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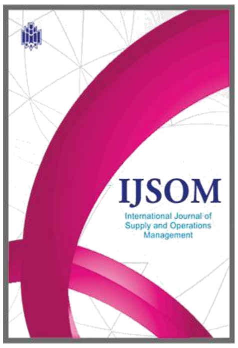

Four Echelons Humanitarian Network Design Considering Capacitated /lateral Transshipment with a Destruction Radius and ABO Compatibility: Tehran Earthquake

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Abstract
During natural disasters, emergency sections try to find the best way to serve defective points and gradually find the optimal location of these service points as blood collection centers in safe areas to restore the system to its previous state. This research proposed a multi-objective mathematical model for the design of a four echelon comprehensive Blood Supply Chain (BSC) network in earthquakes. Here, the impact of the Earthquake Destruction Radius (EDR) on the BSC network and blood group compatibility have been considered simultaneously .In order to be more realistic the effect of multimodal capacitated transportation vehicles accompanied with lateral transshipment have been investigated. In our proposed model four multi-objective decision-making (MODM) methods, as well as the augmented ε-constraint method is adopted for finding Pareto optimal solutions. Finally, the validation of the problem has been explored by Bounded Objective Method (BOM). This model has been implemented based on the real data of Tehran; the capital of Iran; as one of the volunteer cities for tremendous earthquake in the world.

Keywords: Humanitarian network; Destruction radius; Multi-Objective; ABO compatibility; Lateral transshipment; Multiple utilities.

1. Introduction

Blood is one of the most crucial perishable substances in nature, which is closely related to the lives of humans. One of the most important reasons for blood and blood products is its human origin which cannot be artificially produced. In other words, an industrial method for its production has not been invented yet, and there is no chemical alternative to blood. Blood received from donors is called "whole blood". After collecting blood from the donor, it is converted into various products during processes that are based on mechanical separation and centrifugal separation, and then the produced products are used to inject patients who need the blood. The management of blood is a specific problem for the human strain. Until now, the need for blood donation, unlike other replaceable resources, has always existed (Beliën and Forcé 2012). The major challenge in supply chain management is the shortage and wastage of blood products due to the nature of the perishability of blood.This problem would be so vital when supplying procedure disrupted due to several natural disasters such as flood, earthquake, etc. Natural disasters such as earthquakes, volcanoes, tsunamis, and storms, have a substantial effect on human life. Among these, the earthquake is one of the most common and devastating disasters. In the previous century, earthquakes have led to many damages, destruction, and loss of life of many human beings around the world. So the most critical challenge that occurs at the time of the earthquake is providing medical assistance, including blood products to the injured and fast return to the previous state of the system (Kuruppu et al.

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2010). Today, the two vast research fields that are taken into consideration are healthcare operations management and disaster management. With increasing natural disasters, this issue has turn into a challenge for researchers to improve integrated planning decision models in these fields to reduce the amount of damage resulting from natural disasters. In this regard, efficient supply chain planning and management of healthcare-related activities under disaster conditions can reduce a human loss (Samani et al. 2018). Management of the BSC in critical situations (floods, earthquakes, terrorist attacks, etc.) is essential. Disruptions in facilities and services, the destruction of communication channels between suppliers and hospitals, and the sudden increase in demand for blood products during a disaster are among the issues of relevance to the research. As mentioned, an intense earthquake can become a sudden rise in blood demand, so scheming an efficient supply chain in emergencies is essential (Samani et al. 2018). Designing an efficient BSC needs many strategic and operational decisions such as the location of the blood collection facilities, transportation types and capacities for the collected blood from collection centers to distribution centers and just then to hospitals or demand centers (Jabbarzadeh et al. 2014). Blood substitution is one of the most critical problems that should be considered in all BSC planning decisions. The main point is that blood with a similar group type should be transfused to the earthquake refugees. A compatible blood group can be used in emergency situations when the original type does not exist (Duan and Liao 2014). Here in this study, designing an integrated four echelon BSC considering the earthquake destruction radius and ABO compatibility and lateral transshipment have been illustrated. The ABO compatibility matrix is presented in Table 1. Besides the effect of EDR, in times of disaster, the country is in critical condition, and both cost and time play an essential role in this disaster. As a result, lateral transshipments between demand areas are one of the approaches not discussed in the most of previous issue, which has a positive impact on the cost and time of hospitals' accessibility to the blood. Based on the BSC network design by Khalilpourazari and Khamseh (2017). This paper proposed the destruction radius of the earthquake as well as different transportation modes with diverse capacity, cost, speed and lateral transshipments. Finally, our proposed model based on the disaster parameters, could find realistic optimal solutions based on bounded capacity of distribution centers and ABO compatibility.

Table 1. ABO compatibility matrix

	Recipient							
Donor	O-	O+	A-	A+	B-	B+	AB-	AB+
O-	*	*	*	*	*	*	*	*
O+		*		*		*		*
A-			*	*			*	*
A+				*				*
B-					*	*	*	*
B+						*		*
AB-							*	*
AB+								*

The rest of this paper is structured as follows: Section 2 represents a systematic review of the related literature. In Section 3, problem definition and mathematical model formulation are presented. The solution methodology, including decision-making methods as well as the eps-constraint method utilized for finding Pareto optimal solutions, are provided in Section 4. Section 5 is assigned to the implementation of the suggested model and methods on a real case study. Section 6 demonstrated the validity of the model, Section 7 presents the results of the sensitivity analyses, and finally, Section 8 represents the discussion of results and implications.

2. Literature Review

Creating a well-organized supply chain in disaster conditions needs many strategic and operational decisions, for example the location of blood collection facilities, blood transfusion collected from collection centers to main centers, and just then to hospitals or demand centers. In this section we review some research on BSC design. Sha and Huang (2012) presented the multi-period Location-allocation model for emergency blood systems. They have proposed the heuristic algorithm based on "Lagrangian Relaxation". At the end, they rendered a case study in the context of Beijing. Their model searches for the location and assignment decisions, over a given planning horizon, that cause the minimization of the total operating costs. In another survey Jabbarzadeh et al. (2014) suggested a dynamic BSC network design for the supply of blood in disasters. They formulate a robust optimization model for designing an emergency BSC resilient to different disaster situations. Their proposed model determine the BSC network decisions under each situation that minimizes the total supply chain cost. Duan and Liao (2014) focused on the BSC in the normal situation in two stages of supply and distribution. The goal of the problem is inventory management of blood with the minimizing shortage and wastage, which has been solved by metaheuristic methods; ABO compatibility was considered for substitution as well. A single-echelon BSC was proposed by Abdulwahab and Wahab (2014), they considered the issue as a multi-product problem with eight blood groups. The aim of their dynamic programming model is to minimize blood shortages and wastages. Hsieh et al. (2014) presented a supply chain model for supply and distribution that attempts to locate, allocate, and manage inventory with two goals, minimizing the costs and maximizing the satisfaction. They used the genetic search algorithm to solve the problem. Elalof et al. (2015) presented a BSC in a normal condition. They used an exact dynamic programming algorithm that determined the quantity and location of facilities. Their primary purpose is to maximize the benefits of the network. In another research, Gunpinar and Centeno (2015) studied inventory management at the distribution level, which aims to reduce costs in the supply chain. This problem has been solved using the Branch and Bound method in CPLEX software. Zahiri and Pishvaee (2017) suggested a BSC network design, as blood group compatibility; their model minimizes the total cost along with maximizing unsatisfied demand. They proposed a robust possibilistic technique to handle the uncertainty in parameters and finally used real data from a case study in Iran to investigate the model performance. Jabbarzadeh et al. (2017), developing the previous work, provided a bi-objective stochastic model to enterprise an emergency BSC resilient to different disaster situations and considered hospitals as demand zones. The first objective minimizes the total supply chain costs when the second objective minimizes the average delivery time from collection facilities to hospitals. In this field, Salehi et al. (2017) offered a robust two-stage multi-period stochastic model for the BSC network design in disaster. The novel contribution of their model was considering the possibility of transfusion of one blood type along with its derivatives to other types based on the medical necessities. Khalilpourazari and Khamseh (2017) proposed a bi-objective mathematical model to design a BSC network in earthquakes. For the first time, they considered the impact of the earthquake magnitude on the destruction of BSC. Hosseinifard et al. (2018) studied the significance of inventory centralization impacts on BSC sustainability. They found that centralization inventory can increase the resilience and durability of the network. Hamdan and Diabat (2019) suggested a multi-objective programming formulation for BSC management. Their suggested model aims to minimize the total costs, delivery time, and the number of outdated simultaneously. Recently, Motlagh et al. (2019) developed a bi-objective two-stage stochastic programming model. Their model determines inventory decisions for minimization the total cost of the BSC and optimizes a location-allocation model. They presented a robust optimization approach to handle the uncertainty of the BSC environment, and by taking advantage of the TH method their proposed model has been solved. Further, they used real data of Mashhad city, in Iran, to examine practically of their proposed problem. Ergün et al., 2021 developed a game theoretical model for emergency logistic planning. To do this research, they designed a cooperative game model is constructed from a flow problem which occurred after an earthquake in Istanbul. On the other side, they provide some solution concepts for maximizing the transferred commodity. In another research, Fallahi et al., 2021 designed a closed-loop network to achieve more economical and environmental benefits. According to these research, a closed-loop supply chain of blood products that deliberates blood transportation equipment and the relevant quality features is formulated in this paper first. Also, they used a differential evolution algorithm (DE), boosted by extending two new versions of DE for solving the developed mathematical problem. Ergün et al., 2021 developed a game theoretical model for emergency logistic planning. To do this research, they designed a cooperative game model is constructed from a flow problem which occurred after an earthquake in Istanbul. On the other side, they provide some solution concepts for maximizing the transferred commodity. In another research, Fallahi et al., 2021 designed a closed-loop network to achieve more economical and environmental benefits. According to these research, a closed-loop supply chain of blood products that deliberates blood transportation equipment and the relevant quality features is formulated in this paper first. Also, they used a differential evolution algorithm (DE), boosted by extending two new versions of DE for solving the developed mathematical problem. Table 2 shows a comparison of the proposed model and previous studies.

