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An integrated closed-loop supply chain model with location allocation problem and product recycling decisions

Y.T. Chen, F.T.S. Chan* and S.H. Chung

Department of Industrial and Systems Engineering, Hong Kong Polytechnic University, Hong Kong, Hong Kong

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Environmental pollutions caused by improper abandoned cartridges increase dramatically nowadays. In Hong Kong, due to abundant quantity of cartridges being used, producers have to optimise their forward and reverse networks to maximise the recycling rate and their profits. In this paper, a comprehensive closed-loop supply chain (CLSC) model is established. This model contains eight partners in CLSC and describes the existing cartridge recycling situation in Hong Kong. In the literatures, many CLSC models were established and studied, but few of them analysed the delivery activity for different kinds of materials extracted from the used products and also, few papers studied the situation that used products are classified into good and poor quality. In this model, delivery activities of different materials are considered and the used cartridges are classified into good-quality ones and poor-quality ones. Producers will have different methods to process them. This problem is formulated into an Integer programming model. Since both delivery routes and delivery quantities problems are known to be NP hard, a novel modified two-stage genetic algorithm (GA) is proposed. A new two-stage encoding algorithm in the proposed GA reinforces the genetic searching ability in tackling this kind of problem. As the model is new in literature, we used Integer Programming to solve the testing instances and benchmark with the proposed algorithm. The results show that a near-optimal solution can be obtained by the proposed GA in a much shorter computational time.

Keywords: closed-loop supply chain; genetic algorithm; reverse distribution; linear programming

1. Introduction

In recent years, economy with electronic products gains a prosperity development, and the life cycle of electronic devices turn out to be shorter and shorter, making electronic waste the fastest growing part among garbage stream. The environmental and health risks of Waste Electric and Electronic Equipment (WEEE) become high, among which, used cartridges play an important role. Most of the used cartridges are improperly disposed to landfill or incineration. A toner cartridge tossed into landfill will take 450 years or more to decompose and the toxic materials in it, such as lead and mercury, will leak out to cause a great damage to the earth. Every year, about 1.2 trillion inkjet cartridges are used globally, but less than 30% of them being recycled. In Hong Kong, WEEE produced amount to 70,000 tons per year, and the volume has been increasing at an annual rate of 2% in recent years (Panel on Environmental Affairs Meeting Minutes on 28 November 2011). To deal with these growing noxious waste, product recycling becomes popular.

In July 2008, the legislative council enacted the Product Eco-responsibility Ordinance (Cap 603) to provide a legal framework for implementing mandatory producer responsibility schemes. In his 2009–2010 policy address, the chief executive of the Hong Kong SAR also identified this issue as the next target for a producer responsibility scheme. Although this scheme primarily focuses on bulky electrical and electronic equipment and computer products, producers in Hong Kong are perceived to be responsible for the recycling of products they have produced and sold, including printers and cartridges. In Hong Kong, many companies start recycling of ink cartridge and toner cartridge several years ago, for example, Epson HK set up some collection points and collected used cartridges from 2007, Canon HK launched the recycling programme of ink cartridge from 2009. For these companies, they have to carry out an efficient and profitable way to recycle their products. Due to the expensive cost of third-party recycling centres, many cartridge producers choose to establish their own recycling factories. Hence the location and allocation of collection centres and recycling factories has to be optimised. In this sense, producers have to design product-recycling networks along with product-delivery networks according to specific customer regions. Each year, vast used cartridges are discarded and the

*Corresponding author. Email: f.chan@polyu.edu.hk

number is increasing, in this condition, a closed-loop supply chain (CLSC) network including cartridge recovery is needed to be optimised to maximise profits of producers and also protect the environment.

In this paper, a comprehensive CLSC model based on the real situation of cartridge recycling in Hong Kong is established. It integrates both forward chain of product procedure and reverse chain of product recycling. This proposed model contains eight partners in CLSC and describes the cartridge-recycling situation in Hong Kong. The main object of this paper is to solve the following three problems in CLSC with product-recycling decisions: (i) Optimise the location and allocation problem of manufactures, warehouse, retailers, collection centres and recycling centres through the CLSC network. (ii) Optimise the transportation route and delivery volume among the CLSC network. (iii) Make decisions of recycling options for returned products and components in recycling centres considering several materials and the quality of returned products.

To optimise the above three sub problems, a mix integer linear programming model is established in this paper. Since Lingo can only solve the small scale of this problem in an acceptable period of time, genetic algorithm (GA) is implemented to solve the large scale of this problem. For the standard encoding GA, the complexity of this problem tends to make the genetic operation hard and time-consuming to handle and also makes the search easily trapped in the local optimum. Therefore, a novel modified two-stage encoding GA is developed in this paper. The computational experiments are implemented and prove the efficiency of the proposed GA.

The paper is organised as follows. Section 2 is the literature review. Section 3 presents the problem description and model formulations. Section 4 provides the two-stage priority-based GA. The computational experiments and comparison are presented in Section 5. Finally, Section 6 presents the conclusion and directions for future research.

2. Literature review

In the research area of CLSC and product recycling, summarising is made in three aspects in this literature review. Firstly, of the CLSC models. Secondly, of the models' focus on product recycling, especially WEEE recycling. Thirdly, the problem-solving methods in this research field.

2.1 *CLSC models*

In the literatures, many CLSC models were established and studied. The models and studies focus on different aspects and use many different methods.

Barros, Dekker, and Scholten (1998) proposed a two-level location model for a recycling problem and optimised its decision using heuristic procedures. Sheu, Chou, and Hu (2005) proposed a linear multi-objective programming model to solve an integrated CLSC problem. Yang, Wang, and Li (2009) analysed the equilibrium state of the CLSC using the theory of variation inequalities. Huang, Yan, and Qiu (2009) discussed the robust operations in a class of dynamic CLSC models using control theories, and practical experiments in the Chinese steel industry are implemented. Paksoy, Bektas, and Ozceyln (2011) formulated a linear programming model to balance the equilibrium between various costs. Shi, Zhang, and Sha (2011) developed a mathematical model to maximise the total profit of the CLSC by analysing the pricing and production decisions simultaneously. Mitra (2012) proposed a stochastic and deterministic model for a two-level CLSC system, and the relationship between return rate and cost saving was discussed by numerical examples.

Among all the various research directions in CLSC, the closed-loop network structure with product recovery become one of the important directions. Most of the studies formulate this problem into linear or nonlinear programming models. Table 1 shows the major CLSC networks from 2003 to 2014 which formulated into linear or nonlinear programming models.

In Table 1, all of the models considering the closed-loop network with different focuses. Krikke, Bloemhof-Ruwaard, and Vassenhove (2003) optimised both the structure of the logistics network and the structure of the products with a mixed-integer linear programming model. Min, Ko, and Ko (2006) focused on the initial collection points in reverse logistics network. A mixed-integer, nonlinear programming model was proposed to solve the location problem of initial collection points and optimise the return products' holding time in them. Jayaraman (2006) developed a linear programming model for aggregate production planning and control in remanufacturing. In 2009, Kannan, Haq, and Devika (2009) designed a multi-echelon distribution inventory CLSC model for the built-to-order environment. Lee and Chan (2009) proposed a nonlinear programming model to determine the location of collection points so as to minimise the reverse logistics cost and to maximise the coverage of customers. RFID was also suggested to count the quantity of flow in collection points in their study. Kannan, Sasikumar, and Devika (2010) developed a multi-echelon, multi-period, multi-product CLSC network model for product returns, considering transportation and recycling problem. Wang and Hsu (2010) established a generalised closed-loop model as an integer linear programming model which integrated for-

Table 1. CLSC models.

References	Model focus	Objective	Mathematical modelling	Method
Krikke, Bloemhof-Ruwaard, and Vassenhove (2003)	Network structure and product structure	Minimise the total costs	Mixed-integer linear programming	CPLEX
Min, Ko, and Ko (2006)	Initial collection points	Minimise the total costs	Mixed-integer nonlinear programming	GA
Jayaraman (2006)	Remanufacturing	Minimise the total costs	Linear programming	GAMS
Kannan, Haq, and Devika (2009)	The distribution and inventory problem	Minimise the total costs	Linear programming	GA, particle swarm optimisation
Lee and Chan (2009)	Location problem of collection points	Maximise environmental profits	Nonlinear programming	GA, RFID
Kannan, Sasikumar, and Devika (2010)	Transportation and recycling problem	Minimise the total costs	Mixed-integer linear programming	GA
Wang and Hsu (2010)	Transportation and location problem	Minimise the total costs	Integer linear programming	GA
Zhang, Liu, and Tu (2011)	Capacitated production plan problem	Minimise the total costs	Integer linear programming	GA
Amin and Zhang (2012)	Network structure	Maximise the total profits	Multi-objective mixed-integer linear programming	GAMS
Lee and Lee (2012)	Determine the optimal delivery route	Minimise the total costs	Integer linear programming	GA, Lingo
Özkır and Başlıgıll (2012)	Three ways of recovery process	Maximise the total profits	Mixed-integer linear programming	GAMS
John and Sridharan (2013)	Determine the delivery flow and analysis of the impact of parameters	Minimise the total costs	Linear programming	Lingo
Özceylan and Paksoy (2013)	Location problem of plants and retailers	Minimise the total costs	Mixed-integer programming model	GAMS-CPLEX
Soleimani, Seyyed-Esfahani, and Shirazi (2013)	Comprehensive network structure	Maximise the total profits	Mixed-integer linear programming	GA, CPLEX
Demirel et al. (2014)	Analysis of product returns	Maximise the total profits	Mixed-integer programming	GAMS-CPLEX, GA
Zeballos et al. (2014)	Analysis of the uncertain supply and demand	Minimise the total costs	Mixed-integer linear programming	GAMS-CPLEX

