A Robust Location-Allocation Model for Optimizing a Multi-Echelon Blood Supply Chain Network Under Uncertainty

Masoud Asadpour Ahmadchali[1], Mahdi Ebrahimzadeh-Afrouzi[1], Nikbakhsh Javadian[2]

School of Industrial Engineering, Iran University of Science and Technology (IUST), Tehran, Iran

School of Industrial Engineering, Mazandaran University of Science and Technology, Babol, Iran

Abstract

Designing and planning blood supply chains is very complicated due to its uncertain nature, such as uncertain blood demand, high vulnerability to disruptions, irregular donation, and blood perishability. In this vein, this paper seeks to optimize a multi-echelon blood supply chain network under uncertainty by designing a robust location-allocation model. The magnitude of the earthquake as disaster intensity (destruction radius), affecting the severity of the disruption at the blood donation facilities' location, is considered. The Data Envelopment Analysis (DEA) model is mixed into the developed model to evaluate the efficiency of the locations and select high-efficient locations. On the other hand, this study aims to eliminate the gap between blood donors and consumers (patients) to balance the shortage and the wastage of blood units efficiently. As uncertainty plays a central role in the blood supply chain during an earthquake disaster, a specific robust optimization approach is utilized to handle the inherent uncertainty of the model. Finally, a case study of Mashhad city, Iran, is used to validate and show the applicability of the model and its solution approaches. The results showed that a flexible, efficient blood supply chain would be achievable by simultaneously setting an optimal trade-off between costs and blood shortage and wastage based on the decision maker's preferences.

Keywords: Robust optimization; Blood supply chain; Disruption risk; Disaster intensity; Data Envelopment Analysis; Uncertainty.

[1] MSc. Graduate Students (*ma.asadpour1990@gmail.com*, *mehdi.eh90@gmail.com*,)

[2] Professor of Industrial Engineering Department (nijavadian@ustmb.ac.ir)

1. Introduction

In addition to the inherent complexity of blood supply chain issues, managing such chains in times of disaster (e.g., earthquakes, floods, tsunamis, biological threats, such as flu, and human disruption, such as terrorist attacks and wars, etc.) is one of the main challenges for any blood transfusion system. In recent years, a large number of such disasters have occurred all over the world, and Iran is no exception to this rule. According to the International Statistical Institute (ISI), Iran ranks 7^{th} among the 10 most disaster-prone countries in the world, so it is a high-risk country in this area. According to reports, over the past two decades, nearly 10% of the whole population of Iran have been killed, injured and damaged due to natural disasters, which is a significant figure. One of the most devastating disasters is earthquakes [1]. In the earthquake of Ezgeleh Kermanshah, Iran, with 7.3 Richter, which resulted in more than 9,500 injuries and deaths, only 13,000 units (roughly 34%) of 38,000 donated blood units were delivered to earthquake points. Under such a circumstance, disaster management plays a critical role in reducing dire consequences. Disaster management is a set of special operations and processes planned to prevent and reduce the impacts of disasters before, during and after the disaster [2].

Supply chain design with perishable products (e.g. dairy products, fruits and vegetables, medicines and vaccines, flowers, and blood in particular), which have a short lifespan, may lead to specific challenges for any organization, such as disposal costs and environmental impacts. Most studies on the design and management of perishable products supply chain networks are related to the health area due mainly to the importance of availability and timely delivery of healthcare products and services.

Blood is one of the most strategic perishable products, which is of particular significance both during and after a disaster. Blood shortage will have irreparable consequences for society, undoubtedly leading to an increased mortality rate. As there is no substitute for this type of product and its shortage directly deals with human health, the significance of this issue becomes more apparent. Indeed, the wastage of blood is inexcusable because only through blood donation by society members is it possible to supply blood for victims. In addition, there must be a time interval between each donor's donation, and the expiry date of the blood must also be taken into account; Therefore, maintaining and managing a sufficient blood supply is vital in order to meet demands [3].

Given all the mentioned points, one of the most effective ways to solve such problems is to design an optimal blood supply chain system. The blood supply chain consists of blood donors, blood facilities (temporary and permanent), blood centers, distribution centers and demand points (hospitals). To design and optimize such a system, we seek to locate and determine the optimal number of these facilities, the serving region, and the amount of blood both in each facility and at the end of each period (Figure 1).

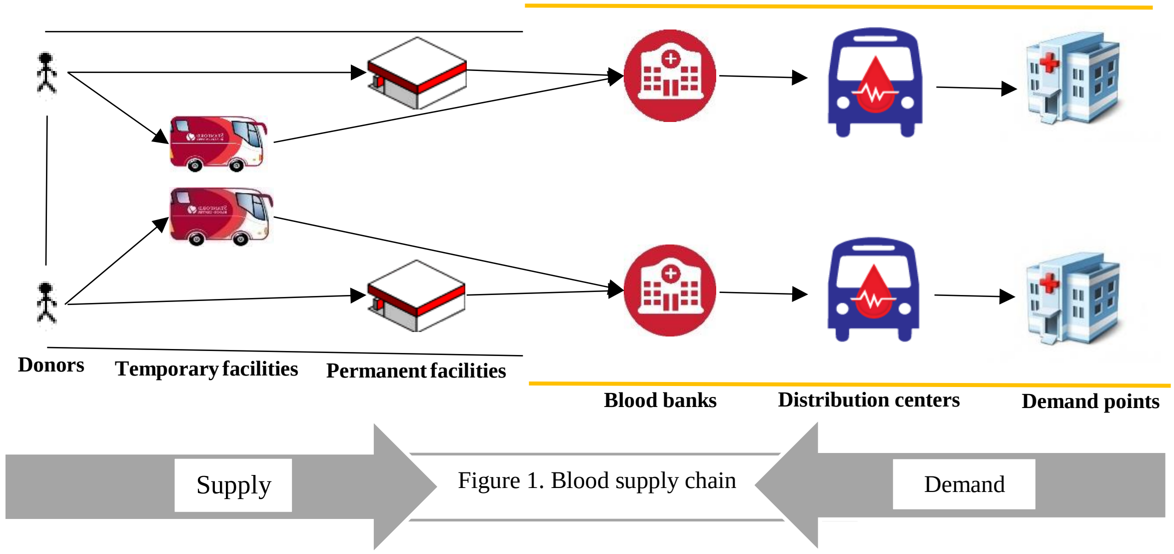

Figure 1. Blood supply chain

Disasters can adversely affect blood donors, blood transfusion staffers, blood bank processes, patients, hospitals, and especially logistics and facilities. In the operational management of the blood transfusion system, the disaster impact on such key factors should be identified first, and then a proper planning should be implemented. One of the levels that can be affected by such disasters is the location of blood transfusion centers and lack of access in case of disruption [4]. In the supply chain, when the service facilities become inaccessible during disruption, we have no choice but to find alternative facilities as soon as possible, otherwise the chain will experience irreparable consequences. In the blood supply chain, the unavailability of established facilities during disaster situations due to various reasons including road damage, traffic, insecurity, and etc., obligates decision-makers of this area to determine the optimal number of facilities and establish the most suitable locations (being away from active earthquake faults) before the disaster considering all possible scenarios in times of disaster [5].

In the blood supply chain, facility location is very significant in finding the optimal spatial pattern upon the determining criteria, such as cost, time, and coverage, in order to minimize supply chain costs and provide fair services to customers. In this vein, the Data Envelopment Analysis (DEA) model as a useful method for measuring efficiency can be utilized as a non-parametric model for locating efficient facilities, and the DEA model upon input-oriented manner is applied for this purpose. Finally, among the candidate locations selected by data coverage analysis for establishing temporary and permanent facilities, it should be determined which locations are most suitable for blood facilities.

Blood is not an ordinary item; as both the supply and the demand for blood products vary in different periods, like in times of disasters, they may increase or decrease. Indeed, it is not straightforward to level supply and demand effectively. In this way, we can take advantage of robust optimization that applies to situations in which the parameters and inputs of the problem are not accurate. Hence, in addition to considering uncertainty for the demand, the costs of opening and establishment facilities and potential hospitals, and shortage are considered stochastic in order to make sense in the real world.

In order to provide a stable, appropriate blood supply in critical situations, this paper presents a robust optimization model for designing a multi-echelon blood supply chain network, including supply points (donors), blood donation facilities (temporary and permanent), blood centers and demand points (potential and existing hospitals), with a case study in Mashhad city, Iran. The key point in the problem is that according to the possibility of natural disasters, each temporary and permanent facility is subject to potential damage and disturbances due to the intensity and magnitude of the earthquake. The proposed model initially seeks to find the most efficient locations for establishing temporary and permanent blood donation facilities based on the data envelopment analysis model before the disasters. Then, after the disasters and according to the magnitude of the earthquake and the resulting disruptions in facilities (destruction of temporary and permanent facilities), locating alternative facilities and temporary field hospitals and allocating them to the blood centers, collecting and delivering blood become the main priority.

The remainder of the paper is organized as follows. In Section 2, a review of previous researches conducted on the area of blood supply chain under normal and disaster situations is examined. In Section 3, the proposed problem is expressed and the design and formulation of the uncertain model are presented and then, the solution approach is presented. In Sections 4 and 5, the model is implemented and evaluated using real data of a case study in order to examine the application of the proposed model and the obtained results. Finally, the conclusion is presented in Section 6.

2. Literature Review

Over about two decades, plenty of researches has been done on blood supply chain management. In this part, papers related to this area are reviewed and classified based on the main characteristics of this study, including location efficiency, disaster intensity and hierarchical level. A list of such papers dealing with such characteristics in blood supply chain management is provided in Table 1.

Table 1. Reviewed researches

Refs.	Year	# of echelon	Hierarchical level	Blood products	Modeling approach	Objective function	Time period	Performance measure		Disaster/disruption	Disaster intensity	Field hospitals	Uncertainty approach	Solution method	Case study
									Location efficiency						
[6]	2010	3	PR	BC	INLP	S	S	C					ST	EX	*
[7]	2012	7	INT	WB/BC	ILP	S	S	C/OB/R					ST	EX	
[8]	2014	2	IN	BC	INLP/S	S	M	OB					ST	He	
[9]	2014	2	PR/IN/DI	WB	(M)INLP	B	S	C/COV/SH	*				-	He	*
[10]	2014	2	IN	BC	SDP	S	M	C/OB/SH					ST	He	
[1]	2014	3	CO	WB	MILP	S	M	C		*			RO	EX	*
[11]	2015	4	INT	BC	MILP	M	S	C/T					-	EX	
[12]	2015	1	INT	WB	S	-	-	-	*				-	EX	*
[13]	2016	2	IN	WB	S	S	M	F/OB/C/SH					ST	EX	
[14]	2017	4	INT	WB	TSSP	M	M	C/T		*			ST	EX	
[15]	2017	3	CO	BC	TSSP	S	M	C		*			RO	EX	*
[16]	2017	5	INT	BC	MILP	M	M	C/SH					FR	EX	*
[17]	2017	3	INT	WB	MILP/S	S	M	C					ST	EX	
[18]	2017	5	IN	BC	MILP	S	M	C		*			ST	EX	*
[19]	2018	4	CO/PR	BC	MIP	S	S	C					-	He	*
[20]	2018	3	IN/CO	WB	MILP	S	M	C/SH		*			RO	EX	
[21]	2018	4	INT	WB/BC	MINLP	B	M	C/F					ST	He	*
[22]	2018	4	CO/PR	BC	MILP	M	M	C/SH					RO	He	
[23]	2019	3	INT	WB	MILP	M	M	C/T		*	*		-	EX	*
[24]	2019	5	INT	WB	MILP	M	M	C/T/R		*			FR	EX	*
[25]	2019	2	IN/CO	BC	MILP	S	M	C					-	He	*
[26]	2019	2	IN	WB	SIP	S	M	C					-	He	
[27]	2019	4	INT	BC	TSSP	M	M	OB/C/T					ST	EX	*
[28]	2020	1	IN	BC	S(M)IP	S	M	C					-	EX	
[29]	2020	4	INT	BC	TSSP	B	M	C/T		*			RO	He	*
[30]	2020	2	INT	WB	MINLP	S	M	C		*			RO	He	*
[31]	2021	4	INT	WB	MILP	M	M	C/COV		*		*	RO	He	*