As presented in Table 2, several researches have been done in this field, but there is a gap for consideration ABO compatibility and radius of the disaster as a whole in a four echelon BSC. Moreover, in most of them, only one type of vehicle is considered, while in the real world, various kinds of vehicles are used, and lateral transshipments between demand areas are allowed.

Table 2. Comparison between the presented model and the former studies

Author		Sha and Huang	Jabbarzadeh et al.	Duan & Liao	Abdulwahab & Wahab	Hsieh	Gunpinar and Centeno	Zahiri and Pishvaee	Jabbarzadeh et al.	Salehi et al	Khalilpourazari and Khamseh	Zahra hosseinifard et al.	Hamdan & Diabat	Motlagh et al.	Fallahi et al	Our study
Year		2012	2014	2014	2014	2014	2015	2017	2017	2017	2017	2018	2019	2019	2021	2022
objective	single	Minimizing costs	Minimizing costs	Minimizing shortage & wastage	Minimizing shortage & wastage		Minimizing costs								Minimizing costs	
	Bi/multi					Minimizing costs & maximizing demand satisfying		Minimizing costs & Minimizing unsatisfied demand	Minimizing costs & minimise times	Minimizing costs & Minimizing unsatisfied demand	Minimizing costs & Minimizing times	Minimizing costs & Minimizing times	Minimizing costs & Minimizing times	Minimizing costs & minimize the number of substituted units of		Minimizing costs & Minimizing times
situation	normal			*	*	*	*	*				*	*		*	
	disaster	*	*						*	*	*			*		*
time period	single				*	*						*		*	*	
	multi	*	*	*			*	*	*	*	*		*			*
Echelon	single				*											
	multi	*	*	*		*	*	*	*	*	*	*	*	*	*	*
transportation		×	×	×	×	×	×	×	×	×	✓	×	×	×	✓	✓
lateral transhipment		×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓
ABO compatibility		×	×	×	×	×	×	×	×	×	×	×	×	×	×	✓
problem		Location & Allocation	Location & Allocation	Inventory management	Inventory management	Location & Allocation	Inventory management	Location & Allocation	Location & Allocation	Location & Allocation	Location & Allocation	Inventory management	location & Inventory	Location & Allocation & Inventory	Location & Allocation	Location & Allocation
solution method		Lagrangian relaxation	Robust optimization	Meta heuristic TA-TS Method	ADP algorithm	NSGAII	CPLEX	Robust possibilistic programming	Epsilon constraint & Lagrangian relaxation	Robust and stochastic programming	MCDM methods	New simulation optimization structure	CPLEX	Mixed possibilistic stochastic flexible robust programming	Adaptive DE algorithm	MCDM methods & augmented ε constraint
Case study		Beijing	Iran	–	–	–	–	Iran	–	Iran	Iran	Iran	Jordan	Iran	–	Iran

3. Problem Definition and Mathematical Model Formulation

A schematic view of our BSC network and all interactions between its elements presented in Fig. 1. As it is obvious, the BSC included blood donors, blood collection facilities, blood centers, and blood demand centers. The responsibility of each facility in the BSC presented in Table 3.

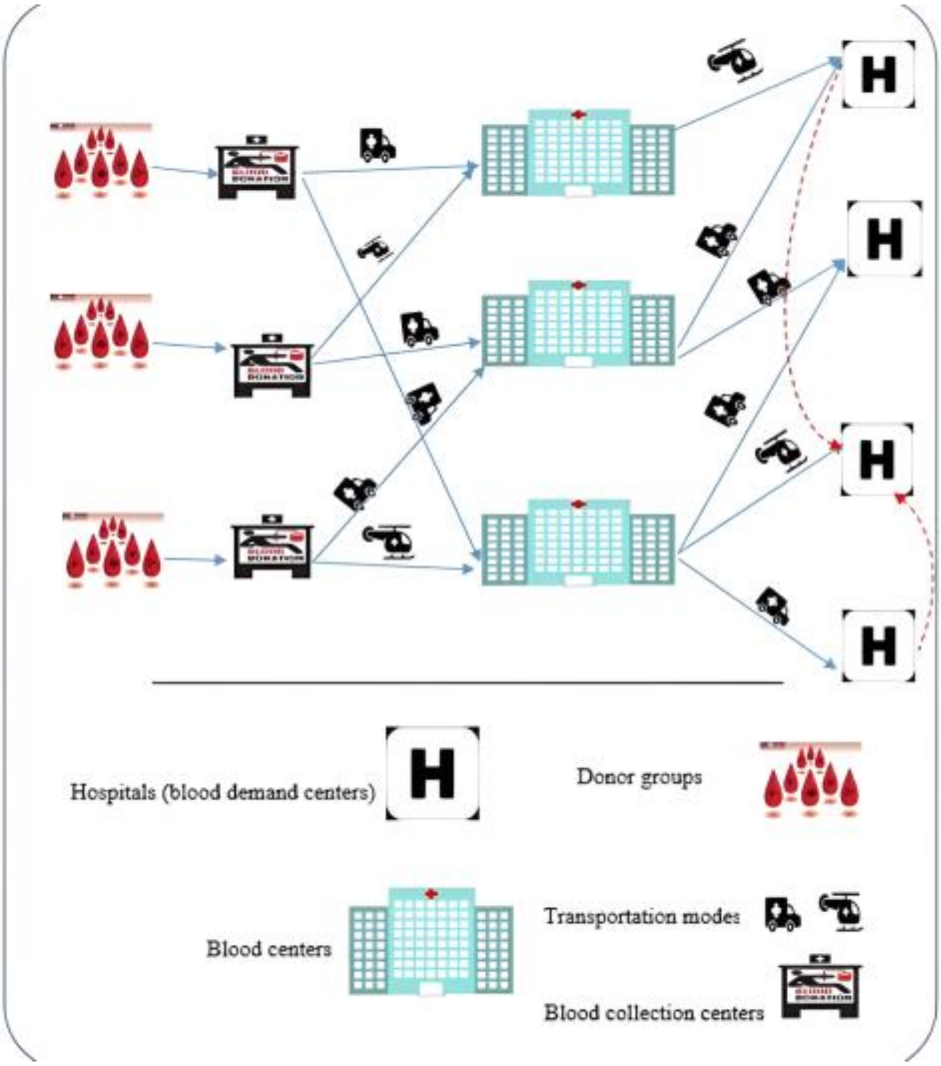

Figure 1. A schematic view of the proposed BS

Table 3. Responsibility of each facility in the BSC

Groups	Responsibility
Blood collection facilities	Blood collection from donors and prepare it for transportation to blood centers
Blood centers	Testing blood for any probable disease, check the compliance of the blood group with the requested blood type and distributing to hospitals and demand centers

The following assumptions are used in this research.

1. The number of available blood transportation equipment is limited in each period and site.
2. The maximum amount of blood donation is known for each donor.
3. The capacity of blood collection facilities is limited.
4. The demand for each demand center is known.