ward and reverse logistics. Zhang, Liu, and Tu (2011) formulated a remanufacturing model discussing the capacitated production plan problem. Amin and Zhang (2012) established a three-stage multi-objective mixed-integer linear programming model designing the configuration and selection process of CLSC simultaneously. Lee and Lee (2012) developed an integrated CLSC model with an integer linear programming determining the optimal delivery route. Özkır and Başlıgıll (2012) proposed a mixed-integer linear programme model to describe a CLSC network, in which three methods of recovery process were considered. In 2013, John and Sridharan (2013) established a CLSC network and analysed it under various situations. This network minimises the total costs and maximises the repaired and recycled products simultaneously. Özceylan and Paksoy (2013) proposed a mixed-integer programming model to describe a multi-period multi-parts CLSC network. This model optimises the flow of manufactured and disassembled products through determining the plants and retailers' locations. Soleimani, Seyyed-Esfahani, and Shirazi (2013) developed a comprehensive structure of CLSC network, including all possible entities and considering minimum limitations on delivery routes. Demirel et al. (2014) proposed a mixed-integer programming model to analyse the situations of returned products and also proposed a fuzzy objective extension to solve the problem in the real world. Zeballos et al. (2014) developed a mixed-integer linear programming to analyse the uncertain customer demands and raw material supplies in the CLSC network.

Among the above literatures, although many CLSC models were studied, few of them analysed the delivery activity for different kinds of materials extracted from used products, and also few papers studied the situation that collected used products are classified. In practice, products can be disassembled into many different parts and recycled into different materials, which have different delivery activities according to their attributes. In this connection, it is important to consider different materials in the product recovery problem under CLSC network. Additionally, the quality of collected products is uncertain which contributes to the uncertain factors in CLSC. It is very important to consider this issue in the network construction. In this model, delivery activities of several kinds of materials are considered and the collected used products are classified into two categories: good-quality ones and poor-quality ones. Producers will have different methods to process them. This problem is also formulated into a mixed-integer linear programming model.

2.2 *WEEE recycling in CLSC models*

Since environmental issues become serious nowadays and WEEE is one of the most poisonous varieties, many studies address the issue of WEEE recycling.

Jorjani, Leu, and Scott (2004) formulated a piece-wise linear concave programme to find the optimal disassembly strategy of electronic equipment. Tsai and Hung (2009) focused on the treatment and recycling process of the system. They proposed a two-stage decision framework which includes treatment stage and recycling stage. Although suppliers' selections were added in this framework, it is not the optimisation of the whole CLSC network. Veenstra et al. (2010) suggested a Markov chain model analysing the flow of WEEE through the reverse chain. Gamberini et al. (2010) established a transportation network in Italy which contained vehicle-routing problem. An integrated solution approach was used to solve it. Mar-Ortiz, Adenso-Diaz, and González-Velarde (2011) optimised the design of reverse chain for the collection of WEEE. In this network, a mixed-integer linear programming model was formulated to address the facility location problem, a new integer programming was established to solve the vehicle-routing problem and a simulation study is implemented to assess the performance of the recovery system. Dwivedy and Mittal (2012) investigated into the WEEE flows in India and used a Markov chain to model the business sector of WEEE trade, which included the informal recycling of WEEE in developing countries. Alumur et al. (2012) proposed a multi-period reverse logistics network which formulated into a mixed-integer linear programming model. A real case of washing machines in Germany was implemented to justify this model. Olugu and Wong (2012) proposed a CLSC performance evaluation system to a company from the automotive industry which reduces the cost of the whole CLSC network prominently. Wang and Huang (2013) established a two-stage robust programming model to decide the recycling volume and time in a CLSC. From the literature, it can be found that the focus of research about WEEE is the reverse network design and optimisation, lacking the research of integrating both forward and reverse network.

In this paper, cartridge recycling is studied as one of WEEE. The model is established according to the situation of cartridge recycling in Hong Kong. It contributes to both the network of CLSC and the WEEE recycling.

2.3 *GA with CLSC models*

From Table 1, it can be seen that GA is widely used in this particular area of CLSC network optimisation.

Min, Ko, and Ko (2006) proposed a GA to solve a nonlinear mixed-integer programming model designing the location problem of return centres. It proposed a binary chromosome with the forepart representing open or close of facilities, and the other part representing days of interval for consolidation by binary system. The information in this chromosome was just about open or not. Gen, Altiparmak, and Lin (2006) developed a priority-based encoding GA to solve a two-stage transportation problem. It proposed an integer chromosome representing the priority of being used for each facility by the numbers. This kind of encoding only conveyed the information of transportation route, as for the product flow, some flow allocation method has to be added after calculation of GA. Similar with this case, Wang and Hsu (2010) established a generalised closed-loop model and a revised spanning-tree-based GA was proposed. The encoding of chromosome contained information of transportation route only and it had to implement the spanning-tree method to allocate the product flow additionally. Kannan, Haq, and Devika (2009) solved the CLSC model with GA and particle swarm optimisation. Lee and Chan (2009) proposed a GA to determine the location of collection points. Kannan, Sasikumar, and Devika (2010) established a CLSC model for product returns, where GA was applied as an efficient methodology. Zhang, Liu, and Tu (2011) proposed a remanufacturing model employing a CLSC strategy and proposed a GA to solve this problem. The results of the computational experiment show that the proposed approach can solve a large-size remanufacturing problem efficiently. Tuzkaya, Gulsun, and Onsel (2011) used GA to design a recovery network for white goods industry in Turkish. The proposed chromosome was also binary strings representing facilities' open or close and their collection periods. The capacity-based product flow allocation was also added up. Lee and Lee (2012) formulated an integrated CLSC model and designed the optimisation approach with a hybrid GA and a priority-based GA by fuzzy logic control. The results of the experiment using real data demonstrated the efficiency of the hybrid GA.

From the literature, it can be inspected that a comprehensive GA solving both transportation route design and product flow allocation are needed. In this study, since both delivery routes and delivery quantities all over the CLSC network have to be optimised, the problem become NP hard (Krarup and Pruzan 1983) and complex to calculate. To deal with this complex calculation, a modified two-stage GA is implemented. The two-stage encoding in this GA reinforces the genetic searching ability in solving this kind of problem. In the numerical experiments, this GA is used to solve different scales of problems. It also been compared LINGO. The results indicate that the proposed GA can solve the integrated closed-loop problem with higher quality and more efficiently.

3. Problem definition

This model is based on a real case study of ink-and-toner cartridge delivering and recycling in Hong Kong. The proposed model contains eight partners in the CLSC network: suppliers (S), manufacturers (M), warehouses (W), retailers (R), customers (Cu), collection points (Co), recycling centres (RC) and waste disposal plant (WDP).

In this model, the demands of customers are preset. In order to fulfil the demand, manufacturers have two choices, one is to produce brand new products using components and the other is to remanufacture the collected used products with good condition/quality. As for the components, manufacturers have two acquisition channels: one is from suppliers and the other is from recycling centres. In the proposed model, it considers that manufacturers purchase several kinds of components from suppliers and recycling centres to produce brand new products, which means multi-products is considered.

In this model, it is assumed that manufactures can make sure that remanufactured products have the same quality as brand new products and also that sale prices in the market are same. After producing new products and remanufacturing used products as brand new ones, manufacturers deliver the products oversea to their warehouses in Hong Kong. Then, from warehouses, products are transported to retailers and finally, the retailers sell them to customers. Since retailers do not belong to manufacturers, this part of revenue and cost is excluded from consideration in the CLSC network optimisation. Therefore, the demand of each retailer also has to be preset, and the sum of all the retailer demands must be equal to the sum of all the customer demands.

Customers always discard the used ink-and-toner cartridge at the end of their life cycle in the corner. In HK situation, collection points will pick used products up from patron. In each customer area, managers of the cartridge company have to consider the vehicle-routing problem of one or more collection points, which will make the CLSC network too complex to solve as whole. For simplicity, it is assumed that collection points will have a round trip in each customer areas to fetch used products. The transportation cost for a round trip is proportional to the quantity of used products collected in this round trip. The unit transportation cost for each used products are preset as a parameter.

No matter which method is used to collect, collection points will pay customers the used products. In this model, it is assumed that the price collection points paid for either good-quality used products or poor-quality used products are the same. After collection, collection points deliver all the used products to recycling centres.

