Multi-Period Configuration of Forward and Reverse Integrated Supply Chain Networks with the Choice of Transport Mode

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Abstract

In today's competitive business, buying and returning products have become a common practice because of incompleteness of the products or its failure to meet the customer's satisfaction or reusing products. Before this cycle can be handled, companies need a proper logistics network because of its impact on the efficiency and responsiveness of the supply chain. In this research, a forward and reverse logistics network is proposed for product distribution and collection. The contribution of this paper is the proposal of a multi-period, multi-echelon integrated forward and reverse supply chain network design problem with transportation mode selection. Different decisions including determination of optimum number and locations of facilities, facilities opening time and transportation mode selection have been considered in this paper. Due to multi-period nature of the problem, the problem is flexible for future periods. A mixed integer nonlinear programming model proposed for the introduced problem considering levels of facility capacities. As another contribution, a genetic algorithm developed to cope with problem's complexity especially for large size instances. Effectiveness and reliability of the algorithm evaluated by solving several random instances, with the obtained numerical results and comparisons confirming capability of the proposed algorithm for finding good solutions within acceptable processing times.

Keywords**:** supply chain network design, forward and reverse logistic, multi-period programming, transportation mode, genetic algorithm.

1. Introduction

Supply chain configuration imposes significant effect on the supply chain effectiveness. A typical supply chain network is composed of forward and reverse logistics. The forward logistics is utilized to transform raw material into finished goods before delivering them to the end-users; this includes suppliers, production centers, and distributors. On the other hand, the reverse logistics is composed of collecting and inspection centers, recycling centers, disposal centers, and centers for reproduction of the returned goods [1]. During the recent years, the reverse logistic strategies have been increasingly regarded by researchers. This is because of the residual value of imperfect, out of fashion, or unsold products at the end of the forward supply chain. The other reason behind the importance of such strategies is to reduce

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or eliminate the waste generation to comply with environmental regulations or other social commitments. As such, the reverse logistics has been mainly focused on management, inspection and arrangements of the waste in terms of material, part, and product collection/delivery from/to processing or repair centers, and tracing their return to other supply chains or markets [2]. Independent design of forward and reverse logistic networks results in suboptimal designs in terms of costs and level of service. Therefore, it has been recommended to design the forward and reverse logistic networks simultaneously to achieve a so-called integrated design [1].

In recent years, a great deal of development has been realized within the field of Supply Chain Network Design (SCND); although a great deal of research has been focused on this topic, most of the works reported so far have been limited to a single period of time, making them less flexible when dealt with periodic variations. However, supply chain networks are expected to be designed with a multi-period scheme to boost their flexibility and provide a basis for taking the advantages of multi-facility networks in multiply periods.

This research is a development to forward and reverse supply chain network design problem wherein a multi-period, multi-echelon model is considered. The multi-echelon helps consider the entire supply chain, while multi-period contribute to better solutions in long run. The proposed problem can be applied to such products as tires, electrical reusable devices, bottle caps or virtually any product which may be returned by customers any reason. Forward and reverse logistics network design is essential for cost reduction by reusing products and decreasing environmental pollution by collecting deteriorated items, and for customer satisfaction enhancement by returning the products which are either not satisfactory from the customer's point of view or no more used by them. The proposed model allows the decision-makers to account for such parameters as transportation cost, purchase cost, etc. by considering their values in different periods. Another feature highlighted in this research is the transportation mode selection. In reality, there are different transportation modes with different associated costs, delivery time, and safety level, etc., so that the choice of transportation mode affects the supply chain performance and responsiveness. Therefore, in order to minimize total transportation costs, one should establish a balance between the fixed initial costs and variable costs of transportation between network nodes. Furthermore, thanks to its comprehensiveness and generalizability, the proposed model can be applied to many of those goods which are to be shipped to the consumer once they were delivered and reproduced. As another contribution to the literature, the present research formulates an appropriate solving algorithm for the newly introduced problem, with its performance verified by examining numerical examples.

The rest of this paper is organized as follows. Section 2 presents a review on existing literature. Section 3 focuses on problem description and mathematical formulation of the model. Section 4 is dedicated to the model validation, while setting out an approach to the solving algorithm that is further tested on numerical examples on various sizes. Finally, Section 5 draws some conclusion and elaborates on future trends.

2. Literature review

As a strategic decision for supply chain management, SCND plays a significant role in determining effectiveness, associated costs, and responsiveness of a supply chain. This problem involves facilities location, flows allocation, products transportation, inventories and storage management, vehicles routing, etc. Most previous researchers addressed the designs of forward and reverse logistic networks independently, leading to sub-optimal results. Considering the fact that reverse logistic network design imposes direct effects on the corresponding forward logistic network, one may suggest the necessity of designing forward and reverse logistic networks together [3]. In this regard, various integrated forward and reverse logistics problems have been defined, such as network design, inventory management, capacity management, pricing, and game theory problems.

Different researchers have introduced various problems based on SCND. Lin *et al.* (2006), Du and Evans (2008), Mehdizadeh *et al*. (2013), Mirmajlesi and Shafaei (2016), Taleizadeh and Sadeghi (2018) and Fathollahi Fard and Hajaghaei-Keshteli (2018) focused on the number of supply chain echelons [4-9]. Some other researchers like Badri *et al.* (2013) and Nobari and Kheirkhah (2018) based their investigations on the number of programming periods [10-11]. Multi-product systems also present an interesting topic for researchers [4], [10]. Cardoso *et al.* (2013), Pedram *et al*. (2017) and Lieckens and Vandaele (2007) worked on the uncertainties associated with the parameters of such systems [12-14]. They considered the demand as the source of such uncertainties and modeled it via a scenario tree-based approach.

Center capacities (i.e. capacity extension or contraction, addition or elimination of storage facilities, etc.) is another significant aspect of SCND. For instance, Aghezzaf (2005) and Shaharudin *et al*. (2017) considered the possibility of expanding the capacity of facilities [15-16], while Lowe *et al.* (2002) proposed a model to design supply chain networks with reducible capacity [17]. Furthermore, Martel *et al.* (2006) developed a logistic model wherein the center capacity could be either increased or decreased [18]. In another research, Karabakal *et al.* (2000) presented the analysis of the supply chain across the American branch of Volkswagen Company [19].

Some researchers addressed the inventory in the SCND. In the literatures on inventory programming, the majority of decisions are related to proper location of the inventory storage facilities [15], [20-22]. Some research works considered the inventory storage as not limited to just one echelon [23-25], while some others focused on the raw material supply and final products storage, e.g. Jang *et al.* (2002), Melo *et al.* (2006), Syam (2002), van Weele (2009), and Cordeau *et al.* (2006) [23-27]. In another study, Yan *et al.* (2003) proposed a multi-echelon, multi-product, single-time period model for SCND as well as raw material supply [28]; and Zhou and Chen (2017) considered an inventory control problem for both forward and reverse logistics [29].

Transportation mode selection has been widely regarded in previous research works. When it comes to the choice of transportation mode in a SCND, either of two cases may arise: (1) a given pair of nodes can be handled via more than one transportation modes [30], (2) only one transportation mode is available between a given pair of nodes [31].

Heydari *et al*. (2017) and Taleizadeh and Sadeghi (2018) proposed pricing strategies in competitive reverse supply chains [8], [32]. Giri *et al.* (2017) and Fathollahi Fard and Hajaghaei-Keshteli (2018) investigated the impacts of cooperation and competition based on game theory [9], [33]. Khakim Habibi *et al.* (2017) presented a collection-disassembly problem in reverse supply chain [34]. Butzer *et al.* (2017) defined a performance measurement system to assess international reverse supply chains [35]. Goh *et al.* (2007) developed a location programming model for international facilities [36].

Different researchers have developed a variety of approaches to solve their proposed problems; these can be classified into exact and approximate methods (heuristic and metaheuristic methods). Lu and Bostel (2007) proposed a Lagrangian relaxation method [37]. Üster *et al.* (2007) employed benders decomposition [38]. Min and Ko (2008), Lee and Chan (2009), Trappey *et al.* (2010) and Fakhrzad and Moobed (2010) used genetic algorithm [39-42]. Mehdizadeh *et al.* (2013) developed a hybrid priority-based genetic algorithm and simulated annealing algorithm [6]. Zegordi *et al.* (2010) considered a gender-based genetic algorithm (GGA) in which two different types of chromosomes with unequal structures were considered. More recently, a number of scholars adopted new algorithms for such a purpose

[43]. In this respect, Modiri-Delshad *et al.* (2016) used back-tracking search algorithm [44]; Kaboli *et al*. (2016) proposed an artificial cooperative search algorithm [45]; Rafieerad *et al.* (2017) applied a multi-objective particle swarm optimization (PSO) [46]; Kaboli *et al.* (2017) introduced rain-fall optimization algorithm; Also Kaboli *et al.* (2017) proposed a gene expression programming for electrical consumption forecasting [47-48]; Sebtahmadi *et al.* (2018) used PSO-DQ Current Control Scheme [49]; Mansouri *et al.* (2012) presented a hybrid neuro-fuzzy- P.I. fed Controller for controlling the rpm of brush-less D.C. motors [50]; Modiri-Delshad *et al.* (2013) proposed an iterative algorithm for economic dispatch in a micro-grid. They further used the algorithm to address economic dispatch in a power system [51].

