmatrix} 1 & -\dfrac{\partial S_e}{\partial P_e} \\ 1 & -\dfrac{\partial D_e}{\partial P_e} \end{vmatrix} = -\frac{\partial D_e}{\partial P_e} + \frac{\partial S_e}{\partial P_e} \succ 0$$

We deduce :

$$\frac{dX_e}{dP} = \frac{\begin{vmatrix} 0 & -\dfrac{\partial S_e}{\partial P_e} \\ \dfrac{dD_e}{dP} & -\dfrac{\partial D_e}{\partial P_e} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{\partial S_e}{\partial P_e} * \dfrac{dD_e}{dP}}{\left|J\right|} \succ 0 \text{ with } \frac{dD_e}{dP} \succ 0 \text{ and } \frac{\partial S_e}{\partial P_e} \succ 0$$

and

$$\frac{dP_e}{dP} = \frac{\begin{vmatrix} 1 & 0 \\ 1 & \dfrac{\partial D_e}{\partial P} \end{vmatrix}}{\left|J\right|} = \frac{\dfrac{dD_e}{dP}}{\left|J\right|} \succ 0$$

- *The effect of the disposal cost* d_N *in the North.*

$$\begin{cases} \dfrac{dX_e}{dd_N} - \dfrac{\partial S_e}{\partial P_e} * \dfrac{dP_e}{dd_N} - \dfrac{dS_e}{dd_N} = 0 \\ \dfrac{dX_e}{dd_N} - \dfrac{\partial D_e}{\partial P_e} * \dfrac{dP_e}{dd_N} = 0 \end{cases}$$

In matrix form :

$$\begin{pmatrix} 1 & -\dfrac{\partial S_e}{\partial P_e} \\ 1 & -\dfrac{\partial D_e}{\partial P_e} \end{pmatrix} * \begin{pmatrix} \dfrac{dX_e}{dd_N} \\ \dfrac{dP_e}{dd_N} \end{pmatrix} = \begin{pmatrix} \dfrac{dS_e}{dd_N} \\ 0 \end{pmatrix} \text{ and } \left|J\right| = \begin{vmatrix} 1 & -\dfrac{\partial S_e}{\partial P_e} \\ 1 & -\dfrac{\partial D_e}{\partial P_e} \end{vmatrix} = -\frac{\partial D_e}{\partial P_e} + \frac{\partial S_e}{\partial P_e} \succ 0$$

We determine:

$$\frac{dX_e}{dd_N} = \frac{\begin{vmatrix} \dfrac{dS_e}{dd_N} & -\dfrac{\partial S_e}{\partial P_e} \\ 0 & -\dfrac{\partial D_e}{\partial P_e} \end{vmatrix}}{\left|J\right|} = \frac{-\dfrac{dS_e}{dd_N} * \dfrac{\partial D_e}{\partial P_e}}{\left|J\right|} \succ 0 \text{ with } \frac{dS_e}{dd_N} \succ 0 \text{ and } \frac{\partial D_e}{\partial P_e} \prec 0$$

and

$$\frac{dP_e}{dd_N} = \frac{\begin{vmatrix} 1 & \dfrac{dS_e}{dd_N} \\ 1 & 0 \end{vmatrix}}{\left|J\right|} = \frac{-\dfrac{dS_e}{dd_N}}{\left|J\right|} \prec 0$$

- *The effect of the disposal cost* d_S *in the South.*

$$\begin{cases} \dfrac{dX_e}{dd_S} - \dfrac{\partial S_e}{\partial P_e} * \dfrac{dP_e}{dd_S} = 0 \\ \dfrac{dX_e}{dd_S} - \dfrac{\partial D_e}{\partial P_e} * \dfrac{dP_e}{dd_S} - \dfrac{dD_e}{dd_S} = 0 \end{cases}$$

In the matrix form :

$$\begin{pmatrix} 1 & -\frac{\partial S_e}{\partial P_e} \\ 1 & -\frac{\partial D_e}{\partial P_e} \end{pmatrix} * \begin{pmatrix} \frac{dX_e}{dd_S} \\ \frac{dP_e}{dd_S} \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{dD_e}{dd_S} \end{pmatrix}$$

and the Jaconbian determinant is : $$\left|J\right| = \begin{vmatrix} 1 & -\frac{\partial S_e}{\partial P_e} \\ 1 & -\frac{\partial D_e}{\partial P_e} \end{vmatrix} = -\frac{\partial D_e}{\partial P_e} + \frac{\partial S_e}{\partial P_e} \succ 0$$

