Green supply chain network design considering inventory-location-routing problem: a fuzzy solution approach

Sobhgol Gholipour

Department of Computer Engineering,
Sharif University of Technology,
Tehran, Iran
Email: Sggholipour52@gmail.com

Amir Ashoftehfard

Department of Industrial Engineering,
College of Engineering,
Islamic Azad University,
Shiraz Branch, Shiraz, Iran
Email: amirashoftehfard@yahoo.com

Hassan Mina*

School of Industrial Engineering,
College of Engineering,
University of Tehran,
Tehran, Iran
Email: hassan.mina@ut.ac.ir
*Corresponding author

Abstract: The growing rate of population and technological advancement have led to an increase in natural resource consumption, which has caused irreparable damage to the environment. The implementation of green supply chain management is one of the most effective ways to deal with environmental degradation. Therefore, in this paper, a bi-objective mixed integer linear programming model is developed to design a green supply chain network. In the proposed model, the possibility of customer storage, being faced with shortage, locating of distribution centres, green vehicle routing problem, split delivery, multi-depot vehicle routing problem (VRP), capacitated VRP, and uncertainty in demands will be considered. The aim of the proposed model is to minimise the total cost and total shortages simultaneously and, therefore, a fuzzy solution approach is applied for this purpose. The results of implementing this model in a production chain of automotive parts in Iran indicate the exact and efficient performance of the proposed model.

Keywords: green supply chain management; mathematical programming; location-routing problem; fuzzy theory.

Reference to this paper should be made as follows: Gholipour, S., Ashoftehfard, A. and Mina, H. (2020) 'Green supply chain network design considering inventory-location-routing problem: a fuzzy solution approach', *Int. J. Logistics Systems and Management*, Vol. 35, No. 4, pp.436–452.

Biographical notes: Sobhgol Gholipour graduated from the School of Computer Engineering, Sharif University of Technology. She received her Bachelor's in Computer Engineering from the University of Isfahan. Her research interests include heuristic and meta-heuristic methods and optimisation methods.

Amir Ashoftehfard is a Master's student of Industrial Engineering, Department of Industrial Engineering, College of Engineering, Islamic Azad University, Shiraz Branch. Formerly, he was an undergraduate student of Industrial Engineering – System Analysis and Planning in the Islamic Azad University Shiraz Branch in Bachelor's degree. As a student in Master's study, his main research interests are focused on supply chain management and optimisation.

Hassan Mina graduated from the School of Industrial and Systems Engineering at University of Tehran. Formerly, he was an undergraduate student of Industrial Engineering-Industrial Production at the Isfahan University of Technology. As a top student in Master's study, his main research interests are focused on operations research, scheduling, supplier selection, green supply chain and multi-criteria decision-making. He also has published some notable papers in those areas in international and domestic journals as well as conference proceedings.

1 Introduction

Nowadays in competitive economic environment, organisations need strategic and operational decisions for optimising and managing their logistic processes more efficiently (Bafrooei et al., 2014; Mina et al., 2014; Moharamkhani et al., 2017). Design of vehicle routes is one of the most important operational decision because it reduces the costs and improves the service quality (Koç and Karaoglan, 2016; Qazvini et al., 2016). The problem of designing optimal routes from one or more depots to some customers considering several side constraints is referred as vehicle routing problem (VRP) (Qazvini et al., 2016). The vehicles that are dispatched from a depot deliver the required goods to the customers and then return to the depot. Each vehicle carries just a limited amount of goods and may also be restricted in the total travelled distance (Baker and Ayechew, 2003). As a first record in the literature of VRP, Dantzig et al. (1954) studied a relatively large scale generalisation of travelling salesman problem (TSP) and proposed a solution method. Since then, a number of variants have been studied in the literature of VRP by the researchers. For example, we may mention to the capacitated VRP (CVRP) in which the customers have a demand for a good and the vehicles have finite capacity. For detailed information refer to review paper provided by Eksioglu et al. (2009), Laporte (2009) and Pillac et al. (2013).

The location routing problem (LRP) is a relatively new field within location analysis with the key property of paying special attention to underlying issues of VRP (Hassanzadeh et al., 2009). LRP aims to solve a facility location and VRPs, simultaneously (Vincent et al., 2010). It is worth to mentioning that, traditionally, these two problems have been taken into account separately. In the past decades, the LRP has advanced and produced a large number of attentions by the researchers. Generally, LRP can be categorised into un-capacitated LRP and capacitated LRP. At the beginning, most of the researches on this field have assumed un-capacitated depots. However, especially in recent years, capacity constraints on depots and vehicles have been considered by some researches such as Barreto et al. (2007). For more information about different types of LRP refer to a comprehensive review paper presented by Prodhon and Prins (2014). The application of LRP has been discussed in many fields such as the distribution of food and beverages, waste collection, newspaper delivery and so on. For example, Lin et al. (2002) studied monthly bill delivery services of a telecommunication service company in Hong Kong as an application of LRP models. See also a survey provided by Nagy and Salhi (2007) for more detailed information about various applications of LRP.

The focus in classical VRP and LRP is only minimising the total distance travelled by all vehicles. However, in recent years in addition to the conventional economic goals, some environmental, ecological and social effects have been taken into account when logistics policies are being designed. Green VRP (GVRP) takes into account both environmental and economic costs by implementing effective routes to meet the environmental concerns and financial indexes (Lin et al., 2014). As a new study in this field, Koç and Karaoglan (2016) extended a simulated annealing heuristic-based exact solution approach to solve the GVRP. GVRP has been noticed by many researches such as Ćirović et al. (2014), Felipe et al. (2014), Montoya et al. (2016), Yin and Chuang (2016) and Soysal et al. (2018). Interested readers are referred to the survey by Lin et al. (2014) for more information about GVRP.