Refs.	Year	# of echelon	Hierarchical level	Blood products	Modeling approach	Objective function	Time period	Performance measure		Disaster/disruption	Disaster intensity	Field hospitals	Uncertainty approach	Solution method	Case study
									Location efficiency						
[32]	2021	4	IN	BC	TSSP	S	M	C					ST	EX	*
[33]	2021	2	IN	WB	TSSP	S	M	C					-	EX	
[34]	2021	3	IN	WB	MILP/S	M	M	F/T/SH					-	EX	*
[35]	2021	3	INT	BC	MILP	B	M	C/T		*			RO	EX	*
[36]	2022	6	INT	WB	MILP	M	M	C		*			FR	EX	*
[37]	2022	3	CO/PR/DI	WB	MILP	S	S	-		*				EX	*
[38]	2022	3	INT	BC	TSSP	M	M	F/T/SH		*			ST	He	*
[39]	2022	4	INT	WB	MILP	M	M	C/T		*			FR	EX	*
[40]	2022	4	INT	BC	MILP	M	M	C/EN						EX	*
[41]	2022	2	IN	BC	MINLP	S	S	C						He	*
Current research		4	INT	WB	MILP	B	M	C	*	*	*	*	RO	EX	*

Thanks to Asadpour et al [42], a review paper updated on the field of blood supply chain under a disaster perspective is available in examining the papers published in this issue. Moreover, a review literature from an optimization perspective, as well as a conceptual framework for planning the blood supply chain network through mathematical programming models have been investigated by Meneses et al [43]. Reviewing the studied papers in the field of blood supply chain design shows that only a few researchers have considered critical situations in their models, while most studies have considered normal circumstances due to being easygoing. Also, to the best of the authors' knowledge, the disruption severity, affected by the magnitude of the disaster (the earthquake), has been addressed only by Khalilpourazari and Arshadi [23] without considering the inherent uncertainty of such problems in crisis situations, while overlooking this matter may lead to mismanagement in crisis management.

For the sake of a considerable mismatch between available resources and blood demands during disasters under the infeasibility of expanding current capacity, "alternative" resources have been exploited by healthcare systems so as to boost their capacities. These systems enlist alternative hospitals like field hospitals to address the capacity challenge during crisis to mitigate the wastage and shortage. According to the review conducted in the area of blood supply chain, field hospitals have been considered only by a handful of articles while no one can deny the key role that such facilities plays during the crisis situation. Although Razavi et al. [31] did not overlook this important matter, they avoided taking into account the disaster intensity (destruction radius) which can affect the facility disruption assessment. Besides, an evaluation approach like the DEA method has not been applied by them for evaluating the candidate field facilities in order to select the best-fit locations.

Table 1 demonstrates that the efficiency to select the best-fit locations for facilities was ignored by most of the reviewed papers. In fact, the proper design of a supply chain affects significantly on the efficiency of each organization. A model will be expanded in certain and uncertain conditions when the efficiency is incorporated in the supply chain model. Therefore, in order to survive in the today's competitive world, an organization equipped with an efficient supply chain design is preferable to simple one. Hsieh [9] developed a bi-objective model considering two factors, such as efficiency for minimizing the system cost and coverage for responsiveness in the blood supply chain network. Zahraee et al. [12] optimized an integrated blood supply chain model through simulation method by considering efficiency to mitigate the system costs. However, in this paper we utilize the concept of efficiency for the best-fit location through taking advantage of the DEA model.

Moreover, most studies have overlooked the severity of disruption, which are resulted from the intensity of disaster or the destruction radius in times of crisis. It is hard to deny that disasters with different severity can lead to varied costs and losses. Therefore, in order to have an optimized supply chain in critical situations, it is suggested to consider the disaster intensity in the problem, especially the blood supply chain which is vital in times of crisis. Determining efficient locations for blood supply chain will be meaningless if the intensity of a disaster is not considered because the intensity undoubtedly plays a key role in the severity of disruption in potential locations. Indeed, without considering the disaster intensity (i.e. the magnitude of earthquake), the selected efficient locations are not efficient completely. Unfortunately, considering efficiency for location and disaster intensity simultaneously has remained quite intact in the literature.

A list of abbreviation to categorize the pertinent literature is provided in Table 2 in order to pinpoint the research gap and as a result of this, the main contributions of this research in the context of blood supply chain design are presented.

Having considered all the mentioned studies and their models, we believe that the gap is filled by considering the main contributions of this paper as follows:

- The probability and severity of disruptions influenced by the intensity of the earthquake is considered in temporary and permanent blood centers and field hospitals.

- As each earthquake fault can make varied disruptions according to its magnitude and its distance from facilities and residential area, the scenarios of the proposed model are considered based on the activation of faults.
- By considering the post-disasters probabilistic scenarios and using an augmented data envelopment analysis (DEA) approach, the efficiency of locations is evaluated and the most efficient locations for establishing blood donation facilities are determined.
- In order to handle the inherent uncertainty of the problem, P-robust and Bertsimas and Sim's approaches are utilized.
- The mathematical model of the problem has been implemented and validated on the data obtained from the Seismic Geophysics Institute of Iran related to the blood transfusion network of Mashhad, Iran (case study).

In this paper, the problem is investigated in two phases. According to the first phase, a potential location for establishing blood collection and donation centers is identified and then ranked based on the data envelopment analysis (DEA) method. In the second phase, location-allocation is implemented in the blood supply chain network design by considering the magnitude of the earthquake. In addition to providing the timely services to the injured in the times of a disaster, the main aim of this study is to minimize the supply chain's costs, such as establishment costs, blood shortages and wastage, etc.

Table 2. Abbreviations presented in Table 1.

Hierarchical level		**Time period**	
Integrated	INT	Single-period	S
Collection	CO	Multi-period	M
Production	PR	**Performance measure**	
Inventory	IN	Cost	C
Distribution	DI	Shortage	SH
Blood products		Outdated blood	OB
Blood components	BC	Freshness	F
Whole blood	WB	Time	T
Modelling approach		Risk	R
		Environmental	EN
Simulation	S	Coverage	COV
Stochastic dynamic programming	SDP	**Uncertainty approach**	
Stochastic integer programming	SIP	Fuzzy	FZ
Two-stage stochastic programming	TSSP	Stochastic	ST
(Mixed) integer linear programming	(M)ILP	Robust	RO
(Mixed) integer nonlinear programming	(M)INLP	Fuzzy-robust	FR
Objective function		**Solution method**	
Single-objective	S	Exact	EX
Bi-objective	B	(Meta)Heuristic	He
Multi-objective	M		

3. Problem description and mathematical modelling

We suppose there are "n" potential locations to establish collection centers and blood donation facilities and try to choose the best-fit sites for establishing facilities based on critical criteria such as social, geographical, technical equipment, coverage radius, etc. In addition to minimizing the cost of the problem, one of the main aims is to have the most efficient coverage (in terms of response time to the crisis or service provision) in the disaster areas in times of crisis. The problem is designed in two phases. In the first phase, using the data envelopment analysis (DEA) approach and based on the criteria mentioned above, the potential points for establishing the facilities are analyzed and then these points are scored and ranked by priority. At the end of the first phase, the places that have obtained the highest degree and have optimal performance for the establishment of facilities enter the second phase as input data. In the second phase, among the proposed efficient points, we apply a location-allocation scheme based on different scenarios in critical situations in order to respond to hospital demands. Due to dealing with uncertainty in the parameters of the problem, mathematical modelling in the second phase is based on a robust optimization approach. The framework of the two-phase approach to this problem is shown in Figure 2.