Given the focus of the present research, i.e. integrated SCND, Amin and Zhang (2013) proposed a multi-objective, multi-echelon, multi-product model that represented a consistent image of integrity across the system [1]. Mirmajlesi and Shafaei (2016) considered a multi-period, multi-product, multi-echelon capacitated supply chain problem for products of short lifetime [7].

As a contribution to forward and reverse logistics problem and to fill in the existing research gap in the literature on SCND, this study develops a deterministic multi-period, multi-echelon model to maximize overall profit. The model determines optimum number and locations of facilities as well as their establishment times. The considered logistics network structure had three echelons in the forward flow and four echelons in reverse flow. Furthermore, the choice of transportation mode between different nodes (facilities) was considered. The present research is among the rare research studies where forward and reverse logistics are combined to address multi-period logistic network design and scheduling simultaneously. This research further considers the choice of transportation mode (with different fixed and variable costs associated with each transportation mode) between the associated nodes, i.e. mathematical programming toward minimizing the transportation costs leads to a proportional balance between the transportation costs and the fixed and variable parameters affecting the chosen transportation mode. Furthermore, given the numerical complexity of the problem, a metaheuristic algorithm was developed to solve the model. Transportation problem concepts comprise a common idea within SCND problems. Due to its superior performance for solving similar problems, genetic algorithm was adopted in this paper. Mixing the transportation problem with the genetic algorithm, one can design an effective solver algorithm for problems of larger sizes.

3. Problem description and modeling

In order to accurately demonstrate a schematic of the problem assumptions, Figure 1 provides a diagram view of a forward and reverse integrated supply chain network. Beginning with the chain, following the forward flow, the required products by the customers are manufactured in the production centers before being dispatched to distribution centers from where they are to be delivered to the customers. Such distribution centers are assigned to deliver all of the received products to the customers within the same period of time when the products were received. In terms of tasks and performances, there are two types of distribution centers: normal distribution centers, which are only utilizable along the forward flow and their only task is to receive the products from the distribution centers and forward them to the end users, and hybrid distribution centers which are not only capable of accomplishing what normal centers do, but also well set to collect the returned products from the customers at the end of the period in a reverse flow. As end customers, end users or retailers are placed at the end of the supply chain with their number and locations known within each period. The demand by these customers is known and the chain must necessarily meet the demands in full.

In the reverse flow, products' end users are assumed to receive the products from the distribution centers and return them to the supply chain once the products were consumed. Each customer has his/her specific rate of return. This rate of return can be different for each period. Following with the reverse flow, there are collecting centers where the returned products from the customers are collected. In this problem, all of returned products must be collected. Normal collecting centers can only be utilized along the reverse flow path to collect the returned products from the customers, while hybrid distribution-collecting centers not only can accomplish the collecting task, but also perform the distribution task along the forward path flow. Once inspected in the collecting centers, the collected products will be sent to the recycling centers if those were recognized as recyclable; otherwise, the collected produced are sent to disposal centers. Different recycling centers may exhibit different rates of recyclable products within each period of time. Once recycled, the collected products either turn into recycled products which can be resold to customers or provide raw material for the production centers. Therefore, the recycled products can be profitable for the chain as they can be sold.

In figure number 1, locating process is performed on the manufacturing, distribution, hybrid distribution-collection, collecting, recycling, and disposal facilities, within each period, so that the demands by the customers can be fulfilled with minimum cost. Various transportation modes are provided for transporting the products between two related facilities. According to the model assumptions, only one transportation mode can be chosen between each pair of nodes, with the choice retained until the end of the current period; however, different transportation modes can be utilized for future periods. Each transportation mode has its own fixed and variable costs. Each facility opens at a limited initial capacity, so that it cannot serve beyond its initial capacity during the initial period. In this research, expandable capacity was considered, with each level of improvement being associated with some cost imposed to the system; for each facility, the capacity level enhancement was allowed just once per period. The presented model was developed for a single-product system.

3.1. Mathematical model

Model sets, indices, parameters, and decision variables are as follows:

a. Sets

v	Set of fixed locations of outer manufacturers	$v = 1, 2, ..., V$
i	Set of potential locations for manufacturing centers	$i = 1, 2, ..., \mathrm{I}$
j	Set of potential locations for distribution centers	$j = 1, 2, ..., \mathrm{J}$
k	Set of fixed locations of customers	$k = 1, 2, ..., \mathrm{K}$
l	Set of potential locations for collection and inspection centers	$l = 1, 2, ..., \mathrm{L}$
h	Set of potential locations for hybrid distribution-collection centers	$h = 1, 2, ..., \mathrm{H}$
g	Set of potential locations for recycling centers	$g = 1, 2, ..., \mathrm{G}$
m	Set of potential locations for disposal centers	$m = 1, 2, ..., \mathrm{M}$
n	Set of available capacity levels for facilities	$n = 1, 2, ..., \mathrm{N}$
c	Set of transport modes between a pair of nodes	$c = 1, 2, ..., \mathrm{C}$
t	Set of time periods	$t = 1, 2, ..., \mathrm{T}$

b. Parameters

DM_{kt}	The demand by the customer k at time period t

PR_{kt}	Product’s unit price for the customer *k* at time period *t*
PRI_{it}	Recycled product’s unit price for the manufacturing center *i* at time period *t*
PRV_{vt}	Recycled product’s unit price for the outer customer *v* at time period *t*
PC_{it}	Unit production cost at the manufacturing center *i* at time period *t*
IC_{lt}	Unit cost of inspection test at the collection and inspection center *l* at time period *t*
IC_{ht}	Unit cost of inspection test at the hybrid distribution-collection center *h* at time period *t*
RC_{gt}	Unit cost of product recycling at recycling center *g* at time period *t*
DC_{mt}	Unit cost of returned product disposal at disposal center *m* at time period *t*
XO_{it}	Fixed cost to establish the manufacturing center *i* at time period *t*, given it was closed at time period *t-1*
XC_{it}	Fixed cost to close the manufacturing center *i* at time period *t*, given it was open at time period *t-1*
FEX_{int}	Fixed cost to expand the manufacturing center *i* with the capacity level of *n* at time period *t*
YO_{jt}	Fixed cost to establish the distribution center *j* at time period *t*, given it was closed at time period *t-1*
YC_{jt}	Fixed cost to close the distribution center *j* at time period *t*, given it was open at time period *t-1*
FEY_{jnt}	Fixed cost to expand the distribution center *j* with the capacity level of *n* at time period *t*
ZO_{lt}	Fixed cost to establish the collection and inspection center *l* at time period *t*, given it was closed at time period *t-1*
ZC_{lt}	Fixed cost to close the collection and inspection center *l* at time period *t*, given it was open at time period *t-1*
$FEZ_{l.nt}$	Fixed cost to expand the collection and inspection center *l* with the capacity level of *n* at time period *t*
UO_{mt}	Fixed cost to establish the disposal center *m* at time period *t*, given it was closed at time period *t-1*
UC_{mt}	Fixed cost to close the disposal center *m* at time period *t*, given it was open at time period *t-1*
FEU_{mnt}	Fixed cost to expand the disposal center *m* with the capacity level of *n* at time period *t*
WO_{ht}	Fixed cost to establish the hybrid distribution-collection center *h* at time period *t*, given it was closed at time period *t-1*
WC_{ht}	Fixed cost to close the hybrid distribution-collection center *h* at time period *t*, given it was open at time period *t-1*
FEW_{hnt}	Fixed cost to expand the hybrid distribution-collection center *h* with the capacity level of *n* at time period *t*
QO_{gt}	Fixed cost to establish the recycling center *g* at time period *t*, given it was closed at time period *t-1*
QC_{gt}	Fixed cost to close the recycling center *g* at time period *t*, given it was open at time period *t-1*
FEQ_{gnt}	Fixed cost to expand the recycling center *g* with the capacity level of *n* at time period *t*
CaI_{it}	Capacity of the manufacturing center *i* at time period *t*