In this paper, a new mixed integer linear programming model to design a green supply chain network considering LRP is proposed. The proposed model takes into account fuel consumption of vehicles, storage, shortage, limited capacity of facilities, multi-depot VRP, split delivery simultaneously. Under uncertainty case, a fuzzy approach is utilised to solve the proposed model. In the following, the problem definition and proposed model are introduced in the Section 2. The Section 3 is dedicated to the implementation of the proposed model in the real world. Next section is allocated to sensitivity analysis and the final section is dealt with the conclusion section.

2 Problem statement and proposed model

Considering the high proportion of distribution costs to the total of supply chain costs, the design of an appropriate logistics system is very important. Two essential elements in distribution systems are attention to the locating and routing problem where the former appears at the strategic level and the latter emerges at the operational level. Therefore, in this paper, a three-echelon supply chain, including supply, distribution, and customer levels has been developed. The proposed model is a bi-objectives model whose primary purpose is to minimise costs, including transport costs, storage costs, supply costs, and location costs; and the secondary purpose is to minimise the total shortages. In this paper, by providing optimal policies, the amount of pollution caused by vehicles is controlled and programmed in the form of costs. In this regard, the criterion of vehicular fuel consumption is used to minimise the pollutant level in the transportation process of the said supply chain. Considering the storage assumption, the vital role of supply chain management in the system under optimisation will be specified more than ever. The final aim of this paper is to provide some policies in order to integrate the constituent processes of building the said supply chain, including supply, distribution, and demand for the sake of achieving the lowest cost and shortage simultaneously. The assumptions of the proposed model are presented below:

2.1 Assumptions

- The desired supply chain in this paper includes levels of supply, distribution and customer.
- The proposed supply chain has been considered as a multi-product and multi-period one.
- The locating of the distribution centres and the selection of supplier are accomplished by the model.
- Suppliers, distribution centres, and vehicles are considered as being capacitated.
- Vehicles will be considered heterogeneous.
- Determination of the number of required vehicles is accomplished by the model.
- The length of time required to pass a specific route by different vehicles has been considered different.
- There is the possibility of storage at the customer level.
- The VRP is among the distribution and demand levels.
- The routing problem is considered as multi-depot.
- The possibility of split delivery has been considered in the model.
- Demand has been considered to be fuzzy.
- There is the possibility of encountering a shortage in the model.

2.2 Mathematical model

Indices

i	Product	$1 \le i \le I$
s	Supplier	$1 \le s \le S$
d	Distribution centres	$1 \le d \le D$
$c, \hat{c}$	Customer	$1 \le c \le C$
v	Vehicle	$1 \le v \le V$
t	Time period	$1 \le t \le T$

Parameters

$cap_{ist}^{\sup}$	Capacity of supplier s for product i in time period t
cap_{idt}^{dist}	Capacity of distribution centre d for product i in time period t

cap_v^{veh}	Capacity of vehicle v
f_{isd}	Maximum flow of transferring product i from supplier s to distribution centre d
dis_{cc}^{cus}	Location distance of customer c from customer $\hat{c}$
$tm_{v\hat{c}c}^{cus}$	Time distance of customer c from customer $\hat{c}$ by vehicle v
dis_{dc}	Location distance of distribution centre d from customer c
tm_{vdc}	Time distance of distribution centre d from customer c by vehicle v
$cost_d^{dist}$	The cost of setting up distribution centre d
$cost_v^{veh}$	The cost of purchasing vehicle v
$cost_{isdt}^{trans}$	The cost of transferring each product unit i from supplier s to distribution centre d in time period t
dem_{ict}	The demand of customer c for product i in time period t
$hold_{it}$	The cost of holding each product unit i in time period t
ψ_v	Rate of fuel consumption per distance unit by vehicle v
$price_{ist}$	The price of purchasing per product unit i from supplier s in time period t
o_{st}	The cost of ordering to supplier s in time period t
c^{fuel}	The price of each unit of fuel
bigm~∞	Big number

Variables

$y_d \begin{cases} 1 \\ 0 \end{cases}$	Binary	If distribution centre d is set up Otherwise
$z_v^{veh} \begin{cases} 1 \\ 0 \end{cases}$	Binary	If vehicle v is purchased Otherwise
$\lambda_{v\hat{c}ct} \begin{cases} 1 \\ 0 \end{cases}$	Binary	If vehicle v travels from customer $\hat{c}$ to customer c in time period t Otherwise
$\beta_{vdt} \begin{cases} 1 \\ 0 \end{cases}$	Binary	If vehicle v is allocated to distribution centre d in time period t Otherwise
$\eta_{isdt} \begin{cases} 1 \\ 0 \end{cases}$	Binary	If distribution centre d purchases product i from supplier s in time period t Otherwise
at_{vct}	Positive	Arrival time of vehicle v to customer c in time period t

$inv_{ict}^{positive}$	Positive	The amount of product *i* in the warehouse of customer *c* in time period *t*
$inv_{ict}^{negative}$	Positive	The shortage of product *i* for customer *c* in time period *t*
inv_{vct}	Free	Inventory
X_{ivdct}	Positive	The amount of product *i* transferred from distribution centre *d* to customer *c* by vehicle *v* in time period *t*
α_{isdt}	Positive	The amount of product *i* purchased from supplier *s* by distribution centre *d* in time period *t*
Transportation cost	Positive	Transportation cost
Storage cost	Positive	Storage cost
Supply cost	Positive	Supply cost
Location cost	Positive	Location cost