In the recycling centre, all the used products will be cleaned and classified according to two categories: good-quality used products and poor-quality used products. The good-quality ones will be packaged and transported to manufacturers. Whereas the poor-quality ones will be disassembled and smashed and raw materials extracted from them through further processes at the recycling centre. During the whole process, most of the substance can be recycled as raw materials. The remaining parts need to be disposed by the waste-disposal plant by burning, or in landfill. The maximal disposal rate is preset in this model. The recycled raw material will finally be delivered to manufacturers for producing new products.

This study will solve three sub problems at the same time in the proposed CLSC problem, as follows: (1) to judge whether each potential facility is active or not, and determine the handling quality of each active facility; (2) to select the transportation route and decide the volume among the whole network; (3) to set the recycling options for rebounded products and components in the recycling centres.

4. Model formulation

Figure 1 displays the whole CLSC network of this proposed model.

The indices, parameters and decision variables are shown as below.

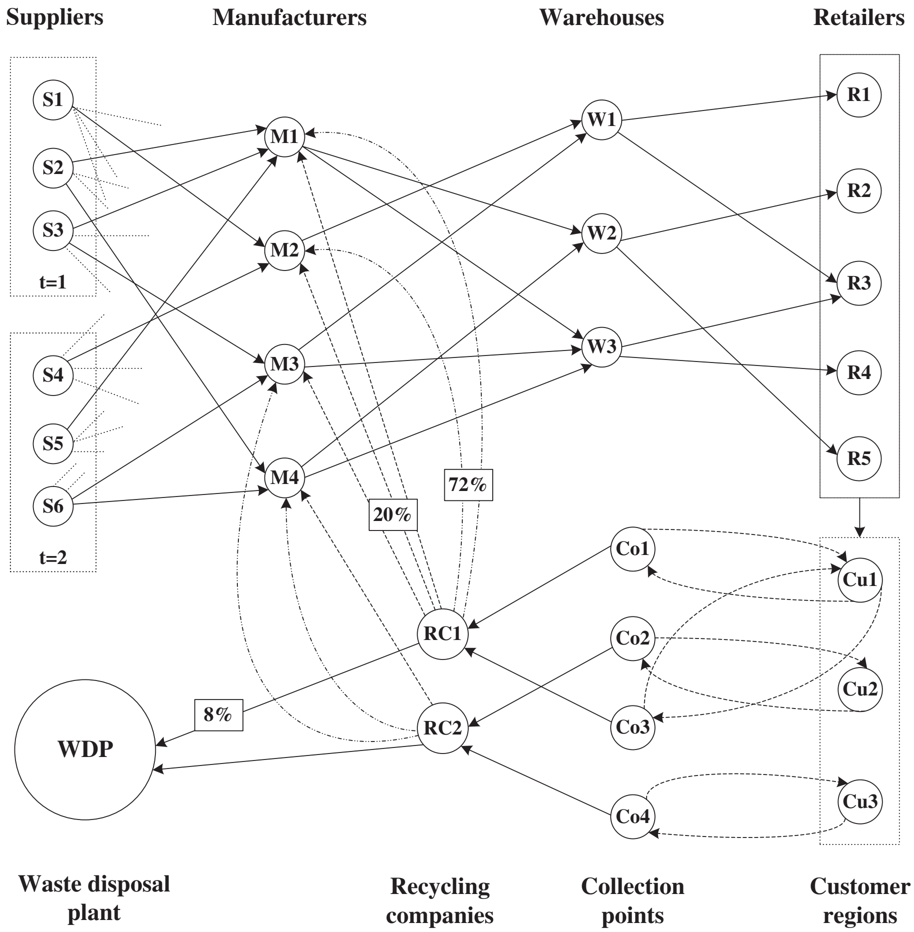

Figure 1. The CLSC network in the proposed model.

Indices

I_t	the number of suppliers supplying material t with $i = 1,2, \ldots ,$I
J	the number of manufacturers with $j = 1,2, \ldots ,J$
K	the number of warehouses with $k = 1,2, \ldots ,K$
L	the number of retailers with $l = 1,2, \ldots ,L$
V	the number of customers with $v = 1,2, \ldots ,V$
M	the number of collection points with $m = 1,2, \ldots ,M$
N	the number of recycling centres with $n = 1,2, \ldots, N$
T	the number of components with $t = 1,2, \ldots ,T$

Parameters

c_i^s	capacity of supplier i
c_j^m	capacity of manufacturer j
c_k^w	capacity of warehouse k
d_l	demand of retailer l
d_v	demand of customers in area v
c_m^{co}	capacity of collection point m
s_{ijt}	unit cost of transportation of component t from supplier i to manufacturer j
m_{jk}	unit cost of transportation from manufacturer j to warehouse k
w_{kl}	unit cost of transportation from warehouse k to retailer l
cu_{vm}	unit cost of round trip transportation for collection point m taking back used products from customers in area v

co_{mn} unit cost of transportation from collection point m to recycling centre n
r_{njt} unit cost of transportation of component t from recycling centre n to manufacturer j
r^0_{nj} unit cost of transportation of good-quality used product from recycling centre n to manufacturer j
f^m_j fixed cost for operating manufacturer j
f^w_k fixed cost for operating warehouse k
f^{co}_m fixed cost for operating collection point m
f^r_n fixed cost for operating recycling centre n
s unit sorting cost for the used product
x_0 unit producing cost of new products using components including component purchase cost
x_1 unit profit for the returned product with good quality of ETN
x_2 unit disassembly cost for the poor-quality used product
x_3 unit dispose cost for the material which cannot be recycled
p_1 the price of new products
p_2 unit cost that collection point pay to customers for the used product
λ the percentage of good-quality used products in all the recycling products
η_t the weight of required quantity of component t to produce one new product
δ_t the recycled percentage for ETN of component t in one used product
μ_v the recycling rate of customer area v
φ the maximal disposal rate
ε unit weight per used product
y^{etn}_t The profit of ETN for component t in unit returned product
y^r_t The profit of recycling as raw materials for component t in unit returned product

Decisions variables

q^s_{ijt} amount of component t shipped from supplier i to manufacturer j
q^m_{jk} amount shipped from manufacturer j to warehouse k
q^w_{kl} amount shipped from warehouse k to retailer l
q^{cu}_{vm} amount shipped from customers in area v to collection point m
q^{co}_{mn} amount shipped from collection point m to recycling centre n
q^{etn}_{njt} amount of component t shipped from recycling centre n to manufacturer j
q^0_{nj} amount of good-quality used product shipped from recycling centre n to manufacturer j
q^z_{nt} amount of disposed t materials from recycling centre n
q^{new}_j amount of new produced products in manufacturer j

$$\alpha_j = \begin{cases} 1 \text{ if production takes place at manufacturer } j \\ 0 \text{ otherwise} \end{cases}$$

$$\beta_k = \begin{cases} 1 \text{ if warehouse } k \text{ is open} \\ 0 \text{ otherwise} \end{cases}$$

$$\delta_m = \begin{cases} 1 \text{ if collection point } m \text{ is open} \\ 0 \text{ otherwise} \end{cases}$$

$$\gamma_n = \begin{cases} 1 \text{ if recycling company } n \text{ is open} \\ 0 \text{ otherwise} \end{cases}$$

Objective function:

$$\max \ TP = TR - TC \tag{1}$$

$$TR = p_1 \sum_l d_l \tag{2}$$

$$TC = TC_1 + TC_2 + TC_3 \tag{3}$$

$$TC_1 = \sum_t \sum_i \sum_j s_{ijt} q_{ijt}^s + \sum_j \sum_k m_{jk} q_{jk}^m + \sum_k \sum_l w_{kl} q_{kl}^w + \sum_v \sum_m cu_{vm} q_{vm}^{cu} + \sum_m \sum_n co_{mn} q_{mn}^{co} + \sum_t \sum_n \sum_j r_{njt} q_{njt}^{etn} + \sum_n \sum_j r_{nj0} q_{nj}^0 \tag{4}$$

$$TC_2 = \sum_j f_j^m \alpha_j + \sum_k f_k^w \beta_k + \sum_m f_m^{co} \delta_m + \sum_n f_n^r \gamma_n \tag{5}$$

$$TC_3 = p_2 \cdot Q + s \cdot Q + x_2 \left(Q - \sum_n \sum_j q_{nj}^0 \right) + x_3 \sum_t \eta_t \sum_n q_{nt}^z + x_0 \sum_j q_j^{new} - \sum_t \left(y_t^{etn} \sum_n \sum_j q_{njt}^{etn} \right) - \sum_t \left(y_t^r \sum_n q_{nt}^r \right) - x_1 \sum_n \sum_j q_{nj}^0 \tag{6}$$

The objective is to maximise the total profit which is the value of total revenue minus total cost as shown in the objective function (1). The total revenue is the revenue of sale of the new product which is displayed in function (2). The total cost consists of the total transportation cost, total facility fixed cost and total processing cost as represented by function (3). Equation (4) shows the total transportation cost in the CLSC network, which consists of seven section costs in different stages shown as follow: component transportation cost from suppliers to manufacturers, new product transportation cost from manufacturers to warehouses, the cost of new products delivered from warehouses to retailers and the round trip cost of collection points to fetch the used products from customers, also the delivery cost for collected used products from collection points to recycling centres, the recycled component transportation cost from recycling centres to manufacturers and the delivery cost of collected good-quality used products from recycling centres to manufacturers. Equation (5) shows the total fixed costs of the manufacturers, warehouses, collection points and recycling centres. Equation (6) displays the sum of used products' obtained costs paid by collection points to customers, used products' sorting costs in recycling centres, good-quality used products' processing costs in manufacturers and poor-quality used products' processing costs in recycling centres, disposed costs and the costs of newly produced products using components in manufacturers.

