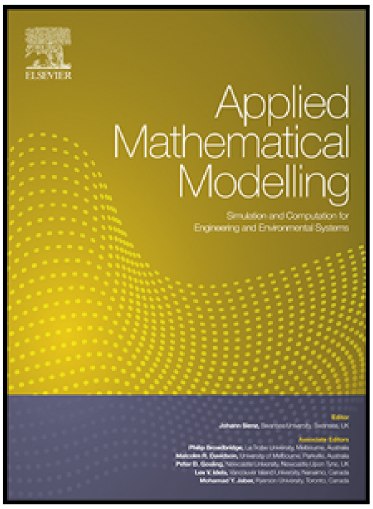

Reverse Logistics Network Design for Product Recovery and Remanufacturing

Tsai-Yun Liao

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Highlights

- A mathematical model for the network design of multi-echelon reverse logistics is developed.
- A hybrid genetic algorithm is proposed to solve the problem.
- The amount of remanufactured products depends on the critical and the most valuable modules.
- The model results produce less CO_2 and reduce the environmental impact.
- The results show the proposed model performs better than current reverse logistics operating in the real city.

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Tsai-Yun Liao
Department of Business Administration, National Chiayi University
No.580, Sinmin Rd., Chiayi City 60054, Taiwan (R.O.C.)
Tel: 886-5-2732935
Fax: 886-5-2732932
Email: tyliao@mail.ncyu.edu.tw

Abstract

Due to environmental concerns, reverse logistics now is becoming an important strategy to increase customer satisfaction. This research develops a generic mixed integer nonlinear programming model (MINLP) for reverse logistics network design. This is a multi-echelon reverse logistics model. It maximizes total profit by handling products returned for repair, remanufacturing, recycling, reuse, or incineration/landfill. A hybrid genetic algorithm (GA) is proposed to solve the problem. The designed model is validated and tested by using a real-life example of recycling bulk waste in Taoyuan City, Taiwan. Sensitivity analyses are conducted on various parameters to illustrate the capabilities of the proposed model. Post-optimality analysis and comparison show that the proposed model performs better than current reverse logistic operations and the proposed hybrid GA demonstrates the efficiency of solving the complex reverse logistics problem.

Keywords: Reverse logistics network; Modularity; Bulk waste management; Mixed integer nonlinear programming mode; Hybrid genetic algorithm

1. Introduction

Due to environmental concerns, reverse logistics now is becoming an important strategy to increase customer satisfaction. Reverse logistics originates from a waste management standpoint. It is complicated due to the presence of driving forces, return reasons, product types, and uncertainty around the reverse flow. Also, how the material is recovered and who will execute and manage the various reverse operations are important issues [1,2]. Since reverse logistics includes a series of processes involving product return, repair, dismantling, refurbishing, recycling, remanufacturing, and disposal of used or end-of-life products, the implementation of a reverse logistics network is a strategic decision. This decision seeks a single objective or multiple objectives of cost minimization, profit maximization, customer satisfaction, or environmental benefit [2,3,4,5]. It includes the determination of locations, the number and capacity of facilities and the flow quantity sent from one facility to another. It is severely complicated by many uncertain factors; therefore, several papers have focused on the design of reverse logistics network [6,7,8,9,10,11,12].

A classification scheme for different types of reverse logistics networks has been identified by Fleischmann et al [13]. The reverse logistics networks range from simple echelons to complex echelons composed of forward and reverse supply chain networks. [14,15,16]. Due to the complexity and economic effect of reverse logistics, a common mathematical model has been developed to solve the network problem [14,15,17,18,19,20,21]. Bazan et al. [22] reviewed mathematical inventory models for reverse logistics from an environmental perspective. A more comprehensive survey of reverse logistics was taken by Agrawal et al. [14], Govindan et al. [16], and Govindan and Soleimani [23].

This research is inspired by the projects related to reverse logistics implementation of bulk waste in Taiwan. In this research, a reverse logistics network is designed and a mixed integer nonlinear programming (MINLP) model is developed to solve the strategic network design of reverse logistics. The proposed model is generic, for maximizing total profit by considering product returns with different fractions of reuse and recycle activities. It is a multi-echelon reverse logistics network designed to find the near optimal location and number of facilities, and the allocation of returned products and modules for profit maximization. Also, we consider various recovery activities based on the quality and high-value modules of recovered products. The number of remanufactured products depends on the critical and most valuable modules, and modularized remanufacturing processes make product recovery more efficient and profitable.

This MINLP model involves an iterative procedure for location and facility selection which requires a computerized optimization procedure. It is known to be an NP-hard problem. Since optimization software such as Lingo or CPLEX can only solve this problem on a small scale within an acceptable time, a hybrid genetic algorithm (GA) is proposed. GAs have been widely used to solve various optimization problems

[2,24,25,26]. A comprehensive review of GAs in solving the reverse logistics problems can be found in [14,16,17,27].

The designed model is validated and tested by using a real-life example of recycling bulk waste in Taoyuan City, Taiwan. Also, sensitivity analyses are conducted on various parameters to present the capabilities of the proposed model. Post-optimality analysis and comparison show that the proposed model performs better than current reverse logistic operations in the city. The contributions of this study include (1) providing a well-structured network design for the reverse logistics; (2) providing a more efficient and profitable product recovery with modularized remanufacturing processes and (3) providing an opportunity for reducing emissions. The proposed hybrid GA also demonstrates the efficiency and effectiveness of solving the complex reverse logistics problem.

This paper is organized as follows: the next section presents a brief review of the related literature. Section 3 describes the problem definition and mathematical model for the network design of the reverse logistics. In Section 4, the hybrid GA is proposed. The computation capability of the hybrid GA and the applicability of the proposed model are illustrated through numerical experiments and compared with in Section 5. In Section 6, the findings of numerical experiments are enhanced through sensitivity analysis. Managerial implications are also discussed. Concluding comments are given in the last section.

2. Literature review

There is a lot of research related to reverse logistics network design and closed-loop supply chains (CLSC) combined with forward and reverse logistics. Several studies have been focused on remanufacturing the returned products. Kim et al. [28] developed a mathematical model for the remanufacturing process of reusable components in reverse supply chains. Chung et al. [29] examined used products and presented a CLSC system for remanufacturing. Demirel and Gökçen [30] proposed a new model for a remanufacturing system including both forward and reverse flows. Mutha and Pokharel [31] developed a mixed integer linear programming (MILP) model for handling product returns by considering modular product structures with different fractions of product recovery. El-Sayed et al. [6] developed a stochastic mixed integer programming model for connecting manufacturing and remanufacturing activities and found that inventory control is of considerable interest in joining the manufacturing and remanufacturing systems in the CLSC network. Das and Chowdhury [21] considered a modular product design architecture for supporting recovery processes and using integrated recovery service providers for handling product recovery. Soleimani et al. [32] developed a remanufacturing model incorporating three risk measures. The three measures are mean absolute deviation, value at risk, and conditional value at risk. Eskandarpour et al. [33] proposed a MILP to determine the proper collection and recycling centers for the reverse and forward logistics. Abdulrahman et al. [3] developed a framework for the strategic decision of remanufacturing for Chinese auto parts manufacturers. Qiang [34] proposed a CLSC production planning model to evaluate the remanufacturing profit.

In addition to the studies concerning remanufacturing, other reverse activities such as reuse, recycling, and repair can be found in various published research [7,15,25,35-41]. Most of them proposed a MILP to describe the complex network configuration of a reverse logistics system, which determines the optimal selection of locations, the capacities of inspection centers, and product recovery facilities.

There are relatively few studies which investigate uncertainty factors in reverse logistics [42,43]. Uncertainty problems are mainly solved by the fuzzy method. Niknejad and Petrovic [44] designed a fuzzy mixed integer programming model for inventory control problems and production planning optimization of an integrated reverse logistics network. The fuzzy reverse logistics model is also found in the studies of Subulan et al. [45], Shekarian et al. [46], and Amin & Baki [47]. For multiple objective problems, Vahdani et al. [48] developed a bi-objective MILP model for a CLSC network, where the uncertainty problem is solved by a combination of robust and fuzzy optimization methods. Amin and Zhang [10] designed a CLSC network under uncertain demand and return. Govindan et al. [49] and Soleimani et al. [50] designed a fuzzy multi-objective optimization model for reverse logistics considering sustainability problems.

Some studies mainly investigate the strategic design and decision making of reverse logistic operations. Krumwiede and Sheu [51] developed a model for helping 3PLs to pursue strategic decision-making for new market of reverse logistics. Ko and Evans [52] designed a MINLP model to solve the dynamic integrated forward/reverse logistics network operated by a 3PL provider. A genetic algorithm was developed to solve the problem. Du and Evans [53] developed a two-objective MILP model for a reverse logistics network operated by third party logistics (3PL) providers. Min and Ko [54] proposed a MINLP model to solve the reverse logistics problem involving the location and allocation of repair facilities for 3PLs. Cheng and Lee [55] found that reverse logistics has rarely been examined from a strategic planning perspective, and a 3PL provider is expected to improve the operational functions in traditional reverse logistics. Jayaram and Tan [56] proposed that there are significant differences between firms with and without logistics providers in their supply chain management. Their results suggested that firms that are engaged in alliances with 3PLs should monitor and improve their performance.

To the best of our knowledge, only a few studies investigate the reverse logistics problem by considering the modularization of recovered products. This research models the remanufacturing processes by using the high-value modules of recovered products. In addition, no research analyzes the real-life example of recycling bulk waste. The results bring the benefits of more efficient and profitable product recovery for bulk waste furniture with modularized remanufacturing processes and the reduction of emissions. The hybrid GA also demonstrates the efficiency and effectiveness of solving the complex reverse logistics problem.

