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A Reverse Logistics Model For Recovery Options Of E-waste Considering the Integration of the Formal and Informal Waste Sectors

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Abstract

Wastes coming from electrical and electronic equipment (EEE) known as e-waste is a major concern because of its alarming increase as well as the hazardous substances within them that could cause harm on humans and the environment if not properly treated. In developing countries, e-waste is collected and recycled by the Informal waste sector (IWS) who neither have the proper training nor the proper equipment/facility. This makes reverse logistics of e-waste and the integration of the IWS to the formal waste sector necessary to minimize the mentioned negative effects.

A mixed integer multi-objective linear programming reverse logistics model was developed in this study to integrate the two waste sectors and address the economic, environmental and health issues brought about by e-waste through the use of different recovery options. The model was able to generate generalizations of when it would be appropriate to use certain options or certain combination of options especially regarding the amount to be given to the IWS as compensation for no longer treating and for integrating with the formal waste sector. It was also found that mandating producers to treat very large amounts of e-wastes may force them to use the IWSs more as treatment facilities

Keywords: Reverse Logistic; Multi-Objective Model; E-waste; IWS

1. Global Trend of E-waste

The electrical and electronics equipment (EEE) industry is one of the fastest growing in the industrialized world. Their products include mobile phones, music players, televisions, refrigerators, computers, printers, and even medical equipment. The industry products are vast and because of technological advancements that aim to make human lives more convenient and flexible. The kinds of products that they make continue to grow. Within the EEE industry, the products can be characterized

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into four based on the sectors they cater to. These have been described in the typology developed by Goggin and Browne [1]. The four sectors are 1.) commercial public where the products are few, sophisticated and have a high end of life value, 2.) commercial private sector where the products are larger in quantity as compared to the public sector but the value is lower, 3.) Large domestic product sector which include the ”white goods” or products like refrigerators and airconditioners, and lastly, 4.) Small domestic products sector which includes televisions, cellular phones, computers and all other gardgets created to make life more convenient for the everyday consumer.

The speed of the industry growth and technological advancements has led to faster obsolescence of products which produce more wastes [35]. Wastes from the discarded EEE industry products, commonly known as e-waste or WEEE, have been increasing at an alarming rate as well.

Although Robinson [2] differentiates the two, other authors [3; 4; 5; 6; 7] appear to consider them to be the same based on their discussion. Based on the former's description, e-wastes are waste electronic goods, such as computers, televisions and cell phones, while WEEE also includes traditionally non-electronic goods such as refrigerators and ovens. However, for this paper, e-waste and WEEE will be used interchangeably as done by the other authors.

Majority of the e-waste comes from items that fall under both large and small domestic products. According to Goggin and Browne [1], these products are harder to collect for the producers. A possible explanation for this is that individuals and even small businesses are allowed to dispose of these into their trashcans or dumped into garbage trucks. On the other hand, the e-waste from the commercial public and private sector (including their large equipments) cannot simply be thrown into the trash can. In addition, the products from these sectors are fewer as compared to those from the domestic sector thus they are easier to keep track of and to collect.

It is estimated that each year, 20-50 million tons of e-waste are generated worldwide [4]. Presently, majority of the waste is being produced by Organization for Economic Cooperation and Development (OECD), which have highly saturated markets for EEE. Comparatively, the market penetration of EEE in industrializing or developing countries is not very high. However, these countries show the fastest growing consumption rates for EEE, and thus large quantities of domestically generated e-waste will become part of the waste stream in them as well in the near future [8].

In addition, industrialized countries export their e-waste to developing countries or more specifically, countries with an IWS. The IWS is composed of small-scale, labour-intensive, largely unregulated and unregistered, low-technology manufacturing or provision of services [9]. Those who work in the IWS have no social and economic security and work under substandard and unhealthy work conditions, and have limited access to basic services [10].

Schwarzer, et al. [4] point out that the export of e-waste to these countries is a dangerous but cost-effective, and sometimes illegal waste management option chosen by some companies in industrialized countries. This option is cheaper because the IWS does not provide any kind of fringe benefits to the laborers and pays them a considerably smaller amount as compared to the salaries in any formal organization. Sometimes illegal export is phrased as or hidden under the umbrella of charity ("computers for the poor") or as recycling. This comes from the fact that environmental and occupational regulations are lax or not well-enforced in some developing countries, and labour costs are much lower than in industrialised ones (for instance, $1.50 per day in China) [33]. It has been reported that 50%–80% of the e-waste collected for recycling in industrialized countries, such as the US, ends up in recycling centers in Asia [which have many countries that make use of the IWS] [11].

Recycling, treatment and disposal of e-waste using the IWS are a serious problem because based on assessments by Wilson et al. [9], Wang and Guo [12], Yu et al. [13] Huo et al. [14], and Xing et al. [15], the IWS has shown severe shortcomings in capacities, skills and technologies put workers and the environment at considerable risk.

2. E-waste in the Formal and IWS

If industrialized/developed countries do not export their e-waste, they make use of the formal waste sectors within their countries. The formal sector has approaches such as extended producer responsibility (EPR), advanced recycling fee and voluntary take-back by producers. The concept of EPR makes the producers or manufacturers of the EEE financially responsible for the entire lifecycle of their products especially when they become obsolete [4]. This will be made possible through some legislation by the government. Since recycling is done by the formal sector, there are proper facilities put in place to handle the toxic and hazardous substances of the e-waste so as to prevent harm to both human health and the environment.

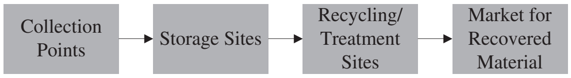

Fig. 1 Material Flow from site to site in the formal waste sector if e-waste (based on the work of Shih **[16]**)

Unfortunately, as mentioned earlier, many industrialized/developed countries with formal waste sectors export their e-waste to countries with an IWS who may not have enough of the proper facilities in place to handle these e-wastes. In fact, many do not have a proper facility at all to handle the e-waste without causing harm to the workers and the environment. EPR becomes crucial here because it is the producers who will have the resources and the funds to be able to establish facilities to properly handle the e-waste.

E-waste provides income opportunities for the people within the IWS thus, this sector cannot simply be eliminated. The existence of a very creative and low-income informal sector, permits a profitable e-waste recycling business thriving on uncontrolled and risky low-cost techniques [8]. Recycling processes here are very manual which include open burning techniques [34]. Gloves and masks are not even used. Some of the informal sector even scavenges from dumpsites to get the e-waste. After taking the valuable materials from the e-waste, the scrap that are left are simply disposed off in dumpsites or landfills. Some of these countries may have formal e-waste recyclers such as India and the Philippines but the IWS remains to be the dominant collection and treatment routes.

Aside from the amount of emissions that each sector generates, another way to differentiate the use of the informal from the formal waste sector for e-waste is in terms of the types of activities done in each site of the sector. For the formal waste sector, collection points, and recycling/treatment sites are separated. It is also possible that their storage sites are separate from the treatment facilities or it could be in the same area. Either way, it can be seen that the activities are in different sites.

On the other hand, for the IWS, the collection points, storage sites and recycling/treatment sites are all in the same general area. This is based on the discussion of Wilson et al. [9]. In their discussion, they showed that the recycling shops are also the collection sites. Their storage area is basically their surrounding area which is usually a dump site. In the case of e-waste, the e-waste to be treated may come from the itinerant waste buyers sent by the recycling shops to collect the discarded electronic products or electrical equipment from households or they may come from the waste pickers who go to the dump sites and manually pick out the e-waste.

The fact that all activities are in the same area minimizes the transportation cost and in effect minimizes the greenhouse gas emissions due to transportation but trade-offs with the increased emissions due to the improper treatment done by the IWS.

Studies by Wang and Guo [12], Yu et al. [13] Huo et al. [14], and Xing et al. [15] have shown the effects of having e-waste handled by the IWS by showing the case of Guiyu, China. Different kinds of hazardous substances such as lead are emitted to air, water and even the soil which are absorbed by humans. High lead exposure leads to different kinds of negative effects. Some of which are lower IQ of children [17] and has been associated with high blood pressure which can lead to cardiovascular diseases [18; 19; 20].

Lead is actually one of the main substances that cause e-waste to become hazardous [21]. Lead is also one of the most widely substances used in electronic devices.

3. Reverse Logistics and Extended Producer Responsibility

A way to handle e-waste and the problems brought about by it is through reverse logistics or more specifically through extended producer responsibility. The next two sub sections will be discussing what these two concepts are.

3.1. Reverse Logistics

According to Fleischmann et al. [22], reverse logistics includes the logistics activities all the way from used products no longer required by the user to products again usable in the market. Reverse logistics in e-waste also involves material recovery since these contains valuable metals.

Reverse logistics networks may be done by the producer themselves but there have been studies that have included other recovery options like the study done by Krumwiede and Sheu [23] and Ko and Evans [24]. Their studies incorporated the use of third party providers. This will allow the producers to focus on their main business functions such as producing goods but the producer may not have control over the costs.

Third parties have generally been used for the forward logistics but the study by Krumweide and Sheu [23] provides a framework that gives the steps to be followed in order for a third party provider to enter into reverse logistics. On the other hand, the study by Ko and Evans [24] provide a more mathematical approach to using third parties in reverse logistics where the task of the third party is to collect and sort the products. For re-use and remanufacturing, this activity of reverse logistics may be enough since the producer is the one who is knowledgeable about its own products and will know how to remanufacture or re-use the recovered products. However, if recycling is to be done where certain materials will be extracted, the producer may not be equipped to handle such activity since their competency and their main business function may simply lie in manufacturing goods and not extracting recoverable material from their products.

Another option that may be used for executing reverse logistics is through pooled/group take back. This can be done by having groups of companies that produce similar products organize themselves to invest on and create the reverse logistics infrastructure for the recovery of their products.

There have been some studies that included all three options (including the producer take back) such as the one done by Spicer and Johnson [25] and by Ravi, Shankar and Tiwari [26]. Spicer and Johnson [25] discussed and compared the approaches. Their discussions were purely descriptive and qualitative. This would make it difficult for producers to see which would be more cost-effective for them. They would need a more quantitative tool to be able to choose between the three options. Ravi, Shankar and Tiwari [26] used analytic network process (ANP) and balanced scorecard to analyze these alternatives. Here, they were able to include corporate citizenship and environmental aspects in the decision-making. Although they were able to provide a more quantitative approach in choosing an alternative, they were not able to provide the network design.

It was observed that the mentioned studies do not show if a combination of the recovery options is feasible. The discussion seem to indicate that only one option may be used at time. However, if the capacity of one option is not enough to meet the treatment requirements or the demand of the producers for the recovered material, then it should be made possible to use other options. Since it may not be possible to explore the different possibilities of combining options in reality, a model becomes necessary to do this especially if network design is involved. One cannot simply open and close facilities on an experimental basis in real life because this would be too costly.

3.2. Extended Producer Responsibility

The studies regarding the three recovery options mentioned in the previous subsection were done in the context of extended producer responsibility The concept of extended producer responsibility (EPR) is a suggested approach to handle products with hazardous substances particularly e-waste or waste coming from products of the EEE industry. The ultimate goal of EPR is sustainable development through environmentally responsible product development and product recovery [5].

Reverse logistics plays an important role in EPR because this is how the producers will be able to take back their products for proper handling and disposal.

Many companies have implemented design for X (recyclability, disassembly, etc.) to make products more environmental. However, if the wastes of these products cannot be recovered or handled properly, then their designs will be useless at the end of the product’s life.

Some policy instruments that lie under EPR umbrella include different types of product fees and taxes, such as, advance recycling fees (ARFs), product take-back mandates, virgin material taxes, and combinations of these instruments as well as pay-as-you-throw, waste collection charges, and landfill bans. [5]. Japan is making it’s consumers shoulder the payment for recycling through a post-paid recycling fee or a pay-as-you-throw but this has led to the illegal dumping and even export of e-waste because many are not willing to pay to throw trash. Although recycling fees and taxes may aid in the collection and recycling processes since these will fund the said processes, a take-back structure is still necessary to be able to bring the e-waste from the consumers to proper recycling facilities.

