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# Optimizing an E-Waste Reverse Supply Chain Model while Incorporating Risk Costs

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**Abstract:** The rapid growth of Electronic Waste (E-waste) in recent years has created serious influences on the environment and society. The highly potential solution to mitigate this issue is the Reverse Supply Chain (RSC) which can reuse and recover E-waste materials. Risks generally derive from a RSC operation such as collection, transportation and treatment risks, but most studies ignore risk effects on the total cost of E-waste treatment in the RSC model. This paper aims to develop a mathematical model for an E-waste RSC considering risk costs. This proposed model applied mixed integer linear programming and solved by a mathematical programming language. An illustrative example is examined to demonstrate the effectiveness of the proposed model. Sensitive analysis is also presented. The results can determine the optimal locations of facilities and the flow of materials or items in a RSC network. Furthermore, the network design decisions have been changed considerably while risk costs are incorporated.

**Keywords:** Mixed Integer Linear Programming, Supply Chain Management, Reverse Logistics, Risk Costs

## Introduction

Due to technological advancements, customers seem to purchase the latest electronics inventions more frequently than ever. According to (Kumar *et al*., 2017), the quantum of E-waste has generated around 14 million tonnes in 2014 and growing from 3 to 5% annually. Around 50 to 80% of E-waste from industrialized countries is sent to poor countries due to lower labor cost and less strict environmental regulations (Namias, 2013). For example, this would be the main reason why a number of old computers in the developing countries is forecasted to be doubled (around 600 million products) compared to the developed nations (nearly 300 million units) by 2030 (Yu *et al*., 2010).

E-waste contains valuable materials like gold, copper, silver (Kang and Schoenung, 2005; Chancerel *et al*., 2009) while it also comprises hazadous substances such as lead, cadmium, mercury and hexavalent chromium (Saphores *et al*., 2012; Phuc *et al*., 2013). To mitigate the quantity of E-waste delivering to landfills and recover useful materials, manufacturers have focused on 3R approaches (Reuse, Recycle and Remanufacture) across the Reverse Supply Chain (RSC) on E-waste management (Kuik, 2013; Nagalingam *et al*., 2013; Kuik *et al*., 2011). RSC is a set of activities required to recover a returned product from a consumer and reuse or dispose it (Van Wassenhove, 2002). RSC operation can bring many advantages for companies such as the competence of enterprises, customer satisfaction and cost reduction (Choy *et al*., 2011; Pishvaee *et al*., 2010).

One of the potential solution to treat end-of-life products is RSC which has been attracted an increasing number of research activies (Sinha-Khetriwal *et al*., 2005; Saphores *et al*., 2012; Bouvier and Wagner, 2011; Li and Tee, 2012; Nagurney and Toyasaki, 2005; Kilic *et al*., 2015; Grunow and Gobbi, 2009; Shih, 2001; Menikpura *et al*., 2014; Niknejad and Petrovic, 2014; Rajagopalan and Liles, 2006; Amer *et al*., 2011). Most studies mainly consider the total cost for processing end-of-life products across RSC (Achillas *et al*., 2010; Dat *et al*., 2012; Phuc *et al*., 2013; Niknejad and Petrovic, 2014; Demirel *et al*., 2016; Fleischmann *et al*., 2001) and apply Mixed Integer Linear Programming (MILP) formulation to their models (John *et al*., 2017). An earlier study about the Reverse Logistic (RL) network for secondary containers using (Kroon and Vrijens, 1995). MILP is investigated by Achillas *et al*. (2010) suggested a RL network for E-waste and focused on the optimization of total cost. The model developed MILP and solved through A Mathematical Programming Language (AMPL). The cost elements taken into account in this model are transportation cost, operation cost and fixed cost. A real case study in Greece was obtained to validate the model. The authors suggested that incentives to consumers need to be considered to encourage a number of old products returned. This model is effective for addressing medium to small scale problems since the number of binary variables is limited. Dat *et al*. (2012) proposed MILP to address a multiple-echelon RL model of multiple types of E-waste. The issue is modeled by applying AMPL and then addressed by CPLEX software. This model can determine the feasible locations for constructing facilities and material flows in RL network. Mahmoudi and Fazlollahtabar (2014) suggested a multi-product RSC with considering the total costs involving shipping, fixed, operation, supply maintenance and remanufacturing costs. Kilic *et al*. (2015) proposed a RL system of E-waste in Turkey with 10 different scenarios of collecting rates. MILP was used to minimize total cost of RSC. Compared to the other existing researches, the model considered different categories of storage and recycling centres. Demirel *et al*. (2016) introduced a RSC model for end-of- life vehicles in Turkey to optimize the total cost for the recovery operation.

Based on the literature review, most studies mainly focus on transportation, fixed and operation costs and income from recovery materials to minimize the total cost of a RSC operation. Unfortunately, risks are largely not considered in the RSC models and having a significant influence on RSC costs (Sheu, 2007). Risks generally happen at treatment facilities and shipping activities because of a variety of hazardous materials contained in E- waste (Fabiano *et al*., 2002; Ho *et al*., 2009; Wilson, 2007). In addition, waste generation is uncertain which can cause risks for collecting areas (Ahluwalia and Nema, 2006). Therefore, the current models are inadequate for representing the RSC system for E-waste. Hence, this paper focuses on a comprehensive RSC model to minimize the overall cost for E-waste treatment incorporating risk costs. This proposed model can be considered as a useful tool for decision makers.