3. Model development

This research proposes a general network for reverse logistics and develops a MINLP to optimize the operations of product recovery and remanufacturing. As shown in Fig. 1, this is designed as a multi-echelon reverse logistics network with corresponding members in the layers. The objective of the proposed model is to maximize total profit within the network. Some assumptions are postulated as follows.

1. The network of multi-echelon reverse logistics is as shown in Fig. 1. To encourage more product recovery, the regional collection centers are installed near customers.
2. There are multiple sources through all the network layers.
3. The potential locations of centers through all the network layers are predefined.
4. The flow between echelons of the networks is related to the maximum percentages of product recovery types. The returned products can be repaired or dismantled into modules.
5. Modules can be reused in different ways such as refurbishing for selling in the spare parts markets, recycling for various purposes, and remanufacturing products by composing modules.
6. The number of remanufactured products depends on which critical modules are available, and which modules will be purchased new from suppliers as needed.
7. Customer demands for repaired and remanufactured products are known.
8. Facility capacities of all the centers are limited and known.

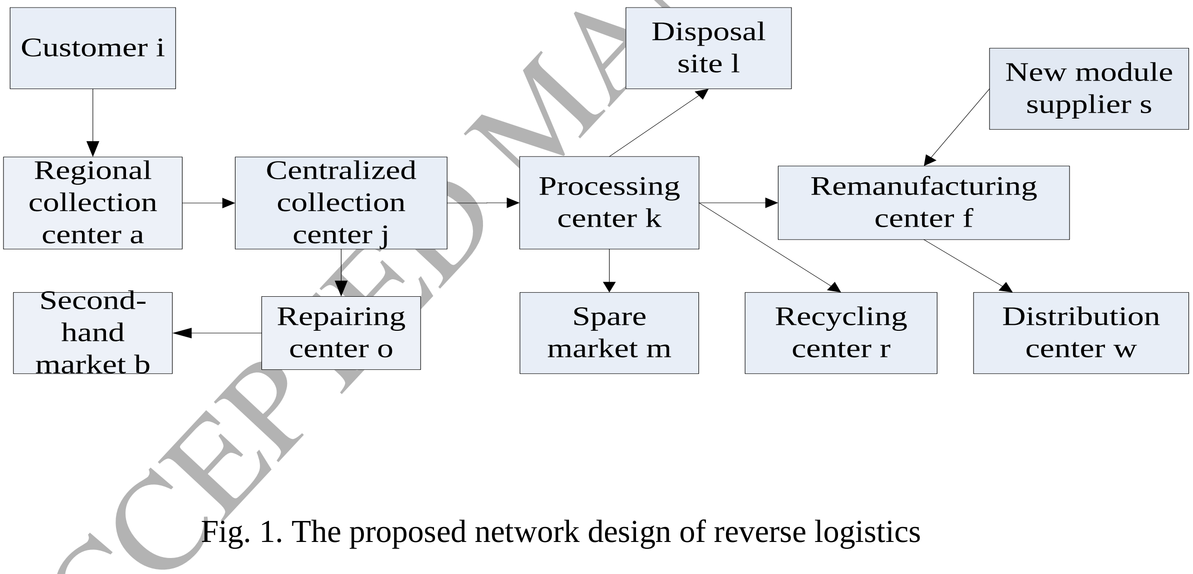


Fig. 1. The proposed network design of reverse logistics

Based on the aforementioned description and assumptions, the generalized reverse logistics model can be formulated. The following parameters and decision variables are used in the model.

Indices:

i	Index of customers, i=1,...,I;
a	Index of regional collection centers, a=1,...,A;
j	Index of centralized collection centers, j=1,...,J;
k	Index of processing centers, k=1,...,K;
o	Index of repairing centers, o=1,...,O;

r	Index of recycling centers, r=1,...,R;
f	Index of remanufacturing centers, f=1,...,F;
m	Index of spare parts markets, m=1,...,M;
l	Index of disposal sites, l=1,...,L;
b	Index of second hand markets, b=1,...B;
w	Index of distribution centers, w=1,...,W;
s	Index of new module suppliers, s=1,...,S;
p	Index of products, p=1,...,P;
n	Index of modules, n=1,...,N.

Parameters:

F_a, F_j, F_k, F_o, F_f	Fixed cost of facility a, j, k, o, f;
T_{pia}	Transportation cost of product p from customer i to regional collection center a;
T_{paj}	Transportation cost of product p from regional collection center a to centralized collection center j;
T_{pjk}	Transportation cost of product p from centralized collection center j to processing center k;
T_{pjo}	Transportation cost of product p from centralized collection center j to repairing center o;
T_{pob}	Transportation cost of product p from repairing center o to second hand market b;
T_{npkm}	Transportation cost for module n of product p from processing center k to spare market m;
T_{npkr}	Transportation cost for module n of product p from processing center k to recycling center r;
T_{npkf}	Transportation cost for module n of product p from processing center k to remanufacturing center f;
T_{npkl}	Transportation cost for module n of product p from processing center k to disposal site l;
T_{npf}^{s}	Transportation cost for new module n of product p by remanufacturing center f from supplier s;
T_{pfw}	Transportation cost for product p from remanufacturing center f to distribution center w;
P_{pb}	Unit price for product p at second hand market b;
P_{npr}	Unit revenue for module n of product p at recycling center r;
P_{npm}	Unit revenue for module n of product p at spare market m;
P_{pw}	Unit price of remanufactured product p for distribution center w;
UC_p	Unit cost for returned product p;
HC_{pj}	Unit handling cost of product p at centralized collection center j;

HC_{pk}	Unit handling cost of product *p* at processing center *k*;
HC_{npl}	Unit handling cost for module *n* of product *p* at disposal site *l*;
MC_{po}	Unit repairing cost of product *p* at repair center *o*;
MC_{pf}	Unit assembly cost of product *p* at remanufacturing center *f*;
IC_{pa}	Inventory cost of product *p* at regional collection center *a*;
IC_{npf}	Inventory cost of module *n* of product *p* at remanufacturing center *f*;
IC_{pf}	Inventory cost of product *p* at remanufacture center *f*;
SC_{npf}^{s}	Unit purchase cost for new module *n* of product *p* by remanufacturing center *f* from supplier *s*;
Q_{pi}	Quantity of returned product *p* from customer *i;*
D_{ia}	Distance from customer *i* to regional collection center *a*;
D_{max}	Maximum allowed distance for returned products delivery;
D_{pb}	Demand of repaired product *p* at second hand market *b*;
D_{pw}	Demand of remanufactured product *p* at distribution center *w*;
α_{pj}	Percentage of product *p* from centralized collection center *j* to repairing center;
g_{np}	Quantity of module *n* needed for assembling one unit of product *p*;
β_{npk}	Percentage of module *n* of product *p* from processing center *k* to remanufacturing center;
γ_{npk}	Percentage of module *n* of product *p* from processing center *k* to recycling center;
δ_{npk}	Percentage of module *n* of product *p* from processing center *k* to spare parts market;
V_p	Unit volume of product *p*;
V_{np}	Unit volume of module *n* of product *p*;
M	A big number;
$\bar{S}_x$	Maximum capacity of facility *x*, *x*=*a, j, k, o, f*;
$\underline{S}_x$	Minimum capacity of facility *x*, *x*=*a, j, k, o, f*.

Decision variables:

$$Y_x = \begin{cases} 1, \text{if a facility } x\ (x = a,\ j, k, o, \text{or } f\,) \text{ is open,} \\ 0, \text{otherwise;} \end{cases}$$

$$Y_{ia} = \begin{cases} 1, \text{if returned products delivered from customer } i \text{ to regional collection} \\ \quad \text{center } a, \\ 0, \text{otherwise;} \end{cases}$$

Q_{pia}	Amount of returned product *p* delivered from customer *i* to regional collection center *a*;
Q_{paj}	Amount of returned product *p* delivered from regional collection center *a* to centralized collection centers *j*;
Q_{pjo}	Amount of returned product *p* delivered from centralized collection centers *j* to repair center *o*;
Q_{pjk}	Amount of returned product *p* delivered from centralized collection centers *j* to processing centers *k*;
RQ_{pob}	Amount of repaired product *p* delivered from *o* to *b*;
NQ_{npkm}	Amount of module *n* of product *p* delivered from processing centers *k* to spare market *m*;
NQ_{npkr}	Amount of module *n* of product *p* delivered from processing centers *k* to recycling center *r*;
NQ_{npkf}	Amount of module *n* of product *p* delivered from processing centers *k* to remanufacturing center *f;*
NQ_{npkl}	Amount of module *n* of product *p* delivered from processing centers *k* to disposal site *l*;
FQ_{pf}	Quantity of product *p* remanufactured at remanufacturing center *f*;
MQ_{pfw}	Quantity of product *p* delivered from remanufacturing center *f* to distribution center *w*;
IQ_{npf}	Inventory of module *n* of product *p* at remanufacturing center *f*;
SQ^{s}_{npf}	Quantity of new module *n* of product *p* ordered by remanufacturing center *f* from supplier s;
IQ_{pf}	Inventory of product *p* at remanufacturing center *f*.