Subject to

$$\sum_j q_{ij}^s \le c_i^s \quad \forall i \tag{7}$$

$$\sum_k q_{jk}^m \le c_j^m \alpha_j \quad \forall j \tag{8}$$

$$\sum_l q_{kl}^w \le c_k^w \beta_k \quad \forall k \tag{9}$$

$$\sum_n q_{mn}^{co} \le c_m^{co} \delta_m \quad \forall m \tag{10}$$

$$\sum_m q_{mn}^{co} \le c_n^r \gamma_n \quad \forall n \tag{11}$$

$$\sum_k q_{kl}^w \ge d_l \quad \forall l \tag{12}$$

$$d_v \mu_v = \sum_m q_{vm}^{cu} \quad \forall v \tag{13}$$

$$\sum_j q_{jk}^m = \sum_l q_{kl}^w \quad \forall k \tag{14}$$

$$\sum_{v} q_{vm}^{cu} = \sum_{n} q_{mn}^{co} \quad \forall m \tag{15}$$

$$\sum_{j} q_{njt}^{etn} \leq \delta_t \left(\sum_{m} q_{mn}^{co} - \sum_{j} q_{nj}^{0} \right) \quad \forall n, \forall t \tag{16}$$

$$\sum_{n} q_{njt}^{etn} + \sum_{i} q_{ijt}^{s} = q_{j}^{new} \quad \forall j, \forall t \tag{17}$$

$$\sum_{n} q_{nj}^{0} + q_{j}^{new} = \sum_{k} q_{jk}^{m} \quad \forall j \tag{18}$$

$$\sum_{j} q_{nj}^{0} \leq \lambda \sum_{m} q_{mn}^{co} \quad \forall n \tag{19}$$

$$\sum_{m} q_{mn}^{co} = \sum_{j} q_{nj}^{0} + \sum_{j} q_{njt}^{etn} + q_{nt}^{r} + q_{nt}^{z} \quad \forall n \tag{20}$$

$$q_{nt}^{z} \leq \varphi \cdot \sum_{m} q_{mn}^{co} \quad \forall n, \forall t \tag{21}$$

$$Q = \sum_{v} d_v \mu_v \tag{22}$$

$$\alpha_j, \beta_k, \delta_m, \gamma_n \in \{0, 1\} \quad \forall j, k, m, n \tag{23}$$

$$q_{ijt}^{s}, q_{jk}^{m}, q_{kl}^{w}, q_{vm}^{cu}, q_{mn}^{co}, q_{njt}^{etn}, q_{nj}^{0}, q_{nt}^{z}, q_{j}^{new} \in N \cup \{0\} \quad \forall i, j, k, l, m, n, v \tag{24}$$

Constraints (7) and (8) formulate the capacity limitation of suppliers and manufacturers. Constraint (9) represents the capacity limitation of DCs. Constraints (10) and (11) show the capacity limitation in reverse logistics for collection points and recycling centres. Constraint (12) restrains that the retailers' demand must be satisfied, which also means the customer demand must be satisfied. Constraint (13) explains the relationship between customer recovery and recovery rate. Constraints (14) and (15) guarantee the inflow equal to outflow in each warehouse and each collection point respectively. Constraint (16) guarantees the output recycled materials will not exceed the maximum value that each recycling centre can extract from used products. Constraint (17) shows that for each material in each manufacturer, the sum of the component from both suppliers and recycling centres can meet the demand for producing and remanufacturing needed new products. Constraint (18) restricts that for each manufacturer, the quantity of the provided products are the sum of the newly produced ones and the remanufactured ones. Constraint (19) restricts that the percentage of good-quality used products in each recycling centre cannot exceed the maximum value preset. Constraint (20) represents that the disposed materials are remaining materials after all of the recycling processes. Constraint (21) restricts that in each recycling centre, the total quantity of disposed materials must be under the acceptable value, the right item of this inequality displays the transformation from the quantity of returned poor-quality products to the weight of the material needs to be disposed of. Constraint (22) explains Q as the total amount of returned used products from all customer areas. Constraint (23) represents the binary variables. Constraint (24) represents the integer variables.

5. A GA with two-stage priority-based encoding

In the proposed model, to deal with three sub-problems described in the part of problem definition, the standard encoding GA has to be expressed in a single chromosome. Hence, the chromosome should cover the information of transportation route and amount, the active state of facilities and also the recycling options. These vast quantities of information in a chromosome tend to make the genetic operation hard and time-consuming to handle. When all these information are considered simultaneously, the search is easily trapped in the local optimum. To solve these problems, a two-stage priority-based GA is developed in this study. This proposed GA decomposes the encoding process into two stages. Figure 2 shows the flow diagram of this developed GA.

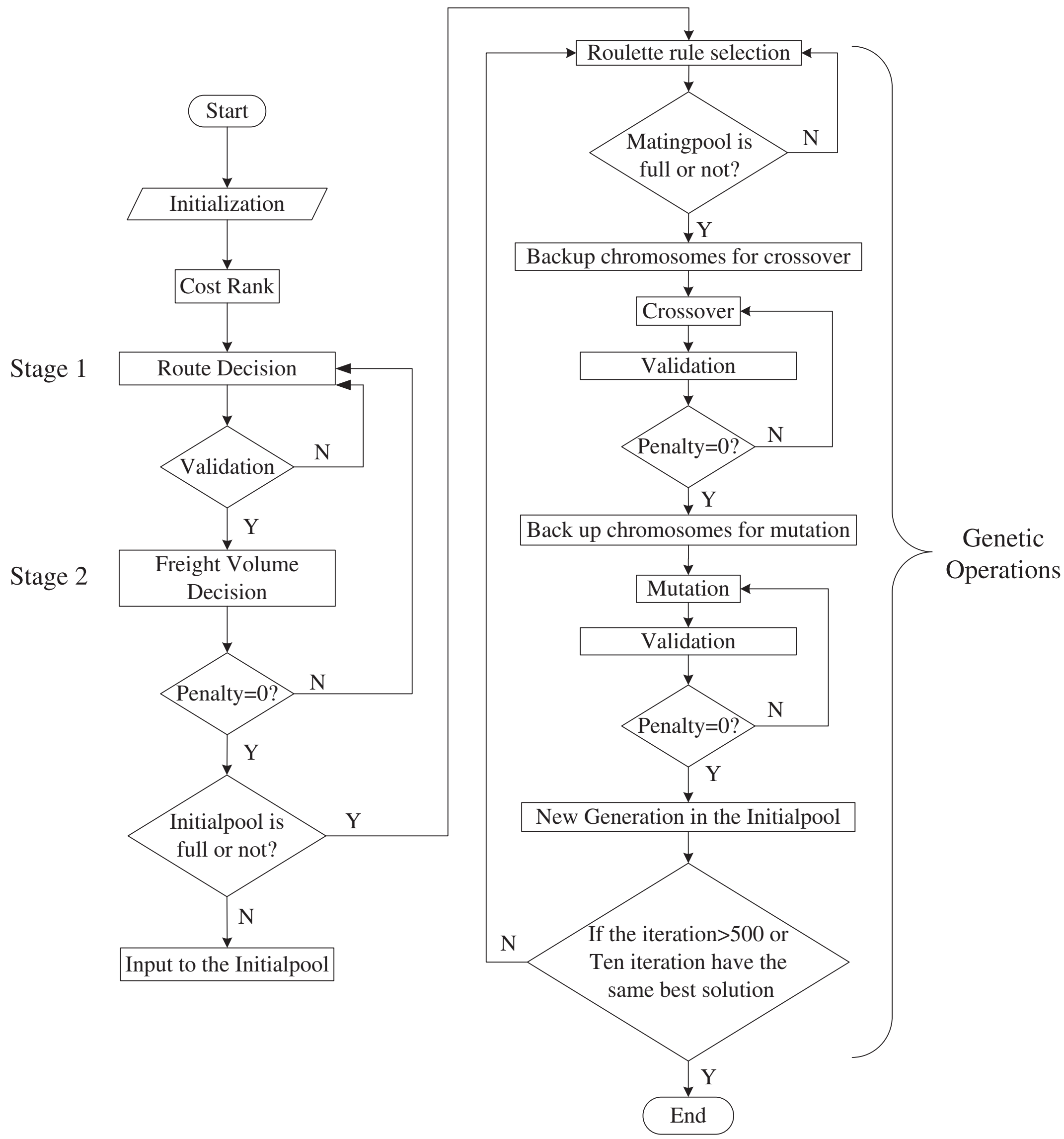

Figure 2. The flow diagram of two-stage priority-based GA.

