Computers & Industrial Engineering 62 (2012) 129–140

Contents lists available at SciVerse ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Reverse production system infrastructure design for electronic products in the state of Texas ☆

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ARTICLE INFO

Article history:
Received 27 October 2008
Received in revised form 2 July 2011
Accepted 1 September 2011
Available online 14 September 2011

Keywords:
Reverse production system design
Reverse logistics
Reverse supply chains design for electronic products

ABSTRACT

Rapid technology advances have shortened the lifecycle of electronic products, resulting in the increasing number of discarded products in recent years. Due to the growing environmental concerns, several state governments have passed new regulations in order to reduce the amount of waste stream, to divert the discarded products from landfills, and to dispose the retired electronic products properly. As a result, an effective reverse logistics infrastructure is required to support the product recovery activities. In this paper, we propose a solution methodology for designing the infrastructure of the reverse production system by utilizing the mixed integer linear programming (MILP) model. A case study for designing the reverse production system in the state of Texas is also presented. Statistical analyses are carefully utilized to estimate design parameters in the case study from the available historical information from previous studies. Finally, discussions, recommendations, and insight information in designing and operating the reverse production system are presented.

1. Introduction and problem statement

In the past decade, rapid changes in computer technology and the emergence of new electronic products have resulted in the fast-growing amounts of retired electronics (e-waste). According to the US Environmental Protection Agency (EPA), e-waste accounts for about one percent of the nation's 210 million tons of solid waste each year and continues to grow rapidly. Electronic products can contain hazardous materials such as lead, mercury and cadmium. For example, each obsolete computer and television display uses a Cathode Ray Tube (CRT) that contains on average four to eight pounds of lead. Monitor glass contains approximately 20% of lead by weight. When this glass is crushed in the landfills, the lead can leach into the soil. Such toxics and hazardous material can threaten quality of water resources in that area. As the result, several state governments have passed new regulations aiming to reduce the amount of waste stream, and to properly dispose the retired electronic products for pollution prevention. Product recovery procedures include repairing, refurbishing, remanufacturing, and recycling.

The product recovery process cannot be successfully completed without an effective infrastructure of the reverse production system. Reverse production system encompasses all production and logistics activities related to used products that the consumer no longer requires through products that are made to be usable again in the market (Fleischmann et al., 1997). In the reverse production system, used products have to be moved backward from end customers back to manufacturers or recyclers. The key issue about the reverse production system is that the return flow of end-of-life products from the consumers is a supply-driven flow, rather than the demand-driven flow as seen in the forward production system. This supply-driven flow creates a high level of uncertainty with respect to quantity, quality, and timing of the returned items (Jayaraman, Guide, & Srivastava, 1999). Moreover, the logistics network of the reverse production system is not necessarily a symmetric picture of the forward production system (Fleischmann et al., 1997). Most logistics activities of the forward production system are not equipped to handle product movement in the reverse distribution. As a consequence, reverse distribution costs may be higher than shipping new products from manufacturers to customers in the forward production system. An illustration of materials flows in forward and reverse production systems is shown below in Fig. 1.

In this paper, we present a MILP model for designing the strategic supply chains infrastructure of the end-of-life electronics recycling system. This mathematical formulation captures the possibilities of materials' obsolescence and the multitasking of processes in the reverse production system. A case study of the proposed model is also presented for designing the reverse production system infrastructure for e-wastes in the state of Texas by utilizing the historical information from previous studies.

☆ This manuscript was processed by Area Editor William G. Ferrell.

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doi:10.1016/j.cie.2011.09.001

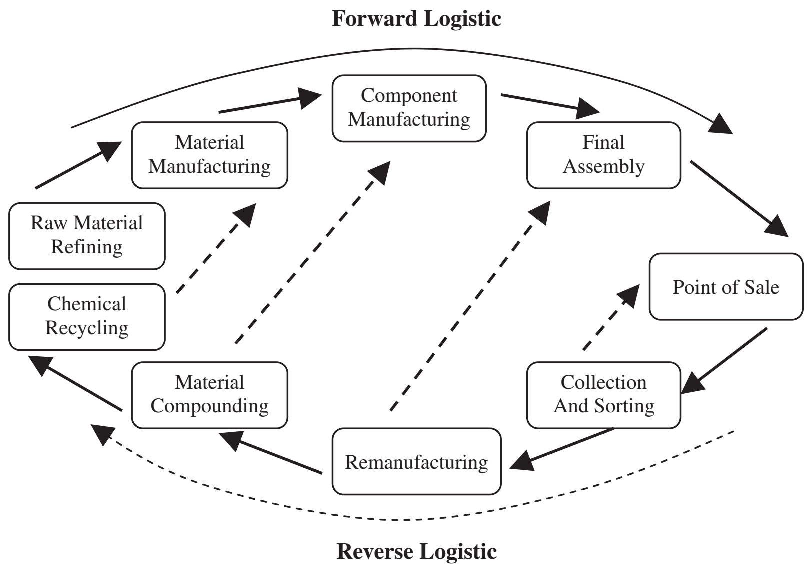

Fig. 1. Material flows in forward and reverse logistics systems.

The types of obsolete electronics considered in this study are personal computers, computer monitors, and televisions, which are the majority of all electronics collected (US EPA Office of Solid Waste and Emergency Response). This work focuses directly on reuse, disassembly, and reassembly activities such as repairing, refurbishing, and remanufacturing of electronic products.

This paper is structured as follows. Section 2 provides the background literature review on reverse production system and related topics. Section 3 summarizes the proposed mathematical formulation of the reverse production system design problem. In Section 4, we present a case study on designing the reverse supply chains infrastructure in the state of Texas and give the through analyses and suggestions from the case study results. Finally in Section 5, we summarize and conclude our finding of the research.

2. Background and literature review

Several researchers have been studying product recovery problems from many points of view. The works by Fleischmann et al. (1997) and Fleischmann, Krikke, Dekker, and Flapper (2000) summarize systematic overviews of the reverse logistic system. Many researchers have been focusing on recycling and resource recovering of specific products such as printer toner cartridge (Bartel, 1995; Degher, 2002; Williams & Shu, 2000) and mobile phone (Wright, McLaren, Jackson, & Parkinson, 1998). Other research works focusing on electronic products include Jayaraman et al. (1999), Jayaraman, Patterson, and Rolland (2003), and Krikke, van Harten, and Schuur (1999). In addition to academic researches, several demonstration projects in US have been conducted to study the management and operation of end-of-life electronic product recovery programs (Diggelman, Rau, Brachman, & Ziemke, 2003; Hainault et al., 2000; Jung & Bartel, 1998). A number of frameworks for reverse logistics and reverse supply chain management have also been studied by Bettac, Maas, Beullens, and Bopp (1999), Knoth, Hoffmann, Kopacek, and Kopacek (2001), and Dowlatshahi (2000, 2002).

Many researchers have utilized mathematical models for allocating product recovery facilities in the reverse supply chains system for different types of discarded products. Ammons, Realff, Newton, and Cerav (1999) present common features of the reverse production system and develop a generic MILP model for determining the infrastructure of the product recovery system. Pochampally and Gupta (2003) develop a three-phase mathematical programming approach to design a reverse logistics network. In phase-1, the algorithm identifies the most economical product from a set of used products. Potential facilities are identified in phase-2 from a set of candidate recovery facilities. Finally in phase-3, the algorithm solves a MILP model to obtain locations of facilities and product flows across the established recovery network. Ammons, Assavapokee, Newton, and Realff (2002) present a MILP model for designing the robust supply chains infrastructure for the product recovery system under uncertainty. Hong et al. (2006) utilize the MILP models for generating the robust reverse production system infrastructure under uncertainty with the min–max regret objective. They also present a case study on designing the robust reverse supply chain network for collecting electronic products in the state of Georgia. Kusumastuti, Piplani, and Lim (2004) provide an approach to design reverse logistics networks with multiple objective functions and planning horizons under uncertainties. They introduce a genetic algorithm to find solutions by utilizing the simulation model. Shih (2001) studies a reverse production system planning for electrical appliances and computers in northern Taiwan. A MILP model is utilized to determine the optimal design of the reverse supply chains infrastructure.

Barros, Dekker, and Scholten (1998) formulate a MILP model for strategic planning of the sand recycling problem in the Netherlands. Caruso and Paruccini (1993) develop a multi-objective mathematical model for the facility location planning of the urban solid waste management system. Kroon and Vrijens (1995) present a case study on a large reverse logistics organization service for returnable containers in the Netherlands. Listes and Dekker (2005) extend their deterministic location model of recycling sand from construction waste in the Netherlands by presenting a stochastic programming model to account for the uncertainties. Louwers, Kip, Peters, Souren, and Flapper (1999) present a mathematical model for the facility location and resource allocation problem for carpet recycling. Realff, Ammons, and Newton (1999) develop a MILP model to design strategic supply chains infrastructure for carpet recycling. Realff, Ammons, and Newton (2000, 2004) further develop a framework of robust optimization for reverse production system, based on their earlier work in Ammons et al. (1999). Schultmann, Engels, and Rentz (2003) propose a MILP model to solve a facility location problem. They apply the proposed model to a case study of spent batteries in Germany. Spengler, Puchert, Penkuhn, and Rentz (1997) develop a MILP model to deal with location and resource allocation planning of recycling installations of steel industry in Germany. Srivastava, Jayaraman, and Kriche (2003) study the reuse of the single-use devices in the healthcare industry. Wang, Even, and Adams (1995) propose a MILP model for designing the reverse logistics system for recovered paper in the State of Iowa.