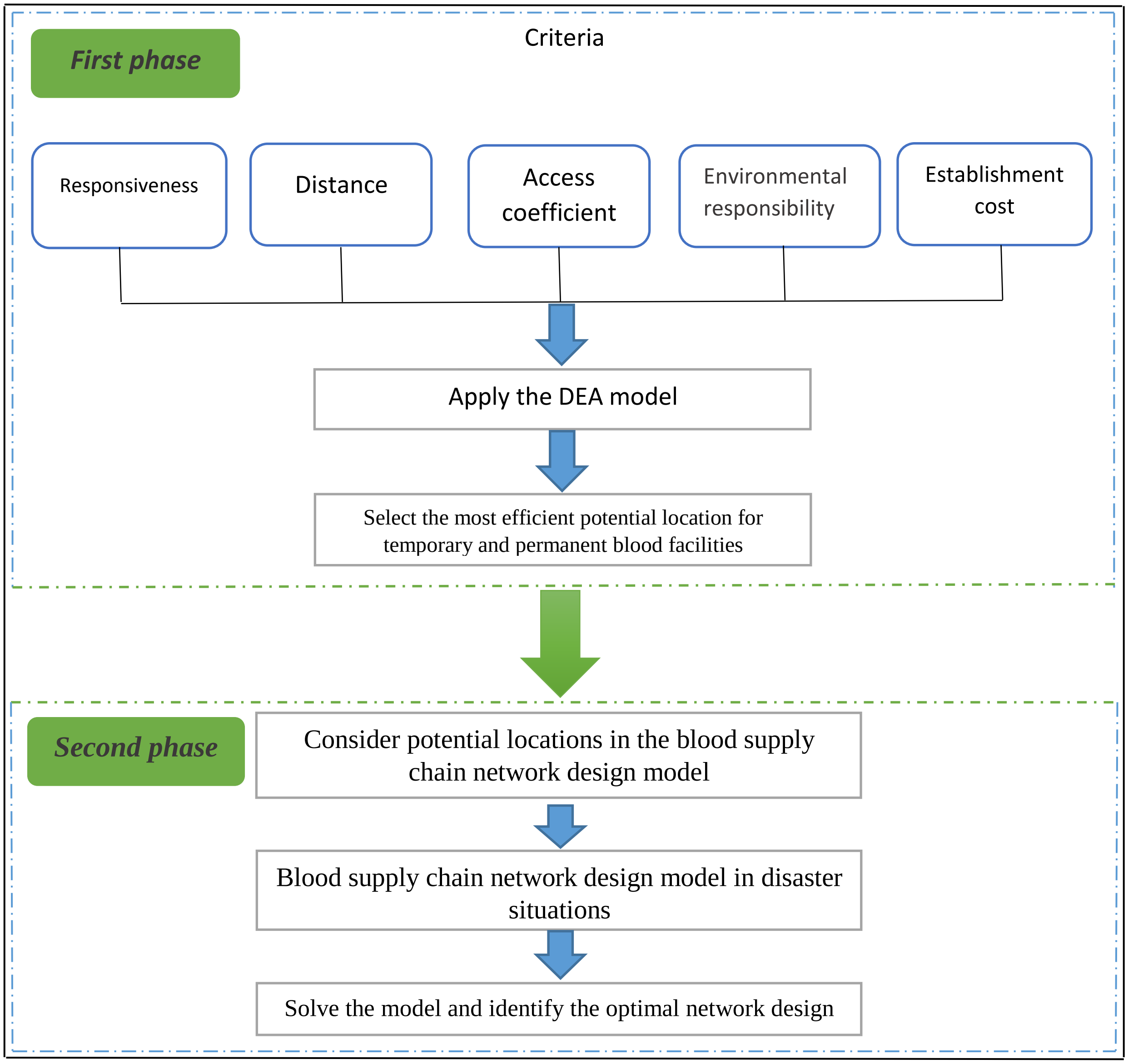

Figure 2. Structure of the proposed two-phase approach

3.1. First phase (Identification of the potential locations for temporary and permanent facilities)

3.1.1. DEA-based model for situating the efficient locations (*objective function I*)

The DEA model was initially introduced by Charnes and et al. (CCR[3] model) [44] and later developed by Bunker and et al. (BCC[4] model) [45]. This method, which is an approach based on mathematical modelling so as to evaluate the efficiency of decision-making units (DMU), defines and operates the relative efficiency of these homogeneous units upon the ratio of outputs to inputs. This method is a powerful tool for determining the relative technical efficiency and uses operational research techniques to calculate the weights assigned to inputs and outputs and determine the efficiency rate. In this research, we consider the candidate locations for permanent and temporary blood distribution centers to be the DMUs and drive the input and output factors for each facility based on the perspective and knowledge of the experts. Due to the fact that this method covers all data, it is known as data envelopment analysis (DEA). In this strategy, the efficiency of each option is evaluated compared to other options, and the relative efficiency of each option is obtained by the ratio of the efficiency of the option to the highest efficiency [46]. A DMU (a candidate location) is considered efficient if the efficiency of the DMU is equal to 1. One of the advantages of relative efficiency is that one of the options has always the efficiency equal to 1. The efficiency score of the oth DMU (the efficiency of the candidate locations for permanent and temporary blood distribution centers), Θ_o, can be calculated by solving the following linear fractional DEA formulation.

$$\text{Max } \Theta_o = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}} \tag{1}$$

$$\begin{aligned} & s.t. = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad \forall j, \\ & u_r \geq 0,\ v_i \geq 0, \end{aligned} \tag{2}$$

Where

$i = 1, \dots, m$ inputs used at DMU,

$r = 1, \dots, s$ outputs produced at DMU,

$j = 1, \dots, o, \dots, n$ DMUs.

Parameters:

y_{rj}: the actual value of the rth output for the jth DMU,

x_{ij}: the actual value of the ith output for the jth DMU.

Decision variables:

u_r: the weight assigned to the rth output,

v_i: the weight assigned to the ith input.

Indeed, when we cannot obtain a certain weight for inputs and outputs, we need to utilize the DEA model to determine a common set of weights so that all units simultaneously took the maximum efficiency score. Because of the nonlinear nature of the above model, the following linear model, called

[3] Charnes, A., Cooper, W. W., & Rhodes, E.

[4] Banker, R. D., Charnes, A., & Cooper, W. W.

the Input-axis CCR model, is obtained by performing a math process so as to calculate the relative weights of inputs and outputs. In the input-axis models, while output amounts are retained at the given level, the inputs are reduced as much as possible.

$$Max\ \Theta_o = \sum_{r=1}^{s} u_r y_{ro} \tag{3}$$

$$s.t.\quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \qquad j = 1, \dots, n \tag{4}$$

$$\sum_{i=1}^{m} v_i x_{io} = 1, \tag{5}$$

$$u_r \ge 0, \qquad r = 1, \dots, s \tag{6}$$

$$v_i \ge 0, \qquad i = 1, \dots, m \tag{7}$$

The objective function shows the sum of the efficiency of the candidate locations for permanent and temporary blood distribution centers, which must be maximized.

To evaluate the efficiency of the location of temporary and permanent blood donation centers through the DEA model, we consider spatial and descriptive data of potential facilities to introduce inputs and outputs according to experts' knowledge. In applying the DEA strategy, identifying single indicators as inputs and outputs data is very important for the accuracy of the final result; hence, the input and output indicators are presented in the case section according to the case's features.

3.1.2. The criteria for input and output

In this part, some criteria are introduced to contribute decisions on the sites of blood centers and field hospitals based on the way described earlier. Such criteria are divided to two classes: inputs and outputs. While we try to increase the outputs, the inputs are aimed to be decreased. In this paper, a DMU is represented by each potential location for blood centers. Due to having different tasks and responsibilities, the most significant criteria are taking into account for each centers as follows:

3.1.2.1. Input parameters

- Establishment cost

The establishment cost parameter is determined based on the number of equipment and staff, the facilities capacity and the estimation of blood donors visiting each temporary and permanent facility.

- Potential environmental pollution

Facilities should be established in places where the burning and burial of waste blood does not lead to various diseases around the area; this parameter is extracted from the Environmental Organization using environmental information.

3.1.2.2. Output parameters

- Access coefficient

The more the number of visits and access to permanent and temporary facilities, the more appropriate the facility's location. The number of donors visiting each facility indicates their capacity and response rate in disaster situations. Absolutely, a facility with more donors is more efficient than a facility with fewer donors and has a higher priority for resource allocation. To obtain this parameter, the donors information in each facility is extracted from the relevant organization.

- Distance (the proximity to disaster regions)

In order to have quick and timely access to facilities in critical situations and timely delivery of blood products to earthquake victims, the location of temporary and permanent centers is of great importance. The location of the facilities should be as close as possible to the place of the disaster, although they should not be too close to the earthquake center to create disruption and interruption in services. Therefore, to assess the usefulness of the current position of the facility in terms of proximity to earthquake events, we apply the average distance of earthquake faults from its potential facilities.

- Responsiveness (The operation speed of the staff and equipment of the facilities)

The location and conditions of the temporary and permanent facility should be in such a way that after the shortest time since the earthquake, the staff should be deployed at the facilities and take suitable action to help the injured. The most important issue in the arrival time is related to the location of the facility, and other key factors include the events communication systems, the number of operational teams, the operation speed of the staff and equipment of the facilities, etc. Our intention is to maximize factors affecting the shipping time of blood units. Since lots of effective parameters are hidden in the time parameter, this parameter can be a good indicator to evaluate the performance and efficiency of a facility.

3.2. Second phase (blood supply chain network design in disaster situations)

Due to living in a rapidly changing world, our knowledge of the future is limited; therefore, even if we have access to past information, there are many uncertainties in the real world. In order to having no information and knowledge about the uncertain parameters, we utilize a robust optimization model to deal with the inherent uncertainty of the problem. Rahimian and Mehrotra [47] investigated the main concept of Robust Optimization (RO) and scrutinized different models applied in robust optimization to cope with the uncertainty in various problems. In this part, along with existing uncertainties in the proposed model, a p-robust model presented by Snyder and Daskin [48] is utilized to set the reliable performance of the problem under disruptions.

3.2.1. P-robust model

In some problems, it is aimed to identify a regret limit for each of the possible scenarios. To set p-robustness in the proposed problem, we consider $p > 0$ as the indication of the desired robustness level, limiting the maximum relative regret for each scenario. For lower-probability scenarios, a greater amount of regret is considered. For each scenario, consider its optimal value, Z_s^*, and the value of the objective function under p is its robust mode defined as follows:

$$Z_s^*(x) - Z_s^* \leq (1 + p)Z_s^* \tag{8}$$

The left side of the equation shows a relative regret for each scenario s which is limited by the maximum value $(1 + p)$ [48]. Now, we can incorporate this model into the proposed model.

3.2.2. Second phase definition (*objective function II*)

The proposed blood supply chain (Figure 3) contains four main echelons, including supply points (blood donors), blood donation facilities (existing and potential temporary and permanent facilities), blood centers and demand points (existing and potential hospitals), under different disaster scenarios. In addition to minimizing the costs, we try to avoid shortages as much as possible. Then the blood units are collected at the facilities to be transferred to the blood centers in order to perform the necessary tests and separate healthy and unhealthy blood from each other. After receiving orders from health centers and hospitals after the disaster, blood and its products are transmitted to these points.

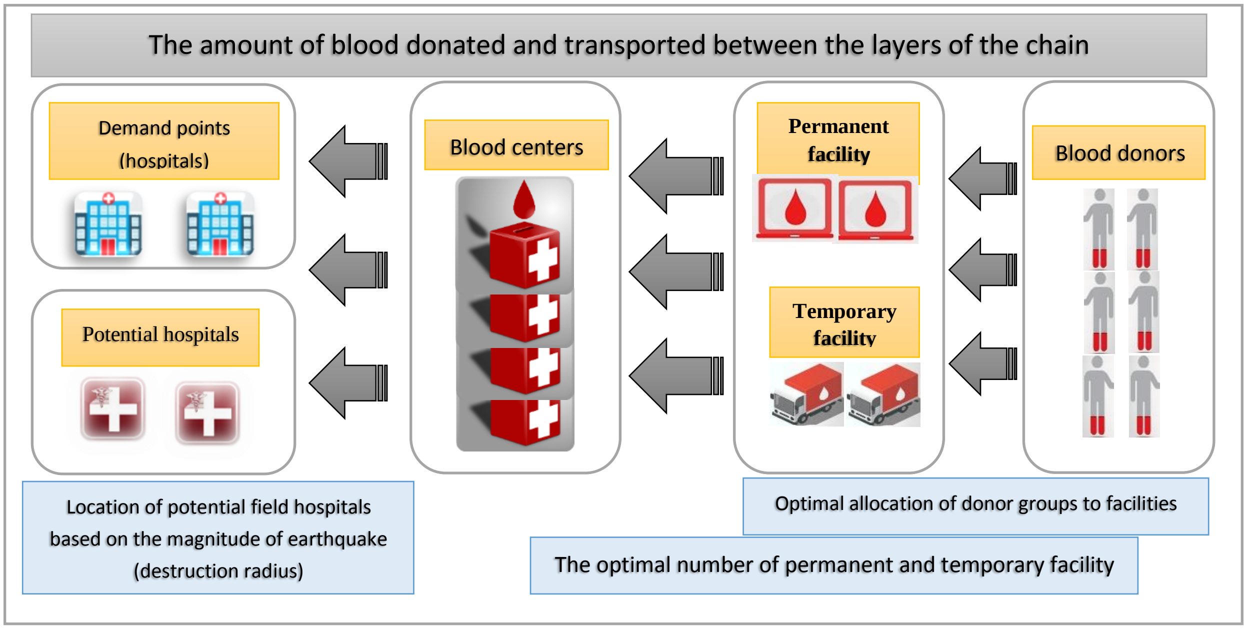

Figure 3. The proposed blood supply chain

The most important part of the supply chain is facilities and their locations. Determining the most suitable locations and allocating donors to them in a disaster situation is effective in increasing the efficiency of the chain. The uncertainty in the location of the blood donation centers (temporary and permanent) during the crisis and its inaccessibility resulting from the intensity of the earthquake makes the decision makers of this area obtain the number and location of the optimal establishment by considering all possible scenarios. Therefore, determining the most suitable location and allocating donors to these facilities with probable scenarios is the main subject that has been addressed in this study. After the earthquake, we will face a sharp increase in the demand for blood. For a more accurate evaluation, we divide this time into four periods. The first period is 0-24 hours, the second period is 24-72 hours, the third period includes the next 72 hours and the last period is next week; The demand in the third and fourth periods is more than in the two former periods.