The following notations have been used for the formulation of the multi-transportation mode, and multi-period location-allocation model for blood SC system in earthquake conditions:

Sets

i	donator areas
j	Locations available for the collection center
k	blood centers
v	transportation modes
t	time periods
h	hospitals and demand areas
g	transmitted blood group types
g'	demanded blood group types

Parameters

F_j	Cost of locating a collection center in the candidate location *j*
ac_{ijt}	Cost of collecting blood from donor area *i* at collection center *j* in period *t*
ac'_{jkv}	Cost of transporting blood from collection center *j* to distribution center *k* at period *t* using transportation mode *v*
hm_{mht}	Cost of transporting blood from demand center *m* to demand center *h* in period *t*
ac''_{khv}	Cost of transporting blood from distribution center *k* to demand center *h* in period *t* using transportation mode *v*
toc_v	The fixed cost of transportation mode *v*
$Ccar$	The fixed cost of the car, use for blood transporting between demand center
$Cacar$	The capacity of the car, use for blood transporting between demand center
t_{jktv}	Time of transporting blood from blood collection center *j* to blood center *k* at period *t* using transportation mode *v*
t_{khtv}	Time of transporting blood from blood center *k* to demand center *h* in period *t* using transportation mode *v*
t_{mht}	Time of transporting blood from demand center *m* to demand center *h* in period *t* using transportation mode *v*
r_{ij}	Distance between the donor area *i* and collection center *j*
$coverage$	Coverage radius of each collection center *j*
$m_{g,i}$	Maximum blood supply of donor area *i* whit blood group type *g*
c_{jt}	The capacity of the collection center *j* at period *t*
$D_{g'ht}$	The demand for blood group g of demand center *h* in period t
Edr	Earthquake destruction radius
ca_v	Maximum capacity of transportation mode *v*
na_{jv}	Number of the available transportation mode *v* at collection center *j*
na'_{kv}	Number of the available transportation mode *v* at blood center *k*
num_h	Number of the available car at demand center *h*
dis_j	The Distance of collection center *j* from the epicenter of the earthquake
$AB_{gg'}$	The ABO compatibility matrix

Decision variable

Q_{gijt}	The blood volume of the group type *g* that will be received by the collecting center *j* from the donor *i* in period *t*.
Q'_{gjktv}	The blood volume of the group type *g* that will be received by the blood center *k* from the collecting center *j* in period *t*.
$Q''_{gg'khtv}$	The blood volume of group type *g* that shipped from blood center *k* to the demand center *h* for the satisfaction of blood demand with group type *g'* in period *t*
$O_{g'mht}$	The blood volume of group type *g*' that shipped from demand center m to the demand center *h* in period *t*
n_{jktv}	Number of transportation mode *v* at blood collection center *j* that required to transport collected blood to blood center *k* at period *t*
n'_{khtv}	Number of transportation mode *v* at blood center *k* that required to transport blood to demand center h in period *t*
nh_{mht}	Number of cars at demand center m that required to transport blood to demand center *h* period *t*

vc_{jktv}	1; if blood transported from collected center *j* to blood center *k* by transportation mode *v* in period *t*, elsewhere 0
vc'_{khtv}	1; if blood transported from blood center *k* to demand center *h* by transportation mode *v* in period *t*, elsewhere 0
vc''_{mht}	1; if blood transported from demand center *m* to demand center *h in* period *t*, otherwise 0
x_{jt}	1; if blood collection center is established at location *j* at period *t*, elsewhere 0
$p_{gg'kht}$	1; if blood with group type *g* used at blood center *k* for the satisfaction of demand center h with group type *g'* in period *t*, elsewhere 0
y_{ijt}	1; if earthquake magnitude is 5–6 Richter, elsewhere 0

3.1. The proposed mathematical model is formulated as follows

$$Min\ z1 \sum_{jt} f_j x_{jt} + \sum_{g,i,j,t} ac_{ijt} Q_{gijt} + \sum_{g,j,k,t,v} ac'_{jkv} Q'_{gjktv} + \sum_{g,g',k.h,t,v} ac''_{khv} Q''_{gg'khtv} + \sum_{j,k,t,v} toc_v n_{jktv} + \sum_{k,h,t,v} toc_v n'_{khtv} + \sum_{g,m,h,t} O_{g'mht} hm_{mht} + \sum_{m,h,t} Ccar\, nh_{mht} \quad (1)$$

The first objective function (1) minimizes the total cost including locating costs of collection centers in each period as well as the flow of blood product costs.

$$Min\ z2 \sum_{j,k,t,v} vc_{jktv} t_{jktv} + \sum_{k,h,t,v} vc'_{khtv} t'_{khtv} + \sum_{m,h,t} vc''_{mht} t''_{mht} \quad (2)$$

The second objective function (2) minimizes the total transportation time of collected blood from blood collection centers to blood centers and to demand centers in the earthquake area.

$$y_{ijt} \le x_{jt} \qquad \forall i,j,t \quad (3)$$

$$\sum_j y_{ijt} \le 1 \qquad \forall i,t \quad (4)$$

Eqs. (3) – (4) ensure that each donor area can be allocated to one of the collection centers at each period.

$$r_{ij} y_{ijt} \le coverage \qquad \forall i,j,t \quad (5)$$

Eq. (5) shows that for allocation a donor area to a collection center, the distance of the donor group from the collection center should be less or equal to the coverage radius of the collection center.

$$\textstyle\sum_j Q_{gijt} \le m_{g,i} \qquad \forall g,i,t \quad (6)$$

Eq. (6) guarantees that the total collected blood from a donor area in a blood collection center is less or equal to the maximum blood supply capacity of the area.

$$\sum_{g,i} Q_{gijt} \le c_{jt} x_{jt} \quad \forall j,t \quad (7)$$

Eq. (7) affirms that the total collected blood from donor areas in a blood collection center is less or equal to the maximum capacity of the blood collection centers.

$$\sum_{\substack{m=1\\m\ne h}} O_{g'mht} - \sum_{\substack{m=1\\m\ne h}} O_{g'hmt} + \sum_{k,v,g'} (Q''_{gg'khtv} * p_{gg'kht}) = D_{g'ht} \qquad \forall g',h,t \quad (8)$$

Eq. (8) guarantees that satisfaction of the demand of demand centers is fulfilled by the blood center and other demand centers.

$$p_{gg'kht} \le AB_{gg'} \qquad \forall g,g',k,h,t \quad (9)$$

Eq. (9), according to the ABO matrix ensures that the blood sent from the blood center is compatible with requested blood.

$$O_{g'hmt} \le vc''_{mht} * M \qquad \forall g',h,m,t \quad (10)$$

$$nh_{mht} \ge \frac{\sum_{g'} O_{g'hmt}}{Cacar} \qquad \forall h,m,t \quad (11)$$

$$\sum_{m} nh_{mht} \leq num_{h} \qquad \forall h,t \tag{12}$$

Eqs. (10) – (12) determine the number of the cars to transport blood from blood demand *m* to blood demand *h* considering the limited number of transportation means.

$$dis_{j} \geq Edr * x_{jt} \qquad \forall j,t \tag{13}$$

Eq. (13) shows the damages affected by the earthquake to the blood collection centers based on EDR.

$$\sum_{k,v} Q'_{gjktv} = \sum_{i} Q_{gijt} \qquad \forall g,j,t \tag{14}$$

Eq. (14) ensures that all of the collected blood send by collection centers to the blood centers.

$$Q'_{gjktv} \leq vc_{jktv} * \sum_{i} Q_{gijt} \qquad \forall g,j,k,t,v \tag{15}$$

$$n_{jktv} \geq \frac{\sum_{g} Q'_{gjktv}}{ca_{v}} \qquad \forall j,k,t,v \tag{16}$$

$$\sum_{k} n_{jktv} \leq na_{jv} \qquad \forall j,t,v \tag{17}$$

$$vc_{jktv} \leq x_{jt} \qquad \forall j,k,t,v \tag{18}$$

$$\sum_{g} Q'_{gjktv} \leq n_{jktv} * ca_{v} \qquad \forall k,h,t,v \tag{19}$$

Eqs. (15) – (19) determine the number of vehicles to carry collected blood from collection centers to blood centers, considering the limited number of each transportation mode.

$$\sum_{h,v,g'} Q''_{gg'khtv} = \sum_{j,v} Q'_{gjktv} \qquad \forall g,k,t \tag{20}$$

Eq. (20) shows that the blood centers send all the received blood to the demand centers.