The objective function of Eq. (1) is to maximize the total profit, the difference between total revenue and total cost. The revenue obtained from the first four items of Eq. (1) includes revenue from repaired products (*RP*), refurbished modules (*MP*), recycled modules (*RCP*), and remanufactured products (*RMP*). The total cost includes fixed cost (*FC*) of establishing different facilities in the reserve logistics, transportation cost (*TRC*) incurred during the flow of products and modules, costs for returned product collection (*CC*) and new module purchase (*SC*), handling costs (*HC*) at collection centers, disposal sites and processing centers, repair cost (*RC*) at repair centers, remanufacturing cost (*RMC*) at plants, and inventory costs (*IC*) of products and modules. Detailed formulations regarding the objection function are described in the following equations from Eq. (2) to Eq. (13).

$$\begin{aligned} Max \quad TC = {} & RP + MP + RCP + RMP \\ & -(FC + CC + TRC + HC + RC + RMC + SC + IC) \end{aligned} \tag{1}$$

Eq. (2) represents the revenue for repaired products. The price of repaired products P_{pb} is estimated based on product value and repairing cost.

$$RP = \sum_{p}\sum_{o}\sum_{b} P_{pb} RQ_{pob} \tag{2}$$

The refurbished modules can be sold in the spare parts market and the revenue is as Eq. (3).

$$MP = \sum_{n \in N^m} \sum_{p} \sum_{k} \sum_{m} P_{npm} NQ_{npkm} \tag{3}$$

The modules are recycled if they cannot be remanufactured or refurbished. They can be broken down and have salvage values. Eq. (4) indicates the possible revenue for recycling modules.

$$RCP = \sum_{n \in N^r} \sum_{p} \sum_{k} \sum_{r} P_{npr} NQ_{npkr} \tag{4}$$

The revenue for remanufactured products is as Eq. (5). The price of remanufactured products P_{pw} for distribution center w is estimated based on the available modules for remanufacturing and the potential purchase of new modules.

$$RMP = \sum_{p} \sum_{f} \sum_{w} P_{pw} MQ_{pfw} \tag{5}$$

The fixed cost for selected centers in the reserve network is as Eq. (6). The facility location is predetermined and the selection of proper centers in the network is restricted to the objectives and constraints of the model.

$$FC = \sum_{a} F_a Y_a + \sum_{j} F_j Y_j + \sum_{k} F_k Y_k + \sum_{o} F_o Y_o + \sum_{f} F_f Y_f \tag{6}$$

The cost for collecting returned products is as Eq. (7). The returned products will only be delivered to the selected regional collection centers depending on the distance proximity.

$$CC = \sum_{p} \sum_{i} \sum_{a} UC_p Q_{pia} \tag{7}$$

The transportation costs of delivering products or modules between different centers are as Eq. (8).

$$\begin{aligned} TRC = {} & \sum_{p} \sum_{i} \sum_{a} T_{pia} Q_{pia} + \sum_{p} \sum_{a} \sum_{j} T_{paj} Q_{paj} + \sum_{p} \sum_{j} \sum_{k} T_{pjk} Q_{pjk} + \sum_{p} \sum_{j} \sum_{o} T_{pjo} Q_{pjo} + \\ & \sum_{p} \sum_{o} \sum_{b} T_{pob} RQ_{pob} + \sum_{n \in N^l} \sum_{p} \sum_{k} \sum_{l} T_{npkl} NQ_{npkl} + \sum_{n \in N^m} \sum_{p} \sum_{k} \sum_{m} T_{npkm} NQ_{npkm} + \\ & \sum_{n \in N^f} \sum_{p} \sum_{k} \sum_{f} T_{npkf} NQ_{npkf} + \sum_{n \in N^r} \sum_{p} \sum_{k} \sum_{f} T_{npkr} NQ_{npkr} + \sum_{n \in N^s} \sum_{p} \sum_{s} \sum_{f} T^s_{npf} SQ^s_{npf} + \\ & \sum_{p} \sum_{f} \sum_{w} T_{pfw} MQ_{pfw} \end{aligned} \tag{8}$$

The handling costs of returned products at centralized collection centers, processing centers, and disposal sites are as Eq. (9). The first item is the handling cost, including product examination at the centralized collection centers. Products which can be repaired are delivered to the repair centers and the others are sent to processing centers for dismantling into modules. The dismantled modules are delivered to remanufacturing centers, spare parts markets, recycling centers, and disposal sites. The second item is the module dismantling cost at the processing centers and the third item is the handling cost at the disposal sites for incineration or landfill.

$$HC=\sum_{p}\sum_{a}\sum_{j}HC_{pj}Q_{paj}+\sum_{p}\sum_{j}\sum_{k}HC_{pk}Q_{pjk}+\sum_{n\in N^{l}}\sum_{p}\sum_{k}\sum_{l}HC_{npl}NQ_{npkl} \tag{9}$$

The cost of repair at repair centers is as Eq. (10) and the remanufacturing cost at factories in Eq. (11). If some types of module are not enough for remanufacturing, then they will be bought from new module suppliers, as shown in Eq. (12).

$$RC=\sum_{p}\sum_{j}\sum_{o}MC_{po}Q_{pjo} \tag{10}$$

$$RMC=\sum_{p}\sum_{f}MC_{pf}FQ_{pf} \tag{11}$$

$$SC=\sum_{n}\sum_{p}\sum_{f}\sum_{s}SC^{s}_{npf}SQ^{s}_{npf} \tag{12}$$

The inventory costs of products and modules are as Eq. (13). The first item is the average inventory cost of the returned products at the regional collection centers. The inventory costs for modules in the remanufacturing centers are given as the second item.

$$IC=\sum_{p}\sum_{i}\sum_{a}IC_{pa}Q_{pia}/2+\sum_{n}\sum_{p}\sum_{f}IC_{npf}IQ_{npf} \tag{13}$$

The constrains involved in the proposed model are expressed as follows.

$$\sum_{a}Y_{ia}=1 \qquad \forall i \tag{14}$$

$$\sum_{i}Y_{ia}<=MY_{a} \qquad \forall a \tag{15}$$

$$D_{ia}Y_{ia}<=D_{max} \qquad \forall i,a \tag{16}$$

$$\sum_{i}\sum_{a}Q_{pi}Y_{ia}=\sum_{i}\sum_{a}Q_{pia} \qquad \forall p \tag{17}$$

$$\sum_{i}Q_{pia}=\sum_{j}Q_{paj} \qquad \forall p,a \tag{18}$$

$$\sum_{o}Q_{pjo}<=\alpha_{pj}\sum_{a}Q_{paj} \qquad \forall p,j \tag{19}$$

$$\sum_{j}\sum_{o}Q_{pjo}=\sum_{o}\sum_{b}RQ_{pob} \qquad \forall p \tag{20}$$

$$\sum_{o}RQ_{pob}=D_{pb} \qquad \forall p,b \tag{21}$$

$$\sum_{k}Q_{pjk}<=(1-\alpha_{pj})\sum_{a}Q_{paj} \qquad \forall p,j \tag{22}$$

$$\sum_{f}NQ_{npkf}<=\beta_{npk}\sum_{j}NQ_{npjk} \qquad \forall n,p,k \tag{23}$$

$$\sum_{r}NQ_{npkr}<=\gamma_{npk}\sum_{j}NQ_{npjk} \qquad \forall n,p,k \tag{24}$$

$$\sum_{m}NQ_{npkm}\leq\delta_{npk}\sum_{j}NQ_{npjk} \qquad \forall n,p,k \tag{25}$$

$$\sum_{l}NQ_{npkl}=\sum_{j}NQ_{npjk}-\sum_{f}NQ_{npkf}-\sum_{r}NQ_{npkr}-\sum_{m}NQ_{npkm} \qquad \forall n,p,k \tag{26}$$

$$FQ_{pf} = Max\left\{ \frac{NQ_{npkf}}{g_{np}} \right\} \qquad \forall n, p, f \qquad (27)$$

$$\sum_{s} SQ^{s}_{npf} = Max\left\{ FQ_{pf} \times g_{np} - \sum_{k} NQ_{npkf}, 0 \right\} \qquad \forall n, p, f \qquad (28)$$

$$IQ_{npf} = Max\left\{ \sum_{k} NQ_{npkf} - FQ_{pf} \times g_{np}, 0 \right\} \qquad \forall n, p, f \qquad (29)$$

$$\mathrm{FQ}_{pf} \geq \sum_{w} MQ_{pfw} \qquad \forall p, f \qquad (30)$$

$$\sum_{f} MQ_{pfw} = D_{pw} \qquad \forall p, w \qquad (31)$$

$$\underline{S}_a Y_a \leq \sum_{p} \sum_{i} Q_{pia} V_p \leq \bar{S}_a Y_a \qquad \forall a \qquad (32)$$

$$\underline{S}_j Y_j \leq \sum_{p} \sum_{a} Q_{paj} V_p \leq \bar{S}_j Y_j \qquad \forall j \qquad (33)$$

$$\underline{S}_k Y_k \leq \sum_{p} \sum_{j} Q_{pjk} V_p \leq \bar{S}_k Y_k \qquad \forall k \qquad (34)$$

$$\underline{S}_o Y_o \leq \sum_{p} \sum_{j} Q_{pjk} V_p \leq \bar{S}_o Y_o \qquad \forall o \qquad (35)$$

$$\underline{S}_f Y_f \leq \sum_{n} \sum_{p} \sum_{k} NQ_{npkf} V_{np} + \sum_{p} FQ_{pf} V_p \leq \bar{S}_f Y_f \qquad \forall f \qquad (36)$$

$$Y_j, Y_o, Y_k, Y_f, Y_r, Y_{ia} \in \{0,1\} \qquad \forall j, o, k, f, r \qquad (37)$$

$$Q_{paj}, Q_{pjk}, Q_{pjo}, Q_{pjl}, RQ_{pob}, NQ_{npkl}, NQ_{npkm}, NQ_{npkf}, NQ_{npkr}, FQ_{pf}, MQ_{pfw}, IQ_{npf},$$
$$SQ^{s}_{npf}, IQ_{pf} \geq 0 \qquad \forall n, p, a, j, k, f, r, l, m, w, s \qquad (38)$$

Constraint (14) ensures that a customer is assigned to a single regional collection center and Constraint (15) ensures that no customer will be assigned to a non operational center. Constraint (16) represents the fact that a customer assigned to any regional collection center should be within the distance range. Constraint (17) indicates that the returned products are transferred from a customer to a regional collection center.