ECI_{int}	Development capacity of the manufacturing center *i* with the capacity level of *n* at time period *t*
CaJ_{jt}	Capacity of the distribution center *j* at time period *t*
ECJ_{jnt}	Development capacity of the distribution center *j* with the capacity level of *n* at time period *t*
CaL_{lt}	Capacity of the collection and inspection center *l* at time period *t*
ECL_{lnt}	Development capacity of the collection and inspection center *l* with the capacity level of *n* at time period *t*
CaH_{ht}	Capacity of the hybrid distribution-collection center *h* at time period *t*
ECH_{hnt}	Development capacity of the hybrid distribution-collection center *h* with the capacity level of *n* at time period *t*
CaG_{gt}	Capacity of the recycling center *g* at time period *t*
ECG_{gnt}	Development capacity of the recycling center *g* with the capacity level of *n* at time period *t*
CaM_{mt}	Capacity of the disposal center *m* at time period *t*
ECM_{mnt}	Development capacity of the disposal center *m* with the capacity level of *n* at time period *t*
CIJ_{ijtc}	Unit transportation cost from the manufacturing center *i* to the distribution center *j* at time period *t* via transport mode *c*
FIJ_{ijtc}	Fixed transportation cost from the manufacturing center *i* to the distribution center *j* at time period *t* via transport mode *c*
CJK_{jktc}	Unit transportation cost from the distribution center *j* to the customer *k* at time period *t* via transport mode *c*
FJK_{jktc}	Fixed transportation cost from the distribution center *j* to the customer *k* at time period *t* via transport mode *c*
CKL_{kltc}	Unit transportation cost from the customer *k* to the collection and inspection center *l* at time period *t* via transport mode *c*
FKL_{kltc}	Fixed transportation cost from the customer *k* to the collection and inspection center *l* at time period *t* via transport mode *c*
CHK_{hktc}	Unit transportation cost from the hybrid distribution-collection center *h* to the customer *k* at time period *t* via transport mode *c*
FHK_{hktc}	Fixed transportation cost from the hybrid distribution-collection center *h* to the customer *k* at time period *t* via transport mode *c*
CIH_{ihtc}	Unit transportation cost from the manufacturing center *i* to the hybrid distribution-collection center *h* at time period *t* via transport mode *c*
FIH_{ihtc}	Fixed transportation cost from the manufacturing center *i* to the hybrid distribution-collection center *h* at time period *t* via transport mode *c*
CLG_{lgtc}	Unit transportation cost from the collecting and inspection center *l* to the recycling center *g* at time period *t* via transport mode *c*
FLG_{lgtc}	Fixed transportation cost from the collecting and inspection center *l* to the recycling center *g* at time period *t* via transport mode *c*
CLM_{lmtc}	Unit transportation cost from the collecting and inspection center *l* to the disposal center *m* at time period *t* via transport mode *c*
FLM_{lmtc}	Fixed transportation cost from the collecting and inspection center *l* to the disposal center *m* at time period *t* via transport mode *c*
CHM_{hmtc}	Unit transportation cost from the hybrid distribution-collection center *h* to the disposal center *m* at time period *t* via transport mode *c*
FHM_{hmtc}	Fixed transportation cost from the hybrid distribution-collection center *h* to the

	disposal center m at time period t via transport mode c
CHG_{hgtc}	Unit transportation cost from the hybrid distribution-collection center h to the recycling center g at time period t via transport mode c
FHG_{hgtc}	Fixed transportation cost from the hybrid distribution-collection center h to the recycling center g at time period t via transport mode c
CGM_{gmtc}	Unit transportation cost from the recycling center g to the disposal center m at time period t via transport mode c
FGM_{gmtc}	Fixed transportation cost from the recycling center g to the disposal center m at time period t via transport mode c
CGI_{gitm}	Unit transportation cost from the recycling center g to the manufacturing center i at time period t via transport mode c
FGI_{gitc}	Fixed transportation cost from the recycling center g to the manufacturing center i at time period t via transport mode c
CGV_{gvtc}	Unit transportation cost from the recycling center g to the outer customer g at time period t via transport mode c
FGV_{gvtc}	Fixed transportation cost from the recycling center g to the outer customer g at time period t via transport mode c
RK_{k}	Rate of return for the used products by customer k
RI	Rate of usable material in the collecting and hybrid distribution-collection centers
RG	Rate of recyclable material in the recycling centers
D_{jt}	Unit distribution cost for the distribution center j at time period t
D_{ht}	Unit distribution cost for the hybrid distribution-collection center h at time period t

c. Non-negative Variables

QIJ_{ijt}	The volume of products sent from the manufacturing center i to the distribution center j at time period t
QJK_{jkt}	The volume of products sent from the distribution center j to the customer k at time period t
QIH_{iht}	The volume of products sent from the manufacturing center i to the hybrid distribution-collection center h at time period t
QHK_{hkt}	The volume of products sent from the hybrid distribution-collection center h to the customer k at time period t
QKL_{klt}	The volume of products sent from the customer k to the collecting and inspection center l at time period t
QKH_{kht}	The volume of products sent from the customer k to the hybrid distribution-collection center h at time period t
QLG_{lgt}	The volume of products sent from the collecting and inspection center l to the recycling center g at time period t
QLM_{lmt}	The volume of products sent from the collecting and inspection center l to the disposal center m at time period t
QHM_{hmt}	The volume of products sent from the hybrid distribution-collection center h to the disposal center m at time period t
QHG_{hgt}	The volume of products sent from the hybrid distribution-collection center h to the recycling center g at time period t
QGM_{gmt}	The volume of products sent from the recycling center g to the disposal center m at time period t
QGI_{git}	The volume of products sent from the recycling center g to the manufacturing center i at time period t

QGV_{gvt} The volume of products sent from the recycling center *g* to the outer customer *v* at time period *t*

d. Binary Variables

X_{it}	$\begin{cases} \text{1: If the manufacturing center } i \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
$EX_{i.nt}$	$\begin{cases} \text{1: If the manufacturing center } i \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
Y_{jt}	$\begin{cases} \text{1: If the distribution center } j \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
EY_{jnt}	$\begin{cases} \text{1: If the distribution center } j \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
Z_{lt}	$\begin{cases} \text{1: If the collecting and inspection center } l \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
$EZ_{l.nt}$	$\begin{cases} \text{1: If the collecting and inspection center } l \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
U_{mt}	$\begin{cases} \text{1: If the disposal center } m \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
EU_{mnt}	$\begin{cases} \text{1: If the disposal center } m \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
W_{ht}	$\begin{cases} \text{1: If the hybrid distribution-collection center } h \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
EW_{hnt}	$\begin{cases} \text{1: If the hybrid distribution-collection center } h \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
Q_{gt}	$\begin{cases} \text{1: If the recycling center } g \text{ is established at time period } t \\ \text{0: Otherwise} \end{cases}$
EQ_{gnt}	$\begin{cases} \text{1: If the recycling center } g \text{ is developed with the capacity level of } n \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
IJ_{ijtc}	$\begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } i \text{ to } j \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
KL_{kltc}	$\begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } k \text{ to } l \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
JK_{jktc}	$\begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } j \text{ to } k \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
HK_{hktc}	$\begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } h \text{ to } k \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$
IH_{ihtc}	$\begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } i \text{ to } h \text{ at time period } t \end{cases}$

0: Otherwise

$$LG_{\mathrm{lg}tc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } l \text{ to } g \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$LM_{lmtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } l \text{ to } m \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$HM_{hmtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } h \text{ to } m \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$HG_{hgtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } h \text{ to } g \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$GM_{gmtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } g \text{ to } m \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$GI_{gitc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } g \text{ to } i \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$GV_{gvtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } g \text{ to } v \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

$$KH_{khtc} \begin{cases} \text{1: If the transport mode } c \text{ is chosen for the route from } k \text{ to } h \text{ at time period } t \\ \text{0: Otherwise} \end{cases}$$

where M is a large number, and RI and RK denote rate of return, can take values between 0 and 1, and express the fraction of original products that were returned. Based on the assumptions, the parameters and variables of the model were defined and the objective function, which was a kind of profit maximization, was formulated as follows:

Objective function and its components

$$\text{Maximise} \quad \text{Profit} = \sum_{t} (Income_t - \mathrm{Cos}\, t_t) \tag{1}$$

$$Income_t = \sum_{j}\sum_{k}(QJK_{jkt} * \mathrm{PR}_{kt}) + \sum_{h}\sum_{k}(QHK_{hkt} * \mathrm{PR}_{kt})$$
$$+ \sum_{g}\sum_{i}(QGI_{git} * \mathrm{PRI}_{it}) + \sum_{g}\sum_{v}(QGV_{gvt} * \mathrm{PRV}_{vt}) \qquad \forall t \tag{2}$$

$$Cost_t = \sum_{i} XO_{it}(1-\mathrm{X}_{i,t-1})X_{it} + \sum_{i} XC_{it} * X_{i,\mathrm{t}-1}(1-\mathrm{X}_{it}) + \sum_{j} YO_{jt}(1-Y_{\mathrm{j},t-1})Y_{jt} + \sum_{j} YC_{jt} * \mathrm{Y}_{\mathrm{j,t}-1}(1-Y_{jt})$$
$$+ \sum_{l} ZO_{lt}(1-Z_{\mathrm{l},t-1})Z_{lt} + \sum_{l} ZC_{lt} * \mathrm{Z}_{\mathrm{l,t}-1}(1-Z_{lt}) + \sum_{m} UO_{mt}(1-U_{\mathrm{m},t-1})U_{mt} + \sum_{m} UC_{mt} * \mathrm{U}_{\mathrm{m,t}-1}(1-U_{mt})$$
$$+ \sum_{h} WO_{ht}(1-W_{\mathrm{h},t-1})W_{it} + \sum_{h} WC_{ht} * \mathrm{W}_{\mathrm{h,t}-1}(1-W_{ht}) + \sum_{g} QO_{gt}(1-Q_{\mathrm{g},t-1})Q_{gt} + \sum_{g} QC_{gt} * \mathrm{Q}_{\mathrm{g,t}-1}(1-Q_{gt}) \tag{3.1}$$