Figure 2 shows that this GA has two stages in the encoding process: route decision and freight volume decision. The route decision stage can decide the delivery route between each level of the supply chain network. Then the freight volume in each selected delivery route is determined in the freight volume decision stage. These two stages are explained in detail in Section 5.1 and Section 5.2, respectively. The right part of Figure 2 states the genetic operations. Section 5.3 gives details of them.

5.1 *Stage 1 – route decision*

In the first stage of encoding, the chromosome has nine sections to represent each level of CLSC, respectively. In each section, the number of genes equals to the product of the number of suppliers and the number of demanders. Totally, in a chromosome, the number of genes is $I \times J \times T + J \times K + K \times L + V \times M + M \times N + N \times J \times (T+1)$.

The first stage of encoding is to determine the appropriate delivery route. In this stage, the generated chromosome composed with binary genes expresses the information of transportation route only. Each binary gene in the chromosome is generated randomly. After generation, the chromosome will be validated in the process of validation. This validation process is explained in detail in Section 5.3.5 Part 1. Figure 3 shows an example of the complete chromosome in this stage.

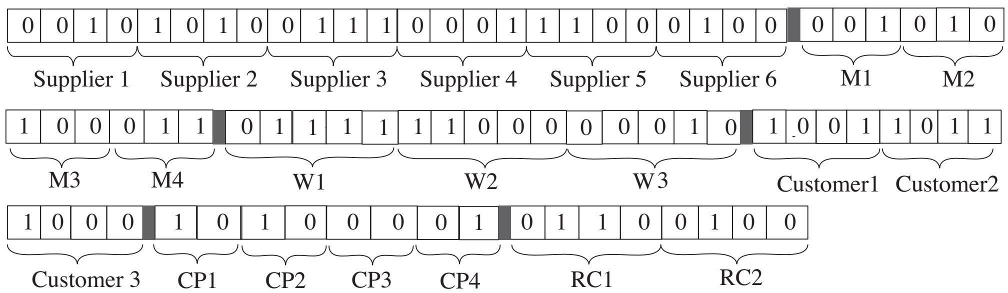

Figure 3. The complete chromosome in Stage 1.

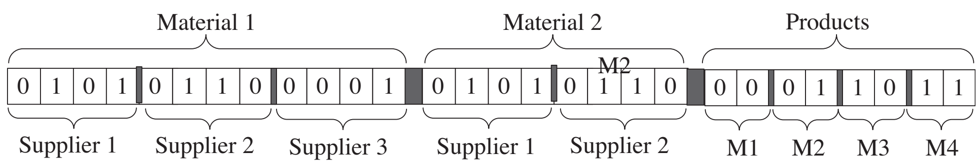

Figure 4. The first three sections of chromosome in Stage 1.

Part of the complete chromosome is chosen as a numerical example. In this numerical example, $T = 2$, $I_1 = 3$, $I_2 = 2$, $J = 4$, $K = 2$. Two kinds of materials are considered. $I_1 = 3$ means the number of suppliers supplying material one is three, $I_2 = 2$ means the number of suppliers supplying material two is two. Suppliers provide materials to four manufacturers, and these four manufacturers will deliver finished products to two warehouses.

Each gene contains a binary number, 1 means the delivery route is used and 0 means not. The chromosome at this stage is shown in Figure 4. Apparently, the first section of the chromosome has $3 \times 4 = 12$ genes; it represents the delivery route of material one: the first four genes represent the situation of supplier one providing material one to manufacturers two and four, but not providing materials to manufacturers one and three. The second four genes represent supplier two with material one, and the third four genes represent supplier three with material one. The second section of the chromosome has $2 \times 4 = 8$ genes, which represents the delivery route of material two. The principle is the same as the first section. The third section of the chromosome has $4 \times 2 = 8$ genes: the first two genes represent the situation of manufacturer one providing finished products to neither of the two warehouses, the second two genes represent manufacturer two, and so on.

5.2 *Stage 2 – freight volume decision*

After the first stage, a chromosome representing the delivery route has been established. The second stage is to decide the freight volume of materials or products according to the generated route. It is called freight volume decision. Figure 5 shows the chromosome after the second stage of encoding.

The structure of the chromosome remains the same as in Stage 1, but the content has been changed. Among the first four genes, the first gene means Supplier One won't delivery any raw material one to Manufacture One, the second gene represents that Supplier One will deliver 50 units of raw material one to Manufacture Two. Other sections have the close principle. The last gene in Figure 5 represents that Manufacture Four will deliver 150 units of products to Warehouse Two.

5.2.1 *Process outline of freight volume decision*

It contains six steps in the freight volume decision. To explain this decision process clearly, the numerical example in Section 5.1 is used. Figure 6 shows the step details. The numbers in parentheses mean the unit shipping cost of that delivery route. The demand of warehouses and the capacity of suppliers and manufacturers are represented by the numbers in the circles.

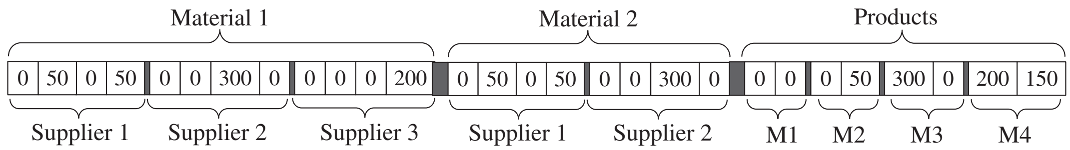

Figure 5. The first three sections of chromosome in Stage 2.

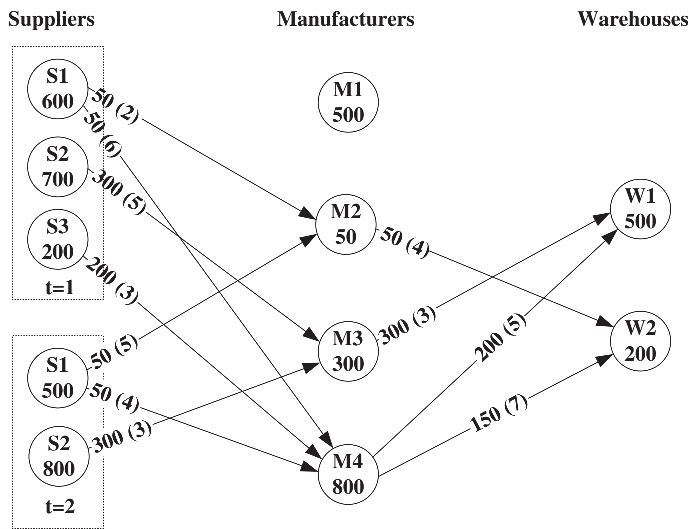

Figure 6. An instance for freight volume decision.

Step 1: Decide the beginning level. In this example, the terminal demand is the warehouses', so the freight volume decision process starts from the level of manufacturer delivering finished products to warehouse.

Step 2: Find out the lowest unit shipping cost among the current level. The delivering route with the lowest unit shipping cost has the highest priority to be used. According to the result of 'Cost Rank', delivering route from Manufacturer 3 to Warehouse 1 own the lowest cost.

Step 3: Check if the top priority delivery route is multiple or not among current level. If yes, count out the number, mark as N and go to Step 4a, if not, go to Step 4b. Step 4a and Step 4b are parallel. Here, the lowest unit shipping cost 3 is unique at current level, so go to Step 4b.

Step 4a: The demand is randomly divided into N parts, allocated to the N top priority delivery routes.

Step 4b: Compare the supply capacity and the demand; allocate the transport flow with the smaller one. Since the supply capacity of Manufacturer 3 is 300 units and the demand of Warehouse 1 is 500 units, the freight volume between them comes out to 300 units.

Step 5: Update the corresponding supply capacity and demand. The remaining supply capacity of Manufacturer 3 is $300 - 300 = 0$ and the updated demand of Warehouse 1 is $500 - 300 = 200$.

Step 6: Move on to the next delivery route according to the results of 'Cost Rank', and then repeat Step 2 to Step 6. When the whole level is finished, return to the next level.

Exceptionally, when the unit shipping cost of several different suppliers delivering to the same demander is identical, the delivery volume will be randomly generated.

5.2.2 *Cost rank*

In Step 1 of freight volume decision, the process 'Cost Rank' is used to decide the priority. It is implemented at the beginning of encoding. This cost rank process contains eight parts representing eight levels in the CLSC. In each part, the unit shipping cost of each delivery route is positive sequence ranked. The results of the rank are prepared for the freight volume decision process.

5.3 *Genetic operations*

Considering the characteristics of chromosomes in this problem, one-point crossover and one-point mutation is implemented to avoid dramatic changes in the genetic structure and prevent random genetic searches.