Several researchers have also paid their attentions to the disassembly strategy for unused products to balance between the amount of effort to put into the recovery process and the value that is recovered from the operations. Research on disassembly strategy include Krikke et al. (1999), Das and Yedlarajiah (2002), Gungor and Gupta (1999), Chen, Navin-Chandra, and Prinz (1994), and Nagurney and Toyasaki (2005).

3. Methodology and mathematical formulation

In this section, we discuss about the characteristics of the reverse production system infrastructure design problems and formulate the considered problem into a MILP model. The proposed model specifically captures the infrastructure design problems at the strategic level. The objective of the proposed model is to find the network infrastructure setting that result in the highest overall profit of the system over multiple time horizons (T time periods), subject to a set of restrictions and constraints.

In order to formulate this problem as the tractable mathematical model, a set of general assumptions are made. These assumptions include (1) all parameters in the mathematical model are deterministic; (2) parameters such as demand, supply, costs, and prices may vary across time periods but they are constant within each time period; (3) all cost functions are linear functions; (4) all possible site locations are predetermined; (5) economic values of products may be reduced with time; and (6) each resource in the system may be able to perform multiple tasks. In order to capture the multi-tasking characteristic for each resource in the model, the notions of main-process (resource) and sub-process (functionality) are introduced. In the proposed model, the main process represents a set of employees, machines, or resources which performs several types of tasks or functionalities (sub-processes). For instance, a set of employees (main-process P) performs several different types of sub-processes ($p_1, p_2, \ldots, p_n$) such as inspecting, disassembling, and repairing products. Note that different type of main-processes can perform the same type of sub-process. By using the concept of main-process and sub-process, the proposed model can represent the multi-tasking characteristic of each main-process which will be discussed in detail in the next subsections.

Under these general assumptions, the strategic reverse production system infrastructure design problem can be formulated as a mathematical programming formulation. The following verbal model represents the general framework of the proposed MILP formulation where the discrete variables represent location decisions and capacity allocations decisions and the continuous decisions represent flows of materials in the resulting network. In the following subsections, we give the detailed discussion on each component in the proposed model including sets, parameters, decision variables, objective functions, and functional constraints.

Maximize Total Profit = Total Revenues − Total Investment and Operating Costs

Subject to
(a) Minimum population coverage constraints
(b) Material flow balance constraints
(c) Product obsolescence constraints
(d) Demand and supply constraints
(e) Labor, collection, storage, and process capacity constraints
(f) Site Incoming and Outgoing material handling capacity constraints
(g) Site opening and closing relationship constraints
(h) Other Logical constraints

3.1. Sets, parameters, and decision variables in the proposed model

In this section, we summarize all sets, parameters, and decision variables required in the proposed model. In the proposed model, the notations *CR*, *CH*, *PR*, *PH*, and *Temp* represent regular collection site, hub collection site, regular processing site, hub processing site, and the site for the temporary collection event respectively.

Sets in the proposed model	
S	Set of all physical locations
I	Set of all possible sites including temporary sites and permanent sites
C	Set of all customers for refurbished products and/or components
K	Set of all possible material types including used products, refurbished products, and components
Mo	Set of all possible transportation modes
MP	Set of all possible processing resources (main processes)
MP(i)	Set of all possible processing resources (main processes) available at site $i \in I$
SP	Set of all possible functionalities (sub processes) for any resource
SP(P)	Set of all possible functionalities (sub processes) that the resource P can perform
TM	Set of all possible planning horizons: {1, 2, ..., T}
Parameters in the proposed model	
S(i)	Physical location of site $i \in I$ where $S(i) \in S$
Type(i)	Type of site $i \in I$ where Type(i) ∈ {Temp, CR, CH, PR, PH}
FO^1_{it}	Fixed costs for holding a temporary collection event at site $i \in I$ where Type(i) = Temp in the horizon t
FO_{it}	Fixed operating costs of site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t
FOp_{it}	Fixed opening costs of site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t
FCl_{it}	Fixed closing costs of site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t
FP_{iPt}	Fixed processing costs at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} per resource of type $P \in MP(i)$ in the horizon t
FC_{it}	Fixed costs per one worker for collection operation at site $i \in I$ where Type(i) ∈ {CR, CH} in the horizon t
VC_{ikt}	Collection costs per standard unit of material $k \in K$at site $i \in I$ where Type(i) ∈ {Temp, CR, CH} in the horizon t
VS_{ikt}	Storage costs per standard unit of material $k \in K$ at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t
VP_{ipPt}	Processing costs per standard unit for sub-process (functionality) $p \in SP(P)$ by utilizing resource $P \in MP(i)$ at the site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t
VT_{ijkmt}	Transportation costs per standard unit for

(*continued on next page*)

transporting material $k \in K$ from site $i \in I$ to site or customer $j \in I \cup C$ by transportation mode $m \in Mo$ in the horizon t

RF_{ikt}, RS_{ck} Revenue per standard unit of material $k \in K$ from the collection fee (from sale) at site $i \in I$ where Type(i) ∈ {Temp, CR, CH} (at customer $c \in C$) in the horizon t

P_{lt} Population size at location $l \in S$ in the horizon t

a_{li} 1 if population in location $l \in S$ can be served if site $i \in I$ where Type(i) ∈ {Temp, CR, CH} is opened; 0 otherwise

ε_{lkt} The minimum fraction of supply at location $l \in S$ of material $k \in K$ that must be collected in the horizon t

ρ_{kp}, $\rho_{kp'}$ Proportion of material $k \in K$ consumed (produced) by sub-process $p \in SP$

Cc_k The maximum amount of material $k \in K$ in standard unit which can be collected by a worker in one time horizon if the worker only collects material k

Cc^1_{it} The maximum amount of all materials (in standard unit) which can be collected per one temporary collection event at site $i \in I$ where Type(i) = Temp in the horizon t

CWC_{it} The maximum number of workers for collection operation at site $i \in I$ where Type(i) ∈ {CR, CH} in the horizon t

NE_{it} The maximum number of temporary collection events which can be held at site $i \in I$ where Type(i) = Temp in the horizon t

CS_i The maximum amount of material (in standard unit) which can be stored at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t

CP_{pP} The maximum amount of material in standard unit which can be handled by a resource of type $P \in MP$ if the resource P only works on the functionality $p \in SP(P)$ in one time horizon

CMP_{iPt} Maximum number of resource $P \in MP(i)$ available at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in the horizon t

S_{lkt} Total available supply of material $k \in K$ at location $l \in S$ in the horizon t

D_{ckt} Total available demand of material $k \in K$ at customer $c \in C$ in the horizon t

$\beta_{k1,k2}$ Proportion of material $k_1 \in K$ that turns into material $k_2 \in K$ in one time horizon due to obsolescence

IL_{it}, OL_{it} Inbound (outbound) capacity of site $i \in I$ where Type(i) ≠ Temp in the horizon t

TA_{ijkmt} The maximum amount of material $k \in K$ which can be transported from site $i \in I$ to $j \in I \cup C$ where Type(j) ≠ Temp by transportation mode $m \in Mo$ in time horizon t

Decision variables in the proposed model

yo_{it} 1 if site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} is operated in time horizon t; 0 otherwise

y^1_{it} The number of temporary collection events held at site $i \in I$ where Type(i) = Temp in time t

yop_{it} 1 if site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} is just opened in time horizon t; 0 otherwise

ycl_{it} 1 if site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} is just closed in time horizon t; 0 otherwise

b_{lt} 1 if location $l \in S$ is covered by collection facility or collection event in time horizon t; 0 otherwise

yc_{it} The number of workers for collection operation at site $i \in I$ where Type(i) ∈ {CR, CH} in time horizon t

yp_{iPt} The number of resource $P \in MP(i)$ required at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in time horizon t

xc_{ikt} The amount of material $k \in K$ collected at site $i \in I$ where Type(i) ∈ {Temp, CR, CH} in time horizon t

xp_{ipPt} The amount of material (in standard unit) processed by resource $P \in MP(i)$ with functionality $p \in SP(P)$ at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} in time horizon t

xse_{ikt} The amount of material $k \in K$ stored at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} at the end of time horizon t

xsb_{ikt} The amount of material $k \in K$ stored at site $i \in I$ where Type(i) ∈ {CR, CH, PR, PH} at the beginning of time horizon t

xt_{ijkmt} The amount of material $k \in K$ transported from site $i \in I$ to customer $j \in C$ or to site $j \in I$ where Type(j) ∈ {CR, CH, PR, PH} by transportation mode $m \in Mo$ in time horizon t

xe_{lkt} The fraction of supply at location $l \in S$ of material $k \in K$ that is collected in the horizon t