$$Q''_{gg'khtv} \leq vc_{khtv} * M \qquad \forall g,g',k,h,t,v \tag{21}$$

$$n'_{khtv} \geq \frac{\sum_{g,g'} Q''_{gg'khtv}}{ca_{v}} \qquad \forall k,h,t,v \tag{22}$$

$$\sum_{h} n'_{khtv} \leq na'_{kv} \qquad \forall k,t,v \tag{23}$$

$$Q'_{gjktv} \leq x_{jt} * M \qquad \forall g,j,k,t,v \tag{24}$$

$$\sum_{g,g'} Q''_{gg'khtv} \leq n'_{khtv} * ca_{v} \qquad \forall k,h,t,v \tag{25}$$

Eqs. (21) – (25) determine the number of vehicles to carry collected blood from blood centers to demand centers considering the limited number of each transportation mode.

$$Q_{gijt} \geq 0 \qquad \forall g,i,j,t \tag{26}$$

$$Q'_{gjktv} \geq 0 \qquad \forall g,j,k,t,v \tag{27}$$

$$Q''_{gg'khtv} \geq 0 \qquad \forall g,g',k,h,t,v \tag{28}$$

$$n_{jktv} \geq 0, Integer \qquad \forall j,k,t,v \tag{29}$$

$$n'_{khtv} \geq 0, Integer \qquad \forall k,h,t,v \tag{30}$$

$$vc_{jktv} \in \{0,1\} \qquad \forall j,k,t,v \tag{31}$$

$$vc'_{khtv} \in \{0,1\} \qquad \forall k,h,t,v \qquad \text{b} \tag{32}$$

$$x_{jt} \in \{0,1\} \qquad \forall j \tag{33}$$

$$vc''_{mht} \in \{0,1\} \qquad \forall m,h,t \tag{34}$$

$$O_{g'mht} \geq 0 \qquad \forall g,m,h,t \tag{35}$$

$$y_{ijt} \in \{0,1\} \qquad \forall \mathrm{i},j,t \tag{36}$$

Eqs. (26) – (36) show the possible values of decision variables.

Linearization

Eqs. (37) – (38) are used to linearize Eq. (8). The linearized upper constraint is as follows:

$$\sum_{\substack{m=1 \\ m\neq h}} O_{g'mht} - \sum_{\substack{m=1 \\ m\neq h}} O_{g'hmt} + \sum_{k,v,g'} (Q''_{gg'khtv}) = D_{g'ht} \qquad \forall g', h, t \tag{37}$$

$$Q''_{gg'khtv} \leq p_{gg'kht} * M \qquad \forall g, g', k, h, t, v \tag{38}$$

4. Solution Approaches

The mathematical formulation presented in the prior section is a bi-objective mixed-integer linear programming (MILP) model. The optimal solution of the developed bi-objective model is an ideal solution that minimizes both objective functions simultaneously. As the objective functions are in conflict, such a solution does not exist (Khalilpourazari and Khamseh 2017; Khalilpourazari and Pasandideh 2016). Here we survey optimization of our bi-objective function through four MODM methods, containing Max-Min, Multi-Choice goal programming (MCGP), goal attainment, and LP-metric.

5. Case study

Iran, as one of the most vulnerable countries in the earthquake, has confronted many destructive earthquakes (Sabzehchian et al. 2006). Some of the devastating earthquakes in Iran presented in Table 4. Fast distribution and adequate supply of blood after intense earthquakes are always a relevant subject (Abolghasemi et al. 2008).

Table 4. Some of the destructive earthquakes in Iran

Location	Date	Deaths	Magnitude
Tabas	September 16, 1978	19600	7.7
Ghaenat	May 10,1997	1500	7.3
Manjil–Rudbar	June 20, 1990	35000	7.4
Bam	December 26, 2003	41000	6.6
Saravan	Apr 16, 2013	34	7.8
Sarpol-e-Zahab	November 12, 2017	620	7.3

One of the deadly earthquakes was the "Sarpol-e-Zahab" earthquake, which quaked Sarpol-e-Zahab for 11 seconds on November 12, 2017, at 9:18 pm local time measuring 7.3 on the Richter scale. Most of the city infrastructure, including hospitals and Emergency Medical Services, were destroyed by the earthquake. More than 620 were killed, 10000 injured, and about 70000 people were displaced. Now suppose that, an earthquake occurred with the 7.8 Richter magnitude with 30km destruction radius in Tehran, the capital of IRAN. Its population is estimated at about 16 million people, with a growth rate of 20% approximately (M. Ashtari et al. 2005). Fig. 2 shows the municipal districts of Tehran. Existent studies show that destructive earthquakes with active faults are associated near Tehran. A geological survey predicts that an earthquake about seven magnitudes in Tehran destroyed 640,000 homes from a total of 1, 100, 000 housing, and more than one million and a half of Tehran's population were killed and about four million and three hundred injured thousand. Considering the above mentioned, we decided to select Tehran as a case study for the implementation of the proposed model. Similar to Jabbarzadeh et al. (2014), we considered the 22 districts of Tehran that each of them has the ability to donate blood, and in all of them, blood collection equipment is also available to send blood to the blood center. Table 5 in the appendix shows the geographical coordination of donor areas and their corresponding blood supply in each district.

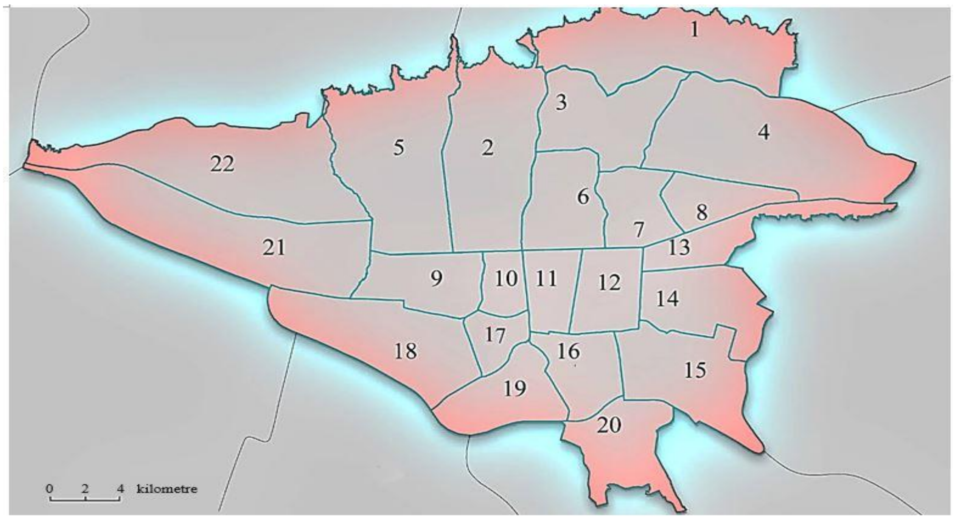

Figure 2. Geographical representation of Tehran's districts

In this paper, we considered that a destructive earthquake with a 7.8 Richter magnitude with a 30 km destruction radius has occurred in the southern Tehran, as presented in Fig. 3 (Heydari and Babai, 2015). Table 6, as proposed in Davoudi-kiakalayeh et al. (2012) and Shen et al. (2003) in the appendix show the real data to solve the mathematical presented model. Tables (7-9) in the appendix present the cost of transportation between collection centers and the blood center, blood center, and the blood demand centers and demand centers for vehicles and helicopters in each district, respectively. Table 10, Table 11, and Table 12 in the appendix present the available number of each transportation mode in collection centers, blood centers, and blood demand centers, respectively (Jabbarzadeh et al. 2014).

Similarly as proposed in Khalilpourazari and Khamseh (2017) the time of transportation between collection centers and the blood center, blood center, and the blood demand centers and demand centers for vehicles and helicopters in each district that obtained from Google Map and Google Earth considering the average speed of vehicles, respectively presented in Table 13, Table 14 and Table 15 in the appendix.