Objective function

$$Min\, z^{Cost} = Transportation\, Cost + Storage\, Cost + Supply\, Cost + Location\, Cost$$

$$Min\, z^{shortage} = \sum_{i,c,t} inv_{ict}^{negative}$$

Subjected to:

$$Transportation\, Cost = c^{fuel} \times \left(\begin{array}{l} \sum_{v,\hat{c},c,t} \psi_v \times \lambda_{v\hat{c}ct} \times dis_{\hat{c}c}^{cus} + \sum_{v,d,c} \psi_v \\ \times \left(\lambda_{v1ct} + \lambda_{vc1t} \right) \times \beta_{vdt} \times dis_{dc} \end{array} \right) + \sum_{i,s,d,t} \alpha_{isdt} \times Cost_{isdt}^{trans} + \sum_{v} z_v^{veh} \times Cost_v^{veh} \tag{1}$$

$$Storage\, Cost = \sum_{i,c,t} hold_{it} \times inv_{ict}^{positive} \tag{2}$$

$$Supply\, Cost = \sum_{i,s,d,t} price_{ist} \times \eta_{isdt} \times \alpha_{isdt} + \sum_{i,s,d,t} o_{st} \times \eta_{isdt} \tag{3}$$

$$Location\, Cost = \sum_{d} cost_d^{dist} \times y_d \tag{4}$$

$$\sum_{d} \alpha_{isdt} \le cap_{ist}^{\sup} \qquad \forall i, s, t \tag{5}$$

$$\sum_{s,d} \alpha_{isdt} \le \sum_{s,d} f_{isd} \qquad \forall i, t \tag{6}$$

$$\sum_{s} \alpha_{isdt} \le cap_{idt}^{dist} \qquad \forall i, d, t \tag{7}$$

$$\sum_{i,c} x_{ivdct} \le cap_v^{veh} \times z_v^{veh} \qquad \forall v, d, t \tag{8}$$

$$\sum_{s} \alpha_{isdt} \geq \sum_{v,c} x_{ivdct} \times \beta_{vdt} \qquad \forall i, d, t \tag{9}$$

$$\sum_{i,d,c} x_{ivdct} \leq bigm \times \sum_{d} \beta_{vdt} \qquad \forall v, t \tag{10}$$

$$\sum_{d} \beta_{vdt} \leq 1 \qquad \forall v, t \tag{11}$$

$$\sum_{\hat{c}} \lambda_{v\hat{c}ct} \leq 1 \qquad \forall v, c, t \tag{12}$$

$$\sum_{\hat{c}} \lambda_{v\hat{c}ct} = \sum_{\hat{c}} \lambda_{vc\hat{c}t} \qquad \forall c, t \tag{13}$$

$$at_{vct} \geq \sum_{\hat{c}} \left(at_{v\hat{c}t} + tm_{v\hat{c}c}^{cus} \right) \times \lambda_{v\hat{c}ct} \qquad \forall c > 1, v \tag{14}$$

$$at_{vct} \geq \sum_{d} tm_{vdc} \times \beta_{vdt} \times \lambda_{vc1t} \qquad \forall v, c, t \tag{15}$$

$$\sum_{i,d} x_{ivdct} \leq bigm \times \sum_{\hat{c}} \lambda_{v\hat{c}ct} \qquad \forall v, c, t \tag{16}$$

$$\sum_{i,d,c} x_{ivdct} \leq bigm \times z_{v}^{veh} \qquad \forall v, t \tag{17}$$

$$inv_{ict} = inv_{ic(t-1)} + \sum_{v,d} x_{ivdct} - dem_{ict} \qquad \forall i, c, t > 1 \tag{18}$$

$$inv_{ic1} = \sum_{v,d} x_{ivdc1} - dem_{ic1} \qquad \forall i, c \tag{19}$$

$$inv_{ict} = inv_{ict}^{positive} - inv_{ict}^{negative} \qquad \forall i, c \tag{20}$$

The purposes of proposing the above model are as follows:

- The first objective function aims to minimise total costs.
- The second objective function aims to minimise the total shortages.

The cost of transportation (fuel consumption of vehicles and the cost of supplying vehicles), the cost of maintaining the goods and products in the customer's warehouse, the cost of supplying the products, and the cost of establishing the distribution centre are presented in constraints (1) to (4), respectively.

The amount of goods transferred from the supplier to the distribution centres not exceeding the supplier's capacity, not exceeding the flow rate transferred from the supplier to the crossover warehouses, and not exceeding the capacity of the distribution centres are shown in constraints (5) to (7), respectively.

Constraint (8) states that the amount of products carried by each vehicle should not exceed its capacity.

The total amount of products transferred from suppliers to the centres in each period should not be less than the amount of products transferred from the centres to customers, which has been included in constraint (9).

According to constraint (10), the condition for the delivery of products to customers by a vehicle is that the vehicle be allocated to a distribution centre. Based on constraint (11), each vehicle is allocated at most to one distribution centre. The possibility of a client visit is possible at most by one vehicle, which is shown in constraint (12).

Based on constraint (13), if we enter a customer's location, we must leave it.

Sub-tour elimination constraint and calculation of the arrival time at each customer's location are presented in constraints 14 and 15.

The condition for the delivery of the product to customers is that the vehicle should visit the customer and the vehicle has been purchased, which have been presented in constraints (16) and (17), respectively.

Constraints (18) and (19) pertain to inventory balances in customers' warehouses.

Finally, the determination of the warehouse inventory and being faced with a shortage have been shown in constraint (20).

2.3 Linearisation process

Although the proposed model is nonlinear, but it is convertible to linear model using the following auxiliary variables. For this purpose, first the nonlinear expression is expressed and then the linear equivalent is given.