$$+ \sum_{i}\sum_{n} FEX_{\mathrm{int}}(EX_{\mathrm{int}} - EX_{in,t-1}) + \sum_{j}\sum_{n} FEY_{\mathrm{jnt}}(\mathrm{EY}_{\mathrm{jnt}} - EY_{jn,t-1}) + \sum_{l}\sum_{n} FEZ_{\mathrm{lnt}}(EZ_{\mathrm{lnt}} - EZ_{ln,t-1}) +$$
$$+ \sum_{m}\sum_{n} FEU_{\mathrm{mnt}}(EU_{\mathrm{mnt}} - EU_{mn,t-1}) + \sum_{h}\sum_{n} FEW_{\mathrm{hnt}}(EW_{\mathrm{hnt}} - EW_{ih,t-1}) + \sum_{g}\sum_{n} FEQ_{\mathrm{gnt}}(EQ_{\mathrm{gnt}} - EQ_{gn,t-1}) \tag{3.2}$$

$$+ \sum_{i}\sum_{j}(QIJ_{ijt} * PC_{it}) + \sum_{i}\sum_{h}(QIH_{iht} * PC_{it}) \tag{3.3}$$

$$+ \sum_{j}\sum_{k}(QJK_{jkt} * \mathrm{D}_{jt}) + \sum_{h}\sum_{k}(QHK_{hkt} * \mathrm{D}_{ht}) \tag{3.4}$$

$$+\sum_{k}\sum_{l}(QKL_{klt}*\mathrm{I}C_{lt})+\sum_{k}\sum_{h}(QKH_{kht}*\mathrm{I}C_{ht}) \tag{3.5}$$

$$+\sum_{l}\sum_{m}(QLM_{lmt}*\mathrm{D}C_{mt})+\sum_{h}\sum_{m}(QHM_{hmt}*\mathrm{D}C_{mt})+\sum_{g}\sum_{m}(QGM_{gmt}*\mathrm{D}C_{mt}) \tag{3.6}$$

$$+\sum_{l}\sum_{g}(QLG_{\mathrm{lg}t}*\mathrm{R}C_{gt})+\sum_{h}\sum_{g}(QHG_{hgt}*\mathrm{R}C_{gt}) \tag{3.7}$$

$$\begin{aligned}
&+\sum_{i}\sum_{j}(QIJ_{ijt}*(\sum_{c}IJ_{ijtc}*\mathrm{CIJ}_{ijtc}))+\sum_{j}\sum_{k}(QJK_{jkt}*(\sum_{c}JK_{jktc}*\mathrm{CJK}_{jktc}))\\
&+\sum_{k}\sum_{l}(QKL_{klt}*(\sum_{c}KL_{kltc}*\mathrm{CKL}_{kltc}))+\sum_{h}\sum_{k}(QHK_{hkt}*(\sum_{c}HK_{hktc}*\mathrm{CHK}_{hktc}))\\
&\sum_{k}\sum_{h}(QKH_{kht}*(\sum_{c}KH_{khtc}*\mathrm{CKH}_{khtc}))+\sum_{i}\sum_{h}(QIH_{iht}*(\sum_{c}IH_{ihtc}*\mathrm{CIH}_{ihtc}))\\
&+\sum_{l}\sum_{g}(QLG_{\mathrm{lg}t}*(\sum_{c}LG_{\mathrm{lg}tc}*\mathrm{CLG}_{\mathrm{lg}tc}))+\sum_{l}\sum_{m}(QLM_{lmt}*(\sum_{c}LM_{lmtc}*\mathrm{CLM}_{lmtc}))\\
&+\sum_{h}\sum_{m}(QHM_{hmt}*(\sum_{c}HM_{hmtc}*\mathrm{CHM}_{hmtc}))+\sum_{h}\sum_{g}(QHG_{hgt}*(\sum_{c}HG_{hgtc}*\mathrm{CHG}_{hgtc}))\\
&+\sum_{g}\sum_{m}(QGM_{gmt}*(\sum_{c}GM_{gmtc}*\mathrm{CGM}_{gmtc}))+\sum_{g}\sum_{i}(QGI_{git}*(\sum_{c}GI_{gitc}*\mathrm{CGI}_{gitc}))\\
&+\sum_{g}\sum_{v}(QGV_{gvt}*(\sum_{c}GV_{gvtc}*\mathrm{CV}_{gvtc}))
\end{aligned} \tag{3.8}$$

$$\begin{aligned}
&+\sum_{i}\sum_{j}\sum_{c}IJ_{ijtc}*FIJ_{ijtc}+\sum_{j}\sum_{k}\sum_{c}JK_{jktc}*FJK_{jktc}+\sum_{k}\sum_{l}\sum_{c}KL_{kltc}*FKL_{kltc}\\
&+\sum_{h}\sum_{k}\sum_{c}HK_{hktc}*FHK_{hktc}+\sum_{i}\sum_{h}\sum_{c}IH_{tc}*FIH_{ihtc}\\
&+\sum_{l}\sum_{g}\sum_{c}LG_{lgtc}*FLG_{\mathrm{lg}tc}+\sum_{l}\sum_{m}\sum_{c}LM_{lmtc}*FLM_{lmtc}+\sum_{h}\sum_{m}\sum_{c}HM_{hmtc}*FHM_{hmtc}\\
&+\sum_{h}\sum_{g}\sum_{c}HG_{hgtc}*FHG_{hgtc}+\sum_{g}\sum_{m}\sum_{c}GM_{gmtc}*FGM_{gmtc}+\sum_{g}\sum_{i}\sum_{c}GI_{gitc}*FGI_{gitc}\\
&+\sum_{g}\sum_{v}\sum_{c}GV_{gvtc}*FGV_{gvtc}
\end{aligned} \tag{3.9}$$

The first term of the expression sets out the general form of the objective function. Based on this general form, it is clear that the profit function is obtained as the difference between the sums of revenues generated along the chain and associated costs. For the sake of simplicity and to obtain an easier-to-understand mathematical expression, the income function and cost function were expressed as the second and third terms, respectively.

Showing income sources of the chain, the second term of the objective function is composed of two components: (1) the sum of incomes provided by the sale of the finished products to the end users in the forward flow during various periods, and (2) total incomes raised by selling recycled products to manufacturing centers or external customers during all programming periods.

Reflecting the incurred costs, the third term of the objective function consists of 9 components. For the sake of simplicity, the 9 components were formulated as follows. The component 3.1 denotes total fixed costs associated with the establishment and termination of centers during all periods. The component 3.2 refers to total fixed costs spent on capacity expansion of the centers from the initial capacity to increased capacity levels. The component 3.3 indicates total manufacturing cost spent, at the manufacturing centers, to fulfill customers' demands within the programming periods. The component 3.4 evaluates the costs incurred upon distributing the products from the distribution or hybrid collection – distribution centers to the end users. The component 3.5 denotes the total cost incurred to inspect and test the collected returned products; it can be seen as a collecting-associated cost. The component 3.6 refers to the sum of disposal costs incurred in the disposal centers. The component 3.7 indicates total product recycling costs induced in the recycling centers. The component 3.8 shows the sum of variable costs of transportation across associated nodes, and finally, the component 3.9 represents total fixed transportation cost.

In the following, **the model constraints** are discussed.

$$\sum_i QIJ_{ijt} = \sum_k QJK_{jkt} \quad \forall \mathrm{t,j} \tag{4}$$

$$\sum_j QJK_{jkt} + \sum_h QHK_{hkt} = DM_{kt} \quad \forall t,k \tag{5}$$

$$\sum_i QIH_{iht} = \sum_k QHK_{hkt} \quad \forall t,h \tag{6}$$

$$\sum_h QKH_{kht} + \sum_l QKL_{klt} = DM_{kt} * RK_k \quad \forall t,k \tag{7}$$

$$RI * \sum_k QKH_{kht} = \sum_g QHG_{hgt} \quad \forall t,h \tag{8}$$

$$(1-RI)\sum_k QKH_{kht} = \sum_m QHM_{hmt} \quad \forall t,h \tag{9}$$

$$RI * \sum_k QKL_{klt} = \sum_g QLG_{lgt} \quad \forall t,\mathrm{i} \tag{10}$$

$$(1-RI)\sum_k QKL_{klt} = \sum_m QLM_{lmt} \quad \forall t,\mathrm{l} \tag{11}$$

$$RG * (\sum_h QHG_{hgt} + \sum_l QLG_{\mathrm{lg}t}) = \sum_v QGV_{gvt} + \sum_i QGI_{git} \quad \forall t,g \tag{12}$$

$$(1-RG)(\sum_h QHG_{hgt} + \sum_l QLG_{\mathrm{lg}t}) = \sum_m QGM_{gmt} \quad \forall t,g \tag{13}$$

$$\sum_j QIJ_{ijt} + \sum_h QIH_{iht} \le CaI_{it} * X_{it} + \sum_n (ECI_{\mathrm{int}} * \mathrm{EX}_{\mathrm{int}}) \quad \forall t,i \tag{14}$$