Constraint (18) is the balance equation for total returned products. The returned products are delivered from regional collection centers to the centralized collection centers for processing. A certain percentage of products are sent to be repaired and sold in the secondary markets, as shown in Constraints (19) and (20). Constraint (21) keeps the amount of repaired products sold in the secondary markets to less than or equal to the demand. Typically, the returned products that can be repaired for reuse will fulfill the demand. The products that cannot be repaired are delivered to the processing centers for other recovery purposes, as shown in Constraint (22).

The returned products will be dismantled into modules in the processing centers. The modules are calculated as $NQ_{npjk} = g_{np} Q_{pjk}$, in which g_{np} indicates the quantity of module n of product p. Constraints (23) to (26) respectively represent the modules delivered to remanufacturing centers, recycling centers, spare parts markets, and disposal sites.

Although the modules delivered to the remanufacturing centers might be in good condition, the remanufacturing process must consider the available reusable critical modules, as shown in Eq. (27). The remanufactured products are equal to the maximum units which can be remanufactured from the available critical modules in each remanufacturing center. Thus, there will be shortage for some modules and surplus for the others. The modules in short supply that need to be purchased from suppliers are given by Constraint (28). The surplus modules in Eq. (29) will be stored for future use.

The remanufactured products are transported to distribution centers for sale. Constraint (30) indicates that the remanufactured products transported from remanufactured centers to distribution centers will not exceed the total amount of remanufactured products. Constraint (31) ensures that the total remanufactured products delivered to distribution centers are equal to demand. Constraints (32) to (36) are the maximum and minimum capacity constraints for the respective facilities. Constraint (37) indicates binary variables. Constraint (38) preserves the non-negativity of decision variables.

4. Hybrid genetic algorithm

In this study, the hybrid genetic algorithm consisting of GA and CPLEX (IBM ILOG CPLEX Optimization Studio) is developed to solve the proposed MINLP, as shown in Fig. 2. The hybrid GA is coded in the Visual C++ programming language and integrated with the CPLEX model. GA has been applied to as an optimization heuristic based on stochastic search [57]. It has been widely used to solve various optimization problems including the reverse logistics problem. More GA in reverse logistics research can be referred to [14,16,22]. CPLEX is an optimization software product. In the hybrid genetic algorithm, the GA is used to designate integer variables Y_x and Y_{ia}. The integer variables Y_x representing facilities should be opened (=1) or closed (=0) in response to the optimal location and number of facilities in the multi-echelon reverse logistics channel. The integer variables Y_{ia} indicate whether returned products should be delivered (=1) or not (=0). Then, a set of binary solutions obtained from the GA will be used as the input parameters for CPLEX to solve the objective function. The GA parameters include data encoding, chromosome representation, a parent selection operator, a crossover operator, and a mutation operator. The known best solution is the best solution after each iteration of GA. The procedure will be repeated until the number of GA generations reaches the pre-defined number.

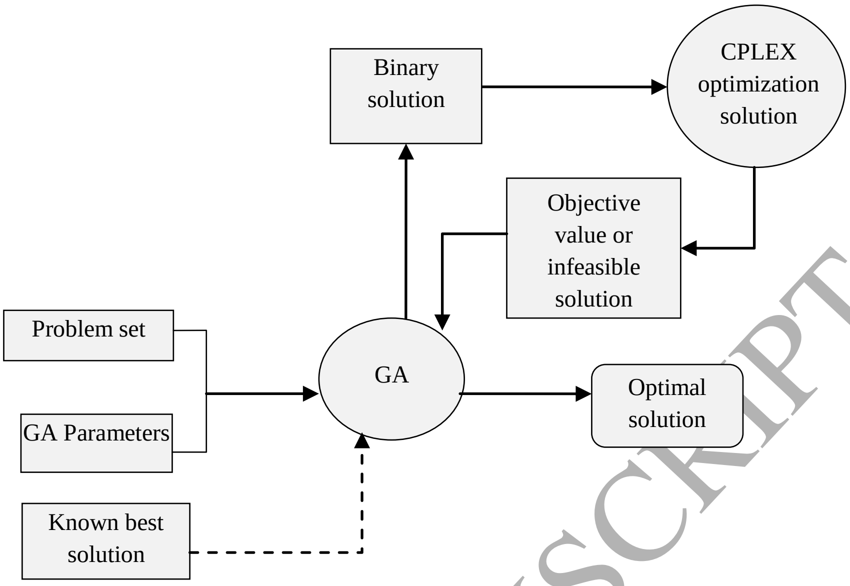


Fig. 2. Framework of hybrid genetic algorithm procedure

The GA begins with the creation of an initial population of chromosomes. Each chromosome consists of binary values, representing decision variables related to regional collection centers (RCC), centralized collection centers (CCC), repair centers (RC), processing centers (PC), and remanufacturing centers (RMC). We use the GA encoding process developed by Chen et al. [25]. An example of the description of a chromosome is illustrated in Fig. 3. The chromosome has 13 points for RCC, two points for CCC, RC, and PC respectively, and 7 points for RMC. Each gene represents an opening (=1) or closing (=0) decision. In the presence of constraints in the proposed model, some generated chromosomes might not be feasible. To guarantee that no product or module is shipped from an upper echelon to a lower echelon if the lower echelon is not open, a penalty value is imposed. The details of the GA solution procedure are discussed in the following.

(1) Parent selection operator

The parent selection operator is an initial population of chromosomes in a GA heuristic. Each gene in the initial population is assigned a random number by independently setting each bit value to either 0 or 1 with equal probability. Then, the associated fitness value is calculated.

(2) Crossover operator

Individuals in the population are selected for reproduction. The probability that the ith individual is selected for production is proportional to the fitness value. The fitness value is f_i = total profit for the ith individual. A one-point crossover is implemented, as shown in Fig. 4. The crossover operator can generate new chromosomes which have the best parts of the parents' chromosomes.

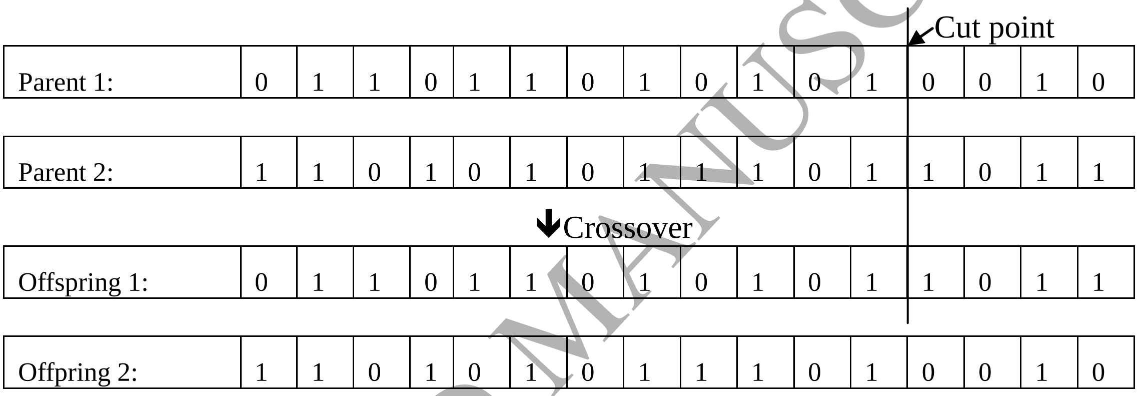
(3) Mutation operator

The goal of the mutation operator is to prevent the solution from being trapped at a local optimum. In the proposed GA, the mutation operator randomly selects a single-bit value of open/close decision variables on a chromosome, and then changes the value, as shown in Fig. 5.

The individuals in the initial population constitute the first generation. After selection, crossover, and mutation, a new population or generation of individuals is formed. In each generation, the inferior chromosomes are removed based on an elimination percentage.

	RCC					CCC		PC		RC		RMC				
Node	1	2	3	.....	13	1	2	1	2	1	2	1	2	3	.....	7
Gene code	0	1	1	.....	1	1	0	1	1	1	0	1	0	1	.....	1

Fig. 3. Gene code structure of the reverse logistics network



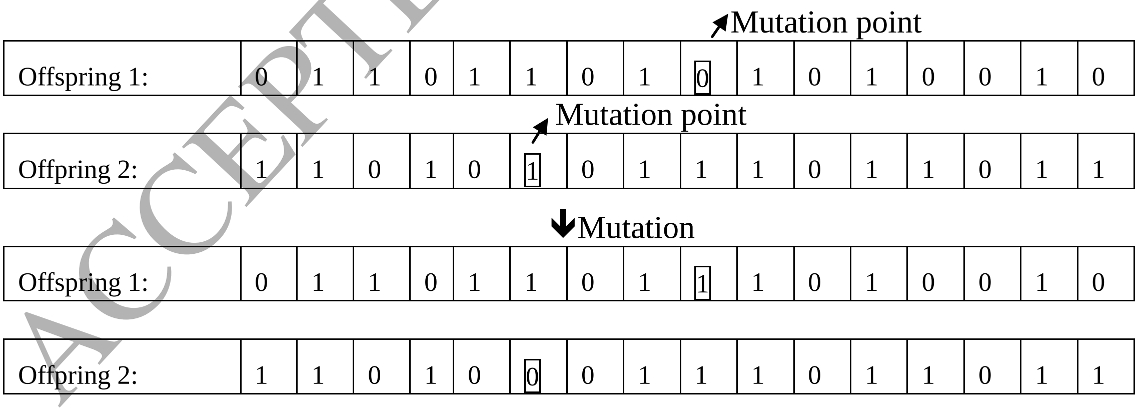
Cut point

Parent 1:	0	1	1	0	1	1	0	1	0	1	0	1	0	0	1	0
Parent 2:	1	1	0	1	0	1	0	1	1	1	0	1	1	0	1	1

Crossover

Offspring 1:	0	1	1	0	1	1	0	1	0	1	0	1	1	0	1	1
Offpring 2:	1	1	0	1	0	1	0	1	1	1	0	1	0	0	1	0