Other assumptions are as follows:

1. The distance between every two different echelons of the chain is considered as a direct distance.
2. The model is based on only one single product, the blood.
3. The capacity of each temporary and permanent facility, blood centers and hospitals (whether existing or potential) is limited and determined.
4. Blood demand changes with different scenarios (uncertain demand).
5. The model is considered a multi-period for a post-disaster short-term planning horizon and is also available for the mid-term and long-term planning horizon.
6. Disruption in the location of the facilities (temporary and permanent) is independent of each other according to different scenarios.
7. All facilities (temporary and permanent) are vulnerable to disaster. When the disruption occurs at the establishment location of a facility, the facility becomes out of service. In other words, the facility's capacity in the region becomes zero.

In this section, according to the described problem, the sets, parameters, and variables of the model are defined as follows:

sets

i	Set of blood donation groups
j	Set of candidate location of a temporary blood collection facility
K	Set of existing locations of a permanent blood collection facility
f	Set of candidate locations of a permanent blood collection facility (Before disaster: establishment; After disaster: contains the establishment of multiple temporary facilities)
n	Set of blood centers
m	Set of existing hospitals
l	Set of field hospitals
t	Set of time periods
s	Set of scenarios (according to the occurrence of the disaster)
$y = k \cup f$	Set of permanent facilities
$h = m \cup l$	Set of hospitals

Parameters

ff_j^s	Establishment cost of blood temporary facility j under scenario s
pp_y^s	Establishment cost of blood permanent facility y under scenario s
v_l^s	Establishment cost of field hospital l under scenario s
C	Testing cost of each blood unit at the blood center
U	Holding cost of each blood unit at the blood center
WW	Transportation cost of blood units (per km)
B'	Shortage cost of each blood unit
dd^{ts}	Demand of centers at period t under scenario s
d_{jn}	Distance between temporary facility j and blood center n
d'_{yn}	Distance between permanent facility y and blood center n
$d"_{nh}$	Distance between blood center n and hospital h
VV	Capacity of the vehicle for transporting blood units
dc_j^{ts}	Capacity of temporary facility j in time period t under scenario s
LC_y^{ts}	Capacity of permanent facility y in time period t under scenario s
cbb_n^t	Capacity of blood center n in period t
ac_l^{ts}	Capacity of field hospital l in period t under scenario s
ac'^{ts}_m	Capacity of existing hospital m in period t under scenario s
E	Earthquake magnitude
dis_j^s	Distance between blood temporary facility j and the earthquake's epicenter under scenario s
dis'^s_y	Distance between blood permanent facility y and the earthquake's epicenter under scenario s
ε_1	The destruction radius of an earthquake with 5–6 Richter magnitude
ε_2	The destruction radius of an earthquake with 6–7 Richter magnitude
ε_3	The destruction radius of an earthquake with 7–8 Richter magnitude
ε_4	The destruction radius of an earthquake with 8–9 Richter magnitude
β	The percentage of blood used after operating in the blood center
λ	Minimum satisfying level of blood demand
α	The percentage of injured people requiring blood
p_s	The probability of happening scenario s
MM	A very large positive number

Binary variables

x_j^s	Equal to 1 if temporary blood collection facility is established at location j and not disturbed under scenario s; and 0 otherwise
x'^s_y	Equal to 1 if permanent blood collection facility is established at location y and not disturbed under scenario s; and 0 otherwise
b_l^s	Equal to 1 if field hospital is established at location l under scenario s; and 0 otherwise
$Z1_{ij}^{ts}$	Equal to 1 if donation group i is assigned to a temporary collection facility at location j in period t under scenario s; and 0 otherwise
$Z2_{iy}^{ts}$	Equal to 1 if donation group i is assigned to a temporary collection facility at location y in period t under scenario s; and 0 otherwise
$Z3_{nl}^{ts}$	Equal to 1 if blood center n is assigned to an field hospital in location l in period t under scenario s; and 0 otherwise
$Z4_{nm}^{ts}$	Equal to 1 if blood center n is assigned to an existing hospitals in location m in period t under scenario s; and 0 otherwise
w_1	Equal to 1 if the magnitude of an earthquake is 5–6 Richter; and 0 otherwise
w_2	Equal to 1 if the magnitude of an earthquake is 6–7 Richter; and 0 otherwise
w_3	Equal to 1 if the magnitude of an earthquake is 7–8 Richter; and 0 otherwise
w_4	Equal to 1 if the magnitude of an earthquake is 8–9 Richter; and 0 otherwise

Positive variables

Q_{ij}^{ts}	The amount of whole blood collected from donor group i at blood temporary facility j in period t under scenario s
Q'^{ts}_{iy}	The amount of whole blood collected from donor group i at blood permanent facility y in period t under scenario s
s_{jn}^{ts}	The amount of whole blood transported from blood temporary facility j to blood center n in period t under scenario s
s'^{ts}_{yn}	The amount of whole blood transported from blood permanent facility y to blood center n in period t under scenario s
$s"^{ts}_{nl}$	The amount of whole blood transported from blood center n to field hospital l in period t under scenario s
s'''^{ts}_{nm}	The amount of whole blood transported from blood center n to existing hospitals m in period t under scenario s
R_n^{ts}	Inventory level of whole blood at blood center n in time period t under scenario s
B_t^s	Shortage level of whole blood in period t under scenario s

3.2.3. Cost measure (*objective function II*)

The ideal state of any blood supply chain is to have sufficient temporary and permanent facilities in different locations and to store enough blood to avoid blood shortages in hospitals. However, since there is always a budget constraint, we need to plan ahead to minimize costs along with an adequate blood supply. Therefore, the objective function of the problem is to minimize the total costs ($TOTC$[5]) ;including the cost of opening temporary facilities, the cost of opening and establishing permanent facilities and the cost of opening field hospitals (fixed costs FC[6]), the cost of testing and processing blood products in blood centers

[5] Total Costs

[6] Fixed Costs

(TC[7]), inventory cost (IC[8]), The cost of collecting blood units from facilities (temporary and permanent) to blood centers and the cost of distributing blood from blood centers to hospitals (existing and potential) (CDC[9]), and shortage cost (SC[10]).

$$FC_s = \sum_s p_s \left(\sum_j ff_j^s \, x_j^s + \sum_y pp_y^s \, x'^s_y + \sum_l v_l^s \, b_l^s\right) \tag{9}$$

$$TC_s = \sum_s p_s \left(C \times \left(\sum_{j,n,t} s_{jn}^{ts} + \sum_{y,n,t} s'^{ts}_{yn}\right)\right) \tag{10}$$

$$IC_s = \sum_s p_s \left(U \times \sum_{n,t} R_n^{ts}\right) \tag{11}$$

$$CDC_s = \sum_s p_s \left(\sum_t \left[WW \times \left(\sum_{j,n} d_{jn} \left[\frac{\sum_j s_{jn}^{ts}}{VV}\right] + \sum_{y,n} d'_{yn} \left[\frac{\sum_y s'^{ts}_{yn}}{VV}\right] + \sum_{n,h} d''_{nh} \left[\frac{\sum_n (s''^{ts}_{nl} + s'''^{ts}_{nm})}{VV}\right]\right)\right]\right) \tag{12}$$

$$SC_s = \sum_s p_s \left(B' \times \sum_t B_t^s\right) \tag{13}$$

The objective function is expressed for each scenario S, and the optimal value of the objective function is called $TOTC_S^*$. According to the P-Robust model, the impact of each scenario should include the optimal blood supply chain structure.

$$TOTC_s = FC_s + TC_s + IC_s + CDC_s + SC_s \tag{14}$$

$$\sum_j Z1_{ij}^{ts} + \sum_y Z2_{iy}^{ts} \leq 1 \qquad \forall i, t, s \tag{15}$$

$$\sum_i Q_{ij}^{ts} \leq dc_j^{ts} \qquad \forall j, t, s \tag{16}$$

$$\sum_i Q'^{ts}_{iy} \leq LC_y^{ts} \qquad \forall y, t, s \tag{17}$$

$$E \geq 5w_1 + 6w_2 + 7w_3 + 8w_4 \tag{18}$$

$$E \leq 6w_1 + 7w_2 + 8w_3 + 9w_4 \tag{19}$$

$$w_1 + w_2 + w_3 + w_4 = 1 \tag{20}$$

$$dis_j^s \geq (\varepsilon_1 w_1 + \varepsilon_2 w_2 + \varepsilon_3 w_3 + \varepsilon_4 w_4) x_j^s \qquad \forall j, s \tag{21}$$

$$dis'^s_y \geq (\varepsilon_1 w_1 + \varepsilon_2 w_2 + \varepsilon_3 w_3 + \varepsilon_4 w_4) x'^s_y \qquad \forall y, s \tag{22}$$

$$Z1_{ij}^{ts} \leq x_j^s \qquad \forall i, j, t, s \tag{23}$$

$$Z2_{iy}^{ts} \leq x'^s_y \qquad \forall i, y, t, s \tag{24}$$

---

[7] Test Cost

[8] Inventory Cost

[9] Collection and Distribution Costs

[10] Shortages Cost

$$Z3_{nl}^{ts} \leq b_l^s \qquad \forall n,l,t,s \qquad (25)$$

$$\sum_i Q_{ij}^{ts} = \sum_n s_{jn}^{ts} \qquad \forall j,t,s \qquad (26)$$

$$\sum_i Q'^{ts}_{iy} = \sum_n s'^{ts}_{yn} \qquad \forall y,t,s \qquad (27)$$

$$\sum_j s_{jn}^{ts} + \sum_y s'^{ts}_{yn} \leq cbb_n^t \qquad \forall n,t,s \qquad (28)$$

$$Q_{ij}^{ts} \leq MM \times Z1_{ij}^{ts} \qquad \forall\, i,j,t,s \qquad (29)$$

$$Q'^{ts}_{iy} \leq MM \times Z2_{iy}^{ts} \qquad \forall i,y,t,s \qquad (30)$$

$$s"^{ts}_{nl} \leq MM \times Z3_{nl}^{ts} \qquad \forall n,l,t,s \qquad (31)$$

$$s'''^{ts}_{nm} \leq MM \times Z4_{nm}^{ts} \qquad \forall n,m,t,s \qquad (32)$$

$$\left(\left(\sum_j s_{jn}^{ts} + \sum_y s'^{ts}_{yn}\right) \times \beta\right) + R_n^{t-1,s} - \left(\sum_{n,l} s"^{ts}_{nl} + \sum_{n,m} s'''^{ts}_{nm}\right) = R_n^{ts} \qquad \forall n,t,s \qquad (33)$$

$$\sum_n s"^{ts}_{nl} \leq ac_l^{ts} \qquad \forall l,t,s \qquad (34)$$

$$\sum_n s"^{ts}_{nm} \leq ac'^{ts}_m \qquad \forall m,t,s \qquad (35)$$

$$\left(\sum_{n,l} s"^{ts}_{nl} + \sum_{n,m} s'''^{ts}_{nm}\right) + B_t^s \geq dd^{ts} \times \alpha \qquad \forall t,s \qquad (36)$$

$$\left(\sum_{n,l} s"^{ts}_{nl} + \sum_{n,m} s'''^{ts}_{nm}\right) \geq \lambda \times (dd^{ts} \times \alpha) \qquad \forall t,s \qquad (37)$$

$$FC_s + TC_s + IC_s + CDC_s + SC_s \leq (1+\varphi)TOTC_s^* \qquad \forall s \qquad (38)$$

$$x_j^s, x'^s_k, b_l^s, Z1_{ij}^{ts}, Z2_{ik}^{ts}, Z3_{nl}^{ts}, Z4_{nm}^{ts}, w_1, w_2, w_3, w_4, w_5 \in [0,1] \qquad (39)$$

$$Q_{ij}^{ts}, Q'^{ts}_{ik}, s_{jn}^{ts}, s'^{ts}_{kn}, s"^{ts}_{nl}, s'''^{ts}_{nm}, R_n^{ts}, B_t \geq 0 \;\&\; int \qquad (40)$$