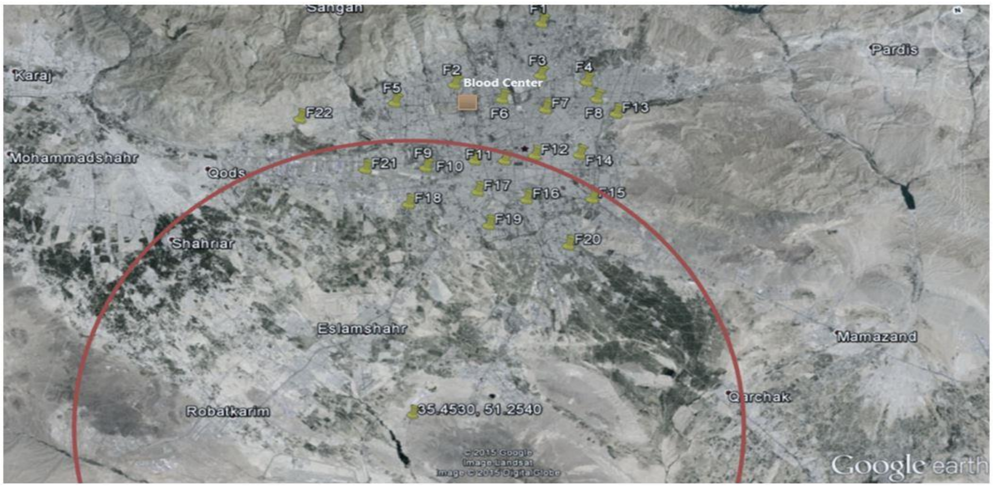

Figure 3. Earthquake in South Tehran fault with 30 km destruction radius source: Khalilpourazari and Khamseh (2017)

Table 5. Donor areas information

AB+	AB-	B+	B-	A+	A-	O+	O-	Supply (units)	Latitude	Longitude	Donors
7	1	14	2	59	10	62	11	166	35.80250	51.45972	1
15	2	34	6	142	25	149	26	399	35.75750	51.36222	2
7	1	17	3	71	12	74	13	198	35.75444	51.44806	3
17	3	46	8	194	34	203	36	543	35.74194	51.49194	4
15	3	43	8	179	32	187	33	500	35.74889	51.30028	5
5	1	12	2	52	9	54	10	145	35.73722	51.40583	6
7	1	17	3	70	12	73	13	195	35.72194	51.44611	7
8	1	20	4	85	15	89	16	238	35.72444	51.49833	8
3	1	8	1	35	6	37	7	99	35.68361	51.31722	9
6	1	16	3	68	12	71	13	191	35.68361	51.36667	10
6	1	15	3	65	11	68	12	182	35.67944	51.39583	11
5	1	13	2	54	10	56	10	151	35.68000	51.42639	12
6	1	15	3	62	11	65	11	174	35.70778	51.51417	13
10	2	26	5	109	19	114	20	305	35.67444	51.47028	14
14	2	34	6	144	25	150	27	402	35.63083	51.47361	15
6	1	15	3	65	11	68	12	181	35.63944	51.40917	16
5	1	13	2	56	10	58	10	156	35.65389	51.36306	17
8	1	21	4	88	15	92	16	246	35.65167	51.29278	18
5	1	13	2	55	10	58	10	155	35.62056	51.36694	19
9	1	18	3	76	13	80	14	214	35.59028	51.44083	20
3	1	9	2	36	6	38	7	102	35.69056	51.25778	21
3	1	7	1	29	5	30	5	82	35.74722	51.20417	22

Table 6. Real value of problem parameters

parameter	value	parameter	value	parameter	value
ca_v	V=1; Ca=100 , V=2; Ca=300	cjt	300	F_j	1500
toc_v	V=1; Ca=3000, V=2; Ca=35000	EDR	30 km	ac_{ijt}	0.069
D_{ght}	35	$coverage$	12 km		

Table 7. Cost of transportation between collection centers candidate and blood center

j	Vehicle	Helicopter	*j*	Vehicle	Helicopter	*j*	Vehicle	Helicopter
j1	134	423	j9	108	417	j17	138	426
j2	53	362	j10	83	405	j18	194	453
j3	74	394	j11	92	415	j19	256	462
j4	142	803	j12	110	418	j20	289	490
j5	65	378	j13	245	460	j21	172	447
j6	60	377	j14	151	444	j22	275	467
j7	77	396	j15	286	881			
j8	147	432	j16	173	448			

Table 8. Cost of transportation between blood center and blood demand centers

	h_1	h_2	h_3	h_4
Vehicle	75	80	134	142
Helicopter	359	362	483	603

Table 9. Cost of transportation between demand centers

	h_1	h_2	h_3	h_4
h_4	0	75	79	15
h_4	75	0	65	78
h_4	79	65	0	81
h_4	115	78	81	0

Table 10. Number of available transportation equipment in each collection centers

j	Vehicle	Helicopter	*j*	Vehicle	Helicopter	*j*	Vehicle	Helicopter
j1	4	1	j9	9	2	j17	4	0
j2	5	2	j10	7	3	j18	4	3
j3	4	2	j11	5	2	j19	6	1
j4	4	1	j12	7	2	j20	5	2
j5	9	2	j13	6	2	j21	10	3
j6	7	3	j14	5	3	j22	10	5
j7	7	2	j15	5	1			
j8	4	0	j16	5	3			

Table 11. Number of available transportation equipment in blood center

	Blood center
Vehicle	8
Helicopter	3

Table 12. Number of car in each demand centers (h_i: i'th demand center)

	h_1	h_2	h_3	h_4
car	2	1	1	2

Table 13. Time of transportation between collection centers candidate and blood center

j	Vehicle	Helicopter	*j*	Vehicle	Helicopter	*j*	Vehicle	Helicopter
j1	142	14.2	j9	139	13.8	j17	144	14.5
j2	102	17.1	j10	132	13.3	j18	168	23
j3	119	10.3	j11	137	13.5	j19	173	27
j4	146	17	j12	140	14	j20	180	35
j5	118	8.8	j13	171	23.6	j21	159	18.9
j6	103	8.2	j14	155	18.5	j22	175	33.2
j7	129	11.5	j15	178	33.9			
j8	150	18.2	j16	164	20			

Table 14. Time of transportation between blood center and blood demand centers

	h_1	h_2	h_3	h_4
Vehicle	48	57	65	75
Helicopter	13	12	17	20

Table 15. Time of transportation between demand centers h_i: ith demand center

	h_1	h_2	h_3	h_4
h_4	0	63	68	96
h_4	63	0	61	74
h_4	68	61	0	69
h_4	96	74	69	0

The distance is calculated using the Eq. (39) (Khalilpourazari and Khamseh 2017; Jabbarzadeh et al. 2014).

$$r_{ij} = \text{Arccos}\left(\sin(\text{Latitude}_i) \times \sin(\text{Latitude}_j) + \cos(\text{Latitude}_i) \times \cos(\text{Latitude}_j) \times \cos(\text{Longitude}_j - \text{Longitude}_i)\right) \times 6371.1 \quad (39)$$

Where 6371.1 is the earth's radius, and Latitude and Longitude are the geographic coordinates of the donor groups multiplied by π/180 (Khalilpourazari and Khamseh 2017).

Because of illustrating the objective functions of conflicts, each objective function is solved by the individual method using the real data of Tehran. According to the results presented in Table 16, the two objective functions are not minimized at the same time. To solve this problem, four MODM methods are used to solve case studies with diverse perspectives. We presented the results in Table 17.

Table 16. The relation between the two objective functions

	Z1*	**Z2***
Z1	459900.527	3218.4
Z2	43310640	258.4

Table 17. Results of the four MODM methods

	Objective	**LP-Metric**	**Max-Min**	**MCGP**	**GA**	**Average**
Base model	Z1	2003621	4320112	3612510	1923650	**2964973**
	Z2	1301	512	581	1794	**1052**
	CPU time	117.05	76.806	29.35	95.051	**79.56**
By considering ABO compatibility	Z1	1900612	3926658	3382571	1836112	2761488
	Z2	1241	494	553	1783	1017.75
	CPU time	163.05	159	135.4	201.02	164.61
By considering lateral transshipment	Z1	1845397	3749810	2991038	1372003	2489562
	Z2	1245	471	539	1774	1007.25
	CPU time	216.04	296.15	268.9	386.3	291.84
By considering ABO compatibility & lateral transshipment	Z1	1706296	3538110	2659061	1027930	**2232849**
	Z2	729	456	522.4	1762	**867.35**
	CPU time	416	795	501.51	870.3	**645.7**