$\lambda\beta_{vd\hat{c}ct} \begin{cases} 1 \\ 0 \end{cases}$	Binary
$at\lambda_{v\hat{c}ct}$	Positive
$\eta\alpha_{isdt}$	Positive
βx_{ivdct}	Positive

Nonlinear expression

$$Transportation\,Cost = c^{fuel} \times \begin{pmatrix} \sum_{v,\hat{c},c} \psi_v \times \lambda_{v\hat{c}ct} \times dis_{\hat{c}c}^{cus} + \sum_{v,d,c} \psi_v \\ \times \left(\lambda_{v1ct} + \lambda_{vc1t}\right) \times \beta_{vd} \times dis_{dc} \end{pmatrix} + \sum_{i,s,d,t} \alpha_{isdt} \times cost_{isdt}^{trans} + \sum_{v} z_v^{veh} \times cost_v^{veh} \tag{1}$$

Linear equivalent

$$Transportation\,Cost = c^{fuel} \times \begin{pmatrix} \sum_{v,\hat{c},c} \psi_v \times \lambda_{v\hat{c}ct} \times dis_{\hat{c}c}^{cus} + \sum_{v,d,c} \psi_v \\ \times \left(\lambda\beta_{vd1ct} + \lambda\beta_{vdc1t}\right) \times dis_{dc} \end{pmatrix} + \sum_{i,s,d,t} \alpha_{isdt} \times cost_{isdt}^{trans} + \sum_{v} z_v^{veh} \times cost_v^{veh} \tag{21}$$

$$\lambda\beta_{vd\hat{c}ct} \le \beta_{vdt} + \left(1 - \lambda_{v\hat{c}ct}\right) \times bigm \tag{22}$$

$$\lambda\beta_{vd\hat{c}ct} \le \lambda_{v\hat{c}ct} + \left(1 - \beta_{vdt}\right) \times bigm \tag{23}$$

$$\lambda\beta_{vd\hat{c}ct} \ge 1 + \left(\lambda_{v\hat{c}ct} + \beta_{vdt} - 2\right) \times bigm \tag{24}$$

$$\lambda\beta_{vd\hat{c}ct} \le \left(\lambda_{v\hat{c}ct} + \beta_{vdt}\right) \times bigm \tag{25}$$

Nonlinear expression

$$Supply\,Cost = \sum_{i,s,d,t} price_{ist} \times \eta_{isdt} \times \alpha_{isdt} + \sum_{i,s,d,t} o_{st} \times \eta_{isdt} \tag{3}$$

Linear equivalent

$$Supply\,Cost = \sum_{i,s,d,t} price_{ist} \times \eta\alpha_{isdt} + \sum_{i,s,d,t} o_{st} \times \eta_{isdt} \tag{26}$$

$$\eta\alpha_{isdt} \ge \alpha_{isdt} - \left(1 - \eta_{isdt}\right) \times bigm \tag{27}$$

$$\eta\alpha_{isdt} \le \alpha_{isdt} \tag{28}$$

$$\eta\alpha_{isdt} \le bigm \times \eta_{isdt} \tag{29}$$

Nonlinear expression

$$\sum_{s} \alpha_{isdt} \ge \sum_{v,c} x_{ivdct} \times \beta_{vdt} \quad \forall i, d, t \tag{9}$$

Linear equivalent

$$\sum_{s} \alpha_{isdt} \ge \sum_{v,c} \beta x_{ivdct} \quad \forall i, d, t \tag{30}$$

$$\beta x_{ivdct} \ge x_{ivdct} - \left(1 - \beta_{vdt}\right) \times bigm \tag{31}$$

$$\beta x_{ivdct} \le x_{ivdct} \tag{32}$$

$$\beta x_{ivdct} \le bigm \times \beta_{vdt} \tag{33}$$

Nonlinear expression

$$at_{vct} \ge \sum_{\hat{c}} \left(at_{v\hat{c}t} + tm^{cus}_{v\hat{c}c}\right) \times \lambda_{v\hat{c}ct} \tag{14}$$

Linear equivalent

$$at_{vct} \ge \sum_{\hat{c}} \left(at\lambda_{v\hat{c}ct} + tm^{cus}_{v\hat{c}c} \times \lambda_{v\hat{c}ct}\right) \tag{34}$$

$$at\lambda_{v\hat{c}ct} \ge at_{v\hat{c}t} - \left(1 - \lambda_{v\hat{c}ct}\right) \times bigm \tag{35}$$

$$at\lambda_{v\hat{c}ct} \le at_{v\hat{c}t} \tag{36}$$

$$at\lambda_{v\hat{c}ct} \le bigm \times \lambda_{v\hat{c}ct} \tag{37}$$

Nonlinear expression

$$at_{vct} \ge \sum_{d} tm_{vdc} \times \beta_{vdt} \times \lambda_{vc1t} \tag{14}$$

Linear equivalent

$$at_{vct} \ge \sum_{d} tm_{vdc} \times \lambda\beta_{vdc1t} \tag{38}$$

3 Case study

In this section, the validation of the proposed model will be followed by its implementation in an automotive parts distribution company in Iran. To this end, the data pertaining to four products, three potential distribution centres, six customers, two time periods, six vehicles, and four suppliers will be used. Table 1 shows each customer's demand for each product at any time period.