The objective function (14) is the p-robust model considering all the scenarios $s \in S$. Constraint (15) ensures that the donors of each demographic area are allocated to only one type of facility (temporary or permanent). Constraints (16) and (17) show that the amount of blood collected in a temporary or permanent facility in each period must be less than or equal to the capacity of that facility. Constraints (18)-(22) indicate the damages (disruption) caused by the earthquake for temporary and permanent blood facilities based on its magnitude. Constraints (23) and (24) represent that donors are allocated to a temporary or permanent blood collection facility if such facilities are established and not out of reach. Constraint (25) shows that a blood bank is assigned to a potential hospital only when the hospital is established. Constraints (26) and (27) indicate that the amount of blood collected in the temporary or permanent facilities has to be equal to the amount of blood transmitted from the facilities to the blood centers. Constraint (28) indicates that the total blood transmitted to a blood center should not exceed the capacity of the blood center. Constraints (29) and (30) indicate that donors donate their blood to temporary and permanent facilities if there is an allocation between them. Constraints (31) and (32) state that if the blood centers are assigned to the hospitals, blood will be transferred from the blood centers to the potential or existing hospitals. Constraint (33) 33 shows the amount of blood stored at the end of each period, which is equal to the amount of blood processed and the inventory of the previous period minus the amount of blood sent to medical centers. Constraints (34) and (35) express that the quantity of blood transmitted to each medical center has to be compatible with the capacity of those centers. 36 shows the demand for blood, which is either met by blood centers or faced with a shortage. Constraint (37) indicates that the quantity of replied blood demand should never be less than a percentage of the demand. Constraint (38) expresses that for each scenario, costs cannot exceed $100(\varphi+1)\%$ optimal cost $TOTC_s^*$ (the value of p is related to the necessity of the scenario). Constraints (39) and (40) specify binary and integer variables.

3.2.4. Linearization

As the presented formulation is nonlinear as a result of the multiplication of binary and continuous variables in constraints (21) and (22), these constraints can be converted to their linear forms as follows:

$$dis_j^s \geq \left(\varepsilon_1 LL1_j^s + \varepsilon_2 LL2_j^s + \varepsilon_3 LL3_j^s + \varepsilon_4 LL4_j^s\right) \qquad \forall j,s \qquad (41)$$

$$LL1_j^s \leq w_1 \qquad \forall j,s \qquad (42)$$

$$LL2_j^s \leq w_2 \qquad \forall j,s \qquad (43)$$

$$LL3_j^s \leq w_3 \qquad \forall j,s \qquad (44)$$

$$LL4_j^s \leq w_4 \qquad \forall j,s \qquad (45)$$

$$LL1_j^s + LL2_j^s + LL3_j^s + LL4_j^s \geq x_j^s \qquad \forall j,s \qquad (46)$$

$$dis'^s_y \geq \left(\varepsilon_1 LL5_y^s + \varepsilon_2 LL6_y^s + \varepsilon_3 LL7_y^s + \varepsilon_4 LL8_y^s\right) \qquad \forall y,s \qquad (47)$$

$$LL5_y^s \leq w_1 \qquad \forall y,s \qquad (48)$$

$$LL6_y^s \leq w_1 \qquad \forall y,s \qquad (49)$$

$$LL7_y^s \leq w_1 \qquad \forall y,s \qquad (50)$$

$$LL8_y^s \leq w_1 \qquad \forall y,s \qquad (51)$$

$$LL5_y^s + LL6_y^s + LL7_y^s + LL8_y^s \geq x'^s_y \qquad \forall y,s \qquad (52)$$

3.2.5. Bertsimas & Sim model for robust optimization (B&S model)

In order to consider this uncertainty and to keep the answer justified (Simultaneously adjusting the uncertain parameters and controlling the linearity of the model), we apply linear programming presented by Bertsimas and Sim [49] as follows:

$$Min \sum_j c_j x_j$$
$$s.t{:}\ \sum_j a_{ij} x_j \geq b_i, \qquad \forall i \qquad (53)$$
$$x_j \geq 0, \qquad \forall j$$

Without ignoring the generality of the problem, we assume that the matrices a and c contain uncertain data and vector b contains deterministic numbers. The coefficients of $a_{ij}, j \in N$ are given as independent random variables, with symmetric and bounded distributions $\hat{a}_{ij}, j \in N$ in the interval $[a_{ij} - \hat{a}_{ij}, a_{ij} + \hat{a}_{ij}]$, and each $c_j, j \in N$ in interval $[c_j, c_j + d_j]$ takes a value, which d_j represents the deviation from the nominal cost coefficient c_j. Also, symmetry is the only assumption for the distribution of coefficient a_{ij}. In order to achieve a feasible robustness answer, we define a new parameter $\Gamma_i, i = 0,1, \dots, m$, which takes a value in the interval $[0, |J_i|]$ since $|J_i|$ is equal to the number of uncertain data in constraint ith. The role of parameter Γ_i in constraints is to set the robust level against the conservatism level of the answer. Parameter Γ_0 controls the level of robustness for the objective function. Therefore, Bertsimas & Sim model is converted as follows:

$$Min \sum_j c_j x_j$$
$$s.t{:}\ \sum_j a_{ij} x_j - \lambda_i \Gamma_i - \sum_{j \in J_i} \mu_{ij} \geq b_i, \qquad \forall i$$
$$\lambda_i + \mu_{ij} \geq \hat{a}_{ij} x_j, \qquad \forall i, j \in J_i \qquad (54)$$
$$\mu_{ij} \geq 0, \qquad \forall i, j \in J_i$$
$$\lambda_i \geq 0, \qquad \forall i$$
$$x_j \geq 0, \qquad \forall j$$

, which λ_i and μ_{ij} are dual auxiliary variables.

In this section, a robust optimization of the deterministic model is considered for demand and cost parameters. Cost parameters include the cost of opening blood temporary facilities, the cost of opening and establishing blood permanent facilities, the cost of establishing field hospitals, and the cost of shortage. Uncertain parameters ff_j^s, pp_y^s, v_l^s, $B'$and dd^{ts} with symmetric and bounded distribution are within the range of nominal value $\overline{ff}_j^s$, $\overline{pp}_y^s$, $\bar{v}_l^s$, $\overline{B'}$ and $\overline{dd}^{ts}$ and the maximum value of $\widehat{ff}_j^s$, $\widehat{pp}_y^s$, $\hat{v}_l^s$, $\widehat{B'}$ and $\widehat{dd}^{ts}$. We assume that only positive deviations in the above parameters are allowed. The robust optimization form is modelled as follows:

parameters

Γ^0	Uncertainty coefficients of nominal value including costs
Γ^{ts}	Uncertainty coefficients of nominal value including demand in each period

variables

$\mu_j^{s\,ff}$	Dual variables related to initial linear optimization constraints

$\mu_y^{s\,pp}$	Dual variables related to initial linear optimization constraints
$\mu_l^{s\,v}$	Dual variables related to initial linear optimization constraints
$\mu^{B'}$	Dual variables related to initial linear optimization constraints
λ^0	Dual variables related to initial linear optimization constraints

$$\begin{aligned} Min\ Z = & \sum_s p_s \Big(\sum_j \overline{ff}_j^s x_j^s + \sum_k \overline{pp}_y^s x'^s_y + \sum_l \bar{v}_l^s b_l^s + \\ & C \times \left(\sum_{j,n,t} s_{jn}^{ts} + \sum_{y,n,t} s'^{ts}_{yn} \right) + U \times \sum_{n,t} R_n^{ts} + \\ & \sum_t \left[WW \times \left(\sum_{j,n} d_{jn} \left[\frac{\sum_j s_{jn}^{ts}}{VV} \right] + \sum_{y,n} d'_{yn} \left[\frac{\sum_y s'^{ts}_{yn}}{VV} \right] + \sum_{n,h} d''_{nh} \left[\frac{\sum_n (s''^{ts}_{nl} + s'''^{ts}_{nm})}{VV} \right] \right) \right] + \\ & \overline{B'} \times \sum_t B_t^s + \lambda^0 \Gamma^0 + \sum_{j,s \in J^{ff}} \mu_j^{s\,ff} + \sum_{y,s \in J^{pp}} \mu_y^{s\,pp} + \sum_{l,s \in J^v} \mu_l^{s\,v} + \mu^{B'} \end{aligned} \tag{55}$$

s.t.

constraints (15-35) and (38-40)

$$\left(\sum_{n,l} s''^{ts}_{nl} + \sum_{n,m} s'''^{ts}_{nm} \right) + B_t^s = \left(\overline{dd}^{ts} + \Gamma^{ts} \widehat{dd}^{ts} \right) \times \alpha \qquad \forall t, s \tag{56}$$

$$\left(\sum_{n,l} s''^{ts}_{nl} + \sum_{n,m} s'''^{ts}_{nm} \right) \geq \lambda \times \left(\left(\overline{dd}^{ts} + \Gamma^{ts} \widehat{dd}^{ts} \right) \times \alpha \right) \qquad \forall t, s \tag{57}$$

$$\mu_j^{s\,ff} + \lambda^0 \geq \widehat{ff}_j^s x_j^s \qquad \forall j, s \in J^{ff} \tag{58}$$

$$\mu_y^{s\,pp} + \lambda^0 \geq \widehat{pp}_y^s x'^s_y \qquad \forall y, s \in J^{pp} \tag{59}$$

$$\mu_l^{s\,v} + \lambda^0 \geq \hat{v}_l^s b_l^s \qquad \forall l, s \in J^v \tag{60}$$

$$\mu^{B'} + \lambda^0 \geq \widehat{B'} \times B_t^s \qquad \forall t, s \tag{61}$$

$$\mu_j^{s\,ff} \geq 0 \qquad \forall j, s \in J^{ff} \tag{62}$$

$$\mu_y^{s\,pp} \geq 0 \qquad \forall y, s \in J^{pp} \tag{63}$$

$$\mu_l^{s\,v} \geq 0 \qquad \forall l, s \in J^v \tag{64}$$

$$\mu^{B'} \geq 0 \tag{65}$$

$$\lambda^0 \geq 0 \tag{66}$$

Constraints (15-35) and (38-40) are the same as in the previous model. The objective function of the presented model is converted to the function (55). Constraints (36) and (37) have been turned into constraints (56) and (57). The constraints (58)-(66) are added to the model based on the Bertsimas and Sim robust optimization.