The rest of the paper is organized as follows; Section 2 presents the proposed mathematical model while a numerical example to demonstrate the possibility of the proposed model is addressed in Section 3. Results and discussion are provided in Section 4. The sensitive analysis is presented in Section 5. Finally, in Section 6 conclusions and possibilities for future research are elaborated.

## Proposed Model for E-Waste Reverse Supply Chain

To overcome the literature gap presnted in Section 1, the proposed model aims to develop a mathematical model for an e-waste RSC model to minimize the total cost. The key difference of the proposed model to other existing models is that risk costs are included across RSC. Risks generally stem from factors such as supply risks, transportation disruptions, or technological issues in RSC (Sharma *et al*., 2012; Gu and Gao, 2012) and might affect the flow of materials in the RSC network. In this model, risks are considered at collection and treatment facilities and transportation between sites in the proposed E-waste RSC. The proposed model focuses on the development of a multi-layer RSC network for multi-products which include four stages as shown in Fig. 1. Firstly, returned products are collected from collection areas (A in Fig. 1) such as stores selling the appliances and designed collection sites by classified groups. They are then sent to dismantling facilities (B). Secondly, after receiving the returned products from collection areas, the main task of this stage is to separate these products into fractions and determine which items (or parts) should be transported to the right centers. For example, toxic materials or hazardous items are then transported to landfill sites (G). Some damaged or broken components are transported to refurbishing facilities (C). The rest of components in need of further treatment are sent to recycling facilities (D). The third stage involves recycling and refurbishing facilities receiving components from dismantling facilities. Damaged components will be treated at refurbishing facilities. In recycling facilities, certain parts such as plastic, ferrous metals and non-ferrous metals will be recycled while toxic substances such as mercury, lead, mercury and barium will be delivered to landfills. The fourth layer consists of landfill sites, material and secondary markets. The recycled materials will be sent to material markets while the secondary markets include directly reusable components and upgraded items. The dangerous or non-recyclable materials will be sent to landfill sites.

Based on this four stage RSC, a mathematical model is developed to find the total cost across the entire RSC, some assumptions are necessary to be made and listed in the below:

- The locations of collecting returned products, landfill sites, material and secondary markets are decided in advance
- The capacities of facilities are limited
- The unit transportation cost is related to the distance traveled
- The likelihood of accidents happening and the loss of such accidents are predetermined

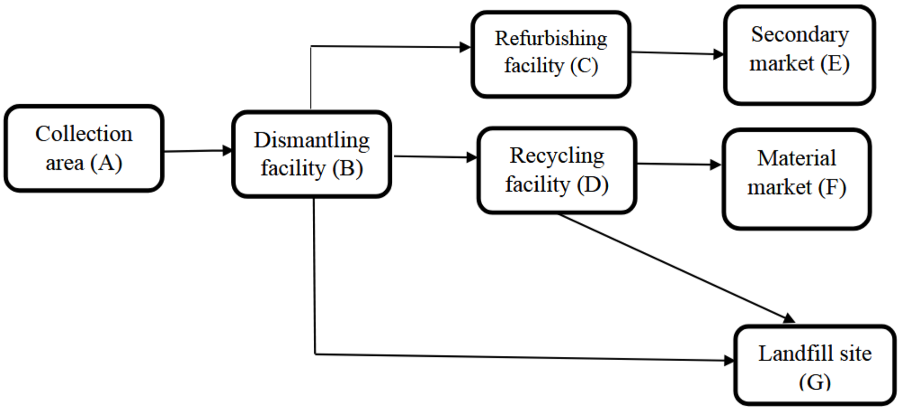


**Fig. 1:** The proposed reverse supply chain for E-waste

The notations and the mathematical model are described below:

*Indexes:*

- $a$ Fixed locations of collection areas, $a \in \{1..A\}$
- b Potential locations of dismantling facilities, $b \in \{1..B\}$
- $c$ Potential locations of refurbishing facilities, $c \in \{1..C\}$
- $d$ Potential locations of recycling facilities, $d \in \{1..D\}$
- $e$ Fixed locations of secondary markets, $e \in \{1..E\}$
- $f$ Fixed locations of material markets, $f \in \{1..F\}$
- $g$ Fixed location of the landfill site, $g \in \{1..G\}$
- $h$ Returned products, $h \in \{1..H\}$
- $i$ Recycling materials, $i \in \{1..I\}$
- $j$ Reusable items, $j \in \{1..J\}$
- $k$ Hazardous materials, $k \in \{1..K\}$
- $n$ Non-recyclable materials, $n \in \{1..N\}$

*Decision Variables*

- $V1_{hab}$ The volume of returned product $h$ delivering From collection area $a$ to dismantling facility $b$
- $V2_{jbc}$ The volume of reusable item $j$ delivering from dismantling facility $b$ to refurbishing facility $c$
- $V3_{ibd}$ The volume of recycling material $i$ delivering from dismantling facility $b$ to recycling facility $d$
- $V4_{kbg}$ The volume of hazardous or disposal material $k$ delivering from dismantling facility $b$ to landfill site $g$
- $V5_{jce}$ The volume of reusable item $j$ delivering from refurbishing facility $c$ to secondary market $e$
- $V6_{idf}$ The volume of recycling materials $i$ delivering from recycling facility $d$ to material market $f$
- $V7_{ndg}$ The volume of non-recyclable material $n$ delivering from recycling facility $d$ to landfill site $g$
- $E_b$ Binary variable, $E_b = 1$ if a dismantling facility is constructed at location $b$; $E_b = 0$ otherwise
- $E_c$ is Binary variable, $E_c = 1$ if a refurbishing facility constructed at location $c$; $E_c = 0$ otherwise
- $E_d$ Binary variable, $E_d = 1$ if a recycling facility is constructed at location $d$; $E_d = 0$ otherwise