Fig. 4. Illustration of crossover process



Mutation point

Offspring 1:	0	1	1	0	1	1	0	1	0	1	0	1	0	0	1	0

Mutation point

Offpring 2:	1	1	0	1	0	1	0	1	1	1	0	1	1	0	1	1

Mutation

Offspring 1:	0	1	1	0	1	1	0	1	1	1	0	1	0	0	1	0
Offpring 2:	1	1	0	1	0	0	0	1	1	1	0	1	1	0	1	1

Fig. 5. Illustration of mutation process

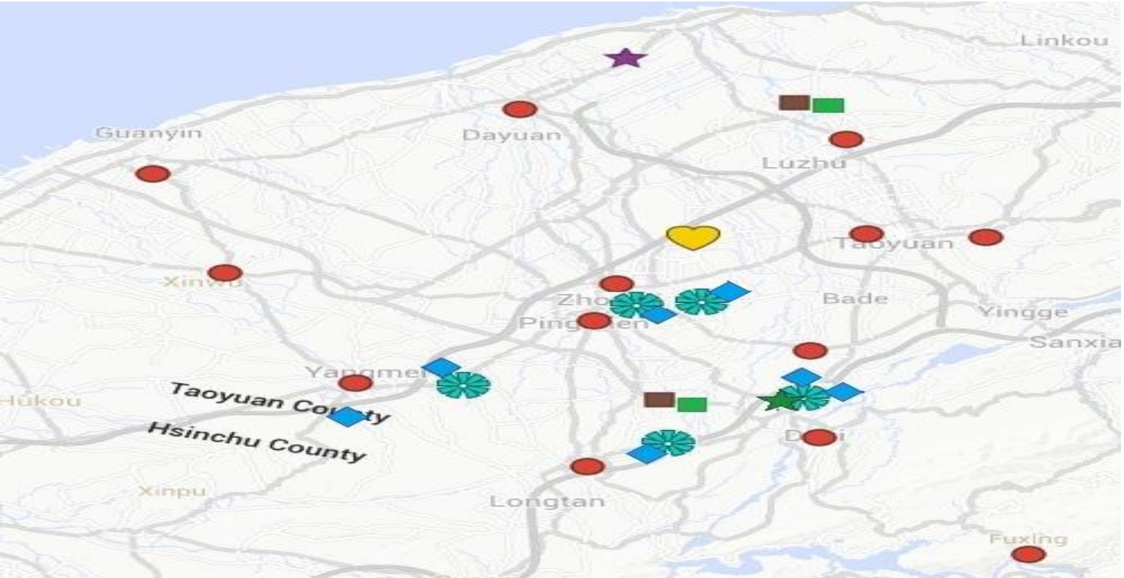
5. Numerical experiments

5.1 Problem description and parameter illustration

The designed reverse logistics model is implemented by using the proposed hybrid GA and validated by using bulk waste recycling data collected in Taoyuan City, Taiwan. In the hybrid GA, the best parameter settings used in these experiments are: (1) the GA initial population is 100 and mutation rate is 0.01, (2) the elimination percentage is 10%, (3) the stopping criteria for the maximum number of generations is 15000, and (4) the penalty value is 99999 for a product or module shipped from an upper echelon to a lower echelon if the lower echelon is not open.

The bulk waste items include discarded furniture, such as sofas, chairs, beds, tables, desks, cabinets, and wardrobes. Bulk waste may be reused after minor repairs (called reused products), remanufactured to be reused after dismantling and assembly (called remanufactured products), or fractured or crushed to be recycled after dismantling (called recycled products). The Environmental Protection Administration in Taiwan (EPAT) has been assisting the local counties or city governments to establish a "Bulk Waste Recycling and Reuse Program" since 2003. Following this, each county or city government set up an organization to design and control a recovery network for bulk waste management. Now more than 21 bulk waste repair and disassembly plants have been established throughout the country [58]. Between 2007 and 2012, EPAT planned to invest NT$500 million in implementing this program. To achieve the goals of the Bulk Waste Recycling and Reuse Program, EPAT reviewed and evaluated the recycling programs with the professionals of the Environment and Development Foundation (EDF), Taiwan. The EDF professionals have a background in environmental science and engineering. They proposed general guidelines for bulk waste processes and supervised the local government in implementing the projects [59]. The statistics show that about 147,790 tons of bulk waste per year were collected in recent years in Taiwan. The recovery rate is 51.6%. Of the bulk waste collected, 61.40% is waste furniture [60].

In our numerical experiments, the designed model is tested and validated through the bulk waste data of returned furniture. The data was collected from 13 districts in Taoyuan City, Taiwan. Currently, there is one individual regional collection center (IC) managed by each distract office. Fig. 6 shows the potential facilities in the reverse logistics network. In addition to the 13 ICs, there are two centralized collection centers (CCC), two processing centers (PC), two repair centers (RC), seven remanufacturing centers (RMC), five distribution centers (DC), and one facility each for spare parts market, recycling center and disposal site. The centralized collection center is close to the processing center. The processing center is a Material Recovery Facility (MRF) which built on a BOO (Build-Own-Operate) approach. If the returned furniture can be repaired, then they will be sent to the repair center and sold on the secondary markets, which are the same places as the DCs in the city. The other returned furniture is dismantled into five modules in processing centers and delivered to remanufacturing centers, recycling centers, spare parts markets, or disposal sites depending on their quality and customer demand.



● Regional collection center a
🟩 Centralized collection center j
🟫 Processing center k
◆ Remanufacturing center f
★ Recycling center r
★ Spare market m
♡ Disposal site l
✹ Distribution center w

Fig. 6. The potential facilities in the reverse logistics network

The bulk waste data of returned furniture is classified into five types (P1: sofas and chairs; P2: beds; P3: table and desks; P4: cabinets; and P5: wardrobes). The local government encourages citizens to make an effort towards the EPAT's policy of "Full Sorted Collection and Zero Waste". The guideline of the wood waste recovery is designed by EPAT. The citizens delivered the recovered bulk waste products for the local government or advised the local government to handle them. In order to model the reverse logistics network, the data in the processes are defined according to the five types and the related parameters are estimated accordingly. The returned products are shown in Table 1. Also, the distance between each district center is presented. The optimal regional collection centers will be chosen based on the capacity constraint of waste management and maximum delivery distance of returned products.

Table 2 represents the parameters related to ICs including fixed costs, capacity, inventory costs, and transportation costs from ICs to CCCs. Similarly, Tables 3, 4, and 5 show the parameters related to CCCs, PCs, RCs and RMCs. Fixed costs and capacity are estimated according to the district's land value and space. Inventory costs, handling costs, and stockout costs are related to product value. Repair and remanufacturing costs are related to product value and the complexity of repair or remanufacturing operations. Transportation costs are estimated based on the distance and the fuel consumed. Since the products were returned by customers themselves or collected by the government, the transportation costs between customers and regional collection centers are not considered. The returned products that can be reused are sent to the repair centers and sold in the secondary markets. Usually, the repair centers are near the secondary markets, thus transportation costs between repair centers and second hand markets are not considered. The same situation applies to the remanufacturing centers and distribution centers. Transportation costs between suppliers and remanufacturing centers are not considered because the suppliers are in charge of the costs.

Table 6 shows the parameters for products, including the module quantity required for remanufacturing each product, demand volume, and the sale price of repaired and remanufactured products. The demands for repaired and remanufactured products are given. The price of repaired products P_{pb} is estimated based on product value and repair cost. The price of remanufactured products P_{pw} for distribution center w is estimated based on the available modules for remanufacturing and the potential purchase of new modules. M1 to M5 indicate markets for repaired products and W1 to W5 are for remanufactured products.

The related parameters of dismantled modules are shown in Table 7. Maximum percentages of useful modules delivered to remanufacturing centers β_{npk}, recycling centers γ_{npk}, and spare parts markets δ_{npk} are 40%, 20%, and 30%, respectively. Revenue can be obtained by selling refurbished modules on the spare parts market and by recycling modules in the recycling centers. In the remanufacturing centers, there are inventory cost or new module buying costs depending on the quantity of remanufactured products and demand. The costs of useless modules N1~N5 are \$5, \$17, \$16, \$11, and \$7.5 for incineration or landfill at disposal sites.

Table 1
Returned products and distance between the ICs.

Regional Collection Center	Returned products					Distance between ICs												
	P1	P2	P3	P4	P5	IC1	IC2	IC3	IC4	IC5	IC6	IC7	IC8	IC9	IC 10	IC 11	IC 12	IC 13
IC1	143	214	428	428	571	0	9	11	9	24	5	34	28	15	8	31	21	15
IC2	94	220	315	441	504	9	0	3	8	12	13	18	14	13	14	31	12	15
IC3	58	107	192	245	225	11	3	0	8	11	15	19	13	15	16	30	10	16
IC4	65	79	161	218	195	9	8	8	0	18	11	28	22	22	16	23	12	7
IC5	36	84	120	178	183	24	12	11	18	0	25	15	9	21	25	38	12	22
IC6	43	80	153	163	178	5	13	15	11	25	0	35	27	20	10	33	23	17
IC7	19	29	59	63	69	34	18	19	28	15	35	0	7	13	26	47	27	31
IC8	17	21	30	57	63	28	14	13	22	9	27	7	0	16	24	41	20	25
IC9	29	35	80	90	88	15	13	15	22	21	20	13	16	0	12	48	24	32
IC10	50	69	147	166	161	8	14	16	16	25	10	26	24	12	0	43	29	27
IC11	3	6	11	11	15	31	31	30	23	38	33	47	41	48	43	0	27	16
IC12	39	52	106	117	143	21	12	10	12	12	23	27	20	24	29	27	0	11
IC13	18	55	73	116	102	15	15	16	7	22	17	31	25	32	27	16	11	0

Table 2
Fixed cost, capacity, and related cost of ICs.