$$\sum_i QIJ_{ijt} \le CaJ_{jt} * \mathrm{Y}_{jt} + \sum_n (ECJ_{\mathrm{jnt}} * \mathrm{EY}_{\mathrm{jnt}}) \quad \forall t,\mathrm{j} \tag{15}$$

$$\sum_k QKL_{klt} \le CaL_{lt} * \mathrm{Z}_{lt} + \sum_n (ECL_{\mathrm{lnt}} * \mathrm{EZ}_{\mathrm{lnt}}) \quad \forall t,\mathrm{l} \tag{16}$$

$$\sum_i QIH_{iht} + \sum_k QKH_{kht} \le CaH_{ht} * \mathrm{W}_{ht} + \sum_n (ECH_{\mathrm{hnt}} * \mathrm{EW}_{\mathrm{hnt}}) \quad \forall t,\mathrm{h} \tag{17}$$

$$\sum_l QLG_{\mathrm{lg}t} + \sum_h QHG_{hgt} \le CaG_{gt} * \mathrm{Q}_{gt} + \sum_n (ECG_{\mathrm{gnt}} * \mathrm{EQ}_{\mathrm{gnt}}) \quad \forall t,\mathrm{g} \tag{18}$$

$$\sum_l QLM_{lmt} + \sum_h QHM_{hmt} + \sum_g QGM_{gmt} \le CaM_{mt} * U_{mt} + (\sum_n ECM_{mnt} * EU_{mnt}) \quad \forall \mathrm{t,m} \tag{19}$$

$$\sum_n EX_{\mathrm{int}} \le X_{it} \quad \forall t,i \tag{20}$$

$$\sum_n EY_{\mathrm{Jnt}} \le Y_{jt} \quad \forall t,\mathrm{j} \tag{21}$$

$$\sum_n EZ_{\mathrm{lnt}} \le Z_{lt} \quad \forall t,l \tag{22}$$

$$\sum_n EU_{\mathrm{mnt}} \le U_{mt} \quad \forall t,m \tag{23}$$

$$\sum_n EQ_{\mathrm{gnt}} \le Q_{gt} \quad \forall t,g \tag{24}$$

$$\sum_n EW_{\mathrm{hnt}} \le W_{ht} \quad \forall t,h \tag{25}$$

$$EX_{in,t-1} \le EX_{int} \quad \forall t,n,i \tag{26}$$

$$EY_{jn,t-1} \le EY_{jnt} \quad \forall t,n,\mathrm{j} \tag{27}$$

$$EZ_{ln,t-1} \le EZ_{lnt} \quad \forall t,n,\mathrm{l} \tag{28}$$

$$EU_{mn,t-1} \le EU_{mnt} \quad \forall t,n,\mathrm{m} \tag{29}$$

$$EQ_{gn,t-1} \le EQ_{gnt} \quad \forall t,n,\mathrm{g} \tag{30}$$

$$EW_{hn,t-1} \le EW_{hnt} \quad \forall t,n,\mathrm{h} \tag{31}$$

$$\sum_{c} IJ_{ijtc} \le 1 \quad \forall t,\mathrm{i},\mathrm{j} \tag{32}$$

$$\sum_{c} JK_{jktc} \le 1 \quad \forall t,\mathrm{j},\mathrm{k} \tag{33}$$

$$\sum_{c} KL_{kltc} \le 1 \quad \forall t,\mathrm{k},\mathrm{l} \tag{34}$$

$$\sum_{c} HK_{hktc} \le 1 \quad \forall t,\mathrm{h},\mathrm{k} \tag{35}$$

$$\sum_{c} IH_{ihtc} \le 1 \quad \forall t,\mathrm{i},\mathrm{h} \tag{36}$$

$$\sum_{c} LG_{\mathrm{lg}tc} \le 1 \quad \forall t,\mathrm{l},\mathrm{g} \tag{37}$$

$$\sum_{c} LM_{lmtc} \le 1 \quad \forall t,\mathrm{l},\mathrm{m} \tag{38}$$

$$\sum_{c} HM_{hmtc} \le 1 \quad \forall t,\mathrm{h},\mathrm{m} \tag{39}$$

$$\sum_{c} GM_{gmtc} \le 1 \quad \forall t,\mathrm{g},\mathrm{m} \tag{40}$$

$$\sum_{c} HG_{hgtc} \le 1 \quad \forall t,\mathrm{h},\mathrm{g} \tag{41}$$

$$\sum_{c} GI_{gitc} \le 1 \quad \forall t,\mathrm{g},\mathrm{i} \tag{42}$$

$$\sum_{c} GV_{gvtc} \le 1 \quad \forall t,\mathrm{g},\mathrm{v} \tag{43}$$

$$\sum_{c} KH_{khtc} \le 1 \quad \forall t,\mathrm{h},\mathrm{k} \tag{44}$$

$$QIJ_{ijt} \le M \sum_{c} IJ_{ijtc} \quad \forall t,i,\mathrm{j} \tag{45}$$

$$QJK_{jkt} \le M \sum_{c} JK_{jktc} \quad \forall t,\mathrm{j},\mathrm{k} \tag{46}$$

$$QKL_{klt} \le M \sum_{c} KL_{kltc} \quad \forall t,\mathrm{k},\mathrm{l} \tag{47}$$

$$QHK_{hkt} \le M \sum_{c} HK_{hktc} \quad \forall t,\mathrm{h},\mathrm{k} \tag{48}$$

$$QIH_{iht} \le M \sum_{c} IH_{ihtc} \quad \forall t,i,\mathrm{h} \tag{49}$$

$$QLG_{\mathrm{lg}t} \le M \sum_{c} LG_{\mathrm{lg}tc} \quad \forall t,\mathrm{l},\mathrm{g} \tag{50}$$

$$QLM_{lmt} \le M \sum_{c} LM_{lmtc} \quad \forall t,\mathrm{l},\mathrm{m} \tag{51}$$

$$QHM_{hmt} \le M \sum_{c} HM_{hmtc} \quad \forall t,\mathrm{h},\mathrm{m} \tag{52}$$

$$QHG_{hgt} \leq M \sum_{c} HG_{hgtc} \quad \forall t, \mathrm{h}, \mathrm{g} \tag{53}$$

$$QGM_{gmt} \leq M \sum_{c} GM_{gmtc} \quad \forall t, \mathrm{g}, \mathrm{m} \tag{54}$$

$$QGI_{git} \leq M \sum_{c} GI_{gitc} \quad \forall t, \mathrm{g}, \mathrm{i} \tag{55}$$

$$QGV_{gvt} \leq M \sum_{c} GV_{gvtc} \quad \forall t, \mathrm{g}, \mathrm{v} \tag{56}$$

$$QKH_{kht} \leq M \sum_{c} KH_{khtc} \quad \forall t, \mathrm{k}, \mathrm{h} \tag{57}$$

$$\begin{gathered} X_{it}, EX_{int}, Y_{jt}, EY_{jnt}, Z_{lt}, EZ_{\ln t}, U_{mt}, EU_{mnt}, Q_{gt}, EQ_{gnt}, W_{ht}, EW_{hnt}, IJ_{ijtc}, JK_{jktc}, KL_{kltc}, HK_{hktc}, \\ IH_{ihtc}, LG_{\lg tc}, LM_{lmtc}, HM_{hmtc}, HG_{hgtc}, GM_{gmtc}, GI_{gitc}, GV_{gvtc}, KH_{khtc} \quad \in \{0,1\} \quad \forall i, j, k, l, h, g, m, \mathrm{v}, n, \mathrm{c}, \mathrm{t} \end{gathered} \tag{58}$$

$$\begin{gathered} QIJ_{ijt}, QJK_{jkt}, QIH_{iht}, QHK_{hkt}, QKL_{klt}, QKH_{kht}, QLG_{\lg t}, QLM_{lmt}, QHM_{hmt}, QHG_{hgt} \\ , QGM_{gmt}, QGI_{git}, QGV_{gvt} \quad \geq 0 \quad \forall i, j, k, l, h, g, m, v, t \end{gathered} \tag{59}$$

Constraints 4 – 6 ensure flow equilibrium within the related nodes to the forward flow path, while constraints 7 – 13 ensure flow equilibrium within those along the reverse flow path. For the purpose of this paper, flow equilibrium shall mean the state of equality between the sum of products received and dispatched by a particular node. Constraints 14 – 19 define the capacity limitations within different centers. Once opened, each center can operate at its initial capacity only, unless a capacity expansion process is undertaken for that center. Constraints 20 – 25 ensure that a capacity expansion can solely be realized for the centers established in the corresponding period. Constraints 26 – 31 introduce impossibility of a capacity reduction to occur in capacity-expanded facilities, i.e. once capacity of a facility is expanded in a given period of time, it cannot be either reduced or returned back to the initial capacity within the same period of time. Constraints 32 – 44 prove that there is only one transportation mode between each pair of nodes during each period of time. Constraints 45 – 57 ensure that no product can be transported between a pair of nodes unless a transportation mode is chosen. And finally, constraints 58 and 59 imply that the variables shall be non-negative and binary, respectively.