In industrialized/developed countries, there have been attempts at product take-back by the producers themselves or through a pooled group of producers. However, they can only take back the products that are within their countries. Products sold in the developing countries are not part of their scope. The producers of these products that are outside the developing countries will need to create a network or take back infrastructure within these countries to be able to recover their products.

Product take-back is not yet mandatory. However, it may become mandatory in the future but regardless of the possibility of a future mandate, product take-back will be needed by producers for a better corporate image and energy savings [27; 5]. There are significant energy savings in recycled materials over virgin ones as shown in Table 1. Producers may also be able to save on cost of materials since the prices of depleting resources have been increasing.

The network design of the reverse logistics to take back these products that contain hazardous substances is important in order to minimize the transportation and the costs that go with it. It is crucial for decision-makers to control reverse logistics costs to remain competitive [28]. In addition, any ecological benefits of recycling are more than offset if the waste has to be transported long distances due to the negative environmental effects of fossil fuel combustion [2] . Hu, Sheu and Huang [29] have actually developed a model for this particular purpose. However, their study lacks in the exploration of the recovery options to be able to minimize all the mentioned costs. In addition, their model only looks into the economic costs.

Table 1 Energy savings from using recycled materials as compared to virgin raw materials (based on [5]).

Material	Energy Savings (%)
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastic	>80

4. The Integration of the Formal and IWS

Based on the discussion in Section 2, the IWS can be taken as a fourth recovery option of e-waste for the countries that have them since producers may buy the recovered materials from them. This recovery option of e-waste may appear to be cheaper in terms of economic cost but it has many negative effects.

E-waste is clearly hazardous and must be handled properly to benefit not only the environment but also the well-being of those handling them. This is especially important for the IWS where the methods of e-waste treatment and material recovery are primitive. Research regarding this has generally been limited to documenting what is currently happening rather than creating a reverse logistics system that can minimize the harmful effects of e-waste in countries with IWSs. The study of Chi et al. [30] regarding the e-waste management of the IWS in China indicates that a key issue is how to set up incentives for informal recyclers so as to reduce improper recycling activities and to divert more e-waste flow into the formal recycling sector. As mentioned earlier, this is not to say that the IWS should be abolished because this is a source of livelihood. It has been suggested as a policy measure to integrate both sectors for the improvement of both but never has this been fully explored strategically.

In the industrialized/developed world, the formal waste management of e-waste is generally handled by the EEE producers. They may also do this in the countries where they sell their products and have IWSs but they will have to work together with the IWS. To execute this, they will not only have to consider the three original options for recovery but also consider those who work in the IWS. In addition to this, to integrate the IWS in their efforts to manage e-waste must not only benefit the producers but also benefit the IWS in order to convince the latter to become part of this integration.

Researches in the field of reverse logistics have not considered the importance of integrating informal waste to the formal waste of e-waste where the decisions and/or policies benefit both stakeholders in terms of economic costs, environmental costs and the emissions of hazardous substances such as lead. Although integration has been mentioned in studies regarding the IWS, it has not been thoroughly discussed how this will benefit both sectors. If there are benefits mentioned, these are mostly qualitative and mostly focus on the benefit of the IWS. There are two stakeholders in this integration thus this act of integration must benefit both and this benefit must be presented to both of them.

This integration aims to minimize the exposure of not only those working in the e-waste industry from the health risks brought about by the e-waste but also those who live near the industry. The problem with the current set-up of the e-waste industry in the IWS is that the workers are exposed to toxic substances. This is because they are neither properly equipped nor trained to handle the e-waste. Toxic and hazardous substances such as lead do not only affect the workers but also the people living in the surrounding area of the e-waste treatment because of the emissions to the air and water environment. All three costs (economic, environment and health) must be minimized for both stakeholders.

5. Objectives of the Study

This study aimed to be able to integrate the formal and IWS of e-waste that will not only be economically and environmentally beneficial but also beneficial to human health. In order to do this, a mathematical model was developed. This mathematical model was run on different scenarios of the amount of e-waste collected, mandated amount of e-waste to be treated and amount charged to the treatment facilities for the collection of e-waste by the IWS. This was done to determine in what scenarios of the mentioned parameters will the different recovery options be combined to minimize the costs of both stakeholders.

This study would like to add to the body of knowledge of reverse logistics recovery options by exploring the effects of increasing or decreasing the said parameters on not only the recovery options chosen but also the number of sites chosen for a particular option. The amount charged by the IWS for the collection of e-waste is important because if they are no longer treating e-waste, they will have to get their profits from their collection activities otherwise, it will not be worthwhile for them to integrate themselves with the formal waste sector. This will be their incentive to become a part of the integration.

The amount of e-waste collected is also important because if the supply is low, there is a possibility that it will no longer be worthwhile to create a reverse logistics network. The mandated amount of e-waste to be treated was also considered because it is a possibility that in the future, this will be implemented by governments around the world. Also, this mandated amount of e-waste to be treated may come from the producers themselves to boost their corporate image.

It may also be possible that a single site was chosen for a particular option as additional capacity for the actual options chosen because the latter already chose all the available sites but still could not handle a portion of the demand for recovered materials from the e-waste or mandated amounts to be treated. This makes it important to look at both the options chosen and the number of sites chosen for those options. Focusing only on which options chosen could lead to wrong conclusions about when to choose a combination of options.

Finally, this study also aims to determine when will the option to integrate or not integrate the informal sector be beneficial to the system.

6. System Definition

Fig. 2 shows an overview general reverse logistics system of the study which starts with the e-waste being collected in the IWS as pointed out by Wilson et al. [9]. For countries with IWSs, their activities are not limited to simply collection but also treatment and extraction of materials as discussed by Ongondo et al. [7]. This study proposes the use of treatment facilities of formal waste sectors in the countries with IWSs to handle the treatment of e-waste to meet the demand of the EEE industry for the materials that can be recovered from the e-waste and/or the mandated amounts to be treated.

As discussed earlier, the key issue for in the IWS is diverting the recycling [or treatment] of e-waste to the formal waste sector [30]. This is because of the high environmental and health impact of e-waste recycling in the IWS. Chi et al. [30] also discussed that the IWS are able to collect more e-waste because they are able to take directly from households. It was also discussed earlier that formal waste sectors have separate collection points from their treatment facilities. Thus, integration can be taken as the IWSs serving as collection points for the formal waste sector and diverting as much of the e-waste recycling and treatment to the formal waste sector (the treatment facilities).

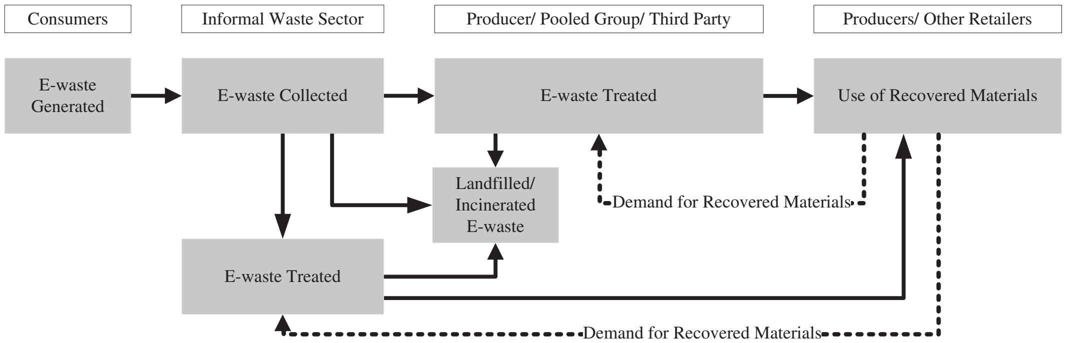

Fig. 2 General Reverse Logistics Model

6.1. Material Flow

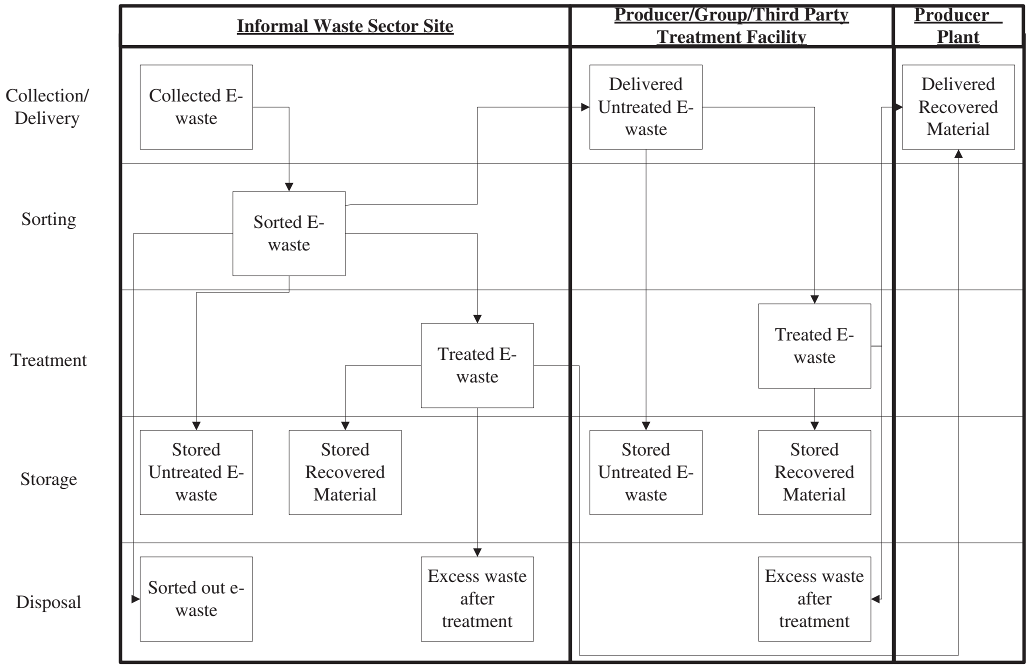

Fig. 3 Material Flow in the System

The e-wastes to be considered are those both produced domestically and imported. The two will be aggregated together since imported obsolete EEE will either be re-used first and later on be part of the e-waste recycling stream or will immediately be part of the e-waste recycling stream.

Since there is already an IWS in place that collects the e-waste, this will remain as the method for collection. Fig. 3 shows the material flow in the system. In the IWS sites, collected e-waste will be sorted. This means that the parts of the e-waste that do not contain the recoverable material will be taken out and disposed of (sorted out e-waste). The inclusion of the sorting activity was based on the discussion of Wilson et al. [9] regarding the role of the IWS in waste management.

The sorted e-waste will then either be stored, treated or delivered to the producer, group or third party facilities. In the succeeding periods, the stored untreated e-waste may also be treated to recover materials or delivered to the facilities but the diagram above only shows the single period flow. The excess material from the e-waste after treatment will also be disposed of. The extracted material after treatment will either be stored or delivered to the producer's plant.

The delivered untreated e-waste in the facilities will either be stored or treated. Similar to the IWS treatment, the recovered material will either be stored to the producer's plant.

The mentioned activities done after sorting of the e-waste were based on the reverse logistics studies of Shih [16] and Hu et al. [29].

6.2. Cost/Impact Considered

The environmental impact and their respective costs that will be considered are the greenhouse gas emissions and lead emissions.

A possible way to incorporate health into the study is by measuring the substance/s that have been proven to cause deterioration to health. Lead has been mentioned earlier to be the most common substance used in electronic devices and this has also been proven to greatly affect health when exposed. Because of this, the amount of lead emissions is also an indicator of human health cost.