IC (=a)	Fixed cost	Capacity	Inventory holding cost (ICpa)					Transportation cost (Tpaj) from ICs to CCCs	
			P1	P2	P3	P4	P5	CCC1	CCC2
IC1	26630	4373	64	46	58	59	51	1.87	1.38
IC2	21381	3865	43	49	36	44	40	1.25	2.15
IC3	6606	2029	27	25	31	28	28	0.86	2.39
IC4	2039	1771	8	8	9	9	7	0.93	2.39
IC5	6836	1483	28	34	29	26	28	1.73	3.21
IC6	10346	1528	44	41	45	46	39	2.16	1.54
IC7	2966	585	14	12	11	12	14	3.11	3.47
IC8	2559	455	12	11	10	10	11	2.18	3.96

IC9	3878	796	18	17	18	15	15	3.21	1.57
IC10	4707	1466	19	22	17	18	22	3.07	0.21
IC11	1269	400	6	5	6	6	6	3.16	5.28
IC12	3303	1124	13	14	12	16	16	0.88	3.81
IC13	2204	890	10	8	8	8	11	1.1	3.71

Table 3
Fixed cost, capacity, and related cost of CCCs.

CCC (=j)	Fixed cost	Capacity	P1	P2	P3	P4	P5	RC1	RC2	PC1	PC2
			Max % of repaired product (α_{pj})					Transportation cost (Tpjo, Tpjk) from CCCs to RCs and PCs			
CCC1	52615	6601	0.2	0.25	0.3	0.33	0.35	3.51	0.92	0	3.09
CCC2	54686	5927	0.2	0.25	0.3	0.33	0.35	1.3	3.69	3.09	0
			Inventory holding cost (ICpj)								
CCC1			1.7	1.6	1.5	1.5	1.8				
CCC2			2.2	2.2	2.1	1.8	2				
			Handling cost (HCpj)								
CCC1			9	9	10	11	9				
CCC2			12	8	8	12	12				

Table 4
Fixed cost, capacity, and related cost of PCs.

PC(=k)	Fixed cost	Capacity	Handling cost (HCpk)					Transportation cost (Tnpkm, Tnpkr, Tnpkl, Tnpkf) from PCs to spare market, recycling center, disposal site and RMCs						
			P1	P2	P3	P4	P5	Spare market		Recycling center		Disposal site		
PC1	63138	7426	21.1	21.8	20.4	20.3	19.8	1.33		1.75		0.2		
PC2	60155	6519	20	19.2	20.9	21.1	19.5	1.26		0.46		0.21		
								RMC1	RMC2	RMC3	RMC4	RMC5	RMC6	RMC7
PC1								0.46	0.42	0.64	0.95	0.54	0.56	0.45
PC2								0.71	0.77	1.08	1.39	0.91	0.94	1.61

Table 5
Fixed cost, capacity, and related cost of RCs and RMCs.

RC (=o)	Fixed cost	Capacity	P1		P2		P3		P4		P5	
			Repairing cost (MCpo)									
RC1	100982	4517	47		48		47		47		46	
RC2	19988	1179	46		47		42		43		47	
RMC(=f)			Remanufacturing cost (MCpf), Inventory cost (ICpf)									
			MC	IC	MC	IC	MC	IC	MC	IC	MC	IC
RMC1	9784	2430	53	6	51	19	54	18	52	12	51	8
RMC2	38494	2497	62	8	60	27	60	26	58	18	58	12
RMC3	12892	2567	56	6	59	19	56	18	58	12	57	8
RMC4	2257	2467	61	9	59	31	59	29	59	20	63	14
RMC5	18887	2542	57	6	56	20	57	19	59	13	59	9
RMC6	3278	2421	62	9	62	31	61	29	60	20	62	14
RMC7	2889	2444	53	7	54	22	57	21	55	14	56	10

Table 6
Parameters related to products.

	No. of module per unit product					Demand volume and sale price									
						Volume	Price	Volume	Price	Volume	Price	Volume	Price	Volume	Price
	N1	N2	N3	N4	N5	M1		M2		M3		M4		M5	
P1	2	1	3	2	1	13	1050	15	1090	19	1065	17	1090	21	1005
P2	1	3	2	1	3	13	2580	20	2580	17	2580	11	2590	17	2585
P3	3	2	1	2	2	14	2320	17	2255	10	2315	18	2320	17	2390
P4	1	1	4	3	2	11	1865	16	1915	14	1930	13	1925	23	1965
P5	3	2	1	4	3	14	1545	20	1550	18	1530	14	1435	18	1510
						W1		W2		W3		W4		W5	
P1						7	1010	13	985	8	1030	14	965	12	990

P2		7	2465	12	2460	12	2455	14	2410	12	2485
P3		10	2275	10	2300	8	2225	9	2265	11	2190
P4		9	1745	13	1755	9	1735	11	1835	13	1835
P5		7	1470	11	1425	7	1470	7	1445	10	1495

Table 7
Parameters related to modules.

	Revenue for spare market (Pnpm)					Inventory cost (ICnpf)						
	P1	P2	P3	P4	P5	RMC1	RMC2	RMC3	RMC4	RMC5	RMC6	RMC7
N1	9.7	50.7	43.3	27.5	21.2	1.3	1	1.6	1.5	1.6	1.7	1
N2	9.3	31.5	49.7	23.7	17.3	1.3	1	1.6	1.5	1.6	1.7	1
N3	12.5	30.2	52.7	35.2	16.7	1.3	1	1.6	1.5	1.6	1.7	1
N4	11.0	41.0	33.2	35.3	24.0	1.3	1	1.6	1.5	1.6	1.7	1
N5	12.8	29.7	26.7	33.5	24.7	1.3	1	1.6	1.5	1.6	1.7	1
	Recycling revenue (Pnpr)					New module buying cost (BCnpf)						
N1	2.0	5.0	6.6	4.7	2.9	9	7.5	7	7	9	6.5	5
N2	1.6	4.3	7.6	4.0	2.2	9	7.5	7	7	9	6.5	5
N3	1.6	7.6	6.0	5.0	2.6	9	7.5	7	7	9	6.5	5
N4	1.5	5.0	5.6	4.4	2.7	9	7.5	7	7	9	6.5	5
N5	1.5	6.7	4.8	5.2	2.7	9	7.5	7	7	9	6.5	5

5.2 Numerical results and analysis

According to the objective function and conditions of the multi-echelon reverse logistics network, the optimal number of collection centers and other facilities for the bulk waste management can be solved through the above numerical data.

Since the purpose of this research focuses on the reverse logistics network design and its useful application in bulk waste recovery, the computation comparison is not a major concern in this paper. The hybrid GA is designed to help solution decisions in reverse logistics. In this paper, only the differences in objective value and computation time between the proposed hybrid GA and Lingo are provided to show the efficiency and effectiveness of the proposed hybrid GA. The numerical experiments are repeated 30 times by using a PC with an Intel(R) Core(TM) i7-3770 CPU @ 3.2 GHz, with 8.0G of RAM. The objective value is the same ($96,677) from both the proposed hybrid GA and Lingo. The average computation time of the proposed GA is 2 seconds, which is much shorter than the 21.75 minutes for Lingo. The average results show that the proposed hybrid GA outperforms Lingo in solving the problem. Thus, the hybrid GA is used to solve the problem and sensitivity analysis. In the future, the proposed hybrid GA can be developed to solve the problem on a larger scale. Further details of the numerical experiments are described as follows.

In the experiment, the current available facilities include thirteen ICs, two CCCs, two RCs, two PCs, and seven RMCs. The optimal locations of reverse processes solved from the designed model are compared with the current implementation. The proper facilities for each echelon of the reverse logistics network solved from the designed model are shown in Table 8.

The local government established one IC in each district to serve its citizens. Most of the ICs are close to the district office for the convenience of handling returned products; thus, some ICs might be far from residents. Proper allocation of ICs not only encourage more waste recovery, but also reduces the recovery cost. In Table 8, there are eight optimal ICs based on the objective function and distance limitation, 20 km. For example, waste recovery in districts 1 and 7 are allotted to CS3. Also, two CCCs, one repairing center RC2, one processing center PC2, and three remanufacturing centers RMC4, RMC6, and RMC7 are selected from the near optimal solution.

Table 8
Optimal selected sites of the reverse logistics network.

IC	District allotted to IC	CCC	RC	PC	RMC
IC3	1, 7	CCC1 CCC2	RC2	PC1	RMC4 RMC6 RMC7
IC4	2				
IC8	9				
IC9	8, 10				
IC10	4, 6				
IC11	13				
IC12	5, 12				
IC13	3, 11				

Table 9 presents the optimum flow of returnable quantity from the selected ICs to CCCs. In terms of transportation fees and handling cost, different products are sent to whichever CCC represents the lowest cost for that product. For example, only 136 units of product P2 are delivered from IC12 to CCC1 and all the products of P3 are sent to CCC2. The returned waste furniture is sent further on to the RCs for repairing or PCs for dismantling into modules, as shown in Table 10. Waste furniture which cannot be repaired is dismantled into modules N1~N5 and delivered to the spare parts market, recycling center, remanufacturing centers, or disposal site to be refurbished, fractured or crushed, remanufactured or disposed of. Table 11 shows the quantity of flow for dismantled modules. Refurbished modules are popular in the spare parts market because they can be used as recyclable material of all sorts such as fiberboard, particle board, chipboard, etc. Modules which cannot be reused are fractured into pieces or crushed in the recycling centers and used as farmyard fertilizer and shade tree mulch. Only a small portion (about 14%) of waste furniture is processed at the disposal sites for incineration or landfill.

Table 9
Optimum flow of returnable quantity from ICs to CCCs.