*Parameters:*

- $H_{ha}$ The need of returned product $h$ at collection area $a$, $h \in \{1..H\}$, $a \in \{1..A\}$
- $SH_h$ The unit shipping cost of returned product $h$
- $SI_i$ The unit shipping cost of recycling material $i$
- $SJ_j$ The unit shipping cost of reusable item $j$
- $SK_k$ The unit shipping cost of hazardous material $k$
- $SN_n$ The unit shipping cost of non-recyclable material $n$
- $FC_b$ Fixed cost for constructing dismantling facility $b$
- $FC_c$ Fixed cost for constructing refurbishing facility $c$
- $FC_d$ Fixed cost for constructing recycling facility $d$
- $DC1_{kg}$ The unit cost for hazardous material $k$ at landfill site $g$
- $DC2_{ng}$ The unit cost for non-recyclable material $n$ at landfill site $g$
- $UJ_{je}$ The unit revenue for reusable item $j$ at secondary market $e$
- $UI_{if}$ The unit revenue for recycling material $i$ at material market $f$
- $CC_h$ Collection cost for returned product $h$
- $OH_{hb}$ The unit operating cost of returned product $h$ at dismantling facility $b$
- $OI_{id}$ The unit operating cost of recycling material $i$ at recycling facility $d$
- $OJ_{jc}$ The unit operating cost of reusable item $j$ at refurbishing facility $c$
- $DT_{ab}$ Distance between collection area $a$ to dismantling facility $b$
- $DT_{bc}$ Distance between dismantling facility $b$ to refurbishing facility $c$
- $DT_{bd}$ Distance between dismantling facility $b$ to recycling facility $d$
- $DT_{bg}$ Distance between dismantling facility $b$ to landfill site $g$
- $DT_{ce}$ Distance between refurbishing facility $c$ to secondary market $e$
- $DT_{df}$ Distance between recycling facility $d$ to material market $f$

$DT_{dg}$ Distance between recycling facility $d$ to landfill site $g$

$\varepsilon 1_{jh}$ The number of units of reusable items $j$ obtained from returned product $h$ at dismantling facilities

$\varepsilon 2_{ih}$ The number of units of recycling material $i$ obtained from returned product $h$ at dismantling facilities

$\varepsilon 3_{kh}$ The number of units of hazardous or disposal material $k$ obtained from returned product $h$ at dismantling facilities

$\alpha 1_d$ The average percentage of recycling material recycled at recycling facility $d$

$\alpha 2_{ni}$ The average percentage of non-recyclable material $n$ obtained from recycling material $i$ at recycling facilities

$MJ_{je}$ Maximum demand of reusable item $j$ at secondary market $e$

$MI_{if}$ Maximum demand of recycling material $i$ at material market $f$

$XK_{kg}$ Maximum capacity for hazardous material $k$ at landfill site $g$

$XN_{ng}$ Maximum capacity for non-recyclable material $n$ at landfill site $g$

$XH_{hb}$ Maximum capacity for returned product $h$ at dismantling facility $b$

$XJ_{jc}$ Maximum capacity for reusable item $j$ at refurbishing facility $c$

$XI_{id}$ Maximum capacity for recycling material $i$ at recycling facility $d$

$L1_{ha}$ Likelihood of occurrence of an accident of collecting returned product $h$ at collection area $a$

$L2_{hb}$ Likelihood of occurrence of an accident of processing returned product $h$ at dismantling facility $b$

$L3_{jc}$ Likelihood of occurrence of an accident of processing reusable item $j$ at refurbishing facility $c$

$L4_{id}$ Likelihood of occurrence of an accident of processing recycling material $i$ at recycling facility $d$

$L5_{ab}$ Likelihood of occurrence of an accident of shipping from $a$ to $b$

$L6_{bc}$ Likelihood of occurrence of an accident of shipping from $b$ to $c$

$L7_{bd}$ Likelihood of occurrence of an accident of shipping from $b$ to $d$

$L8_{bg}$ Likelihood of occurrence of an accident of shipping from $b$ to $g$

$L9_{ce}$ Likelihood of occurrence of an accident of shipping from $c$ to $e$

$L10_{df}$ Likelihood of occurrence of an accident of shipping from $d$ to $f$

$L11_{dg}$ Likelihood of occurrence of an accident of shipping from $d$ to $g$

$I1_{ha}$ The loss of occurrence of an accident of collecting returned product $h$ at collection area $a$

$I2_{hb}$ The loss of occurrence of an accident of processing returned product $h$ at dismantling facility $b$

$I3_{jc}$ The loss of occurrence of an accident of processing reusable item $j$ at refurbishing facility $c$

$I4_{id}$ The loss of occurrence of an accident of processing recycling material $i$ at recycling facility $d$

$I5_{ab}$ The loss of occurrence of an accident of shipping from $a$ to $b$

$I6_{bc}$ The loss of occurrence of an accident of shipping from $b$ to $c$

$I7_{bd}$ The loss of occurrence of an accident of shipping from $b$ to $d$

$I8_{bg}$ The loss of occurrence of an accident of shipping from $b$ to $g$

$I9_{ce}$ The loss of occurrence of an accident of shipping from $c$ to $e$

$I10_{df}$ The loss of occurrence of an accident of shipping from $d$ to $f$

$I11_{dg}$ The loss of occurrence of an accident of shipping from $d$ to $g$

Total cost = collection cost ($C_1$) +constructing cost ($C_2$) +operating cost ($C_3$) + shipping cost ($C_4$) + disposal cost ($C_5$)+ risk costs ($C_6$) – income from selling recovery materials and renew items ($I$).