Economic costs to consider are the collection, transportation, treatment, storage, disposal, investment, deviations, and IWS extraction costs. Collection costs are the costs incurred during collection (excluding transportation). This may include the amount paid to consumers who sell their e-waste to the collectors and the wages of the collectors. Transportation costs include all movement of the e-waste from consumers to IWS, to recyclers and finally to the users of the recovered materials. Storage costs are costs incurred to store e-waste or the recovered materials. Disposal costs are incurred when discarded parts of e-waste (parts that do not have valuable materials to be recovered) are disposed off. Treatment costs are the operating costs of recovering valuable materials from the e-waste. Investment costs are the costs incurred to purchase the technology to recycle and treat the e-waste as well as the cost to open facilities. Deviation costs are the penalties incurred when deviating from mandated amounts of treatment or not meeting demands for recovered materials. Lastly, IWS extraction costs are the costs incurred for having the IWS recover materials from the e-waste. This serves as the revenue of the IWS.

7. The Model

The model developed is a single period model because the only variable that will be connecting them will be the inventory. The model can simply be used over and over again per period holding the sites open if they have been opened.

7.1. Assumptions

- Recycling/Treatment done by the IWS is not included in the amount recycled/treated by the producer/pooled group/third party to meet the minimum amount to treat (whether mandate or for business strategy). (The producer will be the one using the model being formulated and not any other member of the pooled group or customer of a third party)
- Only the collection cost and delivery cost of amounts delivered from IWS sites to treatment facilities will be charged to the producer
- All penalties for emissions (greenhouse gas and lead) of the IWS will be charged to the producer
- Sorting and material extraction rates are known
- Untreated and treated e-waste share the same storage
- Treatment, Storage and Disposal costs of IWS sites will not be charged to the producer
- Third parties serve their clients equally thus the amount of e-waste treated and material extracted will be divided equally among its clients.
- For the pooled group alternative, the amount of e-waste treated and the amount of material extracted credited and delivered to each producer is equal to the number of members in the pooled group.
- Final disposal sites are near the treatment areas thus the transportation costs (both economic and environmental) are minimal and can be grouped with the other costs incurred for disposal (i.e. cost to maintain disposal sites, environmental cost for emissions once disposed of)
- Demand of producer for materials are known
- There is only one producer's plant that will receive deliveries of extracted materials from either IWS sites or treatment facilities
- All recovered materials by the IWS sites are for the producer only
- The waste treatment of the producers are assumed to be the formal waste sector to be integrated with the IWS
- Supply of e-waste will always be greater than mandated amounts

Nomenclature

Model indices

i	IWS collection/treatment sites (1,2,3…*I*)
j	Treatment Facility sites (for any of the alternatives) (1,2,3…*J*)
o	Recovery options/alternatives (*p, g, t*)
k	Product Type (1,2,3…*K*)
v	Valuable Substances to be extracted from the product (1,2,3…*V*)
s	Scenario (1,2,3…*S*)

General model parameters

XC_{kis}	Average amount of product type *k* collected by IWS site *i* in scenario *s*
P_s	Probability of scenario *s* occurring
a_k	Sorting rate of IWS sites (percentage of the product *k* left after sorting out the non-valuable materials)
ei_k	Extraction rate of IWS sites for valuable substances product *k*
ej_k	Extraction rate of treatment facilities for valuable substances from product *k*
$percent_{vk}$	Percent of valuable substance *v* from the extraction done on product *k*
$CASi_i$	Storage capacity of IWS site *i*
$CAST_j^o$	Storage capacity of treatment facility *j* of option *o*
$CATi_i$	Treatment capacity of IWS site *i*
$CATt_j^O$	Treatment capacity of treatment facility *j* of option *o*
MTg	Government mandated amount of e-waste to be treated by a producer
MTb	Producer's predetermined minimum amount of e-waste to be treated
Dis_{ij}	Distance from IWS site *i* to treatment facility *j*
IP_i	Distance from IWS site *i* to producer's plant
TP_j^O	Distance from treatment facility *j* of option *o* to producer's plant
VLi	Maximum amount of e-waste collected that can be loaded into a IWS vehicle
VLj	Maximum amount of sorted e-waste that can be loaded into a vehicle for delivery to treatment facilities
VLp	Maximum amount of extracted material that can be loaded into a vehicle for delivery to the producer's plant
Vj	Total number of vehicles available for transportation from IWS sites to treatment facilities
Vp	Total number of vehicles available for transportation from either IWS sites or treatment facilities to the producer's plant
ADi	Average distance traveled by IWS collectors to collect e-waste from end user/dump sites
DU_v	Producer's demand for valuable substance *v*
$DevC_v$	Amount of CO_2 emitted per amount deviated from the demand of *v*
$DevL_v$	Amount of Lead emitted per amount deviated from the demand of *v*
COi	Average amount of CO_2 emitted per vehicle used to deliver e-waste from e-waste sources (households, dump sites, etc.) to IWS sites

COj	Amount of CO_2 emitted per distance per vehicle used to deliver e-waste from IWS sites to treatment facilities
COp	Amount of CO_2 emitted per distance per vehicle used to deliver e-waste from either IWS sites or treatment facilities to producer's plan
C_o	No. of members in the group for the group take-back or the number of customers the third party serves including the producer who will be using the model (for the producer alternative, the value is 1)
Tc	Number of customers served by the third party including the producer
TCi	Amount of CO_2 emitted per weight of treated e-waste in IWS sites
TCj	Amount of CO_2 emitted per weight of treated e-waste in treatment facilities
FCi	Amount of CO_2 emitted per weight of disposed e-waste (after treatment) in IWS disposal sites
FCj	Amount of CO_2 emitted per weight of disposed e-waste (after treatment) in treatment facilities
LTt_k	Amount of lead emitted during per weight of treated product *k* in the treatment facilities
LFt_k	Amount of lead emitted per weight of disposed product *k* (after treatment) in the disposal sites of treatment facilities
LTi_k	Amount of lead emitted during per weight of treated product *k* in IWS sites
LSi_k	Amount of lead emitted by product *k* during storage in IWS sites
LFi_k	Amount of lead emitted per weight of disposed product *k* (after treatment) in the disposal sites of IWS sites
CollectFactor	Factor multiplied to the revenue gained by the IWS sites for the extraction of recoverable material. This will be used for the collection fee charged by the IWS sites to the treatment facilities. (further explanation of this parameter can be found in the discussion of collection costs incurred by the producer)
Cost parameters	
CC_i	Collection cost per weight in IWS site *i*
R_v	Revenue gained by the IWS sites for extracting recoverable material *v* from the e-waste
IC_j^O	Investment cost to open a treatment facility of option *o* at *j*
TCt_j^O	Treatment cost per weight of e-waste in treatment facility j of option *o*
TCi_i	Treatment cost per weight of e-waste in IWS site *i*
CSi_i	Storage cost per weight of recovered/extracted material or unprocessed e-waste in IWS site *i*
CSt_j^o	Storage cost per weight of recovered/extracted material or unprocessed e-waste in treatment facility *j* of option *o*
CFi_i	Disposal cost per weight of waste generated in IWS site *i* for final disposal
CFt_j^O	Disposal cost per weight of waste generated in treatment facility *j* for final disposal
D_{ij}	Transportation cost per vehicle per distance to deliver sorted e-waste from IWS site *i* to treatment facility *j*
DP_i	Transportation cost per vehicle per distance to deliver sorted e-waste from IWS sites to the producer's plant
DP_j	Transportation cost per vehicle per distance to deliver sorted e-waste from any of the treatment facilities to the producer's plant
DC_v	Cost per weight of deviation from demand for valuable substance *v*
D_j	Cost per weight of deviation from treatment mandate
PGHG	Penalty costs per weight of greenhouse gasses emitted by the system
PLead	Penalty costs per weight of lead emitted by the

Decision variables for IWS sites

XD^{O}_{kijs}	Amount of sorted (unprocessed) e-waste product type *k* to deliver from IWS site *i* to treatment facility *j* of option *o* in scenario *s*
$XSUi_{kis}$	Amount of sorted (unprocessed) e-waste product type *k* to be stored in IWS site *i* in scenario *s*
XTi_{kis}	Amount of sorted e-waste product type *k* to be treated in IWS site *i* in scenario *s*
XSi_{kis}	Amount of valuable substances extracted from product *k* to be stored in IWS site *i* in scenario *s*
XUi_{kis}	Amount of recovered material extracted from product *k* to be delivered from IWS site *i* to the producer's plant in scenario *s*

Decision variables for producers

$XSUt^{O}_{kis}$	Amount of sorted (unprocessed) e-waste product type *k* to be stored in treatment facility *j* of option *o* in scenario *s*
XTt^{O}_{kjs}	Amount of sorted e-waste product type *k* to be treated in treatment facility *j* of option *o* in scenario *s*
XSt^{O}_{kjs}	Amount of valuable substances extracted from product *k* to be stored in treatment facility *j* of option *o* in scenario *s*
XUt^{O}_{kjs}	Amount of recovered material extracted from product *k* to be delivered from facility *j* of option *o* to be utilized to serve the producer's demand scenario *s*

Binary variable

In^{O}_{j}	1 if a treatment facility of option *o* is opened in *j* 0 otherwise

System variables

$EXFi_{ki}$	Amount of sorted out e-waste and waste generated from product k during treatment to be disposed of in the disposal site of IWS site *i*
$EPBXF_{ki}$	The amount of treated product *k to* be disposed of in IWS site *I* that contains traces of lead
$EXFt^{O}_{kj}$	Amount of sorted out e-waste and waste generated from product k during treatment to be disposed of in the disposal site of treatment facility *j* of alternative *o*
$EXDU_{v}$	Expected eviation from demand of valuable substance *v* in scenario *s* (slack)
$NXDU_{v}$	Expected eviation from demand of valuable substance *v* in scenario *s* (surplus)
EXDT	Expected deviation from treatment mandate (slack)
NXDT	Expected eviation from treatment mandate (surplus)
EXV^{O}_{ij}	Expected number of vehicles to be used to transport sorted e-waste from IWS site *i* to treatment facility *j* of option *o*
$EXVip_{i}$	Expected number of vehicles used to transport valuable substances from IWS site *i* to producer's plant
$EXVjp^{o}_{j}$	Expected number of vehicles to be used to transport valuable substances from treatment facility *j* of option *o* to producer's plant
PrCost	Total Cost incurred by the informal waste sector (economic, environmental and health)
IWSCost	Total Costs incurred by the producers
IWSProfit	Total Profit gained by the informal waste sector
D_1	Deviation from the aspiration level of the $Prcost$
D_2	Deviation from the aspiration level of the $IWScost$

7.2. Objective function

There are two objectives: the producer's cost (Prcost) and the IWS's profit (IWSProfit). It may be possible that if the two are merged together, the total cost may be minimized but the cost of one stakeholder may not necessarily minimized.

The producers are used as one of the stakeholders because this model can be used by producers in the EEE industry to execute EPR.

Also, it should be mentioned that there are no environmental or health costs for the IWS and these are totally charged to the producer. This is to make the producer responsible for the handling of the end of life of their products. If they choose to let the IWS handle the e-waste, then these will have a penalty (environmental and health).

7.2.1. Producer's cost

Cost is used for the producers since they will not necessarily be making any profit from the reverse logistics network. It will only help in minimizing costs such as environmental cost.

The complete expression for the producer's cost is shown in *(1)*.

The reciprocal of C_o to many expressions for the producer cost objective function because this will indicate the amount of emissions, e-waste treated, and output credited to the producer. Producer options will have a C_o of 1 while the pooled group option and third party options will depend on the number of members/clients served.