3.2. Objective function and functional constraints in the proposed model

In the proposed model, the objective function is to maximize the net profit defined by total revenue minus total cost. The total revenue of the system includes all collection fees and sales of refurbished products and components. Total cost includes all fixed costs and operational costs incurred while operating the reverse production system. By using the previously defined notations, each component of the net profit in the proposed model can be formulated as follow:

$$\sum_{k\in K}\sum_{t\in TM}\left(\sum_{i\in I}(RF_{ikt}xc_{ikt})+\sum_{c\in C}\left(RS_{ckt}\sum_{i\in I}\sum_{m\in Mo}xt_{ickmt}\right)\right) \tag{1}$$

$$\sum_{t\in TM}\left(\sum_{\substack{i\in I\\ Type(i)\neq Temp}}(FOp_{it}yop_{it}+FCl_{it}ycl_{it}+FO_{it}yo_{it})+\sum_{\substack{i\in I\\ Type(i)=Temp}}(FO^1_{it}y^1_{it})\right) \tag{2}$$

$$\sum_{t\in TM}\left(\sum_{\substack{i\in I\\ Type(i)\in\{CR,CH\}}}\left(FC_{it}yc_{it}+\sum_{k\in K}(VC_{ikt}xc_{ikt})\right)+\sum_{\substack{i\in I\\ Type(i)=Temp}}\sum_{k\in K}(VC_{ikt}xc_{ikt})\right) \tag{3}$$

$$\sum_{t\in TM}\sum_{\substack{i\in I\\ Type(i)\neq Temp}}\sum_{P\in MP(i)}\left(FP_{iPt}yp_{iPt}+\sum_{p\in SP(P)}(VP_{ipPt}xp_{ipPt})\right) \tag{4}$$

$$\sum_{t\in TM}\sum_{k\in K}\sum_{\substack{i\in I\\ Type(i)\neq Temp}}(VS_{ikt}xse_{ikt}) + \sum_{t\in TM}\sum_{k\in K}\sum_{m\in Mo}\sum_{i\in I}\sum_{\substack{j\in I\cup C\\ Type(j)\neq Temp}}(VT_{ijkmt}xt_{ijkmt}) \tag{5}$$

The net profit of the system can be formulated as (1) − [(2) + (3) + (4) + (5)]. The function (1) represents the total revenue of the system from collection fees and sales. The function (2) represents the total fixed site operating, site opening, and site closing costs of the system. The functions (3), (4), and (5) represent the total collecting cost, processing cost, storage and transportation cost of the system respectively.

The proposed model also consists of eight major types of Constraints (a)–(h). The constraints of type (a) ensure that the resulting infrastructure will be able to cover at least a specific proportion (α) of the total population. This type of constraints is quite essential when designing the reverse production system infrastructure in practice especially for the government collection programs. The following Constraints (6) and (7) ensure that at least $\alpha \times 100\%$ of the entire population will be served by the resulting infrastructure.

$$\sum_{\substack{i \in I \\ Type(i) \in \{CR,CH\}}} (a_{li} yo_{it}) + \sum_{\substack{i \in I \\ Type(i) = Temp}} (a_{li} y^1_{it}) \geqslant b_{lt} \quad \forall l \in S,\ t \in TM \tag{6}$$

$$\sum_{l \in S} P_{lt} b_{lt} \geqslant \alpha \sum_{l \in S} P_{lt} \quad \forall t \in TM \tag{7}$$

The constraints of type (b) ensure the conservation of commodities within a network by balancing the flow dynamics of those commodities. The constraints of this type state that the total amount of each commodity transported out, used in production, and stored at each location during each time period must have been transported in from other locations, produced at the location, or stored at the location since the previous time period. The following Constraints (8)–(10) represent these material flow balance constraints in the proposed model.

$$\begin{aligned} xse_{ikt} = {} & xsb_{ikt} + xc_{ikt} + \sum_{m \in Mo} \sum_{j \in I} xt_{jikmt} - \sum_{m \in Mo} \sum_{\substack{j \in I \cup C \\ Type(j) \neq Temp}} xt_{ijkmt} \\ & + \sum_{P \in MP(i)} \sum_{p \in SP(P)} \rho'_{kp} xp_{ipPt} - \sum_{P \in MP(i)} \sum_{p \in SP(P)} \rho_{kp} xp_{ipPt} \quad \forall i \\ & \in I \text{ where } Type(i) \in \{CR, CH\},\ k \in K,\ t \in TM \end{aligned} \tag{8}$$

$$\begin{aligned} xse_{ikt} = {} & xsb_{ikt} + \sum_{m \in Mo} \sum_{j \in I} xt_{jikmt} - \sum_{m \in Mo} \sum_{\substack{j \in I \cup C \\ Type(j) \neq Temp}} xt_{ijkmt} \\ & + \sum_{P \in MP(i)} \sum_{p \in SP(P)} \rho'_{kp} xp_{ipPt} - \sum_{P \in MP(i)} \sum_{p \in SP(P)} \rho_{kp} xp_{ipPt} \quad \forall i \in I \\ & \text{where } Type(i) \in \{PR, PH\},\ k \in K,\ t \in TM \end{aligned} \tag{9}$$

$$\begin{aligned} xc_{ikt} = {} & \sum_{m \in Mo} \sum_{\substack{j \in I \\ Type(j) \neq Temp}} xt_{ijkmt} \quad \forall i \in I \text{ where } Type(i) \\ & = Temp,\ k \in K,\ t \in TM \end{aligned} \tag{10}$$

The constraints of type (c) represent the obsolescence of some materials stored in the storage spaces at any facility. In reverse production systems, it is common that the economic value of the collected products may decrease over time or products may become obsolete or damaged while kept in the storage over some time periods. Our model captures such phenomenon by assuming that a certain fraction of the total amount of each type of material in the storage at the end of each time period is transformed into another similar type of material with lower economic value (becomes obsolete) at the beginning of the next time period. The following Constraint (11) represents these product obsolescence constraints in the proposed model.

$$\begin{aligned} xsb_{ik(t+1)} = {} & \sum_{q \in K \setminus \{k\}} (\beta_{qk} xse_{iqt}) + \left(1 - \sum_{q \in K \setminus \{k\}} \beta_{kq}\right) xse_{ikt} \forall i \\ & \in I \text{ where } Type(i) \in \{CR, CH, PR, PH\},\ \forall k \in K,\ t \\ & \in TM \setminus \{T\} \end{aligned} \tag{11}$$

The constraints of type (d) restrict the amount of materials shipped to each demand point to be no more than the customer demand at that location. They also enforce the minimum level of the collection of e-wastes at each supply location. The following Constraints (12)–(14) represent these demand and supply constraints.

$$\sum_{m \in Mo} \sum_{\substack{i \in I \\ Type(i) \neq Temp}} xt_{ijkmt} \leqslant D_{jkt} \quad \forall j \in C,\ k \in K,\ \forall t \in TM \tag{12}$$

$$\sum_{\substack{i \in I \\ Type(i) \in \{Temp, CR, CH\}}} a_{li} xc_{ikt} = xe_{lkt} S_{lkt} \quad \forall l \in S,\ k \in K,\ t \in TM \tag{13}$$

$$\varepsilon_{lkt} \leqslant xe_{lkt} \leqslant 1 \quad \forall l \in S,\ k \in K,\ t \in TM \tag{14}$$

The capacity constraints of type (e) are introduced in the model in order to specify the capacity limitation on collection, process, and storage at each site in the reverse supply chains network. They also represent the key relationships between discrete variables and continuous variables in the proposed model. The following Constraints (15)–(20) represent these resource capacity constraints.

$$\sum_{k \in K} xc_{ikt} \leqslant Cc^1_{it} y^1_{it} \quad \forall i \in I \text{ where } Type(i) = Temp,\ t \in TM \tag{15}$$

$$\sum_{\substack{k \in K \\ Cc_k > 0}} \left(\frac{xc_{ikt}}{Cc_k}\right) \leqslant yc_{it} \quad \forall i \in I \text{ where } Type(i) \in \{CR, CH\},\ t \in TM \tag{16}$$

$$\begin{aligned} 0 \leqslant xc_{ikt} \leqslant Cc_k CWC_{it} \quad & \forall i \in I \text{ where } Type(i) \in \{CR, CH\},\ \forall k \\ & \in K,\ \forall t \in TM \end{aligned} \tag{17}$$

$$\begin{aligned} \sum_{\substack{p \in SP(P) \\ CP_{pP} > 0}} \left(\frac{xp_{ipPt}}{CP_{pP}}\right) \leqslant yp_{iPt} \quad & \forall i \in I \text{ where } Type(i) \\ & \in \{CR, CH, PR, PH\},\ P \in MP(i),\ t \in TM \end{aligned} \tag{18}$$

$$\begin{aligned} 0 \leqslant xp_{ipPt} \leqslant CP_{pP} CMP_{iPt} \quad & \forall i \in I \text{ where } Type(i) \neq Temp,\ \forall P \\ & \in MP(i),\ \forall p \in SP(P),\ \forall t \in TM \end{aligned} \tag{19}$$

$$\sum_{k \in K} xse_{ikt} \leqslant CS_i yo_{it} \quad \forall i \in I \text{ where } Type(i) \neq Temp,\ t \in TM \tag{20}$$