4. The case study

Iran is very susceptible to seismic hazards because of its geographical location on the Himalayan Alpine earthquake belt. In the last 100 years, about 3500 earthquakes occurred in the Iranian zone, among which

530 earthquakes with a magnitude greater than 4 on the Richter scale took place, which have left a large number of casualties and extensive economic losses. The main concern during and after the earthquake is to provide timely, sufficient blood to mitigate the dire consequences.

The case study of this paper is Mashhad city, the second most populous and the second largest metropolis of Iran with an area of over 328 km^2., the capital of Khorasan Razavi province, is composed of 13 districts with a population of 3371177. It is located in the northeast of Iran, 59 ° 15 'to 60 ° 36' longitude, 35 ° latitude and 43 ° Minutes to 37 degrees and 8 minutes (Fig. 4 and Table 3).

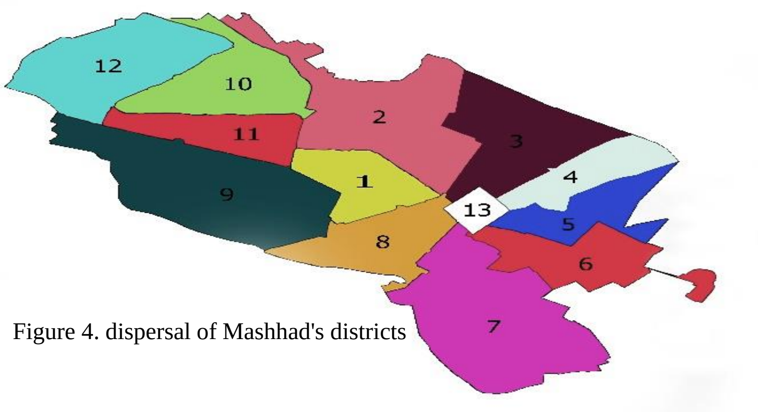

Figure 4. dispersal of Mashhad's districts

Table 3. The rank of regions of Mashhad city in terms of population, area, risk level and earthquake vulnerability

District	population	Population ranking	percentage of the city	Area ranking	Risk ranking
D1	167013	10	5.18	9	6
D2	513365	1	11.23	3	2
D3	417950	2	8.99	4	11
D4	262184	5	4.64	12	10
D5	175603	9	4.86	11	12
D6	232616	7	5.07	10	9
D7	253236	6	16.91	1	8
D8	92543	12	5.57	7	7
D9	327061	3	15.35	2	1
D10	296823	4	7.98	5	5
D11	200161	8	5.45	8	4
D12	105263	11	7.47	6	3
D13'Samen'	13861	13	1.23	13	13

Today, the investigation and recognition of active faults can be a basis for presenting analyzes consistent with reality. Mashhad, with high seismicity potential, 23 km length and unfavorable urban conditions, such as the scattering of worn-out structures, the instability of buildings and the proximity to active faults, faces very complex conditions when severe earthquakes occur. Among the faults scattered in Mashhad, four faults in the south of Mashhad-Chenaran, the north of Mashhad-Toos, Shandiz-Sangbast fault and Kashfrud fault are the closest faults to Mashhad, the activity of each of which leads to an intense and destructive shake. In general, Mashhad is one of the cities where the relative risk of earthquakes is high. For example, from 1900 to 1990, a total of nine earthquakes shook the city; six earthquakes with a magnitude of 5 to 5.5 on the Richter scale, two earthquakes with 5-6 Richter and one earthquake with a magnitude more than 6 Richter [50]. Also, after severe earthquakes, casualties are inevitable, and the demand for blood increases. For better relief, it is necessary to create facilities in more efficient places so that these centers do not get disrupted.

Mashhad Blood Transfusion Center started working at the same time as the Central Organization was established in Tehran in 1953. Now, after more than 44 years, Mashhad has five permanent facilities, one temporary facility, and two blood bank centers, which are responsible for receiving and collecting blood in the city.

The Blood Transfusion Organization (Blood Bank) of Mashhad is responsible for meeting the blood demands of medical centers and hospitals after receiving blood, testing and storing the required blood. There are 30 hospitals and health centers in the city of Mashhad, and the central blood banks are obliged to supply the blood they need. In order to meet the demands on time, the Blood Transfusion Organization aims how to locate and establish temporary and permanent facilities in the candidate regions.

The assumptions for the case study are presented as follows:

1. Since the city of Mashhad has been divided into 13 districts, all regions are considered as blood donors and Blood applicants.
2. There are two blood banks in the city, which perform blood purification, refinement, and storage. Since these centers should not be seriously damaged in times of disaster, experts decided to fortify the centers against earthquakes. Also, according to statistics of the Mashhad Blood Transfusion Organization, the percentage of healthy and usable blood units after blood purification in the Mashhad Blood Bank is 83%.
3. According to Mashhad Blood Transfusion Organization, there are 10 permanent blood donation facilities (5 existing facilities and 5 potential ones) and 5 temporary facilities (1 existing and 4 potential), which have been established in locations determined based on DEA approach before any earthquake. In these centers, the possibility of any earthquake and the destruction of the centers have been taken into account. In addition, 10 locations as potential demand points (in the form of field hospitals after the earthquake disaster) have been considered.
4. In this paper, the possible activation of four faults of Kashfrud (Cheshmeh Gilas), Toos (North of Mashhad), Southern Chenaran (south of Mashhad) and Shandiz-Sangbast is considered as the first, second, third and fourth scenarios, respectively; the probability of each occurrence is 0.25. Considering the worn-out structures announced by the Mashhad municipality and the probability of activation of faults, districts 3, 7, 8, and 9 will have the highest probability of failure after an earthquake. Moreover, these areas are located in the vicinity of Mashhad's southern and Tos faults, which can result in a lot of damage if activated. The locations of the mentioned faults are given on the map of Mashhad (Figure 5 and Table 4 are related to the main faults of Mashhad).

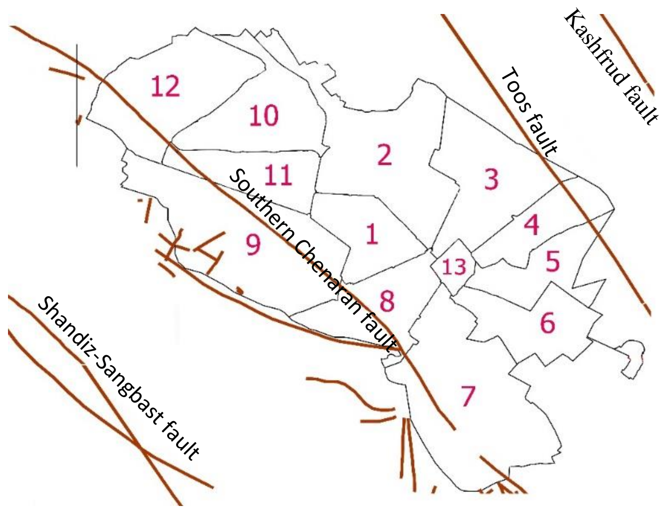

Figure 5. The location of the main faults of Mashhad

Table 4. Specifications of active faults in Mashhad city

Fault name	Mechanism	Longitude (Km)	Maximum magnitude	
			Final(MS)	Distance from the central point (Km)
1. Kashfrud (Cheshmeh Gilas)	Reverse	60	6.8	42
2. Toos (North of Mashhad)	Reverse	60	6.8	10
3. Southern Chenaran (south of Mashhad)	Reverse	100 $\geq$	7.3	5
4. Shandiz-Sangbast	Strike Slip Fault right lateral	85	7.2	15

5. The costs of opening and establishing a blood temporary facility, a permanent facility and a field hospital (potential) are given in Tables 5, 6 and 7.

Table 5. The establishment cost of blood temporary facility under different scenarios (tomans)

Blood temporary facility	**1 Potential**	**2 Potential**	**3 Potential**	**4 existing**	**5 Potential**
Scenario 1	45000	45000	45000	0	45000
Scenario 2	56000	56000	56000	0	56000
Scenario 3	35000	35000	35000	0	35000
Scenario 4	60000	60000	60000	0	60000

Table 6. The establishment cost of blood permanent facility under different scenarios (tomans)

blood permanent facility	1 existing	2 existing	3 existing	4 existing	5 existing	6 Potential	7 Potential	8 Potential	9 Potential	10 Potential
establishment cost	0	0	0	0	0	80000	95000	85000	100000	90000

Table 7. The establishment cost of field hospital (potential) under different scenarios (tomans)

Hospital	1	2	3	4	5	6	7	8	9	10
Scenario 1	50000	50000	50000	50000	50000	55000	55000	55000	55000	55000
Scenario 2	55000	55000	55000	55000	55000	60000	60000	60000	60000	60000
Scenario 3	60000	60000	60000	60000	60000	65000	65000	65000	65000	65000
Scenario 4	65000	65000	65000	65000	65000	70000	70000	70000	70000	70000

6. Hospitals and permanent and temporary blood donation centers in each region can cover their own region and the surrounding areas with which they have a common border.
7. Holding and testing cost of each blood unit (450 ml) is 500 tomans. Also, the processed blood is transported to health centers using specific vehicles; the distance unit cost is 500 Tomans, and the carrying capacity of each vehicle is 100 blood units.
8. In critical situations, a large proportion of injured people are in urgent need of blood. We assume the percentage of injured people as α, and its value is 0.8.
9. To determine the minimum amount of demand, parameter λ is given and equal to 0.65, and demand of injured people is also given in Table 8.

Table 8. Demand for injured people under different scenarios

Period	p1	p2	p3	p4

Scenario 1	10000	11000	12000	12000
Scenario 2	11000	12000	13000	13000
Scenario 3	13000	14000	15000	15000
Scenario 4	12000	13000	14000	14000

10. Tables 9, 10, and 11 present the distance of temporary, permanent and hospital facilities from the blood bank. Moreover, the quantity of blood collected in the facilities, its transfer to the blood centers and then to the health centers depends on the capacity of these facilities. The mentioned tables show the capacities of such facilities for collecting and holding blood. The capacity of blood processing in the blood center is shown in Table 12.