Prcost=

$$\begin{aligned}
&\sum_{0}\frac{1}{C_0}\left\{\begin{aligned}
&\sum_{i=1}^{I}(CC_i)\left[\sum_{k=1}^{1}\frac{1}{a_k}\left(\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}EXD_{kij}^{O}\right)\right]+CollectFactor\sum_{v=1}^{V}R_v\left[\sum_{k=1}^{K}\left(percent_{vk}\sum_{i=1}^{I}\sum_{j=1}^{J}EXD_{kij}^{O}\right)\right]\\
&+D_{ij}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}Dis_{ij}EXV_{ij}^{O}\right)+DP_t\left(\sum_{J=1}^{J}TP_j^{O}\right)EXVjp_j^{o}+\sum_{j=1}^{J}TCt_j\left(\sum_{k=1}^{K}EXTt_{kj}^{O}\right)\\
&+CSt_j^{o}\left(\sum_{k=1}^{K}\sum_{j=1}^{j}EXSUt_{ki}^{O}+\sum_{v=1}^{V}\sum_{j=1}^{j}EXSt_{kj}^{O}\right)+\sum_{j=1}^{J}CFt_j^{O}\sum_{k=1}^{K}XFt_{kj}^{O}+\sum_{j=1}^{J}IC_j^{O}In_j^{O}
\end{aligned}\right\}\\
&+DjEXDT+\sum_{v=1}^{V}DC_v\,EXDU_v+\sum_{v=1}^{V}\sum_{k=1}^{K}R_v\times percent_{vk}\times\sum_{i=1}^{I}EXUi_{ki}\\
&+PGHG\left\{\begin{aligned}
&\sum_{0}\frac{1}{C_0}\left[\begin{aligned}&EXV_{ij}^{O}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}Dis_{ij}\right)COj+EXVjp_j^{o}\left(\sum_{J=1}^{J}TP_j^{O}\right)COp+\\&TCj\sum_{j=1}^{J}\left(\sum_{k=1}^{K}EXTt_{kj}^{O}\right)+FCj\sum_{j=1}^{J}\sum_{k=1}^{K}XFt_{kj}^{O}\end{aligned}\right]+\sum_{v=1}^{V}DevC_vEXDU_v\\
&+COi\times ADi\times\left\{\frac{\sum_{k=i}^{K}\sum_{i=1}^{I}\left(EXC_{ki}-\frac{1}{a_k}\left(\sum_{j=1}^{J}EXD_{kij}^{O}\right)\right)}{VLi}\right\}\\
&+EXVIp_i\left(\sum_{i=1}^{I}IP_i\right)COp+TCi\sum_{i=1}^{I}\sum_{k=1}^{K}EXTi_{ki}+FCi\sum_{k=1}^{K}\sum_{i=1}^{I}EXFi_{ki}
\end{aligned}\right\}\\
&+PLEAD\left\{\begin{aligned}
&\sum_{0}\frac{1}{C_0}\left[\sum_{k=1}^{K}LTt_k\sum_{j=1}^{J}EXTt_{kj}^{O}+\sum_{k=1}^{K}LFt_k\sum_{j=1}^{J}EXFt_{kj}^{O}\right]+\sum_{0}\sum_{v=1}^{V}DevL_vEXDU_v+\\
&\sum_{k=1}^{K}LSi_k\left(\sum_{i=1}^{I}EXSi_{ki}+EXSUi_{ki}\right)+\sum_{k=1}^{K}LTi_k\sum_{i=1}^{I}EXT_{ki}\\
&+\sum_{k=1}^{K}LFi_k\sum_{i=1}^{I}EPBXF_{ki}
\end{aligned}\right\}
\end{aligned}\qquad(1)$$

The producer's cost is composed of the costs shown in *(2), (4), (6), (7),*and *(8).*

Collection cost

The expression for collection cost is shown in (2) where (3) is the equivalent amount collected. The collection cost for the amounts of sorted e-waste delivered to the treatment facilities of the different options can be computed by deriving the equivalent amount of unsorted e-waste collected by the IWS site. This can be done by dividing the amounts delivered to the facilities by the sorting rate of the product ($\mathbf{a_k}$) to get the actual amount that the IWS site collected. This method of charging collection costs has not been done in previous studies. The equivalent amount collected is then multiplied with the sum of the collection cost of the IWS site For each option, the collection cost will be divided with the respective number of customers/members of the group to get the equivalent cost to be paid by the producer. The collection costs for each option will be added together to get the total cost of collection to be incurred by the producer

In addition to charging the collection cost of the equivalent amount collected, the IWS will also be charging a certain amount as compensation. Because they delivered the sorted e-waste to the treatment facilities, they will no longer have the opportunity to gain revenues from extracting the recoverable materials and selling these. As such, the revenue they would have gained per weight of recoverable material (R_v) will be multiplied by a factor (CollectFactor) to serve as compensation and an incentive as well for the IWS sites to not treat the e-waste. In order to know the amount of recoverable material to be multiplied to R_v the amount delivered to treatment facilities$\left(EXD^O_{kij}\right)$ will be multiplied by the extraction rate of the IWS sites and the percentage of the amount of recoverable material v in product k.

$$\sum_{O}\frac{1}{C_O}\left\{\begin{array}{c}\sum_{i=1}^{I}(CC_i)\left[\sum_{k=1}^{1}\frac{1}{a_k}\left(\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}EXD^O_{kij}\right)\right]+\\ \text{CollectFactor}\sum_{v=1}^{V}R_v\left[\sum_{k=1}^{K}\left(\text{percent}_{vk}\sum_{i=1}^{I}\sum_{j=1}^{J}EXD^O_{kij}\right)\right]\end{array}\right\} \quad (2)$$

$$\sum_{k=1}^{1}\frac{1}{a_k}\left(\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}EXD^O_{kij}\right) \quad (3)$$

Transportation cost:

The transportation cost is shown in *(4)* where EXV^O_{ij} and $EXVjp^O_j$ are the number of vehicles used for transportation. The computation for this is shown in *(5).*

$$\sum_{O}\frac{1}{C_O}\left[D_{ij}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}Dis_{ij}EXV^O_{ij}\right)+DP_t\left(\sum_{J=1}^{J}TP^O_j\right)EXVjp^o_j\right] \quad (4)$$

$$\text{No. of vehicles} \geq \text{weight(transported)}\Big/\frac{\text{weight(limit)}}{\text{vehicle}} \quad (5)$$

Treatment, storage, disposal and investment costs (shown respectively):

$$\begin{array}{c}\sum_{O}\frac{1}{C_O}\left[\sum_{j=1}^{J}TCt_j\left(\sum_{k=1}^{K}EXTt^O_{kj}\right)\right]+\\ \sum_{O}\frac{1}{C_O}\left[CSt^o_j\left(\sum_{k=1}^{K}\sum_{j=1}^{j}EXSUt^O_{ki}+\sum_{k=1}^{K}\sum_{j=1}^{j}EXSt^O_{kj}\right)\right]+\\ \sum_{O}\frac{1}{C_O}\left(\sum_{j=1}^{J}CFt^O_j\sum_{k=1}^{K}XFt^O_{kj}\right)+\\ \sum_{O}\frac{1}{C_O}\left(\sum_{j=1}^{J}IC^O_jIn^O_j\right)\end{array} \quad (6)$$

Deviation cost:

The Deviation cost shown in *(7)* include the cost incurred for not meeting the treatment mandate and the demand for recovered materials

$$DjEXDT+\sum_{v=1}^{V} DC_v\, EXDU_v \tag{7}$$

IWS extraction cost:

The IWS will be charging the producer for their extraction services. The economic cost that the producer incurs from this can be expressed as the revenue gained by the IWS sites for extracting recoverable material v from the e-waste (R_v) multiplied by the amount of recoverable material v delivered to the producer's plant.

The amount of recoverable material v delivered to the producer's plant can be computed by multiplying the amount of recovered material extracted from product k to be delivered from IWS site i to the producer's plant ($EXUi_{ki}$) with the percentage of the recoverable material v from the extraction done on product k ($percent_{vk}$)

$$\sum_{v=1}^{V}\sum_{k=1}^{K} R_v \times percent_{vk} \times \sum_{i=1}^{I} EXUi_{ki} \tag{8}$$

Greenhouse gas emission costs:

The greenhouse gas (GHG) emissions are used as the one of the environmental indicators for this study. The computation of this is similar to the mentioned costs earlier (except investment cost) but the factor multiplied to the variables (i.e. $EXD^O_{kij}, EXV^O_{ij}, EXV^O_{jp}, etc.$) will be the GHG cost per unit of the variable and the penalty cost per amount of GHG emitted (PGHG).

As mentioned earlier, the green house gas emissions of the IWS are also included here.

The GHG emissions by the producer are composed of emissions from transportation (from IWS sites to treatment facilities and from treatment facilities back to the producer's plant to be used as raw materials), disposal and deviation from demand. The expressions for these are shown in *(9)*

$$EXV^O_{ij}\left(\sum_{i=1}^{I}\sum_{j=1}^{J} Dis_{ij}\right)COj+EXVjp^o_j\left(\sum_{J=1}^{J} TP^O_j\right)COp+$$
$$TCj\sum_{j=1}^{J}\left(\sum_{k=1}^{K} EXTt^O_{kj}\right) \quad + \quad FCj\sum_{j=1}^{J}\sum_{k=1}^{K} XFt^O_{kj} \tag{9}$$

The GHG emissions by the IWS are composed of emissions from collection, transportation, treatment and disposal. The expressions for these are respectively shown in *(10).*

$$COi\times ADi\times\left\{\frac{\sum_{k=i}^{K}\sum_{i=1}^{I}\left(EXC_{ki}-\frac{1}{a_k}\left(\sum_{j=1}^{J} EXD^O_{kij}\right)\right)}{VLi}\right\} \quad + \quad EXVIp_i\left(\sum_{i=1}^{I} IP_i\right)COp$$
$$TCi\sum_{i=1}^{I}\sum_{k=1}^{K} EXTi_{ki} \quad + \quad FCi\sum_{k=1}^{K}\sum_{i=1}^{I} EXFi_{ki} \tag{10}$$

Lead emission costs:

The lead emission costs can be taken as an environmental indicator as well as a health indicator. The more lead emissions there are, the greater pollution there is in the environment and the higher the health risks are for humans.

The lead emission costs can be computed by multiplying the penalty costs per weight of lead emitted (PLEAD) to the lead emissions from treatment, disposal, storage and deviation from demand. Similar to the GHG emissions, the emissions of the IWS will be included to the producer's cost.

Computations for the lead emissions are similar to the computations of GHG emissions where the amount emitted per weight of e-waste in an activity (treatment, storage, disposal, etc.) is multiplied to the amount of e-waste in that activity.

7.2.2. Informal Waste Sector's Profit

For IWSProfit shown in *(11)* will be maximized because the model needs to ensure that the IWS sites will still be earning money if they decide to integrate with the formal waste sector.

$$\text{IWSProfit} = \text{CollectFactor}\sum_{v=1}^{V} R_v\left[\sum_{k=1}^{K}\left(\text{percent}_{vk}\sum_{i=1}^{I}\sum_{j=1}^{J}\text{EXD}^{O}_{kij}\right)\right] + \sum_{v=1}^{V}\sum_{k=1}^{K} R_v \times \text{percent}_{vk} \times \sum_{i=1}^{I}\text{EXUi}_{ki}$$
$$- \left\{ \sum_{i=1}^{I}\text{CC}_i\left[\sum_{k=1}^{K}\text{EXC}_{ik} - \sum_{0}^{1}\sum_{k=1}\frac{1}{a_k}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\text{EXD}^{O}_{kij}\right)\right] + \sum_{i=1}^{I}\text{TCi}_i\left(\sum_{k=1}^{K}\text{EXTi}_{ki}\right) + \text{EXVip}_i\text{DPi}\left(\sum_{i=1}^{I}\text{IP}_i\right) + \text{CSi}\left(\sum_{v=1}^{K}\sum_{i=1}^{i}\text{EXSi}_{ki} + \sum_{k=1}^{K}\sum_{i=1}^{i}\text{EXSUi}_{ki}\right) + \sum_{i=1}^{I}\text{CFi}_i\sum_{k=1}^{K}\text{EXFi}_i \right\} \qquad (11)$$

The revenues of the IWS sites are composed of the collection revenue (when they sell their collected and unprocessed e-waste to the treatment facilities of the producers) and the extraction revenue (when they treat the e-waste to extract the valuable substances and sell the latter). *(12)* shows the expressions for these revenues.

$$\text{CollectFactor}\sum_{v=1}^{V} R_v\left[\sum_{k=1}^{K}\left(\text{percent}_{vk}\sum_{i=1}^{I}\sum_{j=1}^{J}\text{EXD}^{O}_{kij}\right)\right] + \sum_{v=1}^{V}\sum_{k=1}^{K} R_v \times \text{percent}_{vk} \times \sum_{i=1}^{I}\text{EXUi}_{ki} \qquad (12)$$

The costs incurred are from collection, transportation, treatment, disposal, and storage.