The constraints of type (f) are introduced into the model to restrict the capacity on the inbound and outbound logistics at each operating facility at each time period. The following Constraints (21) and (22) represent this type of constraint in the problem.

$$\sum_{i \in I} \sum_{m \in Mo} \sum_{k \in K} xt_{ijkmt} \leqslant IL_{jt} yo_{jt} \quad \forall j \in I \text{ where } Type(j) \neq Temp,\ t \in TM \tag{21}$$

$$\begin{aligned} \sum_{\substack{j \in I \cup C \\ Type(j) \neq Temp}} \sum_{m \in Mo} \sum_{k \in K} xt_{ijkmt} \leqslant OL_{it} yo_{it} \quad & \forall i \\ & \in I \text{ where } Type(i) \neq Temp,\ t \in TM \end{aligned} \tag{22}$$

The constraints of type (g) control the logical relationship among binary variables representing site opening and site closing decisions. The following Constraints (23)–(25) represent these logical constraints.

$$yo_{it} - yo_{i(t-1)} \leqslant yop_{it} \quad \forall i \in I \text{ where } Type(i) \neq Temp,\ t \in TM \setminus \{1\} \tag{23}$$

$$yo_{i(t-1)} - yo_{it} \leqslant ycl_{it} \quad \forall i \in I \text{ where } Type(i) \neq Temp,\ t \in TM \setminus \{1\} \tag{24}$$

$$yo_{it} \leqslant yop_{it} \quad \forall i \in I \text{ where } Type(i) \neq Temp, \ t = 1 \tag{25}$$

The constraints of type (h) enforce other logical relationships between discrete decision variables, integer and non-negativity constraints of decision variables.

$$yc_{it} \leqslant CWC_{it} yo_{it} \quad \forall i \in I \text{ where } Type(i) \in \{CR, CH\}, \ t \in TM \tag{26}$$

$$yp_{iPt} \leqslant CMP_{iPt} yo_{it} \quad \forall i \in I \text{ where } Type(i) \in \{CR, CH, PR, PH\}, \ P \in MP(i), \ t \in TM \tag{27}$$

$$y^1_{it} \in \{0, 1, \ldots, NE_{it}\} \quad \forall i \in I \text{ where } Type(i) = Temp, \ t \in TM \tag{28}$$

$$yc_{it} \in \{0, 1, \ldots, CWC_{it}\} \quad \forall i \in I \text{ where } Type(i) \in \{CR, CH\}, \ t \in TM \tag{29}$$

$$yp_{iPt} \in \{0, 1, \ldots, CMP_{iPt}\} \quad \forall i \in I \text{ where } Type(i) \neq Temp, \ P \in MP(i), \ t \in TM \tag{30}$$

$$yo_{it} \in \{0,1\}, yop_{it} \in \{0,1\}, \quad ycl_{it} \in \{0,1\} \quad \forall i \in I \text{ where } Type(i) \neq Temp, \ \forall t \in TM \tag{31}$$

$$b_{lt} \in \{0,1\} \quad \forall l \in S, \ \forall t \in TM \tag{32}$$

$$0 \leqslant xt_{ijkmt} \leqslant TA_{ijkmt} \quad \forall i \in I, \ j \in I \cup C \text{ where } Type(j) \neq Temp, \ k \in K, \ m \in Mo, \ t \in TM \tag{33}$$

$$xsb_{ikt} \geqslant 0, xse_{ikt} \geqslant 0 \quad \forall i \in I \text{ where } Type(i) \neq Temp, \ k \in K, \ t \in TM \tag{34}$$

The proposed mathematical model can be summarized as follow:

Maximize $(1) - [(2) + (3) + (4) + (5)]$
Subject to $(6)\text{to}(34)$.

4. Case study

The case study applies the mathematical model for designing the reverse production system infrastructure for collecting and recycling end-of-life electronic products in the state of Texas. Texas is a populated state covering approximately 261,797 square miles with an estimated population of 23.8 million people in 2007 (US Census Bureau). In addition, the population in Texas is currently growing with the rate of approximately 8% per year (US Census Bureau).

National Recycling Coalition, a non-profit organization dedicated to the advancement and improvement of recycling and waste prevention, estimates that 1.5 million computers are discarded in Texas annually, with roughly 162,000 recycled. This leaves more than 1.3 million units stored or sent to landfills. Although there are currently no legislation prohibiting these electronic wastes from entering landfills in Texas, improper disposals of these electronic products will certainly cause serious long-term environmental problems in Texas and nearby States. This case study focuses on analyzing costs, profits, and requirements for developing the reverse supply chains infrastructure for collecting and recycling end-of-life electronic product in the state of Texas covering all 254 counties across the State.

4.1. Case study overview and information on model parameters

4.1.1. General information

There are three main types of end-of-life electronic products. They are televisions (TVs), central processing units (CPUs), and computer monitors (CMs), which currently are the majority of the end-of-life electronic products by weight. The average weights of a CPU, a CM, and a TV used in this case study are 20.6 lbs, 30.0 lbs and 61.6 lbs respectively. We also assume that the relative proportion of the collection amounts (in units) for CPUs, CMs, and TVs of collected material at each location are 25.7%, 38.5%, and 35.8% respectively. The proportion amount and the average weight information are obtained from the statistical data from the State of Florida website. Based on this information, the relative proportion of collection amounts (by weight) for CPUs, CMs, and TVs are calculated as 14%, 30%, and 56% respectively. This information is used to calculate the supply quantity for each product from the estimated total supply quantity of e-wastes in each county.

There are three main types of the process functionalities; inspecting, refurbishing, and disassembling processes in this case study. Each process is conducted at each associated permanent facility. The inspecting process is mainly used to classify collected items or work-in-process items into reusable items or non-reusable items (out-of-date or severely broken units). The refurbishing process is used to transform the reusable items into refurbished items which can be sold to some customers. Finally, the disassembling process is used to decompose the given item into a number of its components. Note that it is also possible to further inspect, refurbish, and/or disassemble these components.

In the case study, we consider five different types of facility including temporary collection event site (*Temp*), regular collection facility (*CR*), hub collection facility (*CH*), regular processing facility (*PR*), and hub processing facility (*PH*). Based on the population size in each of 254 counties in Texas, we pre-select 99 counties to be considered as possible physical locations for opening sites in the model which covers more than 90% of the population in the Texas. In addition, the selected counties with the population size at least 25,000 peoples are assumed to have the potential to hold temporary collection events. Selected counties with the population size at least 100,000 peoples are assumed to have the potential to hold regular permanent facilities. Finally, the selected counties with the population size at least 500,000 peoples are assumed to have sufficient potential to hold hub permanent facilities. The criteria of site location selection are summarized in the following Table 1.

It is assumed that the average life spans of a CPU, CM, and TV are 3–5 years, 4–6 years, and 6–8 years respectively. If the item is newer than its useful life span and still in good condition, it can be refurbished and sold. Any item which is older than their useful life span can be disassembled. The resulting components can then be sold, refurbished, or recycled. In our work, we assume that a CPU can be disassembled into several components including case and cooling fan (58% by weight), power supply (19% by weight), CD and floppy drive (11% by weight), hard drive (6% by weight), processor and circuit boards (2% by weight), wires (2% by weight), and wastes (2% by weight). We also assume that a CM can be disassembled into several components including CRT and glass (46% by weight), steel (27% by weight), plastic (9% by weight), copper scrap (8% by weight), low-grade circuit boards (5% by weight), wires (2% by weight), and waste (3% by weight). Finally, we assume that a TV can be disassembled into a number of components including CRT and glass (31% by weight), steel (26%

Table 1
Criteria for site location selection.

County population	% Population in TX	Number of counties	Possible facilities
500,000–3,596,086	55	9	*CR, CH, PR, PH, Temp*
100,000–499,999	24	26	*CR, PR, Temp*
25,000–99,999	14	64	*Temp*
62–24,999	7	155	–

by weight), plastic (7% by weight), copper scrap (2% by weight), low-grade circuit boards (10% by weight), wires (1% by weight), and waste (23% by weight). The sources of the component information are (1) Municipal Solid Waste in the United States: 2000 Facts and Figures (2) US EPA Office of Solid Waste and Emergency Response, June 2002.