Table 9. The temporary facility's capacity and the distance between the temporary facility and blood center (Km)

		Blood center		Period (P)															
				Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		1	2	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4
Blood temporary facility	1	10	22	800	850	900	950	820	870	920	950	890	940	990	1040	840	890	940	990
	2	11	18	800	850	900	950	820	870	920	950	890	940	990	1040	840	890	940	990
	3	7	13	800	850	900	950	820	870	920	950	890	940	990	1040	840	890	940	990
	4	9	7	800	850	900	950	820	870	920	950	890	940	990	1040	840	890	940	990
	5	12	8	800	850	900	950	820	870	920	950	890	940	990	1040	840	890	940	990

Table 10. The permanent facility's capacity and the distance between the permanent facility and blood center (Km)

		BLOOD CENTER		PERIOD (P)															
				Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		1	2	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4
BLOOD PERMANENT FACILITY	1	9	19	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	2	5	15	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	3	4	14	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	4	11	5	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	5	10	6	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	6	6	12	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	7	4	13	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	8	5	6	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	9	13	5	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100
	10	22	3	1600	2100	2500	2800	1800	2300	2800	3000	2200	2700	3300	3500	2000	2500	3000	3100

Table 11. The hospitals' capacity and the distance between blood center and hospital (km)

		BLOOD CENTER		PERIOD (P)															
				Scenario 1				Scenario 2				Scenario 3				Scenario 4			
		1	2	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4	p1	p2	p3	p4
HOSPITAL (POTENTIAL)	1	7	23	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	2	9	22	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	3	5	18	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	4	6	14	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	5	5	12	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	6	8	7	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	7	13	12	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	8	12	8	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	9	13	4	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
	10	15	7	290	310	350	360	310	360	390	390	380	400	420	420	365	385	405	405
HOSPITAL (EXISTING)	11	9	31	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	12	9	32	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	13	8	31	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	14	5	27	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	15	7	30	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	16	4	28	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	17	4	28	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	18	6	27	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	19	8	28	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	20	7	25	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	21	6	20	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	22	3	20	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	23	4	17	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	24	5	15	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	25	6	14	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	26	5	13	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	27	6	7	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	28	7	6	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	29	9	8	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450

HOSPITAL (EXISTING)	30	8	8	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	31	13	12	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	32	15	11	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	33	12	5	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	34	12	2	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	35	13	4	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	36	15	6	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	37	18	3	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	38	22	6	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	39	23	6	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450
	40	27	8	320	340	380	390	340	390	430	420	430	460	480	490	390	430	460	450

Table 12. Capacity of the blood centers (blood unit)

		Period (P)			
Blood center		P1	P2	P3	P4
	1	8000	9000	11000	10000
	2	9000	10000	12000	11000

11. The magnitude of the earthquake is considered under different scenarios with a uniform distribution between [5-9], and the destruction radius of an earthquake follows a uniform distribution between [5-7] for 5-6 Richter, [7-8] for 6-7 Richter, [8-9] for 7-8 Richter, and [9-11] for 8-9 Richter. The distance of temporary and permanent facilities to the epicenter of the earthquake is also shown in tables 13 and 14.

Table 13. The distance between the temporary facility and the earthquake's epicenter under different scenarios (km)

		Earthquake's epicenter (scenarios)			
		1	2	3	4
Temporary facility	1	37	8	10	17
	2	9	15	4	14
	3	30	7	16	31
	4	45	13	3	16
	5	37	4	10	25

Table 14. The distance between the permanent facility and the earthquake's epicenter under different scenarios (km)

		Earthquake's epicenter (scenarios)			
		1	2	3	4
Permanent facility	1	42	13	5	15
	2	40	8	14	18
	3	50	21	3	9
	4	32	3	15	29
	5	39	7	10	31
	6	45	15	8	23
	7	4	11	15	25
	8	45	16	12	27
	9	33	7	11	24
	10	51	21	9	5

5. Computational results and evaluation

5.1. Computational results

First, the location-allocation problem is formulated and then, we apply the robust optimization approach to deal with uncertain parameters. In this section, we solve the proposed problem on the basis of the two-phase operation defined in the section 3. Then we examine the applicability of the proposed model and evaluate the impact of some parameters on the results. The results of running the proposed model are generated using CPLEX solver in GAMS 24.9 software on a personal computer with the Intel Core i5, CPU 2.1 GHz and 4 GB of RAM. Moreover, real-life data from Mashhad city is applied to solve the model.

5.2. Locating efficient blood centers (phase *I*)

The efficiency of all 13 districts is examined through the DEA model according to the criteria (inputs and outputs) described in subsection (3-1-2-2) and its results and ranking are shown in Tables 15 and 16 and Figures 6 and 7. Among the 15 temporary and permanent locations for DMUs based on the DEA model, 4 potential temporary facilities and 5 potential permanent facilities have been selected for the location section in the 2nd phase of the problem (blood supply chain network design).

Table 15. Results and ranking of potential temporary facility locations based on the DEA

Efficiency Type	Efficiency level	DMUs
Anti-efficient	0.726	DMU1 (District1)
Anti-efficient	0.789	DMU2 (D3)
Anti-efficient	0.905	DMU3 (D2)
Anti-efficient	0.787	DMU4 (D5)
Efficient	1	DMU5 (D11)
Efficient	1	DMU6 (D3)
Anti-efficient	0.774	DMU7 (D6)
Anti-efficient	0.77	DMU8 (D2)
Anti-efficient	0.917	DMU9 (D7)
Anti-efficient	0.818	DMU10 (D4)
Efficient	1	DMU11 (D1)
Anti-efficient	0.932	DMU12 (D9)
Anti-efficient	0.688	DMU13 (D10)
Anti-efficient	0.612	DMU14 (D4)
Efficient	1	DMU15 (D6)

Table 16. Results and ranking of potential permanent facility locations based on the DEA

Efficiency Type	Efficiency level	DMUs
Efficient	1	DMU1 (District 10)
Efficient	1	DMU2 (D2)
Anti-efficient	0.777	DMU3 (D12)
Efficient	1	DMU4 (D5)
Anti-efficient	0.792	DMU5 (D11)
Anti-efficient	0.923	DMU6 (D4)
Efficient	1	DMU7 (D1)
Anti-efficient	0.86	DMU8 (D3)
Anti-efficient	0.467	DMU9 (D8)
Anti-efficient	0.859	DMU10 (D1)
Anti-efficient	0.395	DMU11 (D6)
Efficient	1	DMU12 (D8)
Anti-efficient	0.585	DMU13 (D10)
Anti-efficient	0.983	DMU14 (D13)
Anti-efficient	0.598	DMU15 (D9)

If the efficiency of a facility is less than 1, it is anti-efficient. If a facility has an efficiency equal to 1, no surplus in the input and no shortage in output, it will be efficient. The districts, highlighted in red color in Tables 15 and 16, are the best locations for establishing the temporary and permanent blood donation centers, respectively.

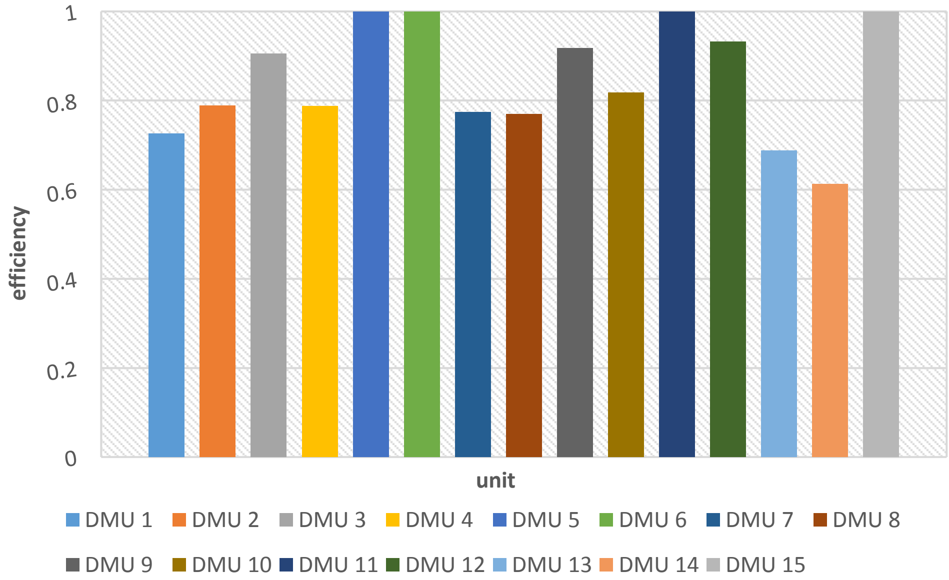

Figure 6. Efficiency of potential temporary facilities units

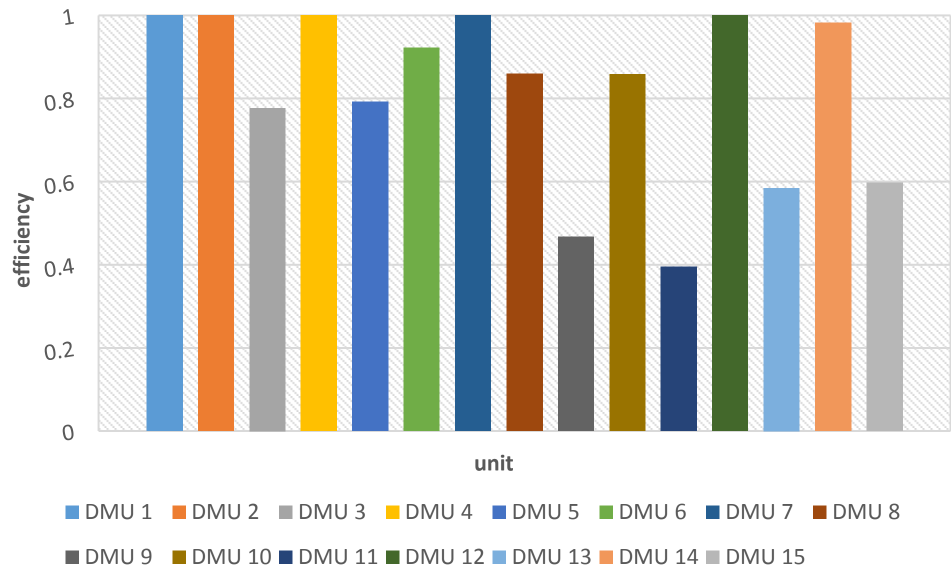

Figure 7. Efficiency of potential permanent facilities units

The optimal locations (L) of the temporary and permanent blood donation centers (existing and potential), blood banks and hospitals (existing and field) in Mashhad city's districts (Ds) are shown in Table 17 and Figure 8.

Table 17. The location (L) of facilities in different districts of Mashhad city

Districts	Temporary facility		Permanent facility		Blood banks	Hospitals	
	Existing	Potential	Existing	Potential		Existing	Field
D1		L3		L9	L1		L1
D2			L5	L8			L2
D3		L2					L3
D4			L4				
D5				L7			L4
D6		L5			L2		
D7			L2				L5, L6