5.3.1 *Fitness function*

In this problem, the fitness is the reciprocal of the total cost. The lower the total cost the stronger the chromosome viability.

5.3.2 *Selector operator*

In the proposed GA, the roulette wheel selection is implemented to generate the mating pool. The roulette wheel function is

$$p_i = \frac{f_i}{\sum_{j=1}^{N} f_j}$$

where P_i represents the probability of being selected for chromosome i, f_i represents the fitness of chromosome i, N is the number of chromosomes in the initial pool.

5.3.3 *Crossover*

In this algorithm, one-point crossover is implemented. In one-point crossover, genes in the parent chromosomes will not be changed greatly, therefore, after several evolutions, weak genes will be easily identified (Chan and Chung 2004). In this particular problem, the chromosomes include several sections representing several levels in CLSC. A weak gene will cause a weak section, hence identification of weak genes in this problem is crucial. Figure 7 shows an example of crossover process.

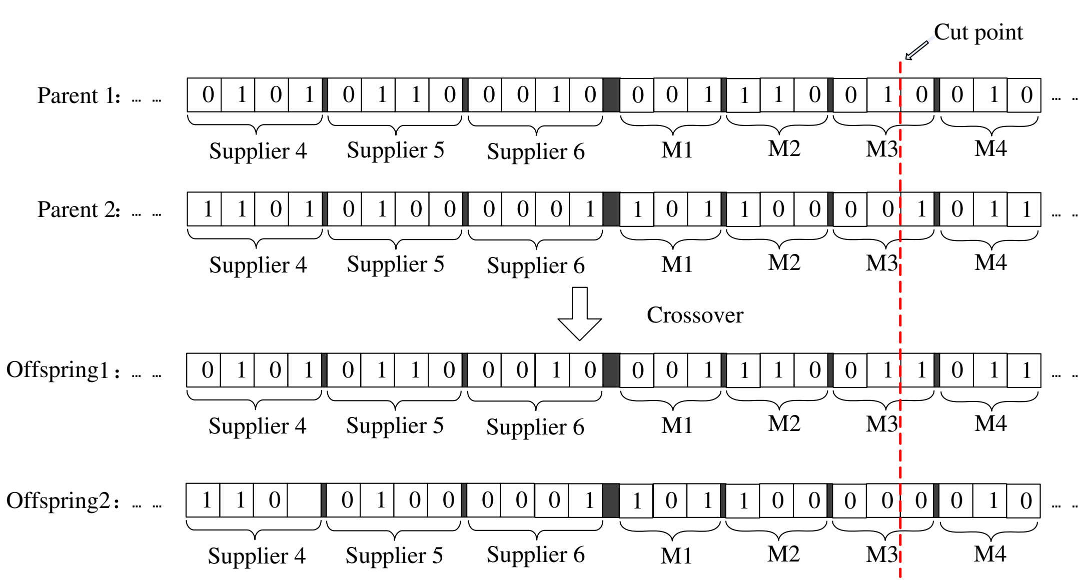

Figure 7. Crossover process.

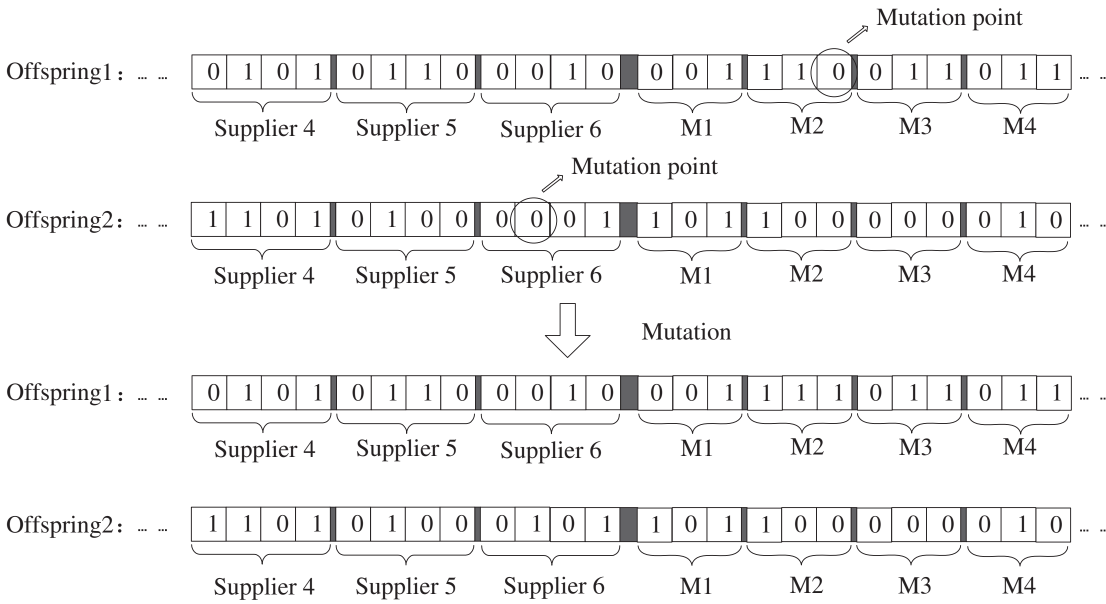

Figure 8. Mutation process.

5.3.4 *Mutation*

The process of mutation here aims at preventing the search trapped in a local optimum. One-point mutation with 1 mutation rate is implemented. Figure 8 shows an example of mutation process.

5.3.5 *Validation*

In the GAs, validation is applied to guarantee the feasibility. In this proposed algorithm, validation is divided into two parts.

Part 1: Capacity check

Part 1 is to check the binary chromosome after the first stage of encoding. If one of the validation requirements is not achieved, crossover and mutation processes will be rollback and done again. The validation requirements are shown as below.

(1) The total capacity of active distribution centres must be able to satisfy the total demand of customers.
(2) The total capacity of active manufacturers must be able to satisfy the total demand of customers.
(3) The genes of each customer cannot be zero simultaneously which means that each customer must return used products to at least one distribution centre.
(4) Since the demand of customers must be satisfied, each customer must have at least one distribution centre to supply the needed products.

For example, in Figure 8, the active manufacturers in offspring 2 are M1, M2 and M4. The total capacity cannot satisfy the total demand of customers causing the invalidation, therefore, the whole process of crossover will be rollbacked. The selected parents will be assigned in the pool after crossover as the offspring.

Part 2: Penalty check

After the capacity check, penalty check will be implemented on the offspring. In this part, it applied on the integer chromosome after the second stage of encoding. In this part, the penalty of the transformed chromosome will be examined. If the penalty is not equal to zero as before, the whole process of respective crossover and mutation will be rollback and done again.

6. Computational experiments

Three sets of experiments are conducted to prove the stability and efficiency of the proposed GA. Experiment 1 shows this computational experiment in an extreme case with large difference between the fixed costs of the entities. Hence,

Table 2. Scale of computational experiments.

Scales	Suppliers ($t = 1$)	Suppliers ($t = 2$)	Manufacturers	Warehouses	Retailers
No. 1	3	3	4	3	5
No. 2	6	6	8	6	10
No. 3	12	12	16	12	20
No. 4	24	24	32	24	40
No. 5	48	48	64	48	80
No. 6	72	72	96	72	120
No. 7	96	96	128	96	160
Scales	Customers	Collection points		Recycling centres	
No. 1	3	4		2	
No. 2	6	8		4	
No. 3	12	16		8	
No. 4	24	32		16	
No. 5	48	64		32	
No. 6	72	96		48	
No. 7	96	128		64	

Experiment 2 and Experiment 3 exhibit normal cases. In Experiment 2, the fixed cost and corresponding capacity of the distribution centres are close. In Experiment 3, the fixed cost and corresponding capacity of the entities within the same level are also close. All three experiments contain seven sub-problems with seven scales from small to large, as shown in Table 2.

6.1 *Experiment 1*

In Experiment 1, Lingo is used to compute the same problem for benchmark. Table 3 shows the capacity and fixed cost in the small scale of Experiment 1. Table 4 shows the unit shipping cost in the small scale of Experiment 1.

Table 3. The capacity and fixed cost in the basic scale of Experiment 1.

Manufacturers		Warehouses		Collection points		Recycling centres		Suppliers	
Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	
500	1300	800	500	100	95	180	300	$t = 1$	$t = 2$
600	1400	900	650	150	110	260	450	600	500
700	1500	1000	900	180	140			700	800
800	1800			200	180			800	850

Table 4. The unit shipping cost in the basic scale of Experiment 1.

Costs		M					W					R		
S	1.5	2.5	2	3	M	10	12	15	W	5	4	8	7	4
	3	1.5	2.5	4		15	13	14		8	6	5	3	5
	2	2.5	2.5	2		9	10	14		9	4	5	6	7
	4.5	6	7.5	6.5		10	11	12						
	7	6	5.5	6.5								M		
	5	6	6.5	6.5						$t = 0$	9	8	7	9
		Co					RC				8	6	10	8
Cu	9	8	12	8	Co	10		10	RC	$t = 1$	5	6	7	4
	7	9	11	12		12		12			6	7	4	4
	9	10	13	10		15		14		$t = 2$	10	13	12	15
						10		15			12	14	13	10

Note: S: Supplier, M: manufacturer, W: warehouse, R: retailer, Cu: customer, Co: collection points, RC: recycling centre.