IC	CCC1					CCC2				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
IC3	143			428	571		214	428		
IC4	94			441	504		220	315		
IC7	48				157		64	139	153	
IC9	63					5	90	177	223	224
IC10						108	159	314	381	373
IC11	18			116	102		55	73		
IC12	75	136		295	326			226		
IC13	61			256	240		113	203		

Table 10
Optimum flow of returnable quantity from CCCs to RC and PC.

CCC	RC2					PC2				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
CCC1	85	34	0	77	84	0	102	0	1029	1235
CCC2	0	44	76	0	0	90	686	1312	507	388

Table 11
Quantity of dismantled modules sent to spare parts market, recycling center, and disposal site.

	Spare market					Recycling center					Disposal site				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
N1	54	236	1181	461	1461	36	158	788	307	974	54	79	394	203	487
N2	27	709	788	461	974	18	473	525	307	649	9	473	1217	713	1539
N3	81	473	394	1844	487	54	315	263	1229	325	27	315	608	2853	770
N4	54	236	788	1383	1948	36	158	525	922	1298	18	79	263	461	649
N5	27	709	788	922	1461	18	473	525	615	974	27	236	263	307	0

The modules used to remanufacture products are filtered from dismantled units and good quality modules are reassembled as remanufactured products. The modules that remanufactured are represented in Table 12 and the remanufactured products are shown in Table 13. In the experiments, modules N2 and N3 are critical modules; therefore, the remanufactured products are based on the maximum assembly modules of N2 or N3. The shortage of 54 units of module N1 needed for product P1 are purchased from new module suppliers. On the other hand, the extra modules are kept in inventories for future use as in Table 14. Since the remanufactured products are based on the maximum assembly modules of N2 or N3 and the demand level is low, the amount of stock is 179 (=236-57) for product P2 in RMC4 and there is no product shortage.

Table 12
Dismantled modules sent to remanufacturing centers.

	RMC4					RMC6					RMC7				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
N1	0	315	144	510	0	36	0	1431	55	126	0	0	0	0	1822
N2	0	709	96	0	0	0	0	0	55	84	36	0	0	0	0
N3	0	473	48	0	0	54	0	0	220	42	54	0	0	0	0
N4	0	315	96	0	0	36	0	954	679	168	36	0	0	1164	2429
N5	0	709	96	754	0	18	236	954	475	126	0	0	0	0	2309

Table 13
Remanufactured products at RMCs.

	Remanufactured products				
	P1	P2	P3	P4	P5
RMC4	0	236	48	0	0
RMC6	18	0	0	55	42
RMC7	36	0	0	0	0

Table 14
Module inventories in RMCs.

	RMC4				RMC6				RMC7			
	P2	P3	P4	P5	P2	P3	P4	P5	P2	P3	P4	P5
N1	79	0	510	0	0	1431	0	0	0	0	0	1822
N4	79	0	0	0	0	954	514	0	0	0	1164	2429
N5	0	0	754	0	236	954	365	0	0	0	0	2309

5.3 Comparison with the current reverse operations in Taoyuan

In order to verify the adaptability of the proposed model, we carried out a comparison and analysis with current operations of recycling processes in Taoyuan, Taiwan. The Taoyuan government encourages each district to make progress on waste recycling and provides a BOO approach with compensation to help achieve EPAT’s policy of "Full Sorted Collection and Zero Waste" [61]. Currently, the thirteen regional collection centers, two centralized collection centers, two repair centers, two processing centers, and seven remanufacturing centers, mentioned in the previous section, were rented or built for recycling activities within the reverse logistics network. Thus, the fixed costs for the current implementation are a steep 58% higher than the optimal results solved from the proposed model, as shown in Table 15.

In Table 15, the total revenue obtained from this study is \$1,804,297 and from the current implementation is \$1,812,778. Although the total revenue of this study is less than that of the current implementation, the total profit is higher. The total profit for this study is \$96,677 and there is a deficit (-\$529,192) for the current implementation. Also, except for the total transportation cost, costs such as total handling cost, total inventory cost, total repair cost, total remanufacture cost of this study are less than those of the current implementation. For the current implementation, all facilities are open and thus the handling cost will be obviously high. The results show that average inventory cost of ICs accounts for the highest amount of overall inventory cost. Therefore, the optimal selection of ICs from the proposed model contributes to reducing a large amount of inventory cost, resulting in a decrease of 41% of total inventory cost.

Under the current implementation, the returned products are remanufactured based on the available modules. For example, the amounts of modules N1~N5 of P2 are 5, 30, 30, 30, 30, 30, thus only 5 products can be remanufactured since there are only 5 available modules of N1. Therefore, there are 5 stockouts for the remanufactured products of P1 and inventories of 22, 83, 175 and 120 for P2 to P5, respectively. From the proposed model, the remanufactured products are based on the available modules of N2 or N3 which are the critical and most valuable components. Thus, a total amount of 54 new modules N1 of product P1 are purchased from new module suppliers, and there are 179 in inventory for product P2. The average remanufactured product rate is 7.58% from the proposed model, which is higher than the statistics data of 3.8% from the EPAT's statistics [52]. Although the remanufacturing rate is not high, the results demonstrate that by using the proposed model, the government can provide more ways for increasing the product remanufacture rate. It turns out that from the prosed model, the total remanufacturing, inventory, and stockout costs are lower than those of the current implementation, as shown in Table 15. Also, the handling cost of incineration/landfill from the proposed model (\$142,644) is much less than the current implementation (\$284,099). With the proper design based on the proposed reverse network, returnable products can be optimally repaired, recycled and remanufactured.

Table 15
Result and comparison of this study versus current implementation.

Notation	Description	Current situation		This study		Improved %
		Results	Sub-total	Results	Sub-total	
Z	Total profit	**$-529,192**		$96,677		$625,869
	Total revenue		$1,812,778		$1,804,297	-0.5%
	Total cost		$2,341,899		$1,707,619	27%
RP	Revenue from repaired products	$743,495		$743,495		
MP	Revenue from spare parts market	$559,237		$547,081		
RCP	Revenue from recycled products	$54,086		$52,901		
RMP	Revenue from remanufactured products	$455,960		$460,820		
FC	Total fixed cost of location sites		$534,769		$222,840	58%
	Fixed cost of ICs	$94,724		$26,972		
	Fixed cost of CCCs	$107,301		$107,301		
	Fixed cost of PCs	$123,293		$60,155		
	Fixed cost of RCs	$120,970		$19,988		
	Fixed cost of RMCs	$88,481		$8,424		
CC	Collection cost of returned products	$948,875	$948,875	$948,875	$948,875	0%
TRC	Total transportation cost		$69,263		$75,031	-8%
	Tran. cost from ICs to CCCs	$10,529		$13,043		
	Tran. cost from CCCs to PCs	0		$7,311		
	Tran. cost from CCCs to RCs	$2,761		$700		
	Tran. cost from PCs to incineration/landfill	$5,175		$2,550		
	Tran. cost from PCs to spare parts market	$24,778		$22,611		
	Tran. cost from PCs to recycling center	$15,692		$5,503		
	Tran. cost from PCs to RMCs	$10,328		$23,313		
HC	Total handling cost		$485,332		$330,727	32%
	Handling cost of ICs	$84,053		$79,652		
	Handling cost of PCs	$117,180		$108,431		
	Handling cost of incineration/landfill	$284,099		$142,644		
IC	Total inventory cost		$148,750		$88,092	41%
	Inventory cost of ICs	$134,346		$67,180		
	Inventory cost of RMCs (Modules)	$8,735		$19,017		
	Inventory cost of RMCs (Remanufactured products)	$5,669		$1,895		
RC	Total repair cost	$117,370	$117,370	$18,027	$18,027	85%
RMC	Total remanufacturing cost	$37,540	$37,540	$23,011	$23,011	39%
SC	Total new module buying cost	0	0	$1,017	$1,017	-

5.4 Emissions reduction

In Table 15, the handling cost of incineration/landfill from the proposed model ($142,644) is much less than the current implementation ($284,099). Our model reduces the amount of incineration or landfill at disposal sites. Thus, it will produce less CO_2 and reduce the environmental impact.

The results of emissions reduction can also be proven from the results of Chen et al.’s study. Chen et al. [62] analyzed CO_2 output by using data collection, participant observation, and depth-interview for recycled waste wood furniture in Chiayi County, Taiwan. Their results showed that the total amount of recycled waste wood was about 4,803 tons from 2004 to 2008. It would produce 7,925 tons of CO_2 by using incineration and 11,095 tons of CO_2 by using landfill. In this model, we consider various activities of recovery based on the quality of recovered products. The network design is based on the strategic planning perspective to find the optimal location and number of facilities, and the allocation of returned products and modules in the reverse logistics network. Our solution increases the recovery activities including module refurbishment and sale in spare parts markets, and the number of modules reconfigured for remanufacturing products. Only a small portion (about 14%) of waste furniture is processed at the disposal sites for incineration or landfill. Therefore, with the proper design based on the proposed reverse network, the emissions can be reduced.

6. Sensitivity analysis

6.1 Sensitivity analysis of changing demands

As mentioned previously, the government in Taiwan has been working to increase demands for repaired products and remanufactured products. In this section, we investigate the effect of increasing the demand for remanufactured products on the performance measures of total reverse logistics cost and revenue. The results of this study in Table 15 is the assumed basic case. The results of demand changes of the basic case, multiplying demand by 1.5, 2, and 2.5, are shown in Table 16. The total profit increases as the demands for remanufactured products increase.

The results are rather intuitive and are as expected. Here, the revenue of remanufactured products increases proportionally to the increase of demand, whereas the relative cost of remanufactured products increases much less under the same circumstances. Since the amount of demand affects the remanufacturing activities under the optimization condition, the increasing demands are met by reallocating reusable modules to the proper factories for remanufacturing. Thus the increased rate of total cost will not be as high as the increased rate of total revenue. Also, the increase in demand results in an increase both in the number of remanufacturing centers and the fixed cost of establishing remanufacturing facilities. However, only four out of the seven remanufacturing facilities are required when demand reaches the maximum ratio of returned products which can be remanufactured. This implies that a possible effective way to eliminate the total cost is to reduce the total number of remanufacturing facilities used in Taoyuan, Taiwan.