Cost of collecting returned products at collection areas is given as follow:

$$C_1 = \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times CC_h \tag{1}$$

Cost of constructing treatment facilities (dismantling, recycling and refurbishing facilities) is described below:

$$C_2 = \sum_{b=1}^{B} E_b FC_b + \sum_{c=1}^{C} E_c FC_c + \sum_{d=1}^{D} E_d FC_d \tag{2}$$

Cost of operation at treatment facilities can be calculated as following:

$$C_3 = \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times OH_{hb} + \sum_{j=1}^{J}\sum_{b=1}^{B}\sum_{c=1}^{C} V2_{jbc} \times OJ_{jc} + \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{d=1}^{D} V3_{ibd} \times OI_{id} \tag{3}$$

Shipping cost from one facility to another facility is presented as below:

$$\begin{aligned} C_4 = & \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times DT_{ab} \times SH_h + \sum_{j=1}^{J}\sum_{b=1}^{B}\sum_{c=1}^{C} V2_{jbc} \times DT_{bc} \times SJ_j \\ & + \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{d=1}^{D} V3_{ibd} \times DT_{bd} \times SI_i + \sum_{k=1}^{K}\sum_{b=1}^{B}\sum_{g=1}^{G} V4_{kbg} \times DT_{bg} \times SK_k \\ & + \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{e=1}^{E} V5_{jce} \times DT_{ce} \times SJ_j + \sum_{i=1}^{I}\sum_{d=1}^{D}\sum_{f=1}^{F} V6_{idf} \times DT_{df} \times SI_i \\ & + \sum_{n=1}^{N}\sum_{d=1}^{D}\sum_{g=1}^{G} V7_{ndg} \times DT_{dg} \times SN_n \end{aligned} \tag{4}$$

Disposal cost for discarding non-recyclable and toxic materials can be calculated as:

$$C_5 = \sum_{k=1}^{K}\sum_{b=1}^{B}\sum_{g=1}^{G} V4_{kbg} \times DC1_{kg} + \sum_{n=1}^{N}\sum_{d=1}^{D}\sum_{g=1}^{G} V7_{ndg} \times DC2_{ng} \quad (5)$$

Risk costs ($C_6$) are the cost happening from the probability of any disruptive appearance that might affect a part of the collection, shipping and operation costs at facilities. According to (Sohani and Chaurasia, 2016), the risk qualification can be calculated by multiplying the likelihood of occurrence and the loss. In this research, for instance, the first component of risk costs in Equation 6 presents the risk arising from the collection activity such as uncertain quality of product returns and having an influence on collection cost. Similarly, the second, third and fourth components of risk costs might arise from the undesirable event like less 22 manpower or technological issues during the processing product returns at dismantling, refurbishing and recycling facilities. The rest parts indicate the shipping risks during RSC network.

$$\begin{aligned}
C_6 &= \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times \frac{L1_{ha} \times I1_{ha}}{Max(L1_{ha} \times I1_{ha})} \times CC_h \\
&+ \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times \frac{L2_{hb} \times I2_{hb}}{Max(L2_{hb} \times I2_{hb})} \times OH_{hb} \\
&+ \sum_{j=1}^{J}\sum_{b=1}^{B}\sum_{c=1}^{C} V2_{jbc} \times \frac{L3_{jc} \times I3_{jc}}{Max(L3_{jc} \times I3_{jc})} \times OJ_{jc} \\
&+ \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{d=1}^{D} V3_{ibd} \times \frac{L4_{id} \times I4_{id}}{Max(L4_{id} \times I4_{id})} \times OI_{id} \\
&+ \sum_{h=1}^{H}\sum_{a=1}^{A}\sum_{b=1}^{B} V1_{hab} \times \frac{L5_{ab} \times I5_{ab}}{Max(L5_{ab} \times I5_{ab})} \times DT_{ab} \times SH_h \\
&+ \sum_{j=1}^{J}\sum_{b=1}^{B}\sum_{c=1}^{C} V2_{jbc} \times \frac{L6_{bc} \times I6_{bc}}{Max(L6_{bc} \times I6_{bc})} \times DT_{bc} \times SJ_j \\
&+ \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{d=1}^{D} V3_{ibd} \times \frac{L7_{bd} \times I7_{bd}}{Max(L7_{bd} \times I7_{bd})} \times DT_{bd} \times SI_i \\
&+ \sum_{k=1}^{K}\sum_{b=1}^{B}\sum_{g=1}^{G} V4_{kbg} \times \frac{L8_{bg} \times I8_{bg}}{Max(L8_{bg} \times I8_{bg})} \times DT_{bg} \times SK_k \\
&+ \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{e=1}^{E} V5_{jce} \times \frac{L9_{ce} \times I9_{ce}}{Max(L9_{ce} \times I9_{ce})} \times DT_{ce} \times SJ_j \\
&+ \sum_{i=1}^{I}\sum_{d=1}^{D}\sum_{f=1}^{F} V6_{idf} \times \frac{L10_{df} \times I10_{df}}{Max(L10_{df} \times I10_{df})} \times DT_{df} \times SI_i \\
&+ \sum_{n=1}^{N}\sum_{d=1}^{D}\sum_{g=1}^{G} V7_{ndg} \times \frac{L11_{dg} \times I11_{dg}}{Max(L11_{dg} \times I11_{dg})} \times DT_{dg} \times SN_n
\end{aligned} \quad (6)$$