Table 1 Each customer's demand values

dem_{ict}		$t = 1$	$t = 2$
$i = 1$	$c = 1$	0	0
$i = 1$	$c = 2$	90	99
$i = 1$	$c = 3$	100	110
$i = 1$	$c = 4$	60	66
$i = 1$	$c = 5$	60	66
$i = 1$	$c = 6$	80	88
$i = 2$	$c = 1$	0	0
$i = 2$	$c = 2$	80	88
$i = 2$	$c = 3$	80	88
$i = 2$	$c = 4$	80	88
$i = 2$	$c = 5$	90	99
$i = 2$	$c = 6$	70	77
$i = 3$	$c = 1$	0	0
$i = 3$	$c = 2$	80	88
$i = 3$	$c = 3$	90	99
$i = 3$	$c = 4$	70	77
$i = 3$	$c = 5$	70	77
$i = 3$	$c = 6$	70	77
$i = 4$	$c = 1$	0	0
$i = 4$	$c = 2$	100	110
$i = 4$	$c = 3$	110	121
$i = 4$	$c = 4$	90	99
$i = 4$	$c = 5$	105	115
$i = 4$	$c = 6$	80	88

For solving fuzzy problems, an approach based on Zimmermann (1978) and Lin (2012) is presented as follows:

$$
\begin{aligned}
& Max\,\xi \\
& Subject\,to: \\
& \xi \le \mu_{z_k^{\min}}(x) \\
& \xi \le \mu_{z_r^{\max}}(x) \\
& \xi \le \mu_{g_l}(x)
\end{aligned}
$$

These membership functions are defined as follows:

$$\mu_{Z_k^{\min}}(x) = \begin{cases} 1 & z_k(x) > z_k^{positive} \\ 0 & z_k(x) < z_k^{negative} \\ f_{\mu_{Z_k^{\min}}} = \dfrac{z_k^{positive} - z_k(x)}{z_k^{positive} - z_k^{negative}}, & z_k^{negative} \le z_k(x) \le z_k^{positive} \end{cases}$$

$$\mu_{Z_l^{\max}}(x) = \begin{cases} 1 & z_l(x) > z_l^{positive} \\ 0 & z_l(x) < z_l^{negative} \\ f_{Z_l^{\max}} = \dfrac{z_l(x) - z_l^{negative}}{z_l^{positive} - z_l^{negative}}, & z_l^{negative} \le z_l(x) \le z_l^{positive} \end{cases}$$

$$\mu_{g_l}(x) = \begin{cases} 1 & g_l(x) > b_l \\ 0 & g_l(x) < b_l + d_l \\ f_{Z_l^{\max}} = \dfrac{1 - [g_l(x) - b_l]}{d_l}, & b_l \le g_l(x) \le b_l + d_l \end{cases}$$

where the objective function z_k (z_l) value changes from lower bound $z_k^{negative}$ ($z_l^{negative}$) to upper bound $z_k^{positive}$ ($z_l^{positive}$); $\mu_{z_k^{\min}}(x)$, $\mu_{z_r^{\min}}(x)$ and $\mu_{g_l}(x)$ represents the membership functions of maximum, minimum, and constraints, respectively and d_l is the tolerance value.

After the determination of the upper and lower bound values and the substitution of $d_l = 10\%$, we will have:

$$\mu_{z^{\cos t}} = \frac{937{,}743{,}500 - z^{\cos t}}{937{,}743{,}500}$$

$$\mu_{z^{shortage}} = \frac{3{,}475 - z^{shortage}}{3{,}475}$$

$$\mu_{z_{dem}}^{+} = \frac{1.1 \times dem_{ict} - \sum_{v,d} x_{ivdct} + inv_{ict} - inv_{ic(t-1)}}{0.1 \times dem_{ict}}$$

$$\mu_{z_{dem}}^{-} = \frac{\sum_{v,d} x_{ivdct} - inv_{ict} - 0.9 \times dem_{ict} + inv_{ic(t-1)}}{0.1 \times dem_{ict}}$$

The previous bi-objective mathematical model will be changed as follows by considering the fuzzy membership function and demand uncertainty:

The output obtained from the model implementation is presented below. The time taken for solving the model by GAMS24.1/Cplex software has been 245.79 seconds.

Table 2 Values of the objective functions

ξ	z^{cost}	$z^{shortage}$
0.634	343,615,700	604

Only, distribution centre 3 has been established ($y_3 = 1$).

The vehicles numbered 1, 3, 4, and 5 have been purchased.

The routes travelled by the vehicles numbered 1, 3, 4, and 5 have been shown below by using $\lambda_{v\hat{c}c}$:

- For the first time period:

$$v=1 \quad (\hat{c} \to c): c_1 \to c_4 \to c_3 \to c_2 \to c_5 \to c_6 \to c_1$$
$$v=3 \quad (\hat{c} \to c): c_1 \to c_6 \to c_4 \to c_3 \to c_2 \to c_5 \to c_1$$
$$v=4 \quad (\hat{c} \to c): c_1 \to c_4 \to c_6 \to c_2 \to c_3 \to c_5 \to c_1$$
$$v=5 \quad (\hat{c} \to c): c_1 \to c_3 \to c_6 \to c_5 \to c_2 \to c_4 \to c_1$$

- For the second time period:

$$v=1 \quad (\hat{c} \to c): c_1 \to c_6 \to c_5 \to c_3 \to c_4 \to c_2 \to c_1$$
$$v=3 \quad (\hat{c} \to c): c_1 \to c_4 \to c_5 \to c_3 \to c_2 \to c_6 \to c_1$$
$$v=4 \quad (\hat{c} \to c): c_1 \to c_3 \to c_6 \to c_5 \to c_2 \to c_4 \to c_1$$
$$v=5 \quad (\hat{c} \to c): c_1 \to c_6 \to c_4 \to c_2 \to c_3 \to c_5 \to c_1$$

Another variable pertains to the allocation of each vehicle to the distribution centre where all vehicles (1, 3, 4, and 5) in both periods of time have been allocated to the third distribution centre (β_{vd}):

$$\beta_{1,3,1} = \beta_{3,3,1} = \beta_{4,3,1} = \beta_{5,3,1} = 1$$
$$\beta_{1,3,2} = \beta_{3,3,2} = \beta_{4,3,2} = \beta_{5,3,2} = 1$$

Variable η_{isdt} has been used to determine the relationship between suppliers and distribution centres for the dispatch of products, as shown below:

$$\eta_{1,4,3,1} = \eta_{1,4,3,2} = \eta_{2,3,3,1} = \eta_{2,4,3,2} = \eta_{3,4,3,1} = \eta_{3,4,3,2} = \eta_{4,4,3,1} = 1$$

As it has been shown, all the products are purchased only from suppliers 3 and 4.