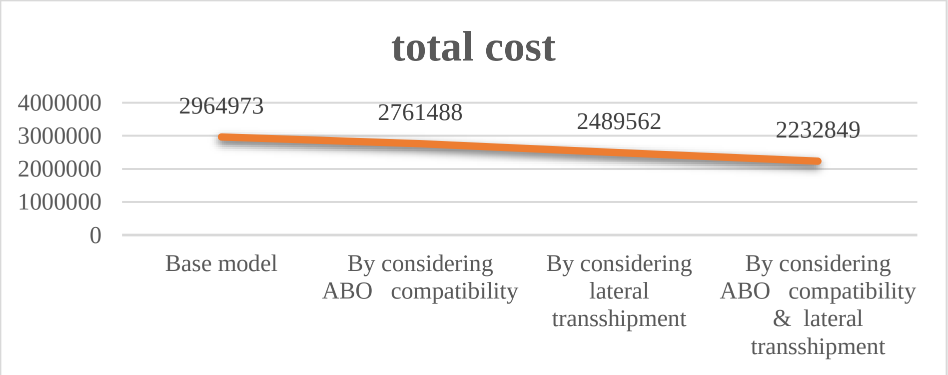

Figure 4. The total cost of the supply chain by applying innovations and before

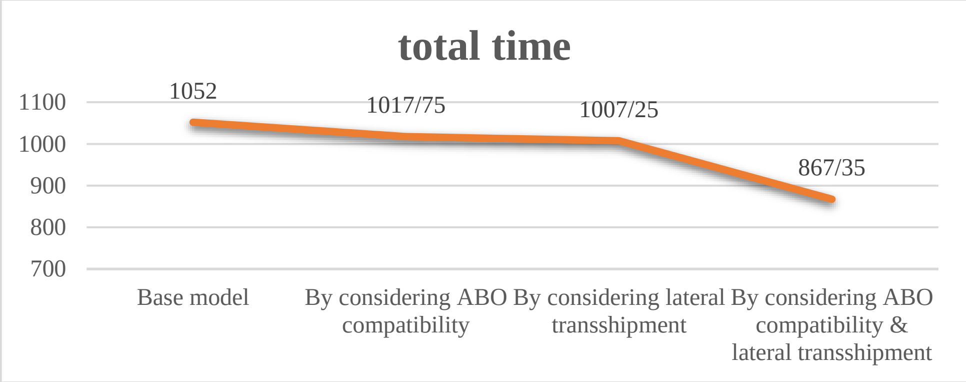

Figure 5. The total time of the supply chain by applying innovations and before

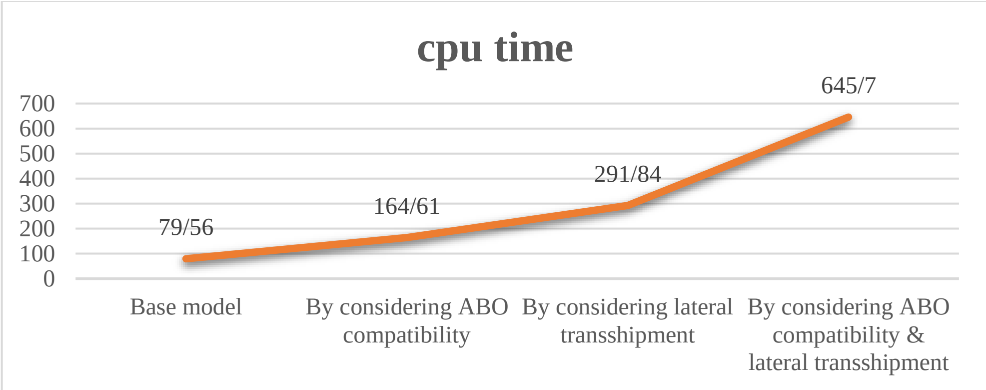

Figure 6. The required CPU time for solving the model by applying innovations and before

In order to prove that the resiliency of the BSC has improved with considering blood group compatibility and the lateral transshipments between demand areas, the case study is solved without taking these innovations by the MODM method and compares it with the result of the solving model without innovations. According to Table 17 and Figs. 4, 5 and 6, which show a summary of Table 17, by considering blood group compatibility and the lateral transshipments between hospitals, we have a 18% reduction in the delivery time to patients and a 25% reduction in the total cost. But the solution time has increased, due to the complexity of the model, this increase seems logical.

5.1. TOPSIS Method for Comparing MODM Methods

A technique for the order preference by similarity to Ideal Solution (TOPSIS) method proposed by Hwang and Yoon (1981). In order to use the TOPSIS method, we illustrate the decision matrix in Table 18, based on Table 17.

Table 18. TOPSIS decision matrix

	Objective	**LP-Metric**	**Max-Min**	**MCGP**	**GA**
By considering ABO compatibility & lateral transshipment	Z1	1706296	3538110	2659061	1027930
	Z2	729	456	522.4	1762
	CPU time	416	795	501.51	870.3

5.2. Shannon Entropy for Weights of Comparison Metrics

The Shannon entropy method is one of the methods for finding weights of comparison metrics. This method is useful for presenting a decision matrix without receiving any information from the decision-maker (Khalilpourazari and Khamseh 2017; Lotfi and Fallahnejad 2010). Table 19 and Table 20 show the weight of each comparison metrics that obtained by Shannon Entropy and the results of using the TOPSIS method, respectively. In Table 20, alternative with the shortest distance from the positive ideal solution and longest distance from the negative ideal solution will be the best.

Table 19. Weights determined by Entropy method

	Average Z1	Average Z2	Average CPU-Time (s)
$weight_i$	0.95	0.801	0.888

Table 20. Results of the TOPSIS method

Methods	Similarity Ratio	Rank
Max-Min	0.419	3
LP-Metric	0.581	1
MCGP	0.260	2
GA	0.564	4

According to the results obtained in Table 20, solving methods are ranked using the similarity ratio, based on considering the method with the highest similarity ratio in the first rank and the method with lowest similarity ratio in the last rank. As can be seen in Table 20, the LP-Metric is the best MODM method to solve the proposed model.

5.3. Augmented ε-constraint method for providing Pareto optimal solution

As presented in Mavrotas and Florios (2013), the augmented ε-constraint method with ignoring the generation of weakly Pareto optimal solutions and redundant iterations, accelerated the whole process. This method has been implemented in GAMS 26.1.0, using the GAMS model library. Here, we take advantage of Pareto optimal solution for our multi-objective mathematical model to make better decisions. In this regard, Table 21 shows the results of using the ε-constraint method to obtain effective Pareto solutions of the multi-objective mathematical model. Fig. 7 shows a schematic view of the comparison between solution methods. When the decision-makers aim to make a suitable trade-off between the objectives functions, they can use one of the methods in the green area in Fig. 7.

Table 21. Pareto optimal solutions obtained by ε-constraint method

Pareto solutions	Z1	Z2
ps1	1396100	1529
ps2	1402503	1471
Ps3	1495100	1349
Ps4	1601412	1271
Ps5	1756003	1011

The first Pareto optimal solution attained by the ε-constraint method is presented to show the values of the decision variables of the model. The location of blood collection centers and the collected blood flow from collection centers to blood centers in the first two periods after the earthquake shown in Fig. 8. In addition, the blood product flow from the blood center to the demand areas also is shown in Fig. 9. The values of flows in Fig. 9 are presented in Tables (22-25).