The collection costs for IWS sites can be computed by subtracting the equivalent amount of collected e-waste delivered to the treatment facilities from the amounts actually collected as shown in *(13)*. To the knowledge of the researcher, this method has not been done before. It is only fair to both the producer and the IWS sites to charge only the collection that goes to them (producers) or remains with them (IWS sites).

Since the model will be dealing with uncertainty and different scenarios the value placed for the amount collected will be the expected value. The expected value is computed by adding the product of the probability of a scenario and the amount collected in that scenario.

The use of expected values in treating uncertainty was patterned after the work of Kara and Onut [31].

$$\sum_{i=1}^{I}\text{CC}_i\left(\sum_{k=1}^{K}\text{EXC}_{ik} - \sum_{0}^{1}\sum_{k=1}\frac{1}{a_k}\left(\sum_{i=1}^{I}\sum_{j=1}^{J}\text{EXD}^{O}_{kij}\right)\right) \qquad (13)$$

For the transportation cost shown in (14), the EXVip_i is the number of vehicles used to transport e-waste from households or from the source of e-waste to the IWS sites. The computation is similar to *(5)*.

$$\text{EXVip}_i\text{DPi}\left(\sum_{i=1}^{I}\text{IP}_i\right) \qquad (14)$$

The expressions treatment, storage and disposal costs are shown respectively in *(15)*.

$$\sum_{i=1}^{I} TCi_i \left(\sum_{k=1}^{K} EXTi_{ki} \right) + CSi \left(\sum_{v=1}^{K} \sum_{i=1}^{i} EXSi_{ki} + \sum_{k=1}^{K} \sum_{i=1}^{i} EXSUi_{ki} \right) + \sum_{i=1}^{I} CFi_i \sum_{k=1}^{K} EXFi_i \quad (15)$$

7.3. Constraints

7.3.1. Material balance constraints

Fig. 4 shows a more detailed diagram of the flow of materials. It is from this figure that the material balance constraints are derived. The material balance constraints are shown in Table 2

Table 3 Material balance constraints

Constraint	Expression	
Sorted e-waste	$(aXC_{kis}) = XTi_{kis} + \sum_{O} \sum_{j=1}^{J} XD^{O}_{kij} + XSUi_{kis}$	$\forall k \forall i \forall s$
Amount of e-waste to be disposed in IWS site	$(EXFi_{ik}) = (1\text{-}a_k)XC_{ki} + (1\text{-}ei_k)EXTi_{ki}$	$\forall k \forall i$
Recovered Material from product k in IWS site	$(ei_k XTi_{kis}) = XUi_{kis} + XSi_{kis}$	$\forall k \forall i \forall s$
Delivered e-waste from IWS sites	$(\sum_{i=1}^{I} XD^{O}_{kijs}) = XTt^{O}_{kjs} + XSUt^{O}_{vjs}$	$\forall k \forall j \forall o \forall s$
Recovered Materials from product k in treatment facilities	$(ej_k XTt^{O}_{kjs}) = XUt^{O}_{vjs} + XSt^{O}_{vjs}$	$\forall v \forall j \forall o \forall s$
Disposal in treatment sites of other recovery options	$(EXFt^{O}_{kj}) = (1\text{-}ej_k)EXTt^{O}_{kj}$	$\forall k \forall j$

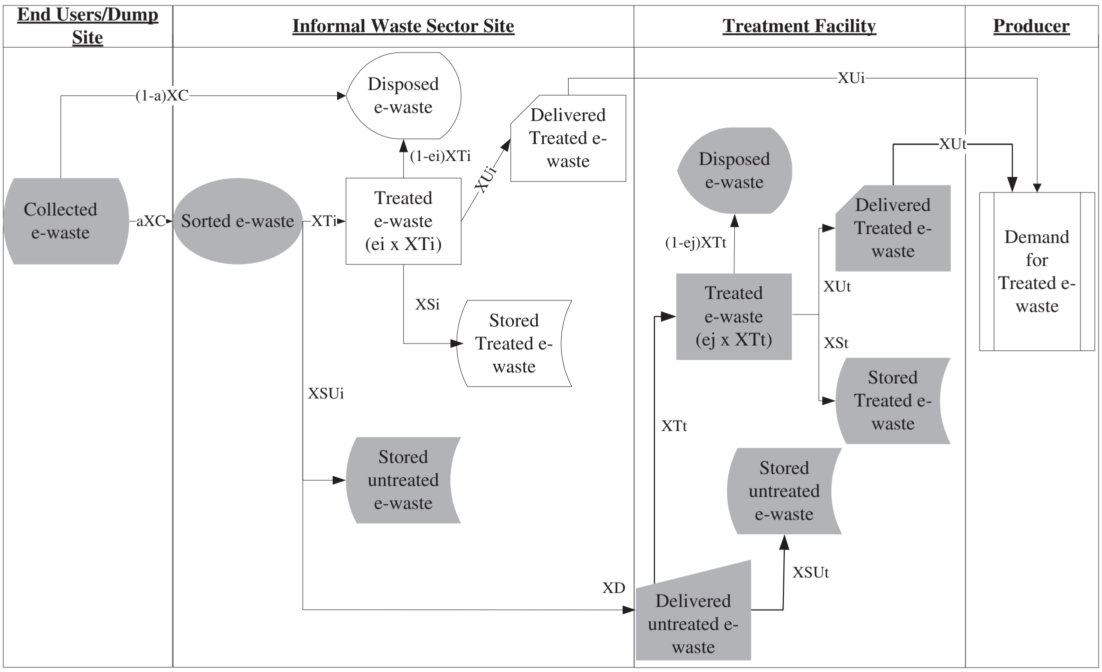

Fig. 4 Flow of Materials

7.3.2. Binary constraint

If facility j is not opened the there should not be any deliveries, storage or treatment done there.

$$\sum_{k=1}^{K} XTt_{kjs}^{O} + XSUt_{kis}^{O} + XSt_{kjs}^{O} \leq MIn_{j}^{O} \qquad \forall j \forall o \forall s$$

where M is a very large number

7.3.3. Capacity constraints

Table 3 shows the capacity constraints and their corresponding expressions.

Table 3 Capacity constraints

Constraint	Expression	
IWS site treatment capacity	$\sum_{k=1}^{K} XTi_{kis} \leq CATi_{i}$	$\forall i \forall s$
Treatment facilities capacity (to treat)	$\sum_{k=1}^{K} XTt_{kjs}^{O} \leq CATt_{j}^{O}$	$\forall j \forall o \forall s$
Transportation capacity	$\sum_{i=1}^{I} \sum_{j=1}^{J} EXV_{ij} \leq Vj$	
	$\sum_{i=1}^{I} EXVip_{i} + \sum_{o} \sum_{j=1}^{I} EXVjp_{j}^{o} \leq Vp$	
Storage capacity	$\sum_{k=1}^{K} XSUi_{kis} + XSi_{kis} \leq CASi_{i}$	$\forall s$
	$\sum_{k=1}^{K} XSUt_{kis}^{O} + XSt_{kjs}^{O} \leq CAST_{j}^{o}$	$\forall j \forall o \forall s$

7.3.4. Minimum treatment constraint

The minimum amount to treat must either be a predetermined value by the producer or mandated by the government. If there are none, then the value on the right-hand side of the constraint may be 0. This was based on the study of Sheu [32]. As mentioned earlier, the amounts treated by the group facilities and third party facilities will be divided based on the number of members or customers. Thus only the share of the producer in the output of the facilities will be considered in meeting the minimum amount to treat. *(16)* shows the expression minimum treatment constraint.

To force the model meet the demand, there will be a penalty imposed on the deviations (EXDT or NXDT) for the minimum treatment. This is the difference between the constraint of Sheu [32] and that of this study.

$$\sum_{O} \frac{1}{C_O} \left(\sum_{k=1}^{K} \sum_{j=1}^{J} EXTt_{kj}^{O} \right) EXDT + NXDT = \max\{MTb, MTg, 0\} \tag{16}$$

7.3.5. Demand constraint

$$\sum_{k=1}^{K} percent_{vk} \left[\sum_{O} \frac{1}{C_O} \left(\sum_{j=1}^{J} EXUt_{kj}^{O} \right) + EXUi_{ki} \right] + EXDU_{v} + NXDU_{v} = DU_{v}$$

Amounts delivered to the producer's plant must be greater than or equal to the demand. Failing to meet the demand (DU_v) will incur costs. The deviation is placed in the objective functions to be able to minimize the incurred costs.

7.3.6. Expected values

Since this is a reverse logistics model, the supply will be highly uncertain. To handle this, the method used by Kara and Onut [31] was used where they input the different possible values of the supply and multiplied these with their respective probabilities to get the expected values.

For the decision variables the expected value can be computed by multiplying the probabilities of each scenario to the values placed to these variables and then adding them together. Table 4 shows the expressions for the expected value constraints

Table 4 Expected value constraints

Constraint	Expression	
Expected amount to treat in IWS sites	$EXTi_{ki} = \sum_{s=1}^{S} P_s\, XTi_{kis}$	$\forall i \forall k$
Expected amount of unprocessed e-waste to store in IWS sites	$EXSUi_{ki} = \sum_{s=1}^{S} P_s\, XSUi_{kis}$	$\forall i \forall k$
Expected amount to be delivered from IWS sites to treatment facilities	$EXD_{kij}^{O} = \sum_{s=1}^{S} P_s \sum_{O} \sum_{j=1}^{J} XD_{kijs}^{O}$	$\forall i \forall k$
Expected amount of extracted materials to be stored in IWS sites	$EXSi_{ki} = \sum_{s=1}^{S} P_s\, XSi_{kis}$	$\forall i \forall k$
Expected amount of extracted materials to be utilized to meet demand	$EXUi_{ki} = \sum_{s=1}^{S} P_s\, XUi_{kis}$	$\forall i \forall k$
Expected amount to treat in treatment facilities	$EXTt_{kj}^{O} = \sum_{O} \sum_{s=1}^{S} P_s XTt_{kjs}^{O}$	$\forall j \forall k \forall o$
Expected amount of unprocessed e-waste to store in IWS sites	$EXSUt_{kj}^{O} = \sum_{O} \sum_{s=1}^{S} P_s XSUt_{kjs}^{O}$	$\forall j \forall k \forall o$
Expected amount of extracted materials to be stored in treatment facilities	$EXSt_{kj}^{O} = \sum_{O} \sum_{s=1}^{S} P_s XSt_{kjs}^{O}$	$\forall j \forall k \forall o$
Expected amount of extracted materials to be utilized to meet demand	$EXUt_{kj}^{O} = \sum_{O} \sum_{s=1}^{S} P_s XUt_{kjs}^{O}$	$\forall j \forall k \forall o$
Expected amount to be disposed of in IWS sites	$EXFi_{ki} = (1\text{-}a_k)EXC_{ik} + (1\text{-}ei_k)EXTi_{ik}$	$\forall i \forall k$
Expected amount to be disposed of in treatment facilities	$EXFt_{kj}^{O} = (1\text{-}ej_k)EXTt_{kj}^{O}$	$\forall j \forall o \forall k$
Expected number of vehicles to be used for transportation from IWS sites to treatment facilities	$EXV_{ij}^{O} = \sum_{O} \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{j=1}^{J} EXD_{kij}^{O} / VLj$	
Expected number of vehicles to be used for transportation from treatment facilities to producer's plant	$EXVjp_j^{o} = \sum_{O} \sum_{j=1}^{J} \sum_{k=1}^{K} EXUt_{jk} / VLp$	
Expected number of vehicles to be used for transportation from IWS sites to producer's plant	$EXVip_i = \sum_{i=1}^{I} \sum_{k=1}^{K} EXUi_{ik} / VLp$	
Expected amount of waste to be disposed after treatment in IWS sites	$EPBXF_{ki} = (1\text{-}ei_k)EXTi_{ki}$	$\forall k \forall i$