The amount of each product purchased from each supplier by each crossover inventory at each price level (α_{isdt}) is given below:

$$\eta_{1,4,3,1} = 390$$
$$\eta_{1,4,3,2} = 429$$
$$\eta_{2,3,3,1} = 400$$
$$\eta_{2,4,3,2} = 369$$
$$\eta_{3,4,3,1} = 380$$
$$\eta_{3,4,3,2} = 418$$
$$\eta_{4,4,3,1} = 485$$

The amount of product transferred from each crossover inventory (x_{ivdct}) to each customer by each vehicle is given below:

$x_{1,1,3,3,1} = 25$ $x_{1,4,3,2,2} = 99$ $x_{1,4,3,3,1} = 75$ $x_{1,4,3,4,2} = 66$
$x_{1,4,3,5,1} = 60$ $x_{1,4,3,6,1} = 80$ $x_{1,5,3,2,1} = 90$ $x_{1,5,3,3,2} = 110$
$x_{1,5,3,4,1} = 60$ $x_{1,5,3,5,2} = 66$ $x_{1,5,3,6,2} = 88$ $x_{2,1,3,4,2} = 88$
$x_{2,3,3,3,1} = 30$ $x_{2,3,3,3,2} = 88$ $x_{2,3,3,5,2} = 99$ $x_{2,3,3,6,2} = 77$
$x_{2,4,3,2,1} = 80$ $x_{2,4,3,3,1} = 50$ $x_{2,5,3,2,2} = 17$ $x_{2,5,3,4,1} = 80$
$x_{2,5,3,5,1} = 90$ $x_{2,5,3,6,1} = 70$ $x_{3,1,3,2,2} = 36$ $x_{3,1,3,3,2} = 99$
$x_{3,1,3,4,1} = 70$ $x_{3,1,3,5,2} = 77$ $x_{3,3,3,2,1} = 80$ $x_{3,3,3,4,2} = 77$
$x_{3,3,3,5,1} = 70$ $x_{3,3,3,6,1} = 70$ $x_{3,3,3,6,2} = 77$ $x_{3,5,3,2,2} = 52$
$x_{3,5,3,3,1} = 90$ $x_{4,1,3,2,1} = 100$ $x_{4,1,3,5,1} = 105$ $x_{4,3,3,3,1} = 110$
$x_{4,3,3,4,1} = 90$ $x_{4,4,3,6,1} = 80$

Finally, the costs presented in detail as follows:

$$Transportation\ Cost = 219,070,000$$
$$Storage\ Cost = 0$$
$$Supply\ Cost = 68,547,000$$
$$Location\ Cost = 56,000,000$$

As it is observed, a significant portion of costs, i.e., about 64% is related to transportation costs, which indicates its high importance. Therefore, the locating-routing problem is directly related to these costs. In this research, these costs were properly managed through optimal routing.

4 Sensitivity analysis

To validate the proposed model, we assess the model sensitivity through two categories of scenarios. To this end, we examine to what extent our expectations of the model are consistent with the obtained results by applying each scenario. The first category of the scenarios is based on demand reduction and the second category is based on demand increase.

4.1 Demand reduction scenario

In this section, some scenarios are formed based on demand reduction. It is expected that costs will be reduced (the value of the objective function does not deteriorate) and the amount of shortages will be minimised (the value of the objective function does not deteriorate) as the demands are reduced. Demand reduction scenarios and the results obtained from its implementation are presented in Table 3.

As it can be observed, the results of the model are in accordance with our expectation of the performance of the proposed model. For the presentation of a clearer explanation of Table 3, the process of changing each objective function is presented in Figures 1 and 2.

Table 3 The results of the sensitivity analysis of demand reduction

Scenario no.	*Demand rate*	z^{cost}	$z^{shortage}$
1	0.7 × *Demand*	272,660,000	453
2	0.75 × *Demand*	285,239,000	514
3	0.8 × *Demand*	291,758,000	532
4	0.85 × *Demand*	305,168,100	546
5	0.9 × *Demand*	320,233,100	570
6	0.95 × *Demand*	328,760,000	590

Figure 1 Results of sensitivity analysis of demand reduction for the cost objective function (see online version for colours)

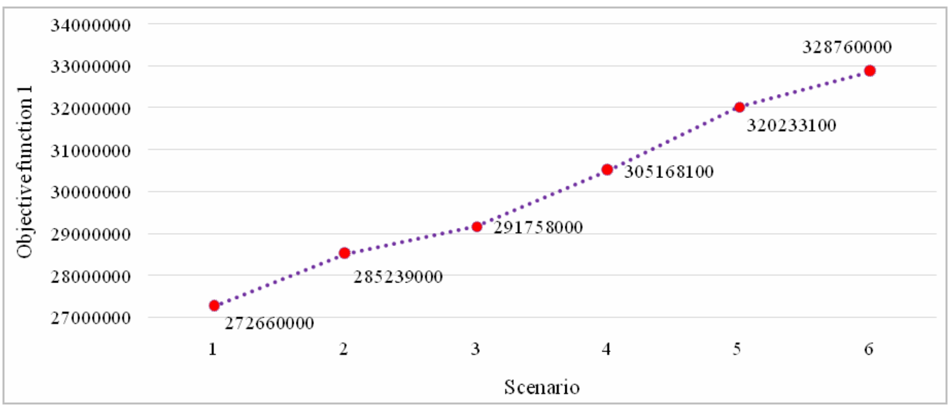
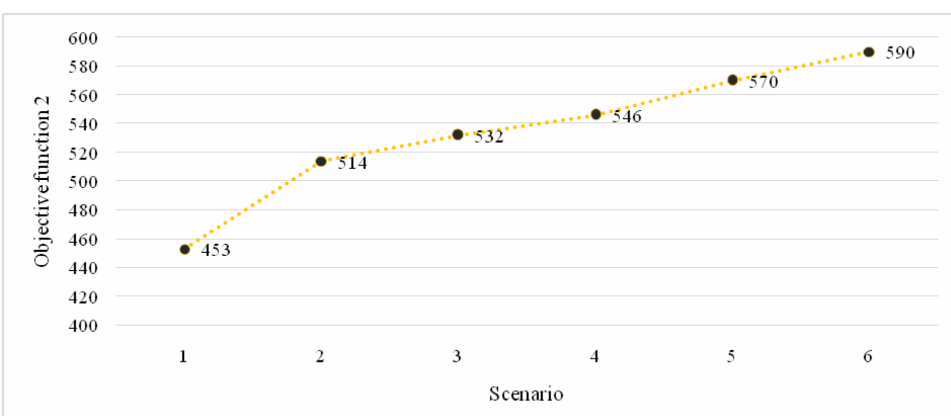