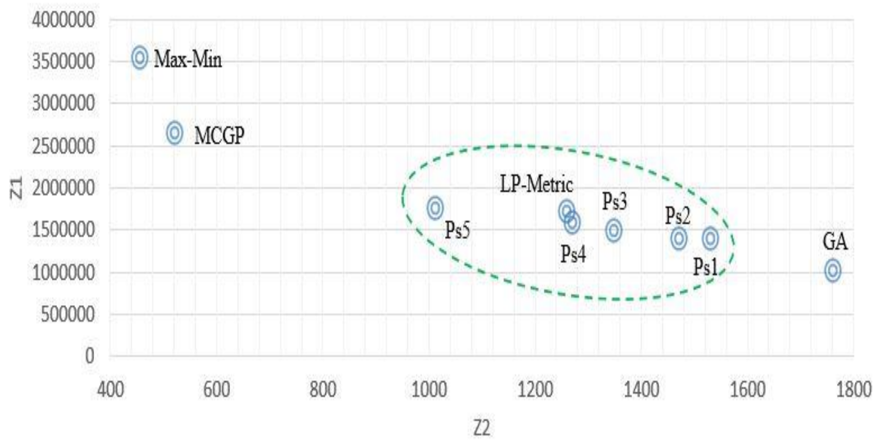

Figure 7. Solutions of the Pareto solution and four MODM method

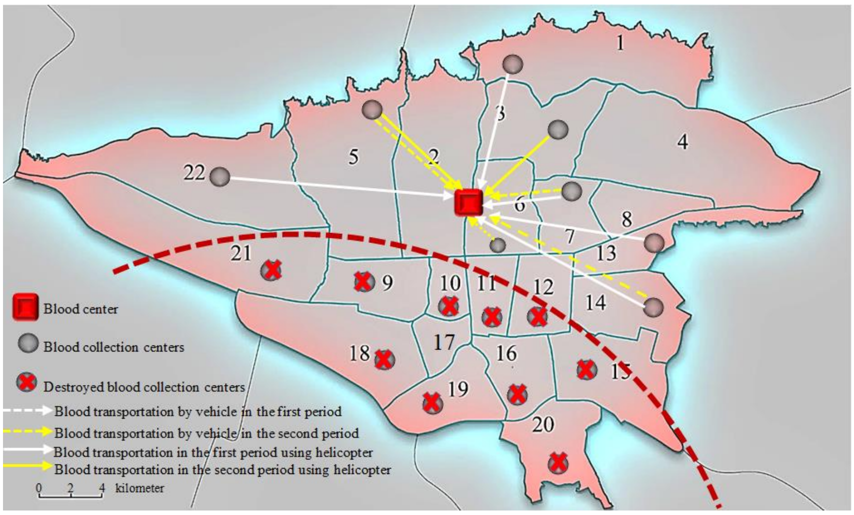

Figure 8. Location of blood collection centers and the collected blood flow

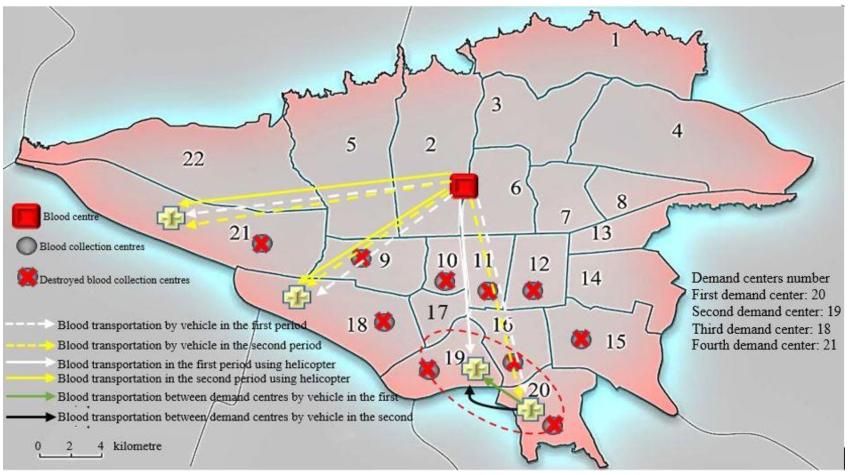

Figure 9. Flow of blood product from blood center to the demand areas

Table.24 Value of blood flow from blood center to demand center in the second period

	sent	requested	H_1	H_2	H_3	H_4
	O-	O-	70	0	35	35
	O-	A-	0	0	13	0
	O-	B-	70	0	15	35
	O+	O+	70	0	35	35
	O+	B+	70	0	0	0
	A-	A-	70	0	22	0
	A-	A+	40	0	0	0
	A-	AB-	14	0	0	0
	A-	AB+	70	0	0	0
v=2	A+	A+	30	0	35	35
	B-	B-	0	0	20	0
	B-	AB-	56	0	0	0
	B+	B+	0	0	35	31
	AB-	AB-	0	0	25	0
	AB+	AB+	0	0	35	35
	O-	A-	0	0	0	35
	O-	AB-	0	0	4	0
v=2	O+	B+	0	0	0	4
	A-	AB-	0	0	6	33
	AB-	AB-	0	0	0	2

Table.22 Value of blood flow from blood center to demand center in the first period

	sent	requested	H_1	H_2	H_3	H_4
	O-	O-	70	0	35	35
	O-	O+	34	0	0	0
	O-	A-	47	0	0	0
	O-	B-	36	0	35	8
	O+	O+	2	0	35	35
	O+	A+	40	0	0	0
	O+	B+	24	0	0	25
	O+	AB+	5	0	0	0
	A-	A-	23	0	35	35
v=2	A-	A+	0	0	35	0
	A-	AB-	51	0	35	35
	A+	A+	30	0	0	35
	A+	AB+	0	0	0	35
	B-	B-	0	0	0	27
	B-	B+	0	0	0	10
	B+	B+	46	0	35	0
	AB-	AB-	1	0	0	0
	AB+	AB+	65	0	35	0
v=2	O+	O+	0	34	0	0
	B-	B-	0	34	0	0
	AB-	AB-	0	18	0	0

Table 25. The amount of blood sent from first demand center to second demand center in second period

Group type	O-	O+	A-	A+	B-	B+	AB-	AB+
value	35	35	35	35	35	35	35	35

Table 23. The amount of blood sent from first demand center to second demand center in first period

Group type	AB+	O-	O+	A-	B-	B+	AB-	AB+
value	35	35	1	35	1	35	17	35

Table 26. The total number of blood that sent to hospitals

Blood group	First period	Second period
O-	300	312
O+	200	214
A-	249	255
A+	100	100
B-	71	76
B+	81	66
AB-	19	27
AB+	100	70

One of the advantages of employing the proposed model is that a compatible blood type can be used instead of the blood type requested, which affects the resiliency and the responsiveness of the BSC. In our proposed model based on the EDR, the decision-maker can find the destruction effects on the blood centers that prepared information to design a more realistic and resilient BSC. According to the problem assumptions, the demand for each hospital for each blood group is 35 units. If we consider the model without considering the compatibility of the blood group, 35 units must be sent from each blood group for each hospital, even if the blood center has to receive the blood from the farthest blood collection center. However, by using the compatibility properties of blood groups, blood compatible with the requested blood type is provided from the nearest center and at the lowest possible cost and time. Table 26 shows the total number of blood that is sent to hospitals; as expected, the highest blood consumption belongs to blood groups that are more compatible than other blood groups (O-, O+, A-).

On the other hand, Lateral transshipments are an essential tool in supply chain management, as they can help reduce costs and/or increase service levels (Stanger, S.H et al. 2013). However, by considering the lateral transshipments between demand areas, we want to reduce as much as possible the total costs and the total time.
Hence, based on Table 23 and Table 25, the model implementation results show that because of the closeness of demand centers 1 and 2, thereupon, sending the entire demand for demand center 2 from the blood center, approximately are satisfied by the demand center 1, this causes a reduction in time and cost of the BSC.

6. Validation

Ever since the discursive problem is obviously a bi-objective one, using each solution method, solutions are obtained at a single point. Therefore, the validation procedure ought to design based on making comparisons between single points achieved by different solution methods. To validate the solutions obtained by Lp-metric (the best method in TOPSIS), a set of 5 small and medium sized instances ((6=i.3=j.2=k.2=h.1=t.2=v), (6.3.1.3.2.2), (15.6.2.3.2.2), (20.6.2.4.2.3), (20.9.2.4.3.3)) are used as shown in Table 27. All the instances are solved using Lp-metric and bounded objective method (BOM), by means of GAMS 26.1.0 (CPLEX solver) on a PC with Core i7 CPU and 8 GB RAM. In the validation procedure, for any problem instance, Lp-metric is used to obtain a single point. At that moment, the points with the same transportation time values (e.g., Z2*) in a single point are considered, and their related cost in a single point is recorded (e.g., C1). At that point, the bounded objective method is used to solve the single-objective version of the bi-objective optimization model, obtained by fixing the transportation time as Z2*. The optimal cost (e.g., C*) is used as a benchmark to validate the related cost of Lp-metric (C1).

For a MODM model with p objectives, of which the ith one has the top priority for the decision-maker, the general form of the bounded objective method is as follows:

$$\text{Minimize } f_i(x)$$
$$\text{Subject to:}$$
$$LB_g \leq f_g(x) \leq UB_g \qquad g=1,\dots,p \quad g\neq i \qquad x\epsilon S \tag{42}$$

Where, $f_g(x)$ specifies the gth objective function, and LB_g and UB_g are the lower and upper bounds of the gth objective function, correspondingly. Moreover, S is the feasible space of the unique problem.

Table 27. Comparative results to specify the performance of LP-Metric.