7.4. Goal programming

Since the model is a multi-objective model, goal programming will be used to solve it. Goal programming is branch of multi-objective optimization. It is a way to make a decision based on multiple criteria. For this study, the goals are to minimize the aggregated economic, environmental and health costs incurred by the producer (goal function 1) and economic profit of the informal waste sector (goal function 2). It is possible to place them both under a single value; however, this may not assure that all goals are truly minimized. The aim of goal programming is to minimize the unwanted deviations from the aspiration levels. The aspiration level is the value of a goal function that the user of the model aspires to or would like to achieve. These unwanted deviations are added together and their sum will be minimized.

$$\textbf{Minimize } D_1^+ + D_1^- + D_2^+ + D_2^- \dagger$$
$$\textbf{Goal Function 1} - D_1^+ + D_1^- = \textbf{Aspiration Level of Goal Funtion 1}$$
$$\textbf{Goal Function 2} - D_2^+ + D_2^- = \textbf{Aspiration Level of Goal Funtion 2}$$

For Archimedean and Non-Archimedean goal programming, aspiration levels are estimated. In the Chebyshev goal programming, the aspiration levels are obtained by prioritizing each of the goal functions one by one. The prioritization is done by ignoring the other goal functions first and placing the prioritized goal function as the objective function. The value of this prioritized goal function will be its best possible value without considering the other goal functions. This best possible value is then used as the aspiration level.

With the exception of the Chebyshev goal programming, other goal programming methods place weights to the unwanted deviations. Since the two objectives (cost incurred by the informal waste sector and cost incurred by the producers) are equally important, no weight will be placed on the two deviations. Although, one could also multiply each of the two deviations with 0.5, this may distort the results because the values of the deviations will then be decreased so the model may interpret that it may continue to deviate from the best possible value since a deviation of 1 is only equal to 0.5 in the objective function.

Thus the goal constraints for this study are shown in *(17)* and *(18).*

$$\text{PrCost-}D_1 = \text{PrCost}' \qquad (17)$$
$$\text{IWSProfit}+D_2 = \text{IWSProfit}' \qquad (18)$$

PrCost' and IWSProfit' are the best possible values of the different goals. D_1 and D_2 are the deviations from the best possible values that will be minimized. The constraints are less than constraints because the whole model is a minimization problem.

The deviation to be considered for the producer's goal is the negative deviation. This is the one to be minimized because the larger the negative deviation necessary to meet the best possible value, the larger the cost is incurred by the producer.

On the other hand the deviation to be considered for the IWS sites goal is the positive deviation. This is to be minimized because the larger the positive deviation necessary to meet the best possible value, the smaller the profit gained.

Finally, the goal programming objective function will be:

$$\text{MINIMIZE } D_1+D_2.$$

As the value of the sum of D_1 and D_2 decreases, the values of the two objectives becomes closer to their best possible values

8. Sensitivity Analysis

GAMS IDE 2.0. 26.8 was used to run the mathematical model to do sensitivity analysis.

The basic purpose of sensitivity analysis is to see what happens to the system if some of the parameters no longer hold true or change.

A design of experiments full factorial was done for the sensitivity analysis. The purpose of the design of experiments was to see how the objective function and the decisions changed as the parameters (those mentioned in Section 5) changed.

It is more likely that more than one of the parameters will change thus it is important to see the effect of these multiple factor changes. A simple one-factor-at-a-time approach would not have sufficed because this would not have shown the interaction of factors. Resolution V was used because no main effect or two-factor interaction is aliased with any other main effect or two-factor interaction, but two-factor interactions are aliased with three-factor interactions. The study no longer concerned itself with the higher-order interactions because of the sparsity of effects principle where the system is likely to be driven primarily by some of the main effects and low-order interactions.

† Only one of the D_1's will have a value and only one of the D_2's will have a value

One of the objectives of the study was to determine in what scenarios (of the amount of e-waste collected, mandated amounts of e-waste to be treated and amount charged by to the treatment facilities for the collection of e-waste) will the different recovery options be combined to minimize the costs of both stakeholders. The factorial run was used to meet this objective. The succeeding sections will be discussing the results regarding this.

In addition to the design of experiments run, additional runs were done since the experiment did not provide as much insight with regards to the use of the group recovery option and the use of the informal waste sector. In the additional runs, for the four different combinations of supply and mandate, the collect factor vas varied over a wider range and smaller increments. For each set of combinations of supply and mandate, the model was first run using the collect factor values as shown in Table 5. The number of sites used for each of the options including the informal waste sector sites was recorded.

After running the values in Table 5, the behavior of each of the options in terms of the number of sites was observed. The number of sites per option was observed to see at which collect factor it became 0. If the number of sites for the collect factor value prior to this was just 1 or 2, then it was assumed that at collect factor values greater than this, the option was no longer be chosen. If the number of sites for the collect factor value prior to the value where the option became zero was greater than two, the model was run at smaller increments between the former collect factor and the latter collect factor. This was done until it was observed that the number of sites for the options became just 1 or 2.

Table 5 Initial set of collect factor values used for the additional runs

Collect Factor
0
0.05
0.1
0.5
1
1.5
10
15
20

The discussion of the results from the additional runs gave added insight to not only the group recovery option and the use of the informal waste sector but also to the producer recovery option and the third party recovery option.

The succeeding sections will be discussing both the results of the design of experiments and the additional runs.

8.1. Producer recovery option

8.1.1. Results from the design of experiments

For the producer recovery option, supply, mandate and their interaction affect the number of producer option sites chosen. Lower supply makes it favorable for the producer option to be chosen. Since the all of the treatment done in the producer option sites can be credited to the producer, the use of this option during low supply and high mandate would be a logical choice. This is to minimize the deviations from mandated amounts of treatment as well as its accompanying penalty cost. Other options would divide the credit for amount treated requiring a higher supply of e-waste.

8.1.2. Results from additional runs

Fig. 5 shows that after a collect factor of 1000% (collect factor of 10) or charging the treatment facilities 1000% of what the IWS sites would normally earn if they were able to sell the extracted materials from sorted e-waste to the producers, the producer option is no longer favorable to use. This 1000% is actually already equivalent to the economic penalties for deviation from demand[‡] since the revenue earned by the IWS sites is 10% of the penalties[§]. This is because the producer's would rather incur the penalties for deviation from demand and deviation from mandated amounts to treat rather than pay the penalties where they would actually be able to already get the materials as compared rather than pay a price only for collection and they would still have to pay for the extraction and the large investment on a treatment plant.

[‡] Penalties for deviation from demand is also the cost of acquiring virgin raw materials
[§] Economic penalty for deviation from demand X (0.1 X 10) = Economic penalty for deviation from demand X (1)

The same pattern of no longer using the producer option when the addition to the collection cost (collect factor) is significantly higher than the economic penalty for deviation for demand or basically, what they would normally pay for the virgin raw material that could have been extracted from the e-waste is seen whether the supply and mandate are high or low (as seen Fig. 6 to Fig. 8).

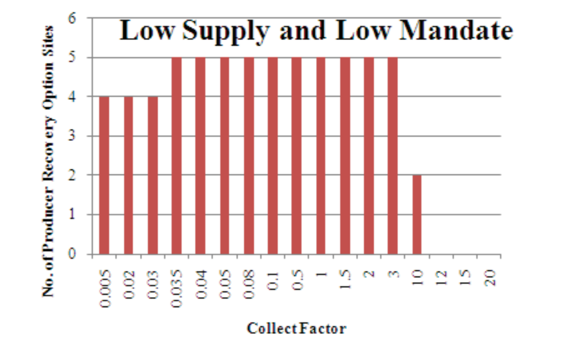

Fig. 5 Effect of increasing the collect factor in low supply and low mandate in the number of producer recovery option sites used

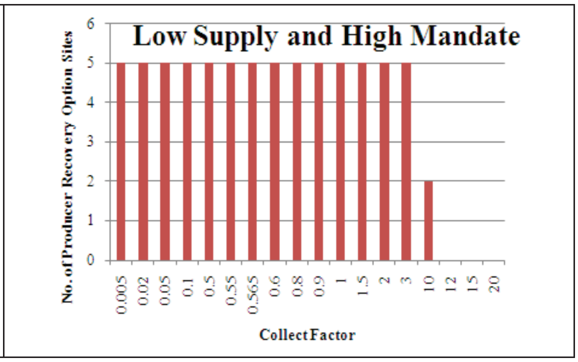

Fig. 6 Effect of increasing the collect factor in low supply and high mandate in the number of producer recovery option sites used

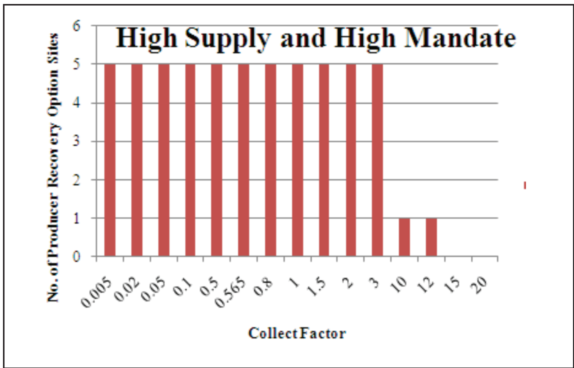

Fig. 7 Effect of increasing the collect factor in high supply and high mandate in the number of producer recovery option sites used

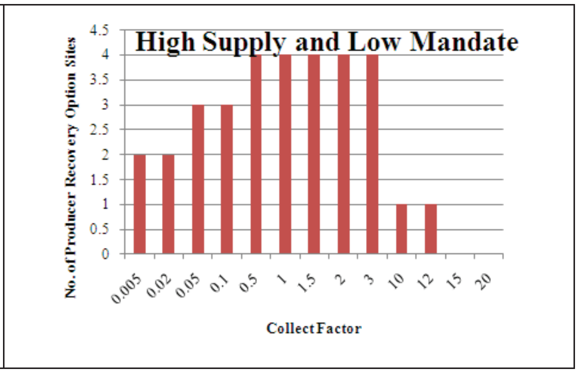

Fig. 8 Effect of increasing the collect factor in high supply and low mandate in the number of producer recovery option sites used

8.2. Group recovery option

8.2.1. Results from the design of experiments

As mentioned earlier, no significant insight was gained for the group recovery option from the design of experiments. It was found that none of the factors varied was significant. Thus, the basis for the group recovery option discussion will only be the additional runs.

8.2.2. Results from additional runs

At low supply and low mandate, it can be seen from Fig. 9 that after a collect factor of 0.0035 or charging the treatment facilities 3.5% of what the IWS sites would normally earn if they were able to sell the extracted materials from sorted e-waste to the producers, the group option is no longer chosen. This is because the group option's treatment is not solely credited to the producer. Although it would have more treatment credited to the producer than the third party option, it does require a high amount of investment, which would increase the costs of the producer. The increasing cost to collect would no longer be worth it beyond a collect factor of 0.0035 because this would be combined with investment cost.