Income from selling recovery materials and renewable items can be addressed as below:

$$I = \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{e=1}^{E} V5_{jce} \times UJ_{je} + \sum_{i=1}^{I}\sum_{d=1}^{D}\sum_{f=1}^{F} V6_{idf} \times UI_{if} \quad (7)$$

Subject to:

$$\sum_{b=1}^{B} V1_{hab} = H_{ha}, \forall h, a \quad (8)$$

$$\sum_{h=1}^{H}\left(\varepsilon 1_{jh} \times \sum_{a=1}^{A} V1_{hab}\right) = \sum_{c=1}^{C} V2_{jbc}, \forall j, b \quad (9)$$

$$\sum_{h=1}^{H}\left(\varepsilon 2_{ih} \times \sum_{a=1}^{A} V1_{hab}\right) = \sum_{d=1}^{d} V3_{ibd}, \forall i, b \quad (10)$$

$$\sum_{h=1}^{H}\left(\varepsilon 3_{kh} \times \sum_{a=1}^{A} V1_{hab}\right) = \sum_{g=1}^{G} V4_{kbg}, \forall k, b \quad (11)$$

$$\sum_{b=1}^{B} V2_{jbc} = \sum_{e=1}^{E} V5_{jce}, \forall j, c \quad (12)$$

$$\sum_{f=1}^{F} V6_{idf} = \alpha 1_d \sum_{b=1}^{B} V3_{ibd}, \forall i, d \quad (13)$$

$$\sum_{i=1}^{I}\left(\alpha 2_{ni} \times \sum_{b=1}^{B} V3_{ibd}\right) = \sum_{k=1}^{K}\sum_{g=1}^{G} V4_{kdg}, \forall d \quad (14)$$

$$\sum_{a=1}^{A} V1_{hab} \le E_b \times XH_{hb}, \forall h, b \quad (15)$$

$$\sum_{b=1}^{B} V2_{jbc} \le E_c \times XJ_{jc}, \forall j, c \quad (16)$$

$$\sum_{b=1}^{B} V3_{ibd} \le E_d \times XI_{id}, \forall i, d \quad (17)$$

$$\sum_{k=1}^{K}\sum_{b=1}^{B} V4_{kbg} + \sum_{n=1}^{N}\sum_{d=1}^{D} V7_{ndg} \le XK_{kg} + XN_{ng}, \forall g \quad (18)$$

$$\sum_{c=1}^{C} V5_{jce} \le MJ_{je}, \forall j, e \quad (19)$$

$$\sum_{d=1}^{D} V6_{idf} \le MI_{if}, \forall i, f \quad (20)$$

$$E_b, E_c, E_e : binary \quad (21)$$

$$V1_{hab}, V2_{jbc}, V3_{ibd}, V4_{kbg}, V5_{jce}, V6_{idf}, V7_{kdg} \ge 0 \quad (22)$$

In the proposed model, the main objective is to minimize the total cost from (1)-(7). Constraint (8) ensures all returned products are collected from collection areas. The outcomes of dismantling facilities are presented by constraints (9)-(11). Constraints (12)-(14) make sure the flow equivalence at different kinds of facilities. Constraints (15)-(18) require that the total quantity of items or components at dismantling, refurbishing, recycling facilities and landfill sites do not exceed the maximum capacity of these facilities. Constraints (19)-(20) guarantee that the amount of items do not exceed the maximum demand of material and secondary markets. Constraints (21)-(22) represent the binary and non-negative variables.

## Numerical Example

This section presents a numerical example to verify the proposed model. In most situation, the size of the reality issue is usually enormous so the process of calculating seems to be difficult to verify the proposed model. Therefore, the size of the suggested problem is considerably chosen to help the readers to simplify the proposed model easily. This model considers two types of returned products. The size of the proposed model and relevant parameters are shown in Table 1-15 adopted from (Dat *et al*., 2012; Phuc *et al*., 2013) with a small adjustment to suit the suggested model. The likelihood score and the loss score of accident occurrence are generated with a scale of 1 (lowest) to 10 (highest) adopted from (El Dabee *et al*., 2014).

**Table 1:** The size of the proposed problem

| *A* | *B* | *C* | *D* | *E* | *F* | *G* | *H* | *I* | *J* | *K* | *N* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 5 | 2 | 2 | 5 |

**Table 2.** Components of each product

| | 1st returned product (unit) | 2nd returned product (unit) |
|---|---|---|
| Reusable items (*j*1, *j*2) | 1 | 1 |
| Recycling materials (*i*1,..,*i*5) | 3 | 2 |
| Hazardous items (*k*1, *k*2) | 1 | 1 |
| Non-recyclable materials (*n*1,...,*n*5) | 3 | 2 |

**Table 3:** The average percentage of recycling material and non-recyclable material generated from recycling facilities

| $\alpha 1_d$ | $\alpha 2_{ni}$ |
|---|---|
| 0.8 | 0.2 |

**Table 4:** The unit shipping cost per unit per km ($)

| Products | | Reusable Items | | Recycling materials | | | | |
|---|---|---|---|---|---|---|---|---|
| $SH_1$ | $SH_2$ | $SI_1$ | $SI_2$ | $SJ_1$ | $SJ_2$ | $SJ_3$ | $SJ_4$ | $SJ_5$ |
| 1.2 | 1 | 0.7 | 0.8 | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 |
| Hazardous items | Non-recyclable materials | | | | | | | |
| $SK_1$ | $SK_2$ | $SN_1$ | $SN_2$ | $SN_3$ | $SN_4$ | $SN_5$ | | |
| 0.4 | 0.4 | 0.3 | 0.5 | 0.2 | 0.4 | 0.2 | | |