4. Model validation and solution approach

In this research, in order to solve small to medium-sized problems, an optimization software called GAMS v.24.2.2 was used without configuring a particular algorithm. The results obtained with this software were used as reference to compare other solution methods and algorithms. All case studies were processed on a laptop powered by an Intel® Core™ 2 Dou CPU operating at 2.4 GHz and further equipped with 4 GB of RAM.

Two important issues were dealt when utilizing GAMS software, namely the value of M (an adequately large number) as well as the choice of the solver. Due to non-linear nature of the mathematical model, BARON solver was employed to solve the illustrative problems. Furthermore, in order to investigate the sensitivity of this solver to the value of M, a set of experiments were designed and their results were analyzed. According to the analyses, the minimum value of M before the problem turns infeasible or unjustified is the maximum value of total demands during different periods. Following this approach, the variable ranges were limited to contract the solution space for the solver, so as to accelerate the process of finding the optimum solution.

Introducing various local techniques for the analysis of supply chain networks, Krarup and Pruzan (1983) investigated the issues associated with the behavior of such techniques for large problems [52], and proved that the SCND problems are NP-Hard. Therefore, for each mathematical model developed for such problems, there is a need to present an appropriate algorithm fitted to the problem structure. In order to prove that the processing time increases with the problem size, several purposive cases were designed with different sizes and then solved by GAMS software. Table 1 reports the obtained processing times. The table makes it clear that an increase in the number of periods adds to the processing time dramatically.

In Table 1, the first 4-digit part of the code indicates, from left to right, the number of manufacturing centers, the number of distribution centers, the number of hybrid collection-distribution centers, and the number of customers, respectively. The second 4-digit part shows, again from left to right, the number of collecting centers, the number of recycling centers, the number of disposal centers, and the number of external customers, respectively. Finally, the third part denotes, from left to right, the number of capacity levels, the number of transportation modes between two related nodes, and the number of programming periods. It is worth mentioning that the parameters in the designed illustrative cases were all set randomly.

4.1. Solving approach

Genetic algorithm is among the widely used algorithms for solving NP-hard problems. It is applicable for problems with large feasible spaces. Furthermore, it is particularly helpful for complex problems where the influences of constraints and parameters are unknown. This method enjoys lower probability of getting trapped in local optimum, as compared to similar techniques. GA’s capability to reach near-optimum solutions has increased its application in large problems. It is a nature-inspired and population-based method with the capability to cope with the problems of the especial structure considered in this research because of its ability to find near optimum solutions and its flexibility to solve a wide range of problems. That is why this algorithm was selected from a pool of various solving approaches. Furthermore, new chromosomes were proposed here to encode the problem. GA has been previously used to solve reverse logistics problems by some researchers, e.g. Min and Ko (2008), Lee and Chan (2009), Trappey *et al.* (2010) and Fakhrzad and Moobed (2010) [39-42]. Accordingly, genetic algorithm was used to solve the problem in this research.

4.2. Algorithm components

Components of the algorithm used in this study are described in this sub-section.

4.2.1. Initiator operator and solution demonstration

In this research common methods in transportation problems were used to present the solution. The number of products transported from manufacturers to customers are organized into a matrix. As mentioned in previously, there is no direct transportation between manufacturers and customers and the matrix just shows the origin of the received products. Another feature of the model was the time periods. For each time period two matrices were used, one for forward logistics and one for reverse logistics. In terms of capacities, if sum of demands in one period exceeds facilities capacities, the capacity increases until the entire deal of demand is addressed.

For each period, the number of products shipped from the manufacturing centers to the customers is expressed in terms of a transportation matrix shown below, so that each period corresponds to a transportation matrix. Transportation matrices can be seen as chromosomes in this algorithm. In other words, the solution of each period can be seen as two transportation matrices, one for the forward flow path and one for the reverse one.

$$X_p = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

(Rows and columns represent the manufacturing centers and customers, respectively)
The following pseudo-code was used to form the above matrix:

1. Form a set, T, including the set of numbers from 1 to mn.
2. Randomly choose a number, k, from the set T.
3. Using the following relationship, extract the row number and column number corresponding to k:

$$\text{Row number } (i) = \left[\left((k-1)\ /n\right) + 1\right]$$
$$\text{Column number } (j) = \left((k-1)\ /mod\ n\right) + 1$$

4. Choose the minimum value across the production values in the ith row and the demand in the jth column, and name it x_{ij}.
5. Subtract x_{ij} from the production in the ith row and the demand in the jth column.
6. Eliminate k from the set T.
7. Repeat the process until all members in T are eliminated.

Once the above matrix was formed, in order to determine the volume of products shipped to customers, each x_{ij} value was randomly decomposed into two parts: the volume of products sent to the distribution centers and that to hybrid distribution-collection centers. Following with the process of chromosome formation, one may find how much volume of products should be redistributed among the facilities along the reverse flow to get to a complete solution after applying the rate of product return by customers. Once the rate of product recycling was applied in collection and hybrid centers and the number of pushed products toward the recycling and disposal centers was obtained (similar to what was done before), the transportation matrix was randomly allocated between two nodes; finally, volumes of the products sent to recycling centers, manufacturers, and external customers were determined via the same approach.

4.2.2. Crossover operator

The following pseudo-code was used to apply the crossover operator once the parents (matrices) were selected as $X_1 = (x^1_{ij})$ and $X_2 = (x^2_{ij})$.

1. Use the following method to define the matrices $D = (d_{ij})$ and $R = (r_{ij})$.

$$d_{ij} = [(x_{ij}^{\ 1} + x_{ij}^{\ 2})/2] \qquad\qquad r_{ij} = (x_{ij}^{\ 1} + x_{ij}^{\ 2})mod\ \ 2$$

2. Divide the matrix R into two matrices of $R_1 = (r^1_{ij})$ and $R_2 = (r^2_{ij})$:

$$R = R_1 + R_2$$
$$\sum_{j=1}^{n} r_{ij}^1 = \sum_{j=1}^{n} r_{ij}^2 = \frac{1}{2}\sum_{j=1}^{n} r_{ij} \quad i = 1, 2, \ldots, m$$
$$\sum_{i=1}^{m} r_{ij}^1 = \sum_{i=1}^{m} r_{ij}^2 = \frac{1}{2}\sum_{i=1}^{m} r_{ij} \quad j = 1, 2, \ldots, n$$

3. Form the offsprings X_1' and X_2' as follows.

$$X_1' = D + R_1 \qquad\qquad X_2' = D + R_2$$

4.2.3. Mutation operator

In order to apply this operator when a transportation matrix is selected, first, a number of rows and columns were randomly selected within the matrix. In the developed sub-matrix, the existing values were manipulated in such a way that the sum of values within each row and column remains unchanged. For instance, assume the following matrix to be subjected to the mutation operator:

Parent X

0	0	5	0	3
0	4	0	0	0
0	0	5	7	0
3	1	0	0	2

Suppose that the 2nd and 4th rows as well as the 2nd, 3rd, and 5th columns are selected randomly; this sub-matrix can be manipulated as follows to meet the mentioned condition:

The selected matrix

4	0	0
1	0	2

The manipulated matric

2	0	2
3	0	0

Consequently, the following offspring will be resulted from the mutation operator:

Offspring

0	0	5	0	3
0	2	0	0	2
0	0	5	7	0
2	3	0	0	0

4.2.4. Fitness function

Fitness function is exactly the same as the problem's objective function; i.e. to maximize the overall profit generated along the chan. This function calculates the incurred costs and gained income along the chain and returns fitness value for each chromosome. Being a maximization function, there was no need to modify the objective function.

4.2.5. Selection mechanisms

Two mechanisms were employed to perform the selection task in the proposed algorithm: the roulette wheel and tournament mechanisms. The designed algorithm was configured in such a way that for each round of selection, 50% of the parents were selected by roulette wheel mechanism while the other 50% were selected according to the tournament approach.

4.2.6. Termination criterion

For the considered algorithm in this research, the termination criterion was set as reaching a limited number of iterations and generation number.

4.3. Setting the GA parameters

In order to set the parameters of the genetic algorithm, a sample problem was designed and then solved using the considered algorithm in MATLAB software. In the next step, for each parameter within the GA, a set of predefined discrete values (reported in the following table) were assumed and the problem was solved. Figure 2 investigates the contributions of crossover parameter variations into the objective function value when other parameters are kept unchanged. As is observed, the objective function is maximal when the crossover parameter takes a value of 0.8. Further, Figure 3 depicts the contribution of variations in the crossover parameter at another level of mutation parameter; and finally, Figure 4 considers the contributions of mutation parameter variations into the objective function value when other parameters are kept unchanged.

The proposed genetic algorithm encompasses five operating parameters. Considering the number and levels of parameters at which each parameter is to be analyzed, one may conclude that it is impossible to consider the contributions of variations in each and any parameter as well as interactions between the parameters. Therefore, using the principles of the design of experiments, instead of performing each and every experimental effort, only 80 tests were considered (including single and coupled ones) to see the effect of such variations on the fitness function. Reported in Table 2 are the GA parameters, the number of investigated levels, and the values obtained.