Table 16
The sensitivity analysis of changing demands.

	Basic case	1.5 times basic case	2 times basic case	2.5 times basic case
Number of RMC	3	4	4	4
Total revenue	$1,804,297	$2,050,346	$2,271,103	$2,515,655
Difference in total revenue	100%	114%	126%	139%
Total cost	$758,745	$766,273	$770,560	$775,305
Difference in total cost	100%	101%	102%	102%

6.2 Sensitivity analysis of capacity changes of regional collection centers

In this section, we carried out a sensitivity analysis to investigate the results of varying the capacity of regional collection centers while the other capacities are fixed. The basic case is the same as in Table 15. The results of capacity changes of regional collection centers are shown in Table 17. With the capacity increases, the number of regional collection centers is reduced and the fixed cost of regional collection centers decreases. However, the total transportation cost varies across the cases. The transportation costs are close for the basic case, 1.5, and 2 times the basic case, but opposite results are obtained when one looks at the case of 2.5 times the basic case. One possible reason for this is the fact that, due to the capacity increase, returned products are transported to the farther regional collection centers, as less regional collection centers are required. Although the total transportation cost is increased, the total fixed cost is reduced with the capacity increase. Overall, the total cost decreases as the capacity increases, which results in a total profit increase.

Table 17
The sensitivity analysis of capacity changes of regional collection centers.

	Basic case	1.5 times basic case	2 times basic case	2.5 times basic case
Number of RCC	8	6	5	4
(IC; District of customer)	(2; 1), (3; 4,12), (4; 2), (5; 5), (8; 7,8), (9; 9), (10; 6,10), (11; 11), (12; 3), (13; 13)	(4; 2,10,12), (8; 7,8), (10; 1,9), (11; 11,13), (12; 3,5), (13; 4,6)	(4; 1,6,10,12), (8; 7,8,9), (11; 13), (12; 3,4,5), (13; 2,11)	(4; 1,2,10,12), (7; 5,7,8,9), (11; 13), (13; 3,4,6,11)
Total profit	$96,677	$124,062	$135,036	$141,770
Difference in total profit	100%	128.0%	139.7%	146.6%
Total cost	$758,745	$732,856	$720,386	$713,652
Difference in total cost	100%	96.6%	94.9%	94.1%
Total fixed cost	$222,840	$211,949	$210,225	$204,346
Difference in total fixed cost	100%	95.1%	94.3%	91.7%
Total transportation cost	$75,031	$74,496	$74,841	$80,784
Difference in total transportation cost	100%	99.3%	99.7%	107.7%

Fig. 7 also presents the change of cost savings by varying the capacity of regional collection centers. It shows that the cost savings increase dramatically with capacity increases up to three times the basic case, above which it does not increase significantly. This analysis shows that the most cost savings can be obtained with a specific capacity level for the regional collection centers.

Finally, increase in capacity at regional collection centers can also cause changes in the flow of returned products and modules. Although the total cost and number of regional collection centers can be reduced with an increase in capacity, in practice, there are certain constraints such as the availability of capacity and delivery convenience of returned products for regional collection centers.

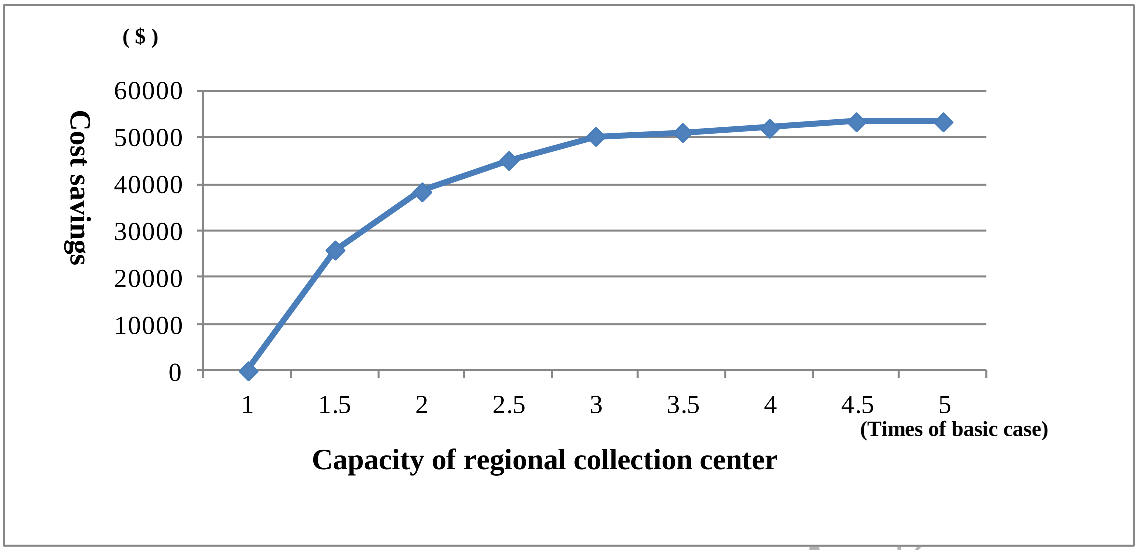


Fig. 7. Sensitivity analysis for the capacity of regional collection center

6.3 Managerial implications

From the above numerical and sensitivity analyses, the benefits that the proposed model brings to the organization are summarized as follows: (1) providing a well-structured network design for the reverse logistics; (2) providing a more efficient and profitable product recovery with modularized remanufacturing processes and (3) providing an opportunity for reducing emissions.

The well-structured network design for the reverse logistics is shown as Fig. 1. It is a strategic network design for reverse logistics used to represent the actual process of product recovery. Some of the reusable returned-products are sent for repair and resale in the secondary market; and others are dismantled into modules to gain revenue from recovery activities. The recovery activities include module refurbishment and sale in spare parts markets, and modules reconfigured for remanufactured products. The remanufactured products are delivered to distribution centers for marketing, and their modules recycled for other use. The modules with no commercial value are disposed of by incineration or landfill.

In addition, this model uses the most valuable module configuration for remanufacturing and maximizes module utilization, as indicated in Eqs. (27)-(29). Thus, recovery processes are more efficient and profitable. The average remanufactured product rate is 7.58% from the proposed model, which is higher than the statistics data of 3.8% from the EPAT's statistics. Also, as shown in Table 15, the processes proposed in this study show increased profitability in comparison to the current implementation in Taiwan.

The objective function of our model is profit maximization through product recovery. The recovered products are dismantled into modules for repair, remanufacturing, recycling, and reuse. Only useless modules are destined for incineration or landfill. Although incineration or landfill cannot be avoided, our model can help managers to reduce them, and thus CO_2 can be reduced when waste products are recovered more effectively.

7. Conclusion

By using a multiple echelon network, it is shown that the proposed MINLP model can be used to represent complex reverse logistics processes in handling product recovery and remanufacturing. The objective of the mathematical model is profit maximization with consideration of multi-product and multi-module returnable products and a variety of recycling channels for the returned products. The numerical experiments reflect the real recovery processes of the used bulk waste products in a city of Taiwan, and the results show some distinctive features.

The proposed model is a generic model and can represent current reverse logistics operated by some industries using existing distribution centers, dismantling centers, warehouses, and factories for returned products. Facility location and available capacity are important issues in reverse logistics networks. By identifying the critical activities and related requirements involved in the processes of reverse logistics operations, the proposed model can determine the optimization of facility locations, their state of operation (open or closed), capacity utilization and the optimal flow of returned products and dismantled modules in the reverse network. The designed model is validated and tested through the proposed hybrid GA by using a real-life example of recycling bulk waste in Taoyuan City, Taiwan. Also, the post-optimality analysis and comparison show the proposed model performs better than current reverse operations in the city.

The model considers fulfilling the demand for repaired and remanufactured products according to the optimal value of returned products and dismantled modules, thus the amount of demand has an important impact on the reverse logistics operation. Typically, the increased demand for repaired products can generate major revenue from the reverse activities. It depends on the demand and the quantity of repairable returned products. The number of products that can be remanufactured depends on the available quantities of the critical and most valuable types of modules, thus the modularized remanufacturing processes make product recovery more efficient and profitable.

From the proposed model, the amount of products that can be remanufactured depends on the available quantities of critical and high-value types of modules. It turns out that the average remanufactured product rate can be increased to 7.58%, which is higher than the 3.8% from the EPAT's statistics. Although the remanufacturing rate is not very high, the results demonstrate that using the proposed model, the government can provide more ways to increase the number of remanufactured products. Also, the results show that there exists an optimal combination of open facilities in the reverse logistics network at which the maximal cost savings can be achieved. With proper settings of the parameters, the model proposed here can serve as a valuable tool for strategic decision making in reverse logistics and thus for more efficient operation of the recycling and remanufacturing processes.

Future research directions are suggested as follows. (1) The proposed nonlinear model is used to represent the real processes of product recovery and product remanufacturing. The model can be extended to consider the factors of product returns or demand uncertainty and product quality level. (2) With advancements in technology and operations, a more accurate proportion of products and modules sent for repair and remanufacturing can be estimated; thus, the maximum percentages of returned products and modules could be calculated for the various recovery activities. The demand forecast for various recovery activities might be an interesting subject for further studies. (3) Since the proposed model is formulated as MINLP, the computational time of mathematical solution algorithms increases exponentially with respect to the size of problem. The proposed hybrid GA outperforms Lingo to solve the model; however, more work on the analysis and comparison of the proposed hybrid GA can be conducted.

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