**Table 5:** Collection and disposal costs per unit ($)

| $CC_1$ | $CC_2$ | $DC1_1$ | $DC1_2$ | $DC2_1$ | $DC2_2$ | $DC2_3$ | $DC2_4$ | $DC2_5$ |
|---|---|---|---|---|---|---|---|---|
| 2 | 1 | 2 | 2.1 | 1.3 | 1.2 | 2 | 1 | 1.4 |

**Table 6:** Income from selling recovery materials and reusable items per unit ($)

| $UJ_{1e}$ | $UJ_{2e}$ | $UI_{1f}$ | $UI_{2f}$ | $UI_{3f}$ | $UI_{4f}$ | $UI_{5f}$ |
|---|---|---|---|---|---|---|
| 3 | 4 | 3 | 3.2 | 3.3 | 2.5 | 2.7 |

**Table 7:** Distance between facilities (km)

| Dist. | $A_1$ | $A_2$ | $C_1$ | $C_2$ | $D_1$ | $D_2$ | $G_1$ | Dist. | $E_1$ | $E_2$ | Dist. | $G_1$ | $F_1$ | $F_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $B_1$ | 18 | 20 | 34 | 36 | 39 | 37 | 23 | $C_1$ | 23 | 26 | *D1* | 24 | 23 | 27 |
| $B_2$ | 22 | 26 | 25 | 42 | 40 | 42 | 29 | $C_2$ | 28 | 24 | *D2* | 26 | 25 | 28 |

**Table 8:** Operating cost at dismantling, recycling and refurbishing facilities ($)

| | Returned Products | | | Recycling materials | | | | | | Reusable items | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $OH_{1b}$ | $OH_{2b}$ | | $OI_{1d}$ | $OI_{2d}$ | $OI_{3d}$ | $OI_{4d}$ | $OI_{5d}$ | | $OJ_{1c}$ | $OJ_{2c}$ |
| *b=1* | 5 | 5 | *d=1* | 3 | 2 | 2 | 1 | 2 | *c=1* | 2 | 3 |
| *b=2* | 4 | 3 | *d=2* | 2 | 2 | 3 | 2 | 3 | *c=2* | 4 | 3 |

**Table 9:** Fixed cost for constructing dismantling, recycling and refurbishing facilities ($)

| | $FC_b$ | | $FC_d$ | | $FC_c$ |
|---|---|---|---|---|---|
| *b=1* | 400 | *d=1* | 300 | *c=1* | 300 |
| *b=2* | 420 | *d=2* | 320 | *c=2* | 310 |

**Table 10:** Maximum capacity at dismantling, recycling and refurbishing facilities (unit)

| | $XH_{1b}$ | $XH_{2b}$ | | $XI_{1d}$ | $XI_{2d}$ | $XI_{3d}$ | $XI_{4d}$ | $XI_{5d}$ | | $XJ_{1c}$ | $XJ_{2c}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *b=1* | 210 | 320 | *d=1* | 248 | 345 | 265 | 352 | 344 | *c=1* | 250 | 300 |
| *b=2* | 360 | 432 | *d=2* | 225 | 230 | 224 | 266 | 300 | *c=2* | 350 | 450 |

**Table 11:** Maximum demand at secondary markets, material markets and landfill site (unit)

| | $MJ_{1e}$ | $MJ_{2e}$ | | $MI_{1f}$ | $MI_{2f}$ | $MI_{3f}$ | $MI_{4f}$ | $MI_{5f}$ |
|---|---|---|---|---|---|---|---|---|
| *e=1* | 245 | 235 | f=1 | 230 | 240 | 135 | 200 | 228 |
| *e=2* | 325 | 330 | f=2 | 253 | 255 | 227 | 234 | 330 |
| | $XK_{1g}$ | $XK_{2g}$ | $XN_{1g}$ | $XN_{2g}$ | $XN_{3g}$ | $XN_{4g}$ | $XN_{5g}$ | - |
| *g=1* | 400 | 400 | 500 | 300 | 360 | 450 | 570 | - |

**Table 12:** The quantity of returned product at collection areas (unit)

| $H_{ah}$ <br> *h\a* | *1* | *2* |
|---|---|---|
| *1* | 120 | 80 |
| *2* | 170 | 130 |

**Table 13:** Likelihood and the loss of accident occurrence at collection areas and dismantling facilities

| Likelihood | | | | | |
|---|---|---|---|---|---|
| | Collection areas | | | Dismantling facilities | |
| | $L1_{1a}$ | $L1_{2a}$ | | $L2_{1b}$ | $L2_{2b}$ |
| *a=1* | 2 | 3 | *b=1* | 4 | 5 |
| *a=2* | 3 | 4 | *b=2* | 2 | 3 |
| The loss | | | | | |
| | $I1_{1a}$ | $I1_{2a}$ | | $I2_{1b}$ | $I2_{2b}$ |
| *a=1* | 3 | 2 | *b=1* | 3 | 4 |
| *a=2* | 2 | 3 | *b=2* | 5 | 5 |