In practice, the condition and quality of a collected electronic unit can vary due to its age and its usage. In this work, we assume that each collected products can be classified into three possible conditions after the inspection process including re-saleable, repairable, and out-of-date conditions. The proportion information used in this case study for each condition type of each collected product type is summarized in the following Table 2.

4.1.2. Supply and collection fee information

In this work, the supply quantities of end-of-life electronic products are forecasted based on the available historical information from a number of studies from several States that have initiated the pilot electronics recycling programs. These States include: New York, Massachusetts, New Jersey, Illinois, West Virginia, Iowa, Missouri, Kansas, Wisconsin, Virginia, Pennsylvania, and Maryland. From these studies, data from 72 one-day collection events and 19 drop-off permanent facilities were collected and the linear regression model is developed to estimate the supply quantities of electronic wastes in each county in the Texas State. Initially, two independent variables are used in developing the linear regression model including the population size and the median income per household in the county. We select these two variables for the regression model based on the following assumption. In the county with larger population size and higher median income per household, it should be more likely that this county contains a larger quantity of available e-wastes. The initial result shows that the median income per household in the county is not significantly relevant to the amount of the e-wastes collected from one-day collection events, while the county population size does show a promising functional relationship. Based on the data from 72 one-day collection events, the linear regression model illustrated in Eq. (35) is constructed. This equation represents the relationship between the total supply (in lbs) of e-wastes collected per one-day collection event and the logarithm function of base 10 of the population size in the county. Some data are outliers during our analysis and excluded from the study. The following Fig. 2 illustrates two scatter plots between supply quantity (in lbs) of e-wastes collected per one-day collection event (y-axis) and the county population size and the function $\log_{10}$(population size in the county) (x-axis) respectively from the study.

$$\text{Total Supply (in lbs) collected per One-Day Collection Event} \\ = -77870 + 19393(\log_{10}(\text{Population})) \tag{35}$$

We then use this regression model to estimate the supply quantity (in lbs) of e-wasted collected per one-day collection event in the same set of counties reported in the 19 studies of the drop-off permanent facilities. The results from these estimations are compared with the actual total supply quantities (in lbs) per month reported in the 19 studies. Our result indicates that the total supply quantity collected at each location in these 19 studies is approximately four times of the estimated value from the regression model. From these results, we obtain the following function (36) that illustrates the relationship between the annual supply quantity (in lbs) of e-wastes and the population size in each county used in this case study.

$$\text{Total Annual Supply (in lbs)of e-wastes} \\ = -3737760 + 930864(\log_{10}(\text{Population})) \tag{36}$$

Note that this model is not intended to estimate the total available amount (in lbs) of e-wastes per year at each location but it is intended to estimate the total amount (in lbs) of e-wastes that will be dropped off at the collection programs per year at each location. In addition, this regression model should only be used to estimate the supply quantity of e-wastes at the county or city level. In the case study, the annual population growth rate of 8% is used for the supply calculation. We also restrict that at least 80% of the population have to be covered by the resulting reverse production system infrastructure.

4.1.3. Demand and material prices information

In this case study, customers are classified into three main types including (1) the secondary market; (2) the online customer; and (3) the municipal landfill. The secondary market customers include wholesalers and/or retailers who buy used products and parts in large quantities and also include material recyclers such as metal smelters, plastic recyclers, and/or glass manufacturers who buy component and/or raw materials such as plastics, glasses, and metals in large quantities for material reclamation. The online customers include individual customers who order small amounts of products such as a computer system, a TV unit, or reusable computer parts. The municipal landfill customers include local landfill sites which accept non-hazardous wastes from the system. In the case study, we assume that the shipments to the online customers are performed by third-party parcel carriers such as United Parcel Service (UPS), DHL, or United States Postal Service (USPS). The shipments to other types of customers and between facilities are performed by third party logistics companies. According to US Census Bureau, there are over 200 non-ferrous secondary metal smelters, 6000 plastics scrap wholesalers, and 14 CRT glass-to-glass recyclers in the United State. To simplify the locations of demands in the case study, all customer types are divided into four zones. The boundary of each transportation zone is adapted from the customer zones of UPS. For instance, according to UPS ground service, if the origin is at Houston, Texas, the area of zone one is the area that UPS can ship the item in a day. Customer zone two covers the areas that UPS can ship the parcel in 2 days by UPS ground and so on. Fig. 3 demonstrates the zoning of customers in the case study.

The population in each customer zone is determined and the total demand of each product and material type is estimated and distributed into each zone. The total demands of refurbished CPUs, CMs, and TVs are assumed to be 50% of the total estimated supply of each product in each zone. The total demands of dismantled materials across the country are estimated from the demand of the product containing the component multiplied by the percentage of the component in the product. The following Table 3 summarizes the number of States and population information of each customer zone.

The selling price for each type of material used in this case study is summarized in Table 4.

4.1.4. Collection facility information

Both temporary and permanent collection facilities are the first consolidation points to gather e-wastes from households into the reverse production system. The recycling fee is collected at the col-

Table 2
Proportion information on initial condition of each collected product.

	Re-saleable (%)	Repairable (%)	Out-of-date (%)
CPU	20	50	30
CM	10	20	70
TV	5	25	70

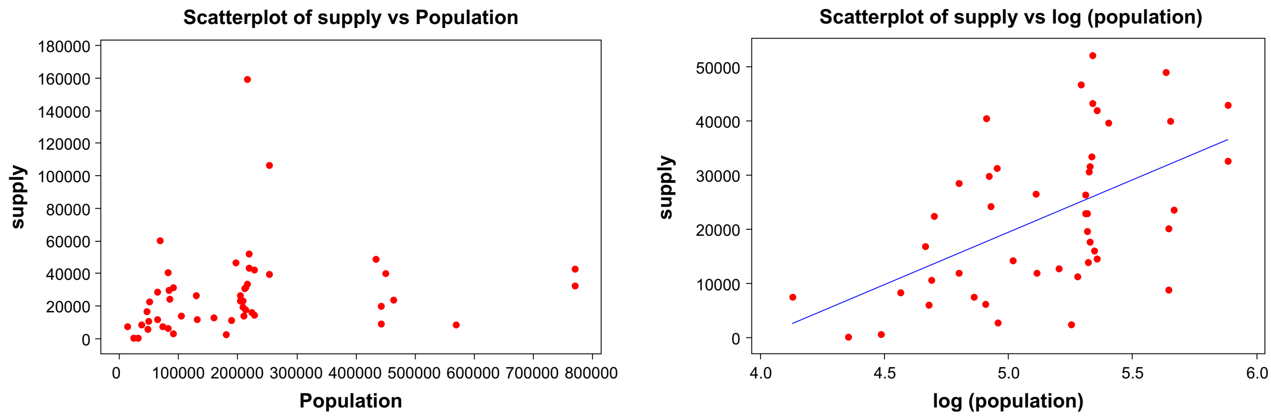

Fig. 2. Scatter plots between supply quantity of e-wastes collected by the one-day collection event (in lbs) vs. population size and $\log_{10}$(Population Size).

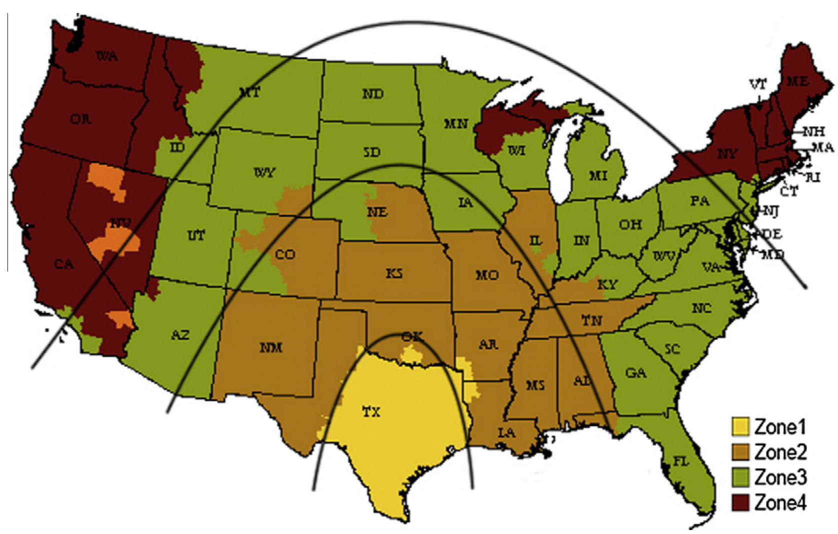

Fig. 3. Zones of customers in the case study. *Source*: www.ups.com.

Table 3
Customer zones information.