	LP-Metric		BOM		Gaps	CPU Time(sec)	
	Objective function value						
Problem Code.	*Cost*	*Transportation Time*	*Cost*	*Transportation Time*	$Gap_{LP-Metric}$	*LP-Metric*	*BOM*
6.3.2.2.1.2	340038.00	140.67	340038.00	140.67	0.000	15.3	10.1
6.3.1.3.2.2	1116195.33	408.67	1116025.5	408.67	0.00015	25.2	21.6
15.6.2.3.2.2	935433.67	429.67	934533	429.67	0.001	425.9	415.4
20.6.2.4.2.3	2131105.23	492.00	2125156.7	492.00	0.003	492.3	467.9
20.9.2.4.3.3	2338036.67	578.33	2330612.4	578.33	0.0032	536.1	512.3
Average	**1372162**	**409.4**	**1371073**	**409.4**	**0.0015**	**298.96**	**285.46**

Table 27 displays the comparative results attained based on the above-mentioned validation procedure to specify the performance of Lp-metric.

According to the results, display the average relative gaps of %0.15 between optimal solutions achieved by BOM and solutions made by Lp-metric, correspondingly. This affirms the decent performance of the Lp-metric for small and medium-sized problem instances due to the relative gaps are negligible. As above-mentioned, for another test problem, the optimization model cannot be solved to optimality by GAMS in a reasonable computational time (1000 sec) by GAMS. Henceforth, for large-sized test problems, the validation procedure is implemented by directly comparing the performance of Lp-metric instead of using the bounded objective method.

7. Sensitivity Analyses

Here we considered four main parameters with change rates 50%, 25%, -25%, -50%. The effect of changes on the values of the target functions in the medium size of test problems is presented in Table 28.

Table 28. Result of ssensitivity analysis

parameter	Change (%)	z1	z2
	-50	1507623	203
	-25	2247661	232
$D_{g'ht}$	0	3207061	261
	25	3694463	284
	50	4438624	320
	-50	3383146	395
	-25	3259763	336
$m_{g,i}$	0	3207061	261
	25	2385731	212
	50	2051146	196
	-50	2130259	192
	-25	2890600	221
EDR	0	3207061	261
	25	3630926	273
	50	infeasible	infeasible
	-50	infeasible	infeasible
	-25	3695676	284
Cov	0	3207061	261
	25	2803686	197
	50	2709654	197

As it is shown in Table 28, the value of both objective functions increases with increasing $D_{g'ht}$ and a small change in it causes a significant change in both objective function values. Both objective functions decrease with increasing $m_{g,i}$, and both objective function values increase with an increase in EDR. In addition, if EDR increases to a +50% rate, the problem will be infeasible. With increased EDR, more collecting facilities may be destroyed, and the remaining facilities may not have the ability to respond to requests; in this situation the problem is infeasible. According to results, an increase in Cov, can decrease both objective functions value because with the increase in coverage of the collection facility, more donor groups may be covered, and there is no need to deploy new collection centers to collect blood from donor groups. Besides, if Cov decreased -50% makes the problem infeasible because the collection centers cannot correctly cover the donor groups and satisfy the demands. Figs. 10 and 11, detail the effects of the main parameter changes in the objective function's value as a schematic view.

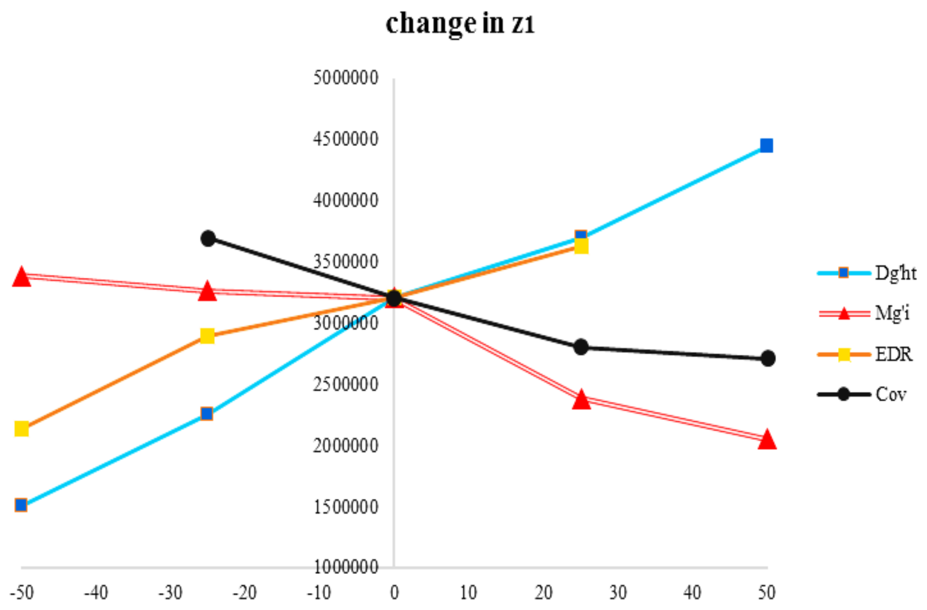

Figure 10. Effects of the main parameter changes in the first objective

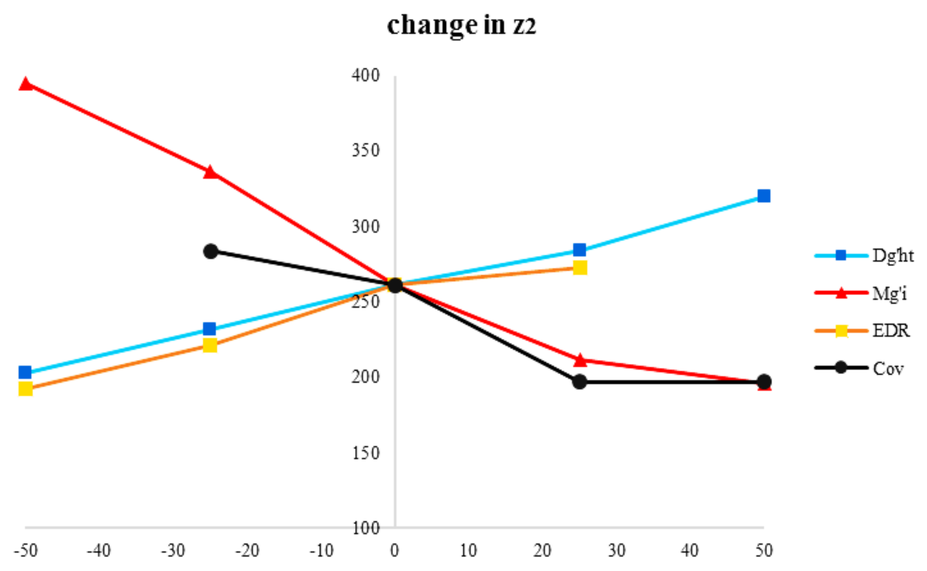

Figure 11. 1Effects of the main parameter changes in the second objective

8. results and implications

In this research, we presented a multi-objective mixed-integer linear programming model that the impact of the EDR on the BSC network and blood group compatibility has been considered simultaneously. As shown in the literature, much research has been done in this field. But still, none of them considered the impact of EDR on the BSC network and blood group compatibility simultaneously. Moreover, in most of them, only one type of vehicle is considered, while in the real world, several types of vehicles are used, and transportation between demand nodes is allowed laterally in our proposed model, which produces more reliable and reasonable answers. The main goal of the model is to optimize the location of blood collection centers in safe areas to restore the system to its previous state quickly, determining the flow of blood product in BSC, and in emergencies, use of a blood type that is compatible with the blood type requested. In addition, we want to reduce as much as possible the total costs and the total time by considering the lateral transshipments between demand areas. As noted above, this research presented a constraint bi-objective mixed-integer linear programming. Naturally, BSC network design is a multi-criteria decision-making problem, because the objectives are in conflict; this is proved by solving the model with the individual method and reported. Augmented ε-constraint method for providing efficient Pareto optimal solutions and four MODM methods for solving the problems were used. Also, the bounded objective method has been applied for the validation of the proposed model. We considered Tehran as a case study for the implementation of the proposed model and considered the 22 districts of Tehran that each of them has the ability to donate blood, and in all of them, blood collection equipment is also available to send blood to the blood center. According to the result, by considering the mentioned innovation's we have an 18% reduction in demand delivery time, when total cost decreased by more than 25%. In addition, according to Figs. 10 and 11, by using sensitivity analyses, we found that an increase in parameter Cov can decrease both objective function value. Finally, the mathematical model can be useful in determining government decisions to measure total cost and transportation times, simultaneously. As it turns out, in emergencies, the speed of action plays an essential role in reducing human casualties (Zhu et al. 2020). For future research, to improve the reality of the problem and model robustness, uncertainty of some deterministic parameters in our proposed model could be suggested.

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