4.4. Generating cases studies and setting the parameters

Most of the problems used for numerical tests investigated in the literatures on SCND have been randomly generated. Accordingly, in this research, problem data was randomly generated using uniform distribution in certain domains. Considering the number of parameters in the model, no comprehensive reference could be found for benchmarking the parameters, so some of the parameters were generated randomly. Therefore, the parameters were generated with reference to Olivares-Benitez *et al.* (2010) as a valid reference [31]. Furthermore, the problem size was assessed based on two criteria: number of periods, and programming number for each problem (Table 3).

For each problem, the programming number is equal to the sum of indices, i.e. the sum of digits in the corresponding group code which can be calculated via the following formula:

$$PN = i + j + h + k + l + g + m + v + n + c + t$$

In Table 4, full details of the problem can be observed. Also the information regarding the exact mathematical solution of GAMS software is presented in this table.

Presumably, an increase in time period of the problem adds to the problem complexity and processing time, and the number of recycling centers affects the complexity of the problem. The designed numerical examples were used to analyze these assumptions. Each problem was designated by a two-digit number, with the first digit from left indicating the number of periods in the problem and the other digit reflecting the number of problems within the corresponding period. Regarding the problem type, an attempt was made to incorporate as much combinations as possible within each period. Average processing times for the two-period and three-period problems were found to be 136 and 2863 seconds, respectively. As expected, the processing time increased by 21 folds when the value of T was changed from 2 to 3. Comparing the processing times obtained for problems 3.1 and 3.4, one can easily find that processing time became doubled when the value of m index (number of recycling centers) changed from 1 to 2. These two comparisons reveal the effect of the parameter T on the sample problem processing time. Furthermore, this table may confirm the performance of the introduced sizing criterion for the sample problems.

In problem 3.1, the processing time was 7200 seconds; i.e. the GAMS was not able to solve the problem in 2 hours and the reported objective value is merely the best integer solution found after 2 hour of running the software. This problem number shows that, in particular numerical examples, especially large ones, the software cannot solve the problem within acceptable time, so that alternative approaches are needed.

Following with the research, some sample problems were solved with genetic algorithm. To do this, first of all, parameters of each exactly solved problem were fitted into the structure of metaheuristic algorithm, so as to establish the same conditions. Subsequently, the sample problems were tested in both GAMS (as the exact solution) and MATLAB (as the heuristic solution). In order to reduce randomness effect of the solving algorithm and prevent it from getting trapped within poor solutions, each sample was five-times launched in MATLAB and the obtained results were averaged before being reported as the final result. Table 5 reports the information of each sample.

The processing times were reported in seconds. Table 6 represents a summary of the above table together with analytical results. Shown in this table are the average values for each sample problem, standard deviation within the results obtained for each sample, and the gap between the average solution and exact solution for each sample. The gap was calculated by dividing the difference between the exact and approximate solution by the exact one. Taking a quick look on this table, one may find that the gap values were generally lower for two-period problems rather than the three-period ones. Considering the gap values for the two-period and three-period problems, it is observed that the value of gap slightly increases by just 2% when the parameter T changes from 2 to 3. This is while, as mentioned before, such a change in parameter T increased the processing time by about 2100% (21 order of magnitudes). Hence, this obvious difference between (2% vs. 2100%) is well justifiable and affordable; indeed, it confirms the significant effect of the proposed metaheuristic algorithm.

A comparison between the results of the proposed algorithm and GAMS reveals that the algorithm found better solutions within reasonable time, while GAMS failed to find the optimum solution in some cases. Also, longer processing times were obtained with GAMS rather than GA. Figures 5 and 6 reveal that GA outperforms GAMS.

Considering all comparisons along with Figures 5 and 6, it can be suggested that advantages offered by the proposed GA for the mathematical model formulated in this research dominate its disadvantages, proving effectiveness of the algorithm, so that it can be used to solve not only two-period and three-period problems, but also problems of higher programming periods. It is worth mentioning that, based on the criteria set by the decision-makers as well as the nature of the logistic network, different measurement units can be used to measure a period.

In Figures 5 and 6, the results and processing times were compared between exact and GA algorithm outputs. The results confirm the superior performance of the proposed algorithm, so that the presented GA provided an efficient approach to the solution of the introduced problem.

Analyzing the algorithm robustness, results of different runs of the algorithm are presented at Table 7.

The results show that, in the worst case (i.e. problem number 2.4), standard deviation to average output ratio was 2.1%, while average ratio for all cases was a s low as 1.1%, indicating robustness of the proposed algorithm.

5. Conclusion and recommendations

Today, organizations need to design integrated distribution-collection networks because of various reasons imposed by governments, society and competitors. Multi-period programming, multi-echelon structure and other design variables must be appropriately taken into consideration before an applicable and close to reality model can be achieved. Furthermore, multi-period programming enhances the level of flexibility. Every transpiration network needs to use different transportation modes, and the resent research considered the choice of transportation mode in various programming periods. Designing such network entails more efforts from the researchers.

Considering these needs, this research started with proposing a mathematical model under several reasonable assumptions taken from the real world. Applicability of the proposed problem and validity of the mathematical model were analyzed by solving the problem in GAMS software. Solution structure and complexity of the mathematical model were further studied, concluding that the mathematical model, especially medium and large-sized cases, was practically impossible to solve via exact approaches as it took extremely long time to be solved. Accordingly, there is a need for a solving algorithm with the capability of returning correct, rational, well-fitted, reliable solutions at an accepted time scale. Studying different solution approaches and the structure of the mathematical models and with the help of available resources and references, metaheuristic genetic algorithm was found to be a proper approach for solving the research problem. GA was designed and coded in MATLAB software. Finally, comparing the results obtained via exact approach and the metaheuristic algorithm outputs, the metaheuristic algorithm was found to be an effective and efficient approach to solve the problem.

In order to enhance supply chain efficiency, a logistics manager should consider various parameters when forming a logistics network. In order to meet particular regulations, reuse products, or decrease wastes, some supply chains need reverse logistics; this paper provides the logistics managers with a proper tool for such supply chains. The results validated the model and performance of the proposed algorithm.

Based on the investigations and studies performed so far and considering the demands arisen in real world, the following recommendations can be proposed for extending the mathematical model and getting it as close to the real world as possible. (1) Considering the idea of multi-objectivity within the model, i.e. interactions among such objectives as maximization of system responsiveness, minimization of negative environmental effects and delivery time, etc., can provide subjects for future research works. (2) Investigation of the uncertainties associated with such parameters as customer demands within different periods, transportation costs, and volume of returned products may be performed in future studies. (3) Performance of other metaheuristic algorithms such as TS and SA in this context can be compared to those of GA in order to further validate it.

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Table 1. Results of solving the illustrative cases

Problem		**Processing time (seconds)**	**Objective function value**	**Problem**		**Processing time (seconds)**	**Objective function value**
Number of periods	**Group code**			**Number of periods**	**Group code**		
T=1	2112-2222-121	2	193246	T=3	2112-2222-123	3220	735079
	2212-2223-121	6	187956		2113-2223-123	323	1629623
T=2	2112-2222-122	70	489659	T=4	2112-2222-124	14400	933059
	3112-2222-222	158	484262				

Table 2. Different levels of GA parameters

Parameter	**Number of levels**	**Value**
Maximum number of iterations	10	400
Population size	10	60
Crossover rate	9	0.8
Mutation rate	9	0.4
Tournament selection size	5	4

Table 3. Sample problem size assessment

Size	**Problem**		**Size**	**Problem**	
	Number of periods	**Programming number**		**Number of periods**	**Programming number**
Small	1	any number	Large	2	greater than or equal 18
Medium	2	lower than 18	Large	3	any number

Table 4. Solutions of two-period and three-period sample problems, as obtained by GAMS software

Example number	**Group code**	**Solve time**	**Objective function value**	**Example number**	**Group code**	**Solve time**	**Objective function value**
3.1	2113-1221-123	7200	556462	2.1	2113-1221-122	74	1179640
3.2	1113-1221-123	950	520647	2.2	3113-1221-122	133	1057865
3.3	2113-1121-123	2157	726932	2.3	3113-1231-122	282	691155
3.4	2113-1211-123	3850	916650	2.4	3113-1331-122	86	386833
3.5	1113-1111-123	160	1022315	2.5	3212-1331-122	105	538735
Average solution time for three-period case		2863		Average solution time for two-period case		136	

Table 5. Values of objective function and processing times for sample problems used with the solving algorithm

instance	**Iteration number**	**1**	**2**	**3**	**4**	**5**	**instance**	**Iteration number**	**1**	**2**	**3**	**4**	**5**
3.1	Solution	475375	476684	487625	489297	488839	2.1	Solution	934420	930074	950265	944300	948471
	Time	182	311	232	252	211		Time	19	16	17	24	18
3.2	Solution	441857	451536	450551	439688	446045	2.2	Solution	920390	924900	914044	937830	918110
	Time	201	179	175	185	197		Time	18	19	18	18	21
3.3	Solution	649945	653505	644582	654642	646721	2.3	Solution	621060	631960	616550	609310	624950
	Time	173	194	245	188	189		Time	19	19	16	20	20
3.4	Solution	765027	791046	762100	787237	781247	2.4	Solution	328980	336650	340090	345040	322150
	Time	173	213	175	263	214		Time	19	21	18	22	18
3.5	Solution	793794	771966	805189	805266	799156	2.5	Solution	510835	502625	520040	503920	511390
	Time	176	183	182	185	222		Time	18	22	18	20	19