Figure 2 Results of sensitivity analysis of demand reduction for the shortage objective function (see online version for colours)



4.2 Demand increase scenario

Based on our expectations of the model in this section, it is desired that the results will be obtained contrary to demand reduction when the demand increase scenario is dominant. Therefore, the results of this implementation are presented in Table 4 and Figures 3 and 4.

Figure 3 Results of sensitivity analysis of demand increase for the cost objective function (see online version for colours)

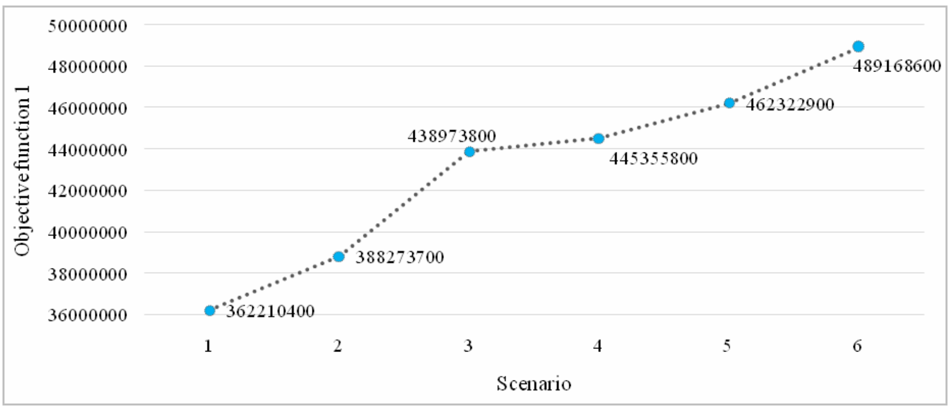
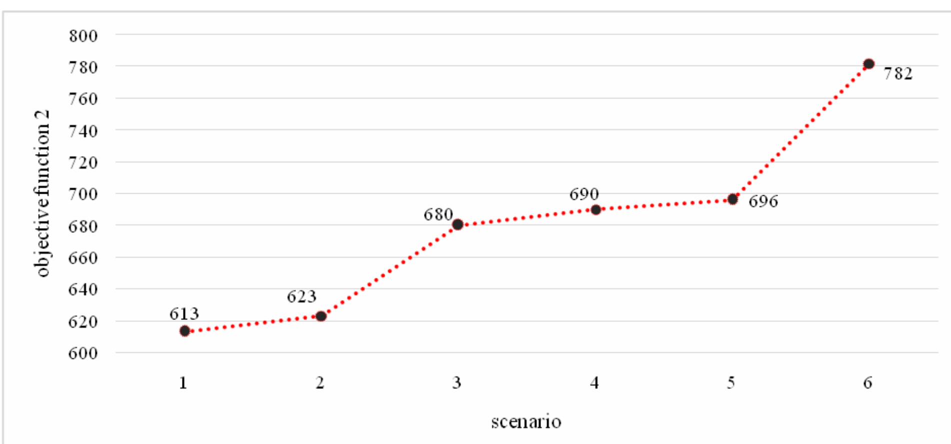


Figure 4 Results of sensitivity analysis of demand increase for the shortage objective function (see online version for colours)



Based on the results obtained from the sensitivity analysis of the model through demand reduction and increase scenarios, it was shown that the results have been in line with our rational expectations of the model. Therefore, it is possible to guarantee the validity of the proposed model and its results using the two proposed scenarios and the obtained results.

Table 4 Results of sensitivity analysis of demand increase

Scenario no.	*Demand rate*	z^{cost}	$z^{shortage}$
1	1.05 × *Demand*	362,210,400	613
2	1.1 × *Demand*	388,273,700	623
3	1.15 × *Demand*	438,973,800	680
4	1.2 × *Demand*	445,355,800	690
5	1.25 × *Demand*	462,322,900	696
6	1.3 × *Demand*	489,168,600	782

5 Conclusions

In this paper, a bi-objective mixed integer linear programming model was developed for designing a green supply chain network under uncertainty. The proposed model simultaneously considers cost minimisation and shortage encounter and it uses a fuzzy approach to take demand uncertainty into consideration and to make the proposed model a single-objective one. Consideration of warehouse for customers, the possibility to encounter shortages, capacity constraint for distribution centres and vehicles, split delivery, multi-depot VRP, inventory-location-routing problem, and heterogeneity of vehicles are among the assumptions given in the proposed mode. It is also noteworthy that the data of a distribution chain of vehicle parts has been used to validate the proposed model whose results indicate the accuracy and validity of the proposed model. Since the proposed model is included in NP-hard problems, as a future research, it is suggested to use a meta-heuristic algorithm to solve the problem in large scale and evaluate the validity of the proposed algorithm in small and medium dimensions by exact solution software.