Zones	Number of states	Population	% Population
1	1	22,490,022	8
2	11	40,868,088	14
3	20	102,262,512	35
4	16	125,562,984	43

lection points when the customers drop off the obsolete electronics. From literature, the collection fee ranges from $5 to $20 per unit depending on the type and condition of products to be disposed and the weight of the electronics. In this work, we assume that the collection fees for a unit of CPU, CM, and TV are $5, $5, and $8 respectively. At each collection facility, there are a manager and two types of workers including collection workers and inspection workers. The manager is responsible for managing and coordinating all activities in the collection facility with the pay rate of $22 per hour. Each collection worker is responsible for handling customers dropping off their items, collecting recycling fees, giving questionnaires, and loading (unloading) products into (out of) the storage and can handle approximately five customers per hour with the pay rate of $10 per working hour. Each inspection worker is responsible for inspecting collected products and classifying them into predefined categories and can inspect up to six units of TVs, CMs, or CPUs per hour with the pay rate of $12 per working hour. In this case study, we also assume that each manager and worker work 8 h per day, 250 days per year. The area of each regular collection facility is assumed to be 2000 sq. ft consisting of the office and working space of 600 sq. ft and the storage space of 1400 sq. ft. The rental cost of $0.75 per sq. ft per month is assumed for renting a collection facility. Additional costs at the collection facility include the forklift rental cost (approximately $850 per month) and the labor cost for a forklift driver ($15 per hour). The information on the forklift rental cost is from the website: http://www.buyerzone.com/industrial/forklifts/bps-forklift-prices2.html. Each hub collection facility is assumed to be 50% larger than the regular collection facility and requires one additional forklift and one additional forklift driver.

As for the temporary collection event, we assume that all collected products have to be transported to nearby permanent facilities and at most two events can be held per month at any location. Each temporary collection event covers 8 h time periods and require the advertisement ($1842 per event), rental cost ($800), a manager ($35 per hour), a forklift ($50 per hour), a forklift driver ($20 per hour), and 20 collection workers ($15 per hour) with responsibilities of communicating with the customers, giving questionnaires, placing products on pallets, finishing the packaging process, and loading pallets onto trucks. Additional costs for the temporary collection event include the costs for pallets ($240),

Table 4
Market values of reusable electronics and their markets. *Source*: (1) www.scrapcomputers.com, (2) www.gaosys.com, (3) Hong et al. (2006).

Items	Price	Destination markets
Refurbished CPU	\$80/item + \$10 shipping	Online customer
Refurbished CM	\$50/item + \$10 shipping	Online customer
Refurbished TV	\$40/item + \$15 shipping	Online customer
Outdated CPU	\$5–10/item	Wholesaler
Outdated CM	\$0/item	Wholesaler
Outdated TV	−\$0.3/lbs	Wholesaler
Case and cooling fan	\$0.20/lbs	Wholesaler
Refurbished power supply	\$20/item + \$5 shipping	Online customer
Outdated power supply	\$0.05/lbs	Wholesaler
Refurbished CD/DVD/floppy drive	\$15/item + \$5 shipping	Online customer
Outdated CD/DVD/floppy drive	\$0.05/lbs	Wholesaler
Refurbished hard drive	\$25/item + \$5 shipping	Online customer
Outdated hard drive	\$0.05/lbs	Wholesaler
Refurbished processor and memory cards	\$15/item + \$5 shipping	Online customer
Outdated processor and memory cards	\$0.5/lbs	Wholesaler
Wire	\$0.20/lbs	Wholesaler
CRT glass	−\$0.10/lbs	Glass Smelter, Lead Smelter
Steel	\$0.02/lbs	Steel Mill
Plastic	\$0.09/lbs	Sold for used in new product
Copper scrap	\$0.08/lbs	Smelter
Printed circuit board	\$0.5/lbs	Wholesaler
Waste	−\$0.028/lbs	Landfill

shrink wraps (\$124), and other miscellaneous costs (\$250). Based on these assumptions, Table 5 summarizes the cost and capacity information for the collection facility in this case study. The fixed cost of a collection facility is calculated from the facility rental cost, the forklift rental cost, and the labor cost for forklift drivers and a manager.

4.1.5. Processing facility information

Processing facilities are considered as the second layer in the reverse production system. Their functionalities include inspecting, refurbishing, recycling, and disassembling e-wastes and their components. Each processing facility is responsible for repairing used electronics for resale and disassembling outdated equipment for component recovery or material reclamation. Like the collection facility, each processing facility can be classified as hub or regular processing facility. The area of each processing facility is assumed to be 20,000 sq. ft consisting of the office and working space of 8000 sq. ft and the storage space of 12,000 sq. ft. The rental cost of this processing facility is \$0.5 per sq. ft per month. At each processing facility there are a manager and two types of workers including repair workers and disassembly workers. The manager is responsible for managing and coordinating all activities in the processing facility with the pay rate of \$22 per hour. Each repair worker is responsible for repairing all types of electronics including CPUs, CMs, and TVs which are in repairable condition and are not out of date and can repair approximately one unit per hour. The pay rate for each repair worker is \$15 per hour. Once electronic products are repaired, they will be carefully stored in the warehouse and will be used to fulfill future customers' orders. Each disassembly worker is responsible for dismantling CPUs, CMs, and TVs and can dismantle up to 2 units per hour with the pay rate of \$10 per hour. The materials or parts derived from dismantled units will be stored in the warehouse and will be used to fulfill demands from secondary markets or material recyclers. Additional costs at the processing facility include the forklift rental cost (approximately \$850 per month) and the labor cost for a forklift driver (\$15 per hour). Each hub processing facility is assumed to be 50% larger than the regular processing facility and requires one additional forklift and one additional forklift driver. Table 6 summarizes the cost and capacity information for the processing facility in the case study. The fixed cost of a processing facility is calculated from the facility rental cost, the forklift rental cost, and the labor cost for forklift drivers and a manager.

4.1.6. Transportation cost information

We consider two types of transportation costs in this case study. The first type represents the transportation costs for transporting materials between facilities and for moving materials from processing facilities to recycler demand points and/or landfill demand points. We perform this type of transportation with a large truck costing approximately \$1/ton/mile. The second type represents the transportation costs for shipping refurbished products and/or components to online customers, which is assumed to be shipped by the private transportation service provider. Table 7 summarizes the reasonable estimates of this type of the transportation cost. These estimates are the amount currently charged by the United Parcel Service (UPS) and the cost information is available at http://www.ups.com.

4.2. Analysis and results of the case study

In this case study, we intend to design the strategic infrastructure of the reverse production system for collecting and processing

Table 5
The summary of cost and capacity information for a collection facility.

Locations	Fixed facility cost	Functions	Fixed processing cost	Material	Capacity
Permanent collection facility (hub/regular)	N/A	Collection	\$20,000/year[a]	CPU	206,000 lbs/year/worker
				CM	300,000 lbs/year/worker
				TV	616,000 lbs/year/worker
		Inspection	\$24,000/year[a]	CPU	247,200 lbs/year/worker
				CM	360,000 lbs/year/worker
				TV	739,200 lbs/year/worker
Temporary event	\$6496/event	Collection	N/A	CPU	16,480 lbs/8 h event
				CM	24,000 lbs/8 h event
				TV	49,280 lbs/8 h event
Regular collection facility	\$102,200/year	Storage	N/A	All	188,919 lbs/factory[b]
Hub collection facility	\$151,400/year	Storage	N/A	All	283,379 lbs/factory[b]

[a] (Labor cost per hour) (8 h/day) (250 days/year).
[b] It is assumed that 1 pallet consists of 24 CPUs or 18 CMs or 12 TVs and one pallet size is 40″ × 48″. We also assume that the warehouse use three layers storage space.

Table 6
The summary of cost and capacity information for a processing facility.

Locations	Fixed facility cost	Functions	Fixed processing cost	Material	Capacity and variable processing cost
Processing facility (hub/regular)	N/A	Repair	$30,000[a]	CPU	41,200 lbs/year/worker $10/unit
				CM	60,000 lbs/year/worker $8/unit
				TV	123,200 lbs/year/worker $8/unit
		Dismantle	$20,000[a]	CPU	82,400 lbs/year/worker
				CM	120,000 lbs/year/worker
				TV	246,400 lbs/year/worker
Regular processing facility	$204,200/year	Storage	N/A	All	1,619,310 lbs/factory[b]
Hub processing facility	$304,400/year	Storage	N/A	All	2,428,965 lbs/factory[b]

[a] (Labor cost per hour) (8 h/day) (250 days/year).
[b] It is assumed that 1 pallet consists of 24 CPUs or 18 CMs or 12 TVs and one pallet size is 40″ × 48″. We also assume that the warehouse use three layers storage space.

Table 7
The shipping cost information for online customers.