Table 6. A comparison between the results of exact and metaheuristic solutions

Instance number	**GAMS output**	**Average of MATLAB outputs**	**Standard deviation of MATLAB outputs**	**MATLAB and GAMS outputs gap**	**Average gap (%)**
3.1	556462	483564	6027	13.10	15/09
3.2	520647	445935	4130	14.34	
3.3	726932	649879	3382	10.59	
3.4	916650	777331	11014	15.19	
3.5	1022315	795074	9755	22.22	
2.1	1179640	941506	7407	20.18	12/40
2.2	1057865	923054	6648	12.74	
2.3	691155	620766	6268	10.18	
2.4	386833	334582	7213	13.50	
2.5	538735	509762	5191	5.37	
					Average total gap
					13.74

Table 7. Results of robustness analysis on the proposed metaheuristic algorithm

Example number	**Minimum value**	**Maximum value**	**Average output**	**Standard deviation**	**Standard deviation to average output ratio (%)**
3.1	475375	489297	483564	6027	1.2%
3.2	439688	451536	445935	4130	0.9%
3.3	646721	654642	649879	3382	0.5%
3.4	765027	791046	777331	11014	1.4%
3.5	771966	805266	795074	9755	1.2%
2.1	930074	950265	941506	7407	0.7%
2.2	918110	937830	923054	6648	0.7%
2.3	609310	631960	620766	6268	1%
2.4	322150	345040	334582	7213	2.1%
2.5	520040	511390	509762	5191	1%

Average	**1.1%**

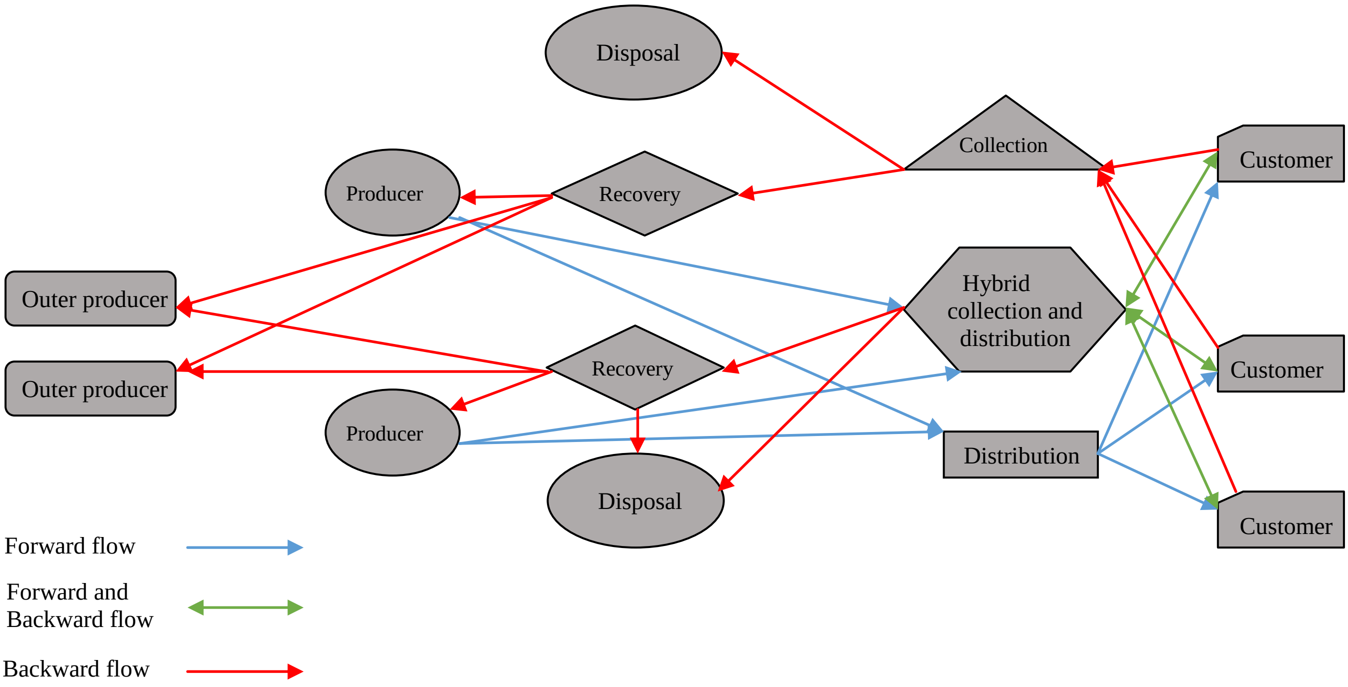

Figure 1. Product distribution and collection diagram

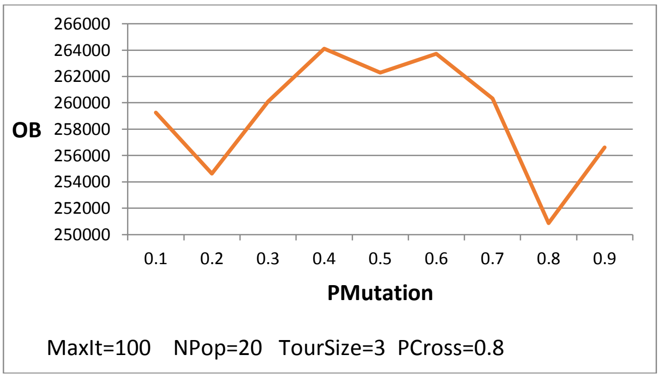

Figure 2. Plot of variations in mutation parameter (1)

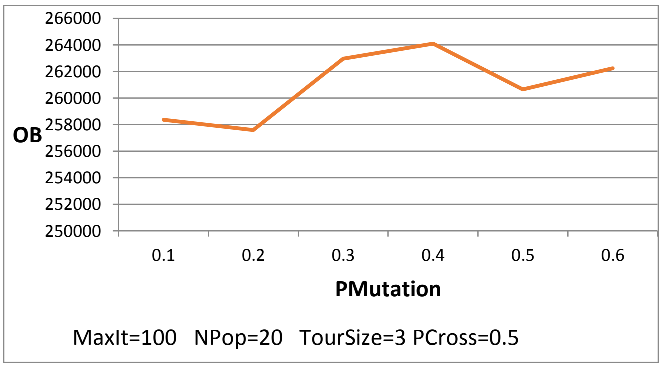

Figure 3. Plot of variations in mutation parameter (2)

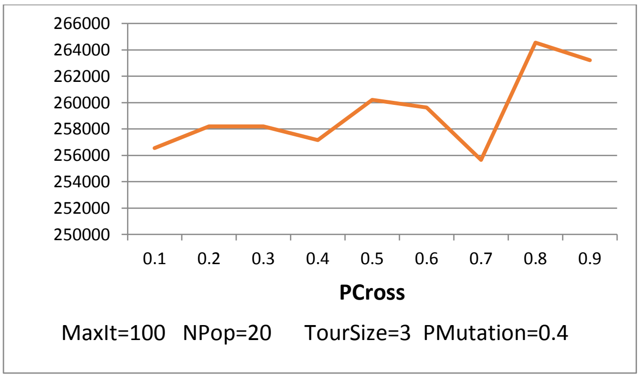

Figure 4. Plot of variations in crossover parameter

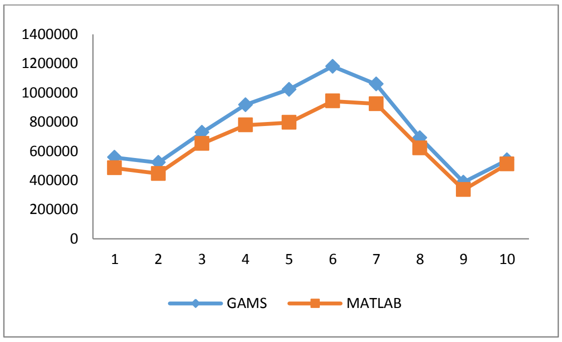

Figure 5. Curve of comparison of the objective function between the exact and metaheuristic solutions

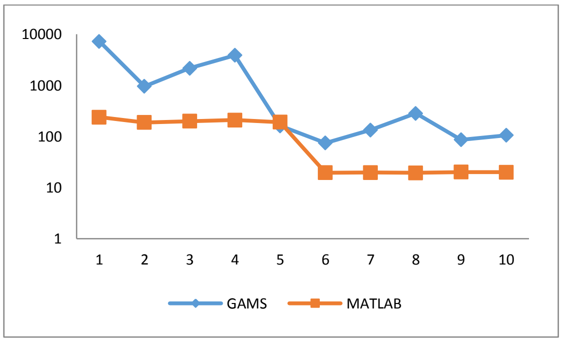

Figure 6. Logarithmic curve of comparison of the processing time between the exact and metaheuristic solutions

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