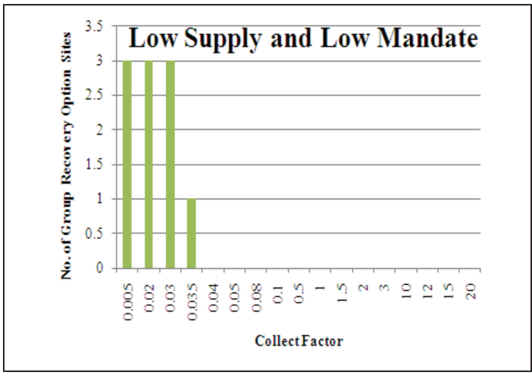

Fig. 9 Effect of increasing the collect factor in low supply and low mandate in the number of group recovery option sites used

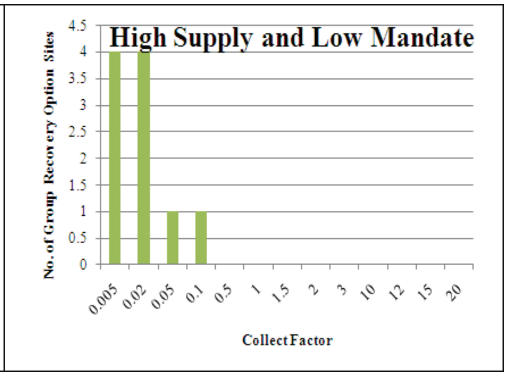

Fig. 10 Effect of increasing the collect factor in high supply and low mandate in the number of group recovery option sites used

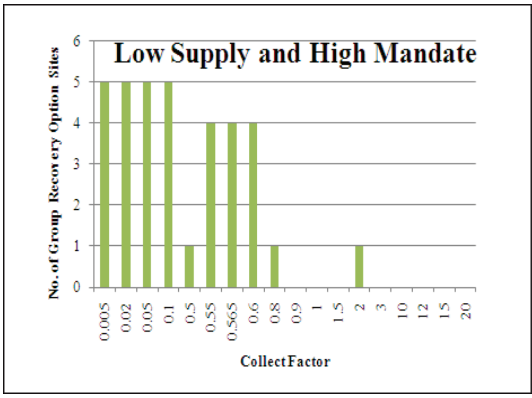

Fig. 11 Effect of increasing the collect factor in low supply and high mandate in the number of group recovery option sites use

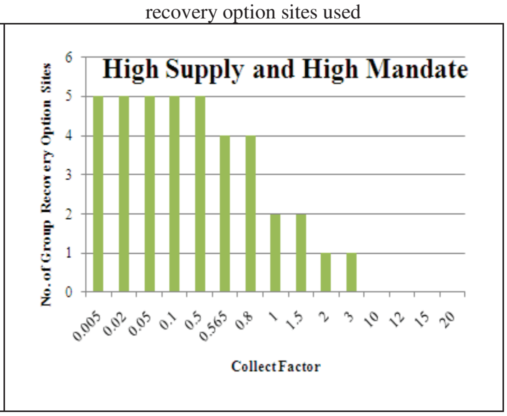

Fig. 12 Effect of increasing the collect factor in high supply and high mandate in the number of group recovery option sites use

8.3. Third party recovery option

8.3.1. Results from the design of experiments

For the third party recovery option, the only significant factor was supply. Generally, higher the supply, the more third party option sites are used. Third parties were assumed to have higher number of member/customers than the group option. This means that the output for the producer and the treatment amounts credited to the producer from the third party will always be less than the other options. This is why there needs to be more IWS sites used in order to meet demands and mandates.

8.2.3. Results from additional runs

The third party recovery option is the opposite of the producer option in terms of investment cost (zero investment), treatment credit and output. The third party recovery option has significantly less of all three.

This is why the third party recovery option is always used for all scenarios and for all ranges of collect factors.

It can be observed though that at high supply, the third party recovery options sites are fully utilized (Fig. 15 and 16). This is in line with the results of the factorial runs where high supply makes it more favorable for this option to be used

This is also in line with the work of Spicer and Johnson [25] who were highlighting the use of the third party recovery option over the other two options. They saw this as the most promising and this study has shown quantitatively how the third party option benefits the e-waste reverse logistics system.

Despite the ability of Spicer and Johnson [25] to see the potential of the third party option, they failed to see that this option generally works in combination with the producer option sites as shown in the results of the factorial run and the additional runs.

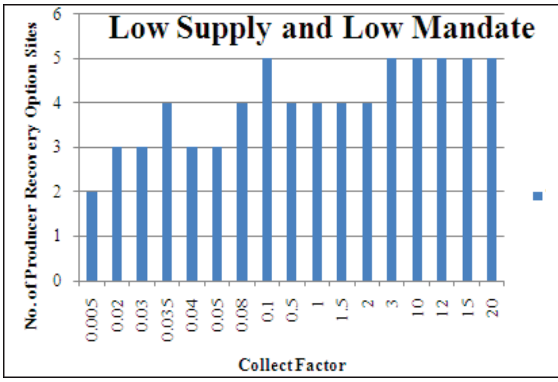

Fig. 13 Effect of increasing the collect factor in low supply and low mandate in the number of third party recovery option sites used

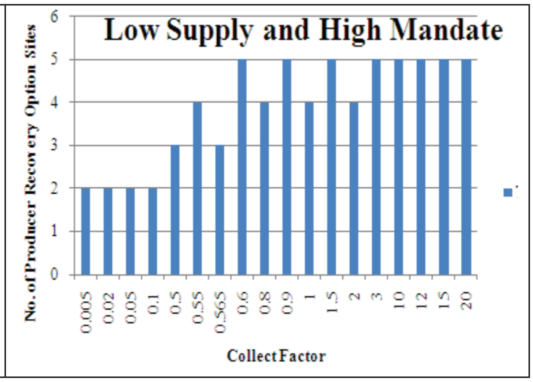

Fig. 14 Effect of increasing the collect factor in low supply and high mandate in the number of third party recovery option sites used

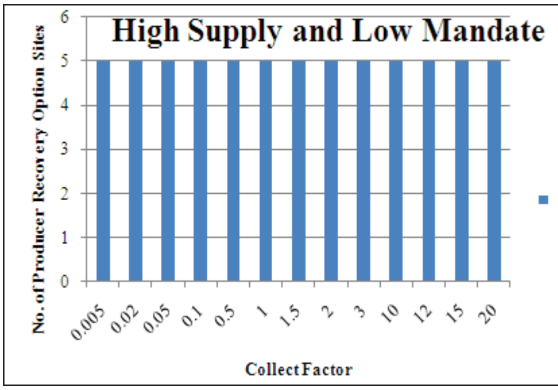

Fig. 15 Effect of increasing the collect factor in high supply and low mandate in the number of third party recovery option sites used

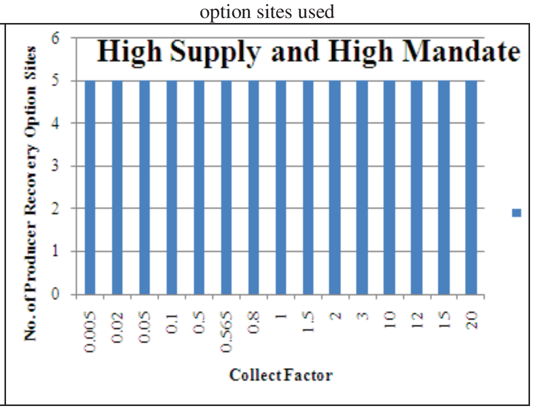

Fig. 16 Effect of increasing the collect factor in high supply and high mandate in the number of third party recovery option sites used

8.4. Use of the informal waste sector for treatment of e-waste

Before proceeding to the discussion of the results for the use of the informal waste sector as treatment facilities, it should be noted that in integration, it is possible to have no integration, partial integration and full integration.

Full integration is when no treatment is done in the IWS sites (making them collection points only). Partial integration is when the IWS sites still do some treatment. The types of integration were based on the observations made during the validation and sensitivity analysis of the model. No integration is when the there are no producer recovery option and group recovery option sites used for treatment. The only sites used for treatment are the informal waste sector sites and the third parties. Third parties are assumed to already be available or will be available since the producers do not have to pay for its investment. Producers may simply choose to use them.

8.4.1. Results from the design of experiments

Based on the design of experiments, the parameters that were studied do not appear to be significant in affecting the use of the IWS sites as treatment facilities. Thus the basis of the discussion for the use of the informal waste sector as treatment facilities will only be the additional runs

8.4.2. Results from additional runs

Fig. 17 to 20 show that even at very low collect factors, there is partial integration because the IWS sites would still be earning back their collection cost and saving on the storage cost.

It was also observed that at low mandate, full integration occurs after at collect factors greater than 0.1 at low mandates while at high mandates, it occurs at collect factors greater than 0.565. A possible explanation for this is that at high mandates, the producer will incur deviations from mandated amounts to treat (due to the limit of the capacities of the treatment facilities). On top of this, they may not also be able to serve all of the demand thus the model chooses to let the IWS sites treat so that some of the demand could be met. This prevents the producer from incurring high penalties for deviation from demand on top of the penalties for deviation from amount to be treated. At low mandates, this is not a concern because the treatment facilities' capacities can meet this mandated amount.

One would expect that that at higher mandates, less treatment would occur in the IWS sites but if the mandates are beyond the capacity of the treatment facilities available, then it this would force the system to use the informal waste sector as treatment facilities. It is therefore suggested to policy makers to ensure that the amounts they mandate producers to treat is within the capacity of the latter's treatment facilities

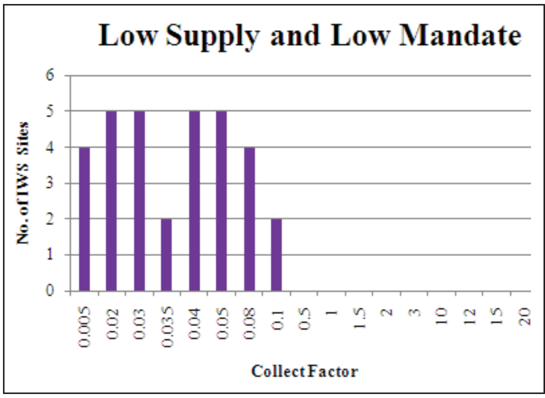

Fig. 17 Effect of increasing the collect factor in low supply and low mandate in the integration of IWS sites

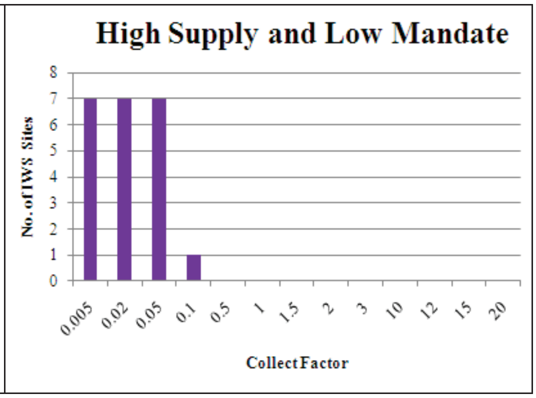

Fig. 18 Effect of increasing the collect factor in high supply and low mandate in the integration of IWS sites

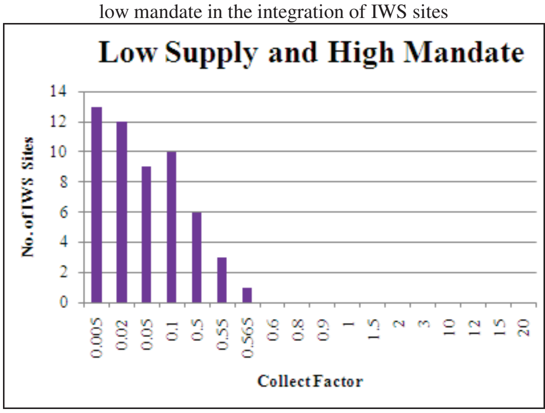

Fig. 19 Effect of increasing the collect factor in low supply and high mandate in the integration of IWS sites

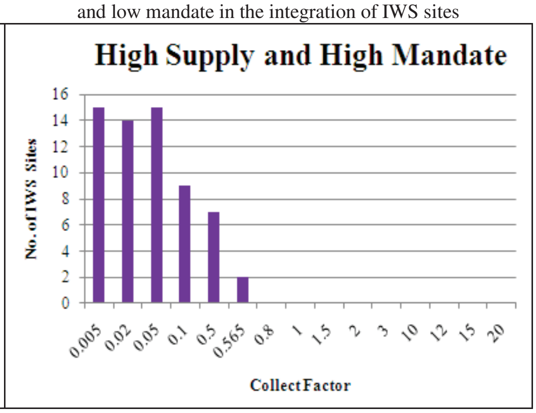

Fig. 20 Effect of increasing the collect factor in high supply and high mandate in the integration of IWS sites

8.4.3. No integration

From the results of the additional runs, the scenario of no integration was not seen. However, it was believed by the researchers that it is possible for no integration to occur when the penalties incurred are lower than the cost of opening a facility for treatment. As mentioned earlier, no integration happens when no facilities are opened (for producer recovery and group recovery options) and treatments are only done in the informal waste sector and third parties.