Customer zone	Shipping cost ($/item)			
	CPU	CM	TV	Component
Zone 1	13.54	14.67	22.82	6.91
Zone 2	17.50	19.19	33.25	8.09
Zone 3	19.50	23.38	40.78	8.36
Zone 4	25.00	34.09	55.77	9.02

e-wastes in the state of Texas over the next 3 years. The commercial optimization solver, GAMS, is used as a front-end interface to CPLEX and to a MS-Excel database to determine the optimal solution of the proposed model. All computations are performed on a Pentium (R) 4 CPU, 3.59 GHz computer with 2 GB of RAM. The total number of rows and columns, representing constraints and variables in the model, are 491,431 rows and 2,182,647 columns respectively. The overall calculation time of the model is approximately 2400 s or 40 min. Based on the mathematical model and design parameters previously described, the results of the case study regarding the infrastructure, resources allocation, associated costs and revenues of the system are delineated as followed.

In the first year, the total of 14 permanent collection facilities (9 hubs and 15 regular facilities), 22 one-day collection events, and 12 processing facilities (8 hubs and 4 regular sites) are opened. All opened collection facilities cover 46 counties with total population of 17,708,391 or approximately 80% of the population in the state of Texas. Hub collection facilities are opened among populated counties such as Harris, Dallas, Tarrant and Bexar counties. Regular collection facilities are opened in the less populated counties such as Fort Bend, Cameron, and Montgomery counties. One-day collection events are open in the smaller counties around hubs and regular collection facilities. The number of one-day collection events in each location ranges from 6 to 10 days per year with the average of 8.4 days per year.

For processing facilities, most of the hub processing facilities are opened in the same county as the hub collection facilities to save

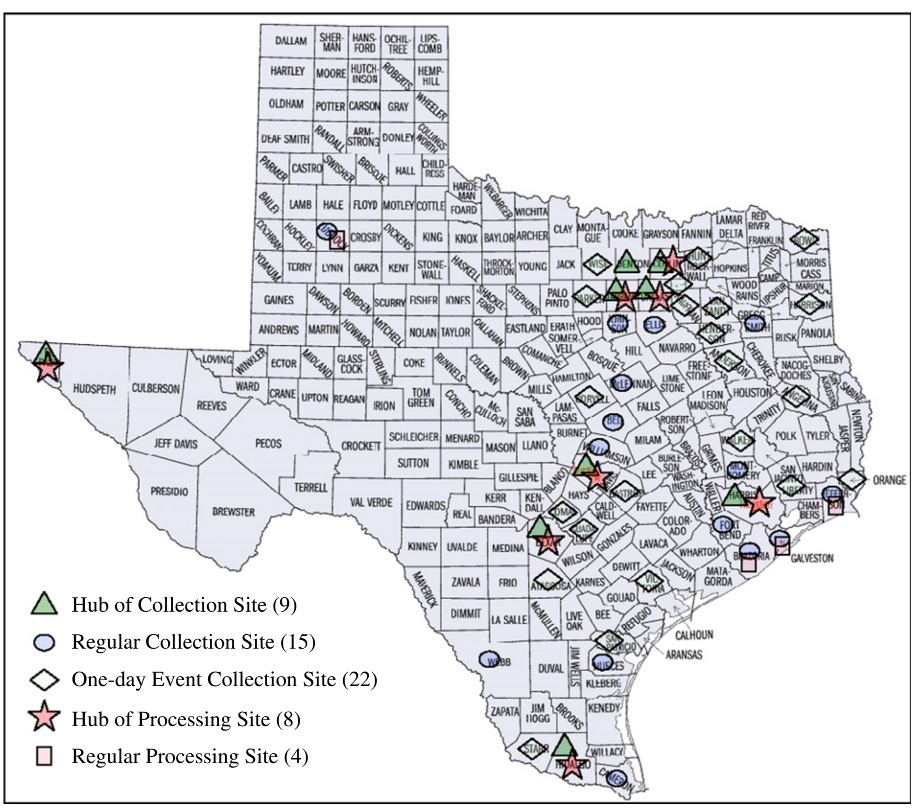

Fig. 4. Reverse production system infrastructure in the first year.

the overall transportation cost. Regular processing facilities are also located among regular collection facilities. Fig. 4 illustrates the reverse production system infrastructure for e-wastes proposed by the model in the first year.

In the second year, all permanent collection facilities opened in the first year are still opened and continue to operate in the second year. Due to the population growth, the growing supply and the requirement to keep the percentage of population coverage above 80%, some locations of one-day collection events are slightly changed. Two new locations of processing facilities at Denton and Nueces counties are opened to support the growing amount of obsolete electronics entering the recycling network. In the third year, all opened permanent collection facilities continue to operate and four additional regular processing facilities are opened due to the growing supply quantities of e-wastes.

The number of workers or resources required to operate each recycling activity is the very important information in operating the reverse production system. The resources considered in this case study are collection, inspection, repair, and disassembly workers. Table 8 illustrates the resources allocation information for each facility in the network over 3 years.

The total weight of e-wastes collected over 3 years is 123.5 million pounds or approximately 70% of the estimated total supply. Eighty-nine percent (by weight) of collected of e-wastes enter the recycling network through permanent collection facilities (hub and regular) and only 11% of e-wastes are collected through temporary collection events.

The overall cost of the reverse production system in this case study is approximately 66 millions dollars. Table 9 summarizes each cost component of the system.

The labor cost from monthly salary of collection and processing workers is $33,139,200 which is approximately 50% and is the major part of the total costs. The result shows that the recycling program is a labor intensive activity and requires large amounts of human effort to drive the program. The second largest cost of the program is the transportation cost, at $16,027,604 to the program or 24% of the total costs.

In addition, cost per pound is also the interesting information in terms of estimating the cost of each type of recycling activity. In this study, total cost per pound is 53 cents. The average costs per pound for site opening, collection, storage, processing and transportation are 10.2, 9.4, 0.4, 20.4, and 13.0 cents respectively.

The total revenue of recycling program is 52,916,683, which comes from collection fees 20,543,028 (38.8%) and sale of materials 32,373,655 (61.2%). The percentage of collection fee is 64% for TVs while 18% for both Monitors and CPUs. Revenue from the sale of CPUs is approximately $20 million while the sum of revenue for monitor and TV together is around $13 million. This is due to the higher price of CPU units and parts even though weight of CPUs collected is of the smallest percentage at 16% of total weight. Using total costs and revenue, the recycling program yields the net cost of $13,057,919 ($65,973,373 – 52,915,454) or the net cost per pound of $0.106 per pound. Therefore, other sources of financial support to local governments or state grant funding is required to make the program financially viable approximately $4,352,640 per year.

In summary, in order to make the recycling program self sustainable without the financial support, the additional collection fees for recycling service are considered to balance the net cost and meet operating costs of the recycling operations. The balanced collection fees are be computed by subtracting Sale of Products ($32,372,42) from Total Costs ($65,973,372), or $33,600,946.

Therefore, to make the operation viable based on the predicted electronics supply, the program requires the total collection fees of $33,600,946/$20,543,028 or 1.64 times of the current fees collected. Table 10 presents the recommended collection fee for the statewide recycling program in Texas.

Nevertheless, the recycling collection fee can cause undesirable effects on the overall participation rate of the program because the participant is very sensitive to the recycling collection fees. Hence, the calculated additional collection fee may be included in the selling price of electronics. The retailer must inform customers about this increased price, which is relatively small compared to the price of the new products.

As shown in Table 9 that recycling program is a labor intensive operation, one approach to recruit volunteers especially in one-day collection events could reduce the total cost of the program. Therefore, the training program for volunteers may be required to obtain the effective use and desirable safety level during the operation.

Another approach is to reduce the site opening costs and storage costs. For example, the permanent drop-off collection program can work together with other existing on-going municipal waste programs in order to drive down the costs from location rental and collection labor. Another way to cut down the site location cost for one-day collection event is that the collection event can take place on the public locations such as fair grounds, municipal landfills, and school parking lots.

Table 8
Resource Allocation Information for Each Facility.

Facilities	Types of sites	Functions	Average numbers of resources required at each facility (persons)		
			Year 1	Year 2	Year 3
Collection facility	Hub	Collection	13	14	14
		Inspection	5	6	7
	Regular	Collection	9	10	10
		Inspection	2	3	4
Processing facility	Hub	Repair	4	4	4
		Disassembly	23	25	27
	Regular	Repair	2	2	2
		Disassembly	6	7	7

Table 9
Summary of associated costs.

Types	Costs	Percent of total costs
Site opening cost (office, forklift, opening/closing cost)	12,568,920	19
Fixed collection cost (labor cost)	11,658,240	18
Fixed storage cost (warehouse rental)	470,400	1
Fixed processing cost (labor cost)	21,480,960	32
Variable processing cost (spare parts)	3,775,201	6
Variable transportation cost (between sites and to customers)	16,019,651	24
Total	65,973,372	100

Table 10
Recommended collection fees.