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**Table 14:** Likelihood and the loss of accident occurrence at recycling and refurbishing facilities

| Likelihood | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Recycling facilities | | | | | | Refurbishing facilities | |
| | $L4_{1d}$ | $L4_{2d}$ | $L4_{3d}$ | $L4_{4d}$ | $L4_{5d}$ | | $L3_{1c}$ | $L3_{2c}$ |
| *d=1* | 3 | 4 | 4 | 5 | 4 | *c=1* | 4 | 4 |
| *d=2* | 2 | 1 | 3 | 2 | 2 | *c=2* | 2 | 3 |
| The loss | | | | | | | | |
| | $I4_{1d}$ | $I4_{2d}$ | $I4_{3d}$ | $I4_{4d}$ | $I4_{5d}$ | | $I3_{1c}$ | $I3_{2c}$ |
| *d=1* | 5 | 4 | 5 | 3 | 4 | *c=1* | 3 | 2 |
| *d=2* | 6 | 6 | 7 | 5 | 6 | *c=2* | 4 | 3 |

**Table 15:** Likelihood and the loss of accident occurrence from shipping between nodes

| | Likelihood | | The loss | |
|---|---|---|---|---|
| Shipping a-b | $L5_{1b}$ | $L5_{2b}$ | $I5_{1b}$ | $L5_{2b}$ |
| *b=1* | 3 | 2 | 2 | 3 |
| *b=2* | 3 | 3 | 2 | 3 |
| Shipping b-c | $L6_{1c}$ | $L6_{2c}$ | $I6_{1c}$ | $I6_{2c}$ |
| *c=1* | 4 | 5 | 2 | 2 |
| *c=2* | 2 | 3 | 3 | 4 |
| Shipping b-d | $L7_{1d}$ | $L7_{2d}$ | $I7_{1d}$ | $I7_{2d}$ |
| *d=1* | 4 | 3 | 4 | 3 |
| *d=2* | 2 | 2 | 5 | 5 |
| Shipping b-g | $L8_{1g}$ | $L8_{2g}$ | $I8_{1g}$ | $I8_{2g}$ |
| *g=1* | 5 | 3 | 5 | 7 |
| Shipping c-e | $L9_{1e}$ | $L9_{2e}$ | $I9_{1e}$ | $I9_{2e}$ |
| *e=1* | 5 | 4 | 4 | 3 |
| *e=2* | 4 | 3 | 5 | 5 |
| Shipping d-f | $L10_{1f}$ | $L10_{2f}$ | $I10_{1f}$ | $I10_{2f}$ |
| *f=1* | 4 | 5 | 4 | 5 |
| *f=2* | 3 | 3 | 6 | 6 |
| Shipping d-g | $L11_{1g}$ | $L11_{2g}$ | $I11_{1g}$ | $I12_{2g}$ |
| g=1 | 6 | 4 | 5 | 6 |

## Results and Discussion

The proposed mathematical model is solved by using AMPL with processor Intel ® Core i5–3.3 GHz and 8 GB RAM. The optimal total cost is equal to \$65727 with risk costs while the total cost is \$57453 without risk costs. The result indicates that risk costs in the RSC operation have a remarkable impact, accounting for 14.4% of the total cost. In consideration of risk costs, the opening facilities and the flow of materials and items in the network have been changed. The noticeable difference between the model without considering risk costs and the one with integrating risk costs is the opening of recycling facilities in the network. Without incorporating risk costs, only d1 should be opened while d1 and d2 should be built in the model that risk costs are incorporated (Table 16). As a result, this can lead to the differences in the flow of items ($V3_{ibd}$, $V6_{idf}$, $V7_{ndg}$) transported in the network in the two situations (Table 17-18).

**Table 16:** Opening facilities in the network

| Type of facility | Without risk costs | With risk costs |
|---|---|---|
| Dismantling facilities | b1 | b1 |
| Refurbishing facilities | c1 | c1 |
| Recycling facilities | **d1** | **d1, d2** |

**Table 17:** The values of decision variables with risk costs (unit)

| No | $V1_{hab}$ | $V2_{jbc}$ | $V3_{ibd}$ | $V4_{kbg}$ | $V5_{jce}$ | $V6_{idf}$ | $V7_{ndg}$ |
|---|---|---|---|---|---|---|---|
| 111 | 120 | 200 | **0** | 200 | 200 | **0** | **0** |
| 121 | 80 | 0 | **0** | 0 | **160** | **40** | |
| 112 | 0 | 0 | **200** | 0 | 0 | **0** | |
| 122 | 0 | 0 | **0** | 25 | **0** | | |
| 211 | 170 | 300 | **0** | 300 | 235 | **0** | **0** |
| 221 | 130 | 0 | **0** | 0 | 0 | **160** | **40** |
| 212 | 0 | 0 | **200** | 65 | **0** | | |
| 222 | 0 | 0 | **0** | 0 | **0** | | |
| 311 | | | **188** | | | **135** | **38** |
| 312 | | | **12** | | | **16** | |
| 321 | | | **0** | | | **0** | **2** |
| 322 | | | **0** | | | **9** | |
| 411 | | | **250** | | | **200** | **50** |
| 412 | | | **50** | | | **0** | |
| 421 | | | **0** | | | **0** | **10** |
| 422 | | | **0** | | | **40** | |
| 511 | | | **244** | | | **195** | **49** |
| 512 | | | **56** | | | **0** | |
| 521 | | | **0** | | | **33** | **11** |
| 522 | | | **0** | | | **12** | |