References

Bafrooei, A.A., Mina, H. and Ghaderi, S.F. (2014) 'A supplier selection problem in petrochemical industry using common weight data envelopment analysis with qualitative criteria', *International Journal of Industrial and Systems Engineering*, Vol. 18, No. 3, pp.404–417.

Baker, B.M. and Ayechew, M.A. (2003) 'A genetic algorithm for the vehicle routing problem', *Computers & Operations Research*, Vol. 30, No. 5, pp.787–800.

Barreto, S., Ferreira, C., Paixao, J. and Santos, B.S. (2007) 'Using clustering analysis in a capacitated location-routing problem', *European Journal of Operational Research*, Vol. 179, No. 3, pp.968–977.

Ćirović, G., Pamučar, D. and Božanić, D. (2014) 'Green logistic vehicle routing problem: routing light delivery vehicles in urban areas using a neuro-fuzzy model', *Expert Systems with Applications*, Vol. 41, No. 9, pp.4245–4258.

Dantzig, G., Fulkerson, R. and Johnson, S. (1954) 'Solution of a large-scale traveling-salesman problem', *Journal of the Operations Research Society of America*, Vol. 2, No. 4, pp.393–410.

Eksioglu, B., Vural, A.V. and Reisman, A. (2009) 'The vehicle routing problem: a taxonomic review', *Computers & Industrial Engineering*, Vol. 57, No. 4, pp.1472–1483.

Felipe, Á., Ortuño, M.T., Righini, G. and Tirado, G. (2014) 'A heuristic approach for the green vehicle routing problem with multiple technologies and partial recharges', *Transportation Research Part E: Logistics and Transportation Review*, Vol. 71, No. 1, pp.111–128.

Hassanzadeh, A., Mohseninezhad, L., Tirdad, A., Dadgostari, F. and Zolfagharinia, H. (2009) 'Location-routing problem', in *Facility Location*, pp.395–417, Physica, Heidelberg.

Koç, Ç. and Karaoglan, I. (2016) 'The green vehicle routing problem: a heuristic based exact solution approach', *Applied Soft Computing*, Vol. 39, No. 1, pp.154–164.

Laporte, G. (2009) 'Fifty years of vehicle routing', *Transportation Science*, Vol. 43, No. 4, pp.408–416.

Lin, C., Choy, K.L., Ho, G.T., Chung, S.H. and Lam, H.Y. (2014) 'Survey of green vehicle routing problem: past and future trends', *Expert Systems with Applications*, Vol. 41, No. 4, pp.1118–1138.

Lin, C.K.Y., Chow, C.K. and Chen, A. (2002) 'A location-routing-loading problem for bill delivery services', *Computers & Industrial Engineering*, Vol. 43, Nos. 1–2, pp.5–25.

Lin, R.H. (2012) 'An integrated model for supplier selection under a fuzzy situation', *International Journal of Production Economics*, Vol. 138, No. 1, pp.55–61.

Mina, H., Mirabedin, S.N. and Pakzad-Moghadam, S.H. (2014) 'An integrated fuzzy analytic network process approach for green supplier selection: a case study of petrochemical industry', *Management Science and Practice*, Vol. 2, No. 2, pp.31–47.

Moharamkhani, A., Bozorgi-Amiri, A. and Mina, H. (2017) 'Supply chain performance measurement using SCOR model based on interval-valued fuzzy TOPSIS', *International Journal of Logistics Systems and Management*, Vol. 27, No. 1, pp.115–132.

Montoya, A., Guéret, C., Mendoza, J.E. and Villegas, J.G. (2016) 'A multi-space sampling heuristic for the green vehicle routing problem', *Transportation Research Part C: Emerging Technologies*, Vol. 70, No. 1, pp.113–128.

Nagy, G. and Salhi, S. (2007) 'Location-routing: Issues, models and methods', *European Journal of Operational Research*, Vol. 177, No. 2, pp.649–672.

Pillac, V., Gendreau, M., Guéret, C. and Medaglia, A.L. (2013) 'A review of dynamic vehicle routing problems', *European Journal of Operational Research*, Vol. 225, No. 1, pp.1–11.

Prodhon, C. and Prins, C. (2014) 'A survey of recent research on location-routing problems', *European Journal of Operational Research*, Vol. 238, No. 1, pp.1–17.

Qazvini, Z.E., Amalnick, M.S. and Mina, H. (2016) 'A green multi-depot location routing model with split-delivery and time window', *International Journal of Management Concepts and Philosophy*, Vol. 9, No. 4, pp.271–282.

Soysal, M., Bloemhof-Ruwaard, J.M., Haijema, R. and van der Vorst, J.G. (2018) 'Modeling a green inventory routing problem for perishable products with horizontal collaboration', *Computers & Operations Research*, Vol. 89, No. 1, pp.168–182.

Vincent, F.Y., Lin, S.W., Lee, W. and Ting, C.J. (2010) 'A simulated annealing heuristic for the capacitated location routing problem', *Computers & Industrial Engineering*, Vol. 58, No. 2, pp.288–299.

Yin, P.Y. and Chuang, Y.L. (2016) 'Adaptive memory artificial bee colony algorithm for green vehicle routing with cross-docking', *Applied Mathematical Modelling*, Vol. 40, Nos. 21–22, pp.9302–9315.

Zimmermann, H.J. (1978) 'Fuzzy programming and linear programming with several objective functions', *Fuzzy Sets and Systems*, Vol. 1, No. 1, pp.45–55.