Products	Current fees per unit	Recommended fess per unit	Recommended fees per pound
CPU	$5	$8	$0.315
Monitor	$5	$8	$0.315
TV	$8	$13	$0.503

5. Conclusion

In this paper, our proposed mathematical model successfully creates a strategic design of reverse supply chains system for the planning of statewide electronic recycling program in the state of

Texas. The academic contributions of this paper are the modeling approach and the case study data. This model is distinguished from previous approaches to this problem by the way that it captures the possibility of obsolescence of electronic products and the possibility of multitasking of resources. The ideas of hub and regular permanent facility and one-day event temporary facility are also included into the model. Because of the large scale of the case study which contains millions of variables and constraints, the case study provides a challenging large scale benchmark data set for other researchers.

The decisions considered in this model include facility locations, resource allocations, and material flows in the reverse supply chains system. The model is applied to create a design for used electronics reverse supply chains system infrastructure in the state of Texas. The large-scale case study contains millions of variables and constraints. Some historical data from many previous recycling projects in several states are gathered and extracted for generating the case study. In addition, the data based on a variety of sources has been used to approximate the regional electronics recycling infrastructure design for Texas. Because very little available data exist for relatively new problem in the US, the data provided in this paper may be helpful to other designers of e-scrap collection and processing systems as well.

The possible extension of this work is to include other types of e-scrap such as printers, laptop computers, cell phones, telephones, personal digital assistant products (PDAs), and portable music player in the case study analysis. Also, the addition of collection sites and processing alternatives would extend the study to be more comprehensive. Finally, investigations on effects of preloading the free software systems or removing the operating systems in refurbished computers are also interesting future direction.

Acknowledgement

The authors would like to thank Thammasat University for the academic and financial support in conducting this research. Also, the authors would like to thank the reviewers for valuable comments.

References

Ammons, J. C., Assavapokee, T., Newton, D., & Realff, M. J. (2002). Reverse production system design for recycling under uncertainty. *Proceedings of SPIE – The International Society for Optical Engineering, 4569*, 1–12.

Ammons, J. C., Realff, M. J., Newton, D., & Cerav, S. (1999). Determining reverse production systems infrastructure for electronic assemblies. *IEEE International Symposium on Electronics and the Environment*, 257–262.

Barros, A. I., Dekker, R., & Scholten, V. (1998). A two-level network for recycling sand: A case study. *European Journal of Operational Research, 110*, 199–214.

Bartel, T. (1995). Recycling program for printer toner cartridges and optical photoconductors. *IEEE International Symposium on Electronics and the Environment*, 225–228.

Bettac, E., Maas, K., Beullens, P., & Bopp, R. (1999). RELOOP: Reverse logistics chain optimization in a multi-user trading environment. *IEEE International Symposium on Electronics and the Environment*, 42–47.

Caruso, C. C. A., & Paruccini, M. (1993). The regional urban solid waste management system: A modelling approach. *European Journal of Operational Research, 70*(1), 16–30.

Chen, R. W., Navin-Chandra, D., & Prinz, F. (1994). A cost-benefit analysis model of product design for recyclability and its application. *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A*, 502–507.

Das, S., & Yedlarajiah, D. (2002). An integer programming model for prescribing material recovery strategies. *IEEE International Symposium on Electronics and the Environment*, 118–122.

Degher, A. (2002). HP's worldwide take back and recycling programs: Lessons on improving program implementation. *IEEE International Symposium on Electronics and the Environment*, 224–227.

Diggelman, C., Rau, G., Brachman, S., & Ziemke, B. (2003). Wisconsin end-of-life electronics study. *IEEE International Symposium on Electronics and the Environment*, 352–357.

Dowlatshahi, S. (2000). Developing a theory of reverse logistics. *Interfaces, 30*(3), 143–155.

Dowlatshahi, S. (2002). A framework for strategic factors in reverse logistics. *Proceedings – Annual Meeting of the Decision Sciences Institute*, 425–430.

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E. A., van Nunen, J. A. E. E., & van Wassenhove, L. N. (1997). Quantitative models for reverse logistics: A review. *European Journal of Operational Research, 103*, 1–17.

Fleischmann, M., Krikke, H. R., Dekker, R., & Flapper, S. D. P. (2000). A characterisation of logistics networks for product recovery. *Omega, 28*, 653–666.

Gungor, A. G., & Gupta, S. M. (1999). Issues in environmentally conscious manufacturing and product recovery: A survey. *Computers and Industrial Engineering, 36*(4), 811–853.

Hainault, T., Smith, D. S., Cauchi, D. J., Thompson, D. A., Fisher, M. M., & Hetzel, C. (2000). Minnesota's multi-stakeholder approach to managing electronic products at end-of-life. *IEEE International Symposium on Electronics and the Environment*, 310–317.

Hong, I., Assavapokee, T., Ammons, J. C., Boelkins, C., Gilliam, K., Oudit, D., et al. (2006). Planning the e-scrap reverse production system under uncertainty in the state of Georgia: A case study. *IEEE Transactions on Electronics Packaging Manufacturing, 29*(3), 150–162.

Jayaraman, V., Guide, V. D. R., Jr., & Srivastava, R. (1999). A closed-loop logistics model for remanufacturing. *Journal of the Operational Research Society, 50*(5), 497–508.

Jayaraman, V., Patterson, R. A., & Rolland, E. (2003). The design of reverse distribution networks: Models and solution procedures. *European Journal of Operational Research, 150*, 128–149.

Jung, L. B., & Bartel, T. (1998). An Industry approach to consumer computer recycling: The San Jose Project. *IEEE International Symposium on Electronics and the Environment*, 36–41.

Knoth, R., Hoffmann, M., Kopacek, B., & Kopacek, P. (2001). A logistic concept to improve the re-usability of electric and electronic equipment. *IEEE International Symposium on Electronics and the Environment*, 115–118.

Krikke, H. R., van Harten, A., & Schuur, P. C. (1999). Business case Oce: Reverse logistic network re-design for copiers. *OR Spektrum, 21*, 381–409.

Kroon, L., & Vrijens, G. (1995). Returnable containers: An example of reverse logistics. *International Journal of Physical Distribution and Logistics Management, 25*(2), 56–68.

Kusumastuti, R. D., Piplani, R., & Lim, G. H. (2004). An approach to design reverse logistics networks for product recovery. In *IEEE international engineering management conference, Vol. 3, Proceedings – 2004 IEEE international engineering management conference: Innovation and entrepreneurship for sustainable development, IEMC 2004* (pp. 1239–1243).

Listes, O., & Dekker, R. (2005). A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research, 160*, 268–287.

Louwers, D., Kip, B. J., Peters, E., Souren, F., & Flapper, S. D. P. (1999). A facility location allocation model for reusing carpet materials. *Computers and Industrial Engineering, 36*, 855–869.

Nagurney, A., & Toyasaki, F. (2005). Reverse supply chain management and electronic waste recycling: A multitiered network equilibrium framework for e-cycling. *Transportation research part E: Logistics and Transportation Review, 41*(1), 1–28.

Pochampally, K. K., & Gupta, S. M. (2003). A multi-phase mathematical programming approach to strategic planning of an efficient reverse supply chain network. *IEEE International Symposium on Electronics and the Environment*, 72–78.

Realff, M. J., Ammons, J. C., & Newton, D. J. (1999). Carpet recycling: Determining the reverse production system design. *The Journal of Polymer–Plastics Technology and Engineering, 38*(3), 547–567.

Realff, M. J., Ammons, J. C., & Newton, D. J. (2000). Strategic design of reverse production systems. *Computers and Industrial Engineering, 24*(2), 991–996.

Realff, M. J., Ammons, J. C., & Newton, D. J. (2004). Robust reverse production system design for carpet recycling. *IIE Transactions (Institute of Industrial Engineers), 36*(8), 767–776.

Schultmann, F., Engels, B., & Rentz, O. (2003). Closed-loop supply chains for spent batteries. *Interfaces, 33*(6), 57–71.

Shih, L. H. (2001). Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. *Resources, Conservation and Recycling, 32*, 55–72.

Spengler, T., Puchert, H., Penkuhn, T., & Rentz, O. (1997). Environmental integrated production and recycling management. *European Journal of Operational Research, 97*(2), 308–326.

Srivastava, R., Jayaraman, V., & Kriche, E. (2003). Reverse logistics in healthcare. *Proceedings – Annual Meeting of the Decision Sciences Institute*, 2079–2084.

Wang, C. H., Even, J. C., & Adams, S. K. (1995). A mixed-integer linear model for optimal processing and transport of secondary materials. *Resources, Conservation and Recycling, 15*, 65–78.

Williams, J., & Shu, L. H. (2000). Analysis of toner-cartridge remanufacturer waste stream. *IEEE International Symposium on Electronics and the Environment*, 260–265.

Wright, L., McLaren, J., Jackson, T., & Parkinson, S. (1998). Mobile phone takeback and recycling: Analysis of the ECTEL project. *IEEE International Symposium on Electronics and the Environment*, 54–59.