**Table 18:** The values of decision variables without risk costs (unit)

| No | $V1_{hab}$ | $V2_{jbc}$ | $V3_{ibd}$ | $V4_{kbg}$ | $V5_{jce}$ | $V6_{idf}$ | $V7_{ndg}$ |
|---|---|---|---|---|---|---|---|
| 111 | 120 | 200 | **200** | 200 | 200 | **160** | **40** |
| 121 | 80 | 0 | **0** | 0 | **0** | **0** | |
| 112 | 0 | 0 | **0** | 0 | 0 | **0** | |
| 122 | 0 | 0 | **0** | 25 | **0** | | |
| 211 | 170 | 300 | **200** | 300 | 235 | **160** | **40** |
| 221 | 130 | 0 | **0** | 0 | 0 | **0** | **0** |
| 212 | 0 | 0 | **0** | 65 | **0** | | |
| 222 | 0 | 0 | **0** | 0 | **0** | | |
| 311 | | | **200** | | | **135** | **40** |
| 312 | | | **0** | | | **25** | |
| 321 | | | **0** | | | **0** | **0** |
| 322 | | | **0** | | | **0** | |
| 411 | | | **300** | | | **200** | **60** |
| 412 | | | **0** | | | **40** | |
| 421 | | | **0** | | | **0** | **0** |
| 422 | | | **0** | | | **0** | |
| 511 | | | **300** | | | **228** | **60** |
| 512 | | | **0** | | | **12** | |
| 521 | | | **0** | | | **0** | **0** |
| 522 | | | **0** | | | **0** | |

## Sensitivity Analysis

In this proposed model, all parameters are assumed constant over time. However, these parameters might change due to unexpected elements in the real world and consequently might affect the solution of the model. To mitigate this issue, a sensitivity analysis is utilised to investigate the variation of the result and the model.

**Table 19:** Sensitivity analysis results

| Parameters | Parameter changes % | New total cost (a) | Current total cost (b) | Total cost changes (a-b)/b*100% (c) | Opening facilities (d) |
|---|---|---|---|---|---|
| Demand | +20 | 79981 | 65727 | **21.69** | **b1,b2,c1,c2,d1,d2** |
| | -20 | 52460 | | **–20.19** | b1,c1,d1,d2 |
| Shipping cost | +20 | 77752 | 65727 | **18.30** | b1,c1,d1,d2 |
| | –20 | 53694 | | **–18.31** | b1,c1,d1,d2 |
| Operation cost | +20 | 67095 | 65727 | 2.08 | b1,c1,d1,d2 |
| | –20 | 64342 | | –2.11 | b1,c1,d1,d2 |
| Fixed cost | +20 | 65962 | 65727 | 0.36 | b1,c1,d1,d2 |
| | –20 | 65491 | | -0.36 | b1,c1,d1,d2 |
| Collection cost | +20 | 65877 | 65727 | 0.23 | b1,c1,d1,d2 |
| | –20 | 65577 | | –0.23 | b1,c1,d1,d2 |
| Disposal cost | +20 | 65998 | 65727 | 0.41 | b1,c1,d1,d2 |
| | –20 | 65456 | | -0.41 | b1,c1,d1,d2 |
| Likelihood of accident occurrence | +20 | 67346 | 65727 | 2.46 | b1,c1,d1,d2 |
| | –20 | 64104 | | –2.47 | b1,c1,d1,d2 |
| Revenue | +20 | 64813 | 65727 | –1.39 | b1,c1,d1,d2 |
| | –20 | 66640 | | 1.39 | b1,c1,d1,d2 |

The sensitivity analysis is conducted by changing the value of one parameter in a range from –20 to +20% while the remaining parameters are unchanged. Comparison between parameters only showing the value of the highest level (+20%) and the lowest level (–20%) are presented in Table 19. Furthermore, a new total cost is obtained by optimizing the model with the modified parameters. The model sensitivity is shown in Table 19 (Columns a-c) with the proportion of change between the new and current total cost.

Generally, as can be seen in Column c of Table 19, the total cost is slightly sensitive to the majority parameters changed. It is also shown that the fluctuation of the parameters by 20% lead to changes in the total cost by less than 2.5% only. However, the variation of demand and shipping cost strongly affect the overall cost. Determining the number of opening facilities in the RSC network is not really affected by the changes of most input parameters by 20%, except for the demand changed (Column d, Table 19).

## Conclusion

This paper suggests a comprehensive E-waste reverse supply chain model integrating risk costs during collection, shipping and treatment of returned products in RSC activities. Multi-product and multi-layer RSC model consisting of many recycling processes for different types of electronics waste are considered. The suggested model is addressed by using AMPL which can provide exact solutions and handle large-scale optimization. From the numerical test, it is illustrated that risk costs regarding the RSC operation have a vital effect on the overall cost. The flow of materials or items have significantly changed in the RSC network in consideration of risk costs. This proposed model is able to assist decision makers in designing RSC network for E-waste.

For future research, a case study in which the proposed model is applied for a particular industry should be conducted to validate the practical application of this study. This proposed model has not considered the way to reduce risks. Therefore, this model can be extended to trade-off between risks and cost. Furthermore, one of the main issues related to establishing RSC activities is the level of uncertainty in terms of the amount of returned products, cost and risk factors and this problem may be addressed in future work.

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## Author‘s Contributions

**Linh Thi Truc Doan:** Developed the proposed model and solved the model. Prepared the manuscript under the supervision of Dr Yousef Amer and Dr Sang-Heon Lee.

**Yousef Amer:** Contributed to the analysis of the results and reviewing the manuscript. Gave final approval of the version to be submitted.

**Sang- Heon Lee:** Contributed to the structure of the manuscript and the numerical example. Discussed the results and comments on the manuscript.

**Phan Nguyen Ky Phuc:** Supported the mathematical model and sensitive analysis. Gave comments on the manuscript

## Ethics

This manuscript is original. The corresponding author would like confirm that all authors have approved the manuscript and no ethical issues involved.

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