We deduce that :

$$\frac{dX_e}{dd_S} = \frac{\begin{vmatrix} 0 & -\frac{\partial S_e}{\partial P_e} \\ \frac{dD_e}{dd_S} & -\frac{\partial D_e}{\partial P_e} \end{vmatrix}}{\left|J\right|} = \frac{\frac{\partial S_e}{\partial P_e} * \frac{dD_e}{dd_S}}{\left|J\right|} \prec 0 \text{ with } \frac{dD_e}{dd_S} \prec 0 \text{ and } \frac{\partial S_e}{\partial P_e} \succ 0$$

and

$$\frac{dP_e}{dd_S} = \frac{\begin{vmatrix} 1 & 0 \\ 1 & \frac{dD_e}{dd_S} \end{vmatrix}}{\left|J\right|} = \frac{\frac{dD_e}{dd_S}}{\left|J\right|} \prec 0$$

- *The effect of the difference in the disposal costs between the North and the South (*d_N-d_S=b)

We determine the effect on the quantity of e-waste as:

$$\frac{dX_e}{db} = \frac{dX_e}{dd_S} * \frac{\partial d_S}{\partial b} + \frac{dX_e}{dd_N} * \frac{\partial d_N}{\partial b}$$

$$= -\frac{dX_e}{dd_S} + \frac{dX_e}{dd_N} = -\frac{\frac{\partial S_e}{\partial P_e} * \frac{dD_e}{dd_S}}{\left|J\right|} - \frac{\frac{dS_e}{dd_N} * \frac{\partial D_e}{\partial P_e}}{\left|J\right|} \succ 0$$

The effect on the price of e-waste is:

$$\frac{dP_e}{db} = \frac{dP_e}{dd_S} * \frac{\partial d_S}{\partial b} + \frac{dP_e}{dd_N} * \frac{\partial d_N}{\partial b} = -\frac{dP_e}{dd_S} + \frac{dP_e}{dd_N} \begin{cases} \succ 0 \text{ if } \frac{dP_e}{dd_N} \succ \frac{dP_e}{dd_S} \\ \prec 0 \text{ otherwise} \end{cases}$$

- *The effect of the degree of the monitoring* σ

The derivative of the system gives:

$$\begin{cases} \frac{dX_e}{d\sigma} - \frac{\partial S_e}{\partial P_e} * \frac{dP_e}{d\sigma} - \frac{dS_e}{d\sigma} = 0 \\ \frac{dX_e}{d\sigma} - \frac{\partial D_e}{\partial P_e} * \frac{dP_e}{d\sigma} - \frac{dD_e}{d\sigma} = 0 \end{cases}$$

In matrix form :

$$\begin{pmatrix} 1 & -\frac{\partial S_e}{\partial P_e} \\ 1 & -\frac{\partial D_e}{\partial P_e} \end{pmatrix} * \begin{pmatrix} \frac{dX_e}{d\sigma} \\ \frac{dP_e}{d\sigma} \end{pmatrix} = \begin{pmatrix} \frac{dS_e}{d\sigma} \\ \frac{dD_e}{d\sigma} \end{pmatrix} \text{ and } |J| = \begin{vmatrix} 1 & -\frac{\partial S_e}{\partial P_e} \\ 1 & -\frac{\partial D_e}{\partial P_e} \end{vmatrix} = -\frac{\partial D_e}{\partial P_e} + \frac{\partial S_e}{\partial P_e} \succ 0$$

We deduce that :

$$\frac{dX_e}{d\sigma} = \frac{\begin{vmatrix} \frac{dS_e}{d\sigma} & -\frac{\partial S_e}{\partial P_e} \\ \frac{dD_e}{d\sigma} & -\frac{\partial D_e}{\partial P_e} \end{vmatrix}}{|J|} = \frac{-\frac{dS_e}{d\sigma} * \frac{\partial D_e}{\partial P_e} + \frac{\partial S_e}{\partial P_e} * \frac{dD_e}{d\sigma}}{|J|}$$

with $\frac{dD_e}{d\sigma} \succ 0$, $\frac{\partial S_e}{\partial P_e} \succ 0$, $\frac{\partial D_e}{\partial P_e} \prec 0$ and $\frac{dS_e}{d\sigma} \prec 0$ $(\frac{dD}{d\sigma} \prec 0; \frac{dQ}{d\sigma})$;

$$\frac{dX_e}{d\sigma} \begin{cases} \prec 0 \\ \succ 0 \end{cases}$$

and

$$\frac{dP_e}{d\sigma} = \frac{\begin{vmatrix} 1 & \frac{dS_e}{d\sigma} \\ 1 & \frac{dD_e}{d\sigma} \end{vmatrix}}{|J|} = \frac{\frac{dD_e}{d\sigma} - \frac{dS_e}{d\sigma}}{|J|} \succ 0$$