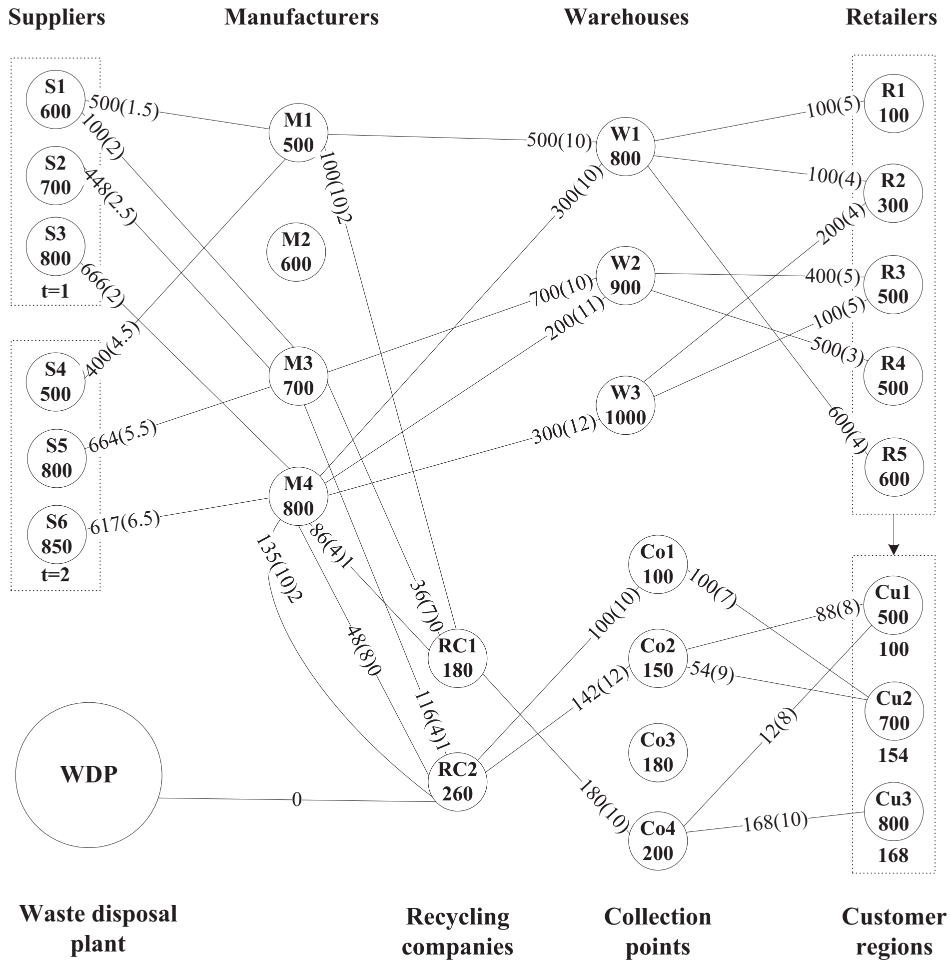

Figure 9. Result of basic scale problem in Experiment 1.

A sample solution for illustrating the detail is shown in Figure 9, for instance No. 1. To further test the proposed two-stage priority-based GA, six larger scale problems are calculated with the same data-set. Table 5 shows the results of the comparison between the proposed GA and Lingo using a PC with Intel(R) Core(TM) i7-2600 CPU @ 3.4 GHz, 8.0G RAM. The results in the original paper used a PC with Intel® Pentium® M processor 1.86 GHz, 1.0G RAM.

Table 5 shows the results of the comparison between Lingo 11.0 and the proposed GA with seven scales. The row of 'absolute difference' donates the results of the Lingo minus the results of the proposed GA and the minus sign means disparity. Take Scale 2, for example, the value of the absolute difference is -717, and value of the percentage difference is −0.59%, which means that the result of proposed GA is 0.59% disadvantageous compared with that of Lingo. However, the average time of the proposed GA is only 72 s, which is only 65.5% of the time for Lingo. In Scale 3, the result of the proposed GA is 2.62% disadvantageous compared with that of Lingo, and the running time is less than 8.89% of that of Lingo. In Scale 4, the result is 0.73% disadvantageous than that of Lingo, while the running time is less than 17% of that of Lingo. In Scale 5, although the quality of proposed GA is 2.73% behind Lingo, the time is faster than Lingo by almost three times. Therefore, it can be seen that the proposed GA is more effective than Lingo in solving the problems, but the solution obtained is at most only 3.06% different.

6.2 *Experiment 2*

In Experiment 1, Figure 9 shows that Manufacturer 2 and Collection point 2 are not used because they are of high fixed cost and low capacity. To simulate the normal situation as in Experiment 2, the fixed cost of manufacture and distribution are changed, while some of the unit shipping costs are changed to allow more entities to be used. As a result, the

Table 5. Results comparison between the proposed GA and Lingo.

Thirty times each problems	Scale	Numerical examples 1	2	3	4	5	6	7
Lingo 11.0	Solutions (US$)	61513.5*	122,124*	243,419	497,629	974,069	1,459,770	1,962,190
	Time(s)	1 s	110 s	>30 mins	>30 mins	>50 mins	>60 mins	>90 mins
Two-stage priority-based GA (population size = 100)	Solutions (US$)	61513.5	122,841	249,790	501,275	1,000,663	1,504,369	2,010,220
	Absolute difference	0	−717	−6371	−3646	−26,594	−44,599	−48,030
	Percentage difference	0	−0.59%	−2.62%	−0.73%	−2.73%	−3.06%	−2.45%
	Average cost (US$)	61,812	123,389	250,051	502,136	1,001,252	1,510,245	2,020,254
	Average time (s)	1 s	72 s	160 s	306 s	987 s	2018 s	3812 s
	Percentage of time	100%	65.5%	<8.89%	<17%	<32.9%	<56.06%	<70.6%

Note: Solutions by Lingo 11.0, with * are optimal, others are feasibility solutions obtained.

fixed cost and corresponding capacity of all the collection points are close to each other, which make the optimal solution tighter and the optimal search more difficult.

The comparison is developed between the proposed GA and Lingo. Due to the doubled and redoubled relationship between the small scale and the other scales, only the data-set of the small scale is shown for simplicity. Table 6 shows the capacity, fixed cost and demand in Experiment 2. Table 7 shows the changed unit shipping cost for each stage in Experiment 2. Table 8 shows the results of the comparison between the proposed GA and Lingo. Figure 10 shows the verification of the basic scale.

As can be seen in Table 8, the compute speed of the proposed GA is far faster than that of Lingo, although the quality of results is reduced slightly. In Scale 2, the quality result of the proposed GA is 1.37% disadvantageous than that of Lingo, but the running time of the proposed GA is only 1.33% of Lingo. When it comes to Scale 3, the result of the proposed GA is 2.21% poor than that of Lingo, but the running time of the proposed GA is only 1.39% of it. In Scale 4, the result of the proposed GA is 2.23% disadvantageous to that of Lingo, but the running time required only 6.89%

Table 6. Capacity, fixed cost (US$) and demand in Experiment 2.

Manufacturers		Warehouses		Collection points		Recycling centres		Suppliers	
Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	
500	1300	800	500	80	65	180	300	$t=1$	$t=2$
600	1400	900	650	100	90	260	450	600	500
700	1500	1000	900	120	100			700	800
800	1800			150	140			800	850

Table 7. Unit shipping cost for each stage (US$) in Experiment 2.

Costs		M					W					R		
S	1.5	2.5	2	3	M	10	12	15	W	5	6	8	7	4
	3	1.5	2.5	4		15	13	14		8	6	5	3	5
	1.5	2.5	2.5	2		9	10	14		9	4	5	6	7
	4.5	6	7.5	6.5		10	11	12						
	7	6	5.5	6.5								M		
	5	6	6.5	6.5					RC	$t=0$	9	8	7	9
		Co					RC				8	6	10	8
Cu	9	10	10	8	Co	10		13		$t=1$	5	6	7	4
	7	9	7	12		12		12			6	7	4	4
	9	10	12	10		13		14		$t=2$	10	13	12	15
						10		15			12	14	13	10

Note: *S*: Supplier, *M*: Manufacturer, *W*: warehouse, *R*: retailer, Cu: customer, Co: collection points, RC: recycling centre.

Table 8. Comparison with Lingo in Experiment 2.