To show that it is possible, penalty for deviation from demand was significantly lowered (it was lowered from $10,000/kg to $1/kg of deviation from mandated amounts of treatment). The lead penalties which were also very large ($1000/kg of lead emitted) were changed to $10/kg of lead emitted. The greenhouse gas penalty was no longer lowered because this was already quite low at $0.025/kg of greenhouse gas emitted. These were done in the scenario of high supply and high mandate and low supply and high mandate. High mandate was used to see in the scenario of high supply and high mandate and low supply and high mandate. High mandate was used to see if no integration will happen even at a high chance of not meeting the treatment mandate.

Fig. 21 shows what happens to the costs when the values for the penalty parameters were changed. The costs of opening recovery sites for the producer and group options are higher than the penalties that the producer would incur. This results to no integration since no facilities are opened by the producer (using the producer or group option)

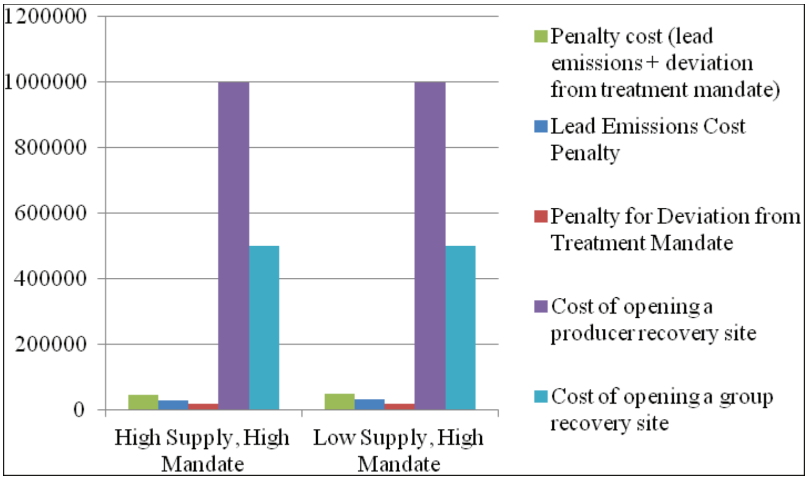

Fig. 21 Comparison of the cost of opening recovery sites/facilities to the incurred penalty costs for not opening the treatment facilities

8.5. Combination of options

The possibility of combining options was explored in this study. The model was allowed to run until the global optimum was reached (optimality gap of 0). There were several scenarios where all the sites for each of the options were not fully used. Instead, there was a combination of options. From here, it can be said that combining options would be beneficial not only economically but also in terms of the environment and the human health.

Generally, the third party recovery option should be used as often as possible considering its very low investment cost. This combination is generally combined with the producer option. However, at a collect factor greater than 10 or at a collection mark up greater than the cost of the virgin raw materials, the third party option will be the only one to be chosen because to invest on treatment facilities at such high collection costs would be more expensive than incurring the penalties (for deviation from demand and deviation for treatment).

The group option is used generally used for low collect factors most especially at low mandates (a collect factor of less than one). For high mandates, it can be used and combined with the producer and third party option until a collect factor of 3 (3 times what the IWS sites would normally earn if they extracted the raw materials from the e-waste or 30% of the cost to purchase the virgin materials).

The IWS sites will be used (or partial integration will happen) a collect factor or 0.1 for low mandates and until a collect factor of 0.565 for high mandates. At collect factors higher than these, full integration will happen.

Table 6 shows a summary of when the combinations can be done based on the sensitivity analysis

Table 6 Scenarios when combination of options can be done

Combination	Scenarios			
	Low Supply Low Mandate	High Supply Low Mandate	Low Supply High Mandate	High Supply High Mandate
Combination of all 4 options	Until a collect factor of 0.035	Generally, until a collect factor of 0.8	Until a collect factor of 0.1	Until a collect factor of 0.565
Combination of producer, group and third party	---	---	Until a collect factor of 2	Until a collect factor of 3
Combination of producer, third party and IWS	Until a collect factor of 0.1	Until a collect factor of 0.1	---	---
Combination of producer and third party	Generally until a collect factor of 10			

8.6. Effects on the environment and human health

The aim of integration is not only for economic benefits but also environmental. Fig. 22 and 23 show how increasing the collect factor affects the GHG emissions cost and lead emissions costs (caused by the informal waste sector). It can be seen that increasing the collect factor benefits the environment because the IWS sites are more willing to integrate fully into the reverse logistics system.

The lead emissions cause by the informal waste sector was the only one considered because the lead emissions caused by the producers are highly theoretical since the lead emission penalties for deviation for demand were hypothetical. On the other hand, the lead emissions by the informal waste sector were estimated from real data. It's also important to see this because as discussed earlier, emissions of hazardous substances such as lead in the informal waste sector could greatly affect their health. This study has shown that through integration and (through the increase of the collect factor) the exposure of those in the informal waste sector to hazardous substances such as lead could be decreased which would benefit their health.

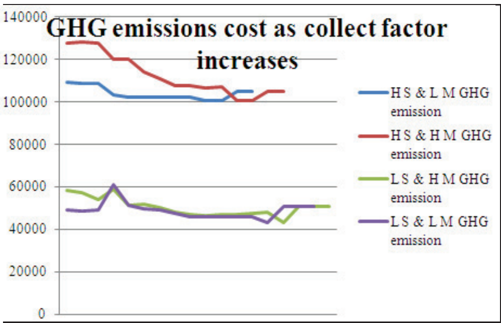

Fig. 22 Greenhouse gas emissions cost as the collect factor increases

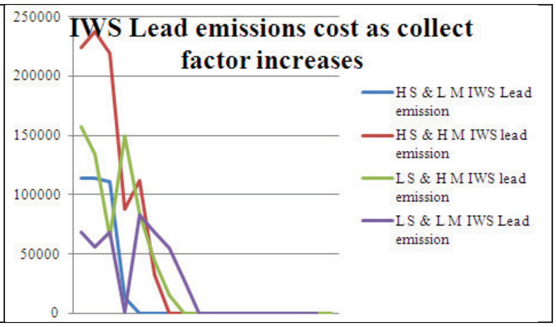

Fig. 23 Lead emissions cost caused by the Informal Waste Sector Sites as the collect factor increases

9. Conclusions and Recommendations

9.1. Conclusions

The use of treatment facilities in the countries with informal waste sectors would bring about significant improvements. These significant improvements are not only gained by the informal waste sector whose exposure to hazardous substances (such as lead) decreases but also for the formal e-waste sector or the producer who will have to rely less on virgin materials.

Only three of the several parameters were considered in the sensitivity analysis. These are the amount of e-waste collected, the amount that the informal waste sector would charge for their collection services and the mandated amounts to be treated.

The full factorial run provided insight regarding the relationships of the parameters to the objective functions and when certain options should be used.

The producer recovery option is best used for low supply and is also used until the collection cost is equivalent to the actual cost of obtaining the virgin raw materials. It is the best for low supply because the amounts treated in the producer option are all credited to the producer thus the mandate is easily met and the penalties for deviating from mandate are avoided. To use other options would lead to a division of credit for treating the already low amounts of e-waste. To charge the producer option sites with a collection cost mark up greater than the actual cost of obtaining the virgin raw materials would no longer make the investment worthwhile. They could just buy virgin raw materials and save their investment funds for the penalties to be incurred.

The ***third party option can be used for all scenarios and is generally combined with the producer option. The third party option was used in every run during the factorial runs.*** This was even used when none of the other options were being used. This supports Spicer and Johnson's [25] belief that the use of third parties for extended producer responsibility is the most promising. This option does greatly benefit both stakeholders. This option takes away the treatment activities from the IWS sites without causing them to lose the opportunity to make profits. The option also benefits the producer because there are no investment costs which makes up a significant portion of the economic costs of the producer in the reverse logistics system.

The group recovery option can generally be used only until a collection cost of 30%of the actual cost of obtaining the virgin raw materials (or a collect factor of 3).

There are two types of integration: partial and full. This was observed during the several runs of the model where there were times when the treatment facilities still treated despite being part of the reverse logistics system (partial integration) and times when they served only as collection and sorting sites (full integration).

Partial integration is achieved so long as the collection mark up is greater than zero.

Full integration can be achieved through a collection mark up of greater than 1% of the actual cost of obtaining the virgin raw materials for low mandates (a collect factor of 0.1) and 5.65% (a collect factor of .565) for high mandates.

No integration occurs when the penalty costs are lower than the investment cost to open a single facility for either producer or group recovery option.

Increasing mandated amounts to treat may not necessarily prevent treatments from being done in the informal waste sector. It was found that if the mandated amount to be treated is greater than the capacities of the treatment facilities, the producer will opt to use the informal waste sector to decrease the penalties incurred from deviation of demand which would make up for the penalties to be incurred from the deviation from mandated amounts to be treated.

Increasing the collection mark up charged to treatment facilities for the collection services of the informal waste sector encourages full integration and benefits the environment and human health. It was observed that as the collection factor or collection mark up charged to treatment facilities for the collection services of the informal waste sector, the less informal waste sector sites were used as treatment facilities. This benefited both the environment and human health because the informal waste sector has higher emissions of greenhouse gases and lead (or any other hazardous substance) when they treat.

9.2. Recommendations

The following are the recommended areas for future study in the field of reverse logistics and e-waste in the informal waste sector:

- Considering other methods such as robust programming to handle the uncertainty in reverse logistics and see the effect of this in the recovery options chosen
- Including social aspects such as job employment/generation to make the study not simply be geared towards eco-efficiency (economic and environmental issues only) but towards sustainability (economic, environmental and social aspects)
- A method for converting all hazardous substances to an equivalent hazardous substance similar to how all greenhouse gases are converted to their equivalent carbon dioxide amounts. This will allow a better approximation of the hazardous substances emitted to the environment and those affecting the human health.
- Use the model as a way to create thresholds of acceptable values for uncertain parameters. Some of the parameters in the model used real data or a realistic estimate of the data. The uncertain parameters could be varied while the realistic data could be held constant to see how small or how large the values of the uncertain parameters could be before they are deemed unacceptable. An example would be given that the penalty for greenhouse gas emissions is known, what could be the maximum distance of a treatment facility is before it will no longer be considered as a viable option?

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