		Numerical examples						
Thirty times each problems	Scale	1	2	3	4	5	6	7
Lingo 11.0	Solutions (US$)	61964.5*	123,027	244,615	490,442	974,016	1,476,620	1,945,480
	Time(s)	1 s	>20 mins	>30 mins	>30 mins	>50 mins	>100 mins	>170 mins
Two-stage priority-based GA (population size = 100)	Solutions (US$)	61964.5	124,708	250,011	501,383	1,004,215	1,513,106	2,020,155
	Absolute difference	0	−1681	−5396	−10,941	−30,199	−36,486	−74,675
	Percentage difference	0	−1.37%	−2.21%	−2.23%	−3.1%	−2.47%	−3.84%
	Average cost (US$)	62,102	125,012	250,126	502,549	1,005,638	1,522,145	2,025,413
	Average time (s)	1 s	16 s	25 s	124 s	524 s	1026 s	2653 s
	Percentage of time	100%	<1.33%	<1.39%	<6.89%	<17.47%	<17.1%	<26%

Note: Solutions with * are optimal solutions, others are near-optimum solutions.

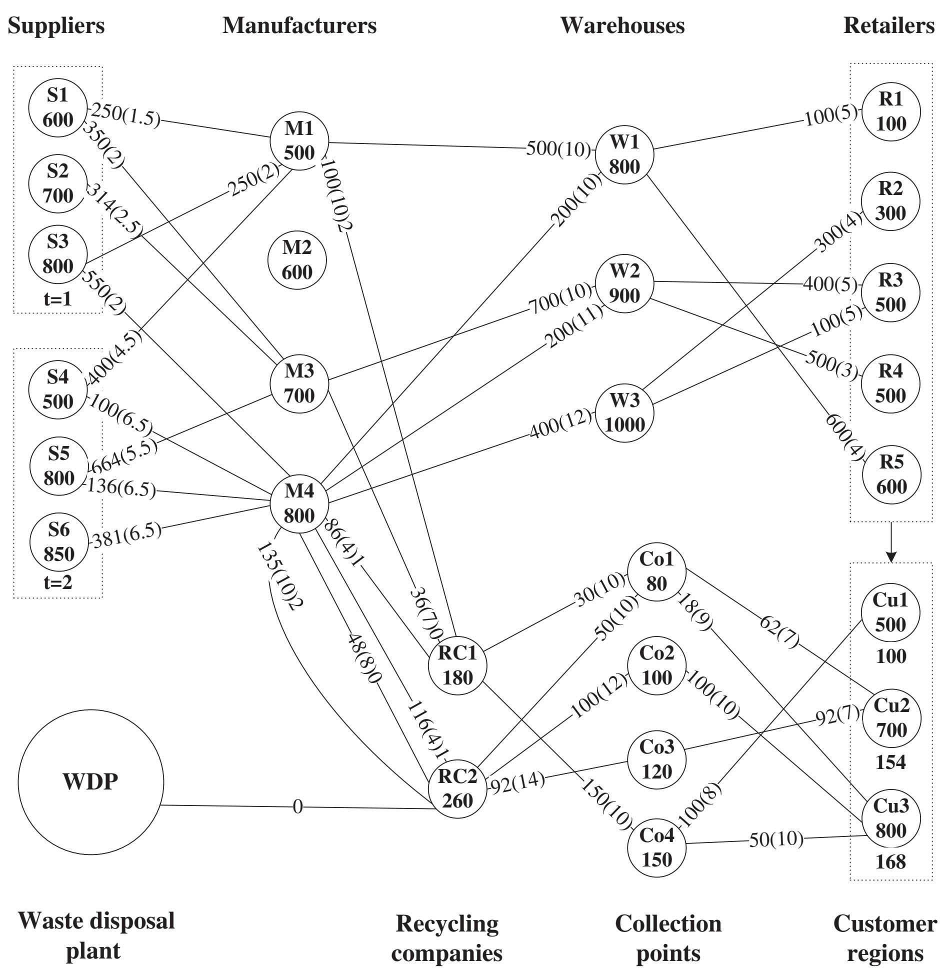

Figure 10. The network of the results.

of it. In Scale 5, the result becomes 3.1% disadvantageous to that of Lingo, but the running time is only 17.47% of it. The ‘Percentage difference’ row states that all the reduced quality of results are below 3.9%, while the running time of proposed GA in the row of ‘Percentage of time’ is 10 times faster than that of Lingo.

6.3 *Experiment 3*

Similar to Experiment 2, the fixed cost of entities and the unit shipping cost are further varied in Experiment 3, causing almost all of the entities within the same level to be of close fixed cost and corresponding capacities. This makes the solution of the whole network tighter, and the search for the optimal solution more difficult. Table 9 shows the capacity and fixed cost in the basic scale of Experiment 3. Table 10 shows the unit shipping cost for each stage in Experiment 3. Table 11 is the results of the comparison between the proposed GA and Lingo.

Table 11 shows the optimal solution of the basic scale in Experiment 3. It can be seen that five manufacturers and four collection points are being used.

Table 11 shows the results of the comparison between the proposed GA and Lingo. In Scale 1, the time of the proposed GA, used to get the optimal solution, is only 50% of that of Lingo. In Scale 2, the result of the proposed GA is

Table 9. The capacity and fixed cost in the basic scale of Experiment 3.

Manufacturers		Warehouses		Collection points		Recycling centres		Suppliers	
Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	Fixed cost	Capacity	
500	1100	800	500	80	65	180	300	$t=1$	$t=2$
600	1400	900	650	100	90	260	450	600	500
600	1500	1000	900	120	100			700	800
800	1800			150	140			800	850

Table 10. The unit shipping cost in the basic scale of Experiment 3.

Costs		M					W					R		
	1.5	2.5	2	3		10	12	15		5	6	8	7	4
	3	1.5	2.5	4	M	15	13	14	W	8	6	5	3	5
S	2	2.5	2.5	2		9	10	14		9	4	5	6	7
	4.5	6	7.5	6.5		10	11	12						
	7	6	5.5	6.5								M		
	5	6	6.5	6.5						$t=0$	9	8	7	9
		Co					RC				8	6	10	8
Cu	9	8	10	8	Co	10		13	RC	$t=1$	5	6	7	4
	7	9	10	12		12		12			6	7	4	4
	9	10	12	10		13		14		$t=2$	10	13	12	15
						10		15			12	14	13	10

Note: S: Supplier, M: manufacturer, W: warehouse, R: retailer, Cu: customer, Co: collection points, RC: recycling centre.

Table 11. Comparison with Lingo in Experiment 3.

Thirty times each problems	Scale	Numerical examples 1	2	3	4	5	6	7
Lingo 11.0	Solutions (US$)	63709.5*	125,118	249,030	496,338	988,044	1,512,670	2,324,090
	Time (s)	2 s	>30 mins	>30 mins	>40 mins	>60 mins	>120 mins	>120 mins
Two-stage priority-based GA (population size = 100)	Solutions (US$)	63,767	126,281	250,389	503,841	1,015,874	1,527,508	2,307,488
	Absolute difference	−57.5	−1163	−1359	−7503	−27,830	−14,838	16,602
	Percentage difference	−0.09%	−0.93%	−0.55%	−1.51%	−2.82%	−0.98%	0.71%
	Average cost (US$)	63,767	126,389	260,054	505,956	1,020,251	1,538,960	2,329,846
	Average time (s)	1 s	18 s	56 s	189 s	784 s	2520 s	4850 s
	Percentage of time	50%	<1%	<3.1%	<7.88%	<21.78%	<35%	<67.4%

Note: Solutions with * are optimal solutions, others are near-optimum solutions.

0.93% disparity to that of Lingo, but the running time of the proposed GA is only 1% of it. When grows to Scale 3, the result of the proposed GA is a 0.55% disadvantage to that of Lingo, but the time is only 3.1% of it. In Scale 4, although the quality result is 1.51% disadvantageous to Lingo, the running time is only 7.88% of it. In Scale 5, the result is 2.82% poor than Lingo, but the running time is only 21.78% of it. Although the optimal search in Experiment 3 is very difficult, it can be observed from the 'Percentage difference' row that the error rate is still below 2.9%. From the row of 'Percentage of time', the advantage of the running time is obvious. The Lingo calculation time in this table is the time when Lingo first came out the feasible solution. In this experiment, each scale of Lingo have been run for 24 h, but even after 24 h, the solution of Lingo cannot have much improvement.

7. Conclusions and suggestions of future work

With the booming development of electronic industry, the exponential growth of waste cartridges has polluted the environment seriously. Producers are perceived to be responsible for the recycling of products they have produced. However, few manufacturers adopted proper measures to deal with this because of expensive costs. To solve this problem, a comprehensive CLSC model of cartridge recycling is established in this paper. This model, which based on the real situation of cartridge recycle in Hong Kong, integrates both forward and reverse flow of products and contains eight partners in CLSC. In this research area, although many researchers discuss CLSC models, few of the models analyse the delivery activity for different kinds of materials that are extracted from used products, and also few studies classify the collected used products according to the quality. The model proposed in this paper can address these issues. Moreover, this problem is formulated into an Integer programming model and solved with a modified two-stage priority-based encoding GA which enhances the genetic searching ability. The adopted algorithm optimises the CLSC network and the results show a near-optimal solution, which can provide producers a reliable decision support.

In the real case, the return rate is uncertain. Hence, for the future research, the return rate in this model can be set as variable, which means the interaction between demand and return, the uncertainty of returns can be considered.

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