D8				L10	
D9			L3		L7, L8
D10			L1	L6	L9
D11		L1			L10
D12					
D13	L4				

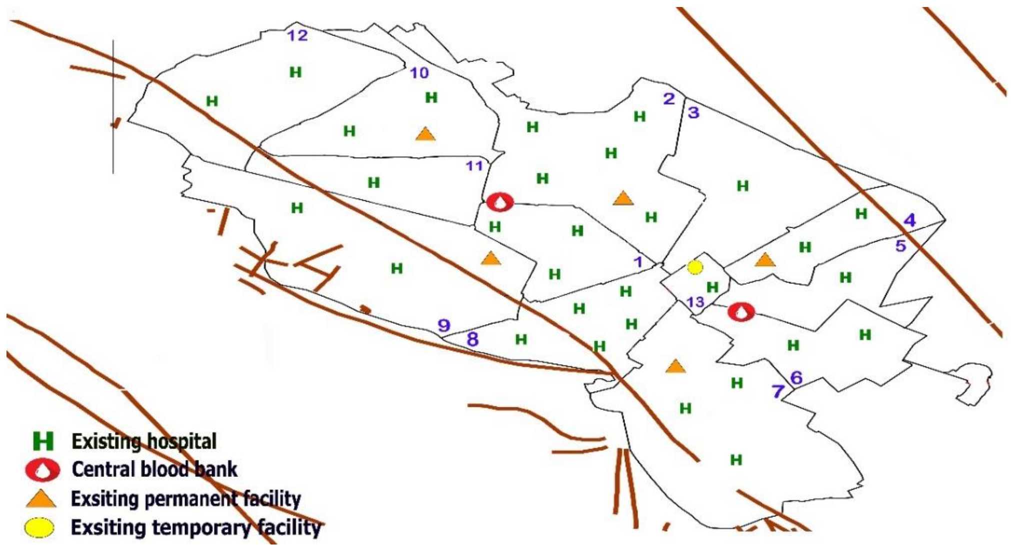

Figure 8. The location of existing facilities

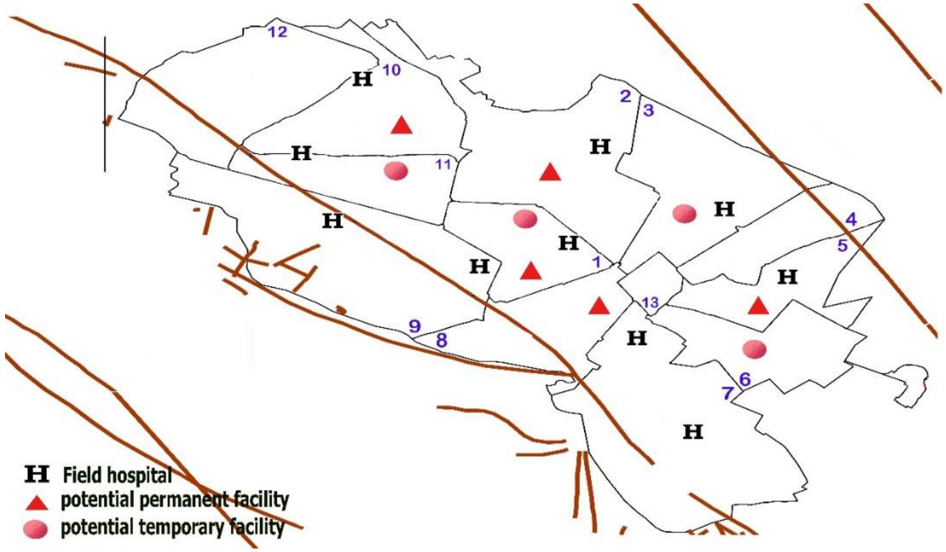

Figure 9. The efficient locations of potential facilities determined by the DEA model

By solving the location-allocation and the DEA models, the best-fit locations are determined in Figure 9. Besides, the value of the objective function in the deterministic state according to the magnitude of different earthquakes is shown in Figure 10.

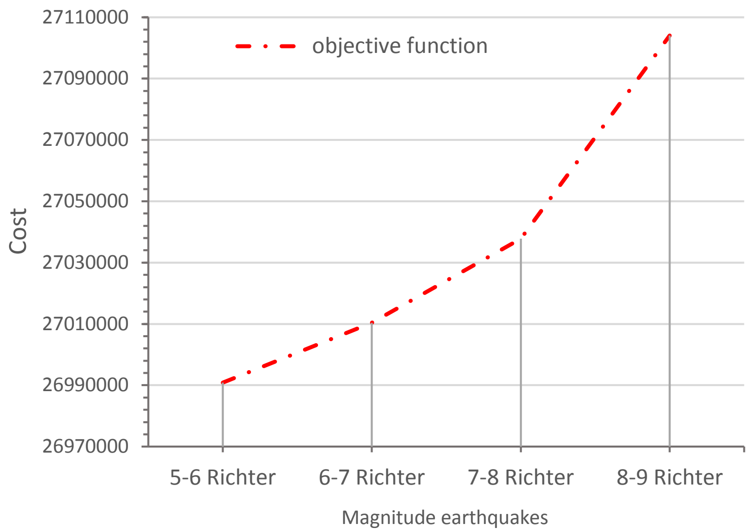

Figure 10. The amount of objective function in the deterministic model according to the magnitude of various earthquakes

As you can see in the figure, the value of the objective function (total cost) has an upward trend based on the magnitude of the earthquake due to the resulting disruption in the temporary and permanent facilities, meaning that the more intense the earthquake, the higher the costs.

5.3. Sensitivity analysis

In this section, to show the performance of the proposed model, the sensitivity analysis is operated on uncertain parameters due to the key role they play in critical situations. In this way, GAMS software is used to evaluate the model in real size. The following tables and figures indicate the results.

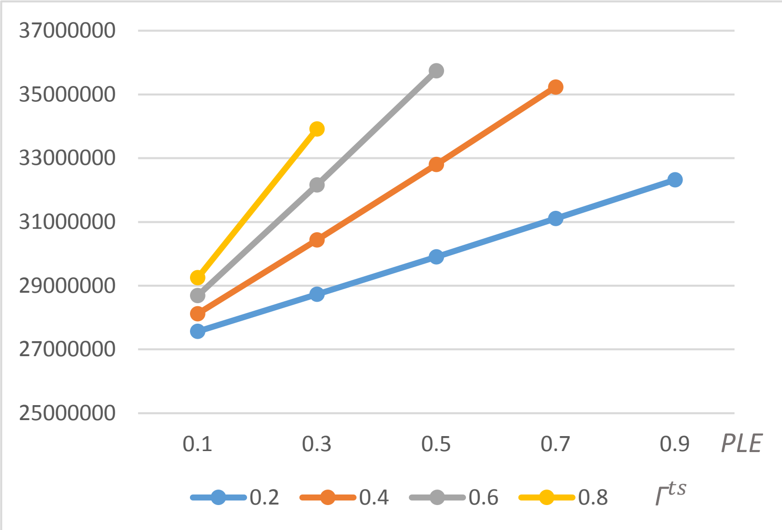

Figure 11. Amount of the objective function in earthquake magnitude 5-6 Richter

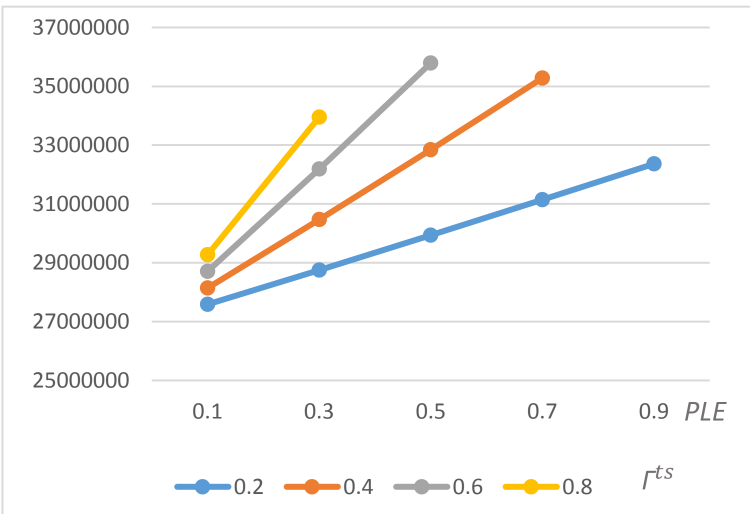

Figure 12. Amount of the objective function in earthquake magnitude 6-7 Richter

Table 18. Amount of the objective function in earthquake magnitude 5-6 Richter

SET SIZES	UNCERTAIN PARAMETER COEFFICIENT OF COSTS AND DEMAND ON B & S	UNCERTAIN COEFFICIENT OF NOMINAL VALUE INCLUDING DEMAND IN EACH PERIOD	OBJECTIVE FUNCTION
	PLE	Γ^{ts}	uncertain
$\lvert i\rvert * \lvert j\rvert * \lvert y\rvert * \lvert n\rvert * \lvert h\rvert * \lvert t\rvert * \lvert s\rvert$ 13*5*10*2*40*4*4	0.1	0.2	27564963.8845
	0.3		28726525.9939
	0.5		29904223.8533
	0.7		31105519.0491
	0.9		32317996.7018
	0.1	0.4	28121833.3471
	0.3		30434420.8127
	0.5		32800903.4603
	0.7		35233722.6622
	0.9		Infeasible
	0.1	0.6	28688525.9937
	0.3		32155246.6983
	0.5		35739500.8720
	0.7		Infeasible
	0.1	0.8	29248258.0449
	0.3		33915111.6558
	0.5		Infeasible

Tabel 19. Amount of the objective function in earthquake magnitude 6-7 Richter

SET SIZES	UNCERTAIN PARAMETER COEFFICIENT OF COSTS AND DEMAND ON B & S	UNCERTAIN COEFFICIENT OF NOMINAL VALUE INCLUDING DEMAND IN EACH PERIOD	OBJECTIVE FUNCTION
	PLE	Γ^{ts}	uncertain
$\lvert i\rvert * \lvert j\rvert * \lvert y\rvert * \lvert n\rvert * \lvert h\rvert * \lvert t\rvert * \lvert s\rvert$ 13*5*10*2*40*4*4	0.1	0.2	27586479.2141
	0.3		28751815.1049
	0.5		29936832.436
	0.7		311441160.5824
	0.9		32362481.6413
	0.1	0.4	28143226.8373
	0.3		30464414.8743
	0.5		32839261.8967
	0.7		35278729.4122
	0.9		Infeasible
	0.1	0.6	28709565.1047
	0.3		32187731.6368
	0.5		35791175.3228
	0.7		Infeasible
	0.1	0.8	29269027.6512
	0.3		33949248.7024
	0.5		Infeasible

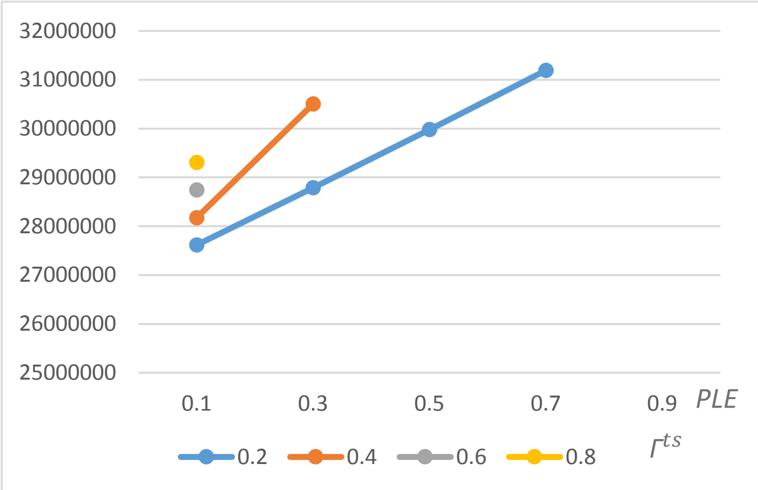

Figure 13. Amount of the objective function in earthquake magnitude 7-8 Richter

Tabel 20. Amount of the objective function in earthquake magnitude 7-8 Richter

SET SIZES	UNCERTAIN PARAMETER COEFFICIENT OF COSTS AND DEMAND ON B & S	UNCERTAIN COEFFICIENT OF NOMINAL VALUE INCLUDING DEMAND IN EACH PERIOD	OBJECTIVE FUNCTION
	PLE	Γ^{ts}	uncertain
$\|i\| * \|j\| * \|y\| * \|n\| * \|h\| * \|t\| * \|s\|$ 13*5*10*2*40*4*4	0.1	0.2	27616556.0103
	0.3		28787144.9246
	0.5		29977468.5823
	0.7		31190416.1548
	0.9		Infeasible
	0.1	0.4	28173930.1495
	0.3		30503359.6047
	0.5		Infeasible
	0.1	0.6	28740894.9087
	0.3		Infeasible
	0.1	0.8	29300983.9763
	0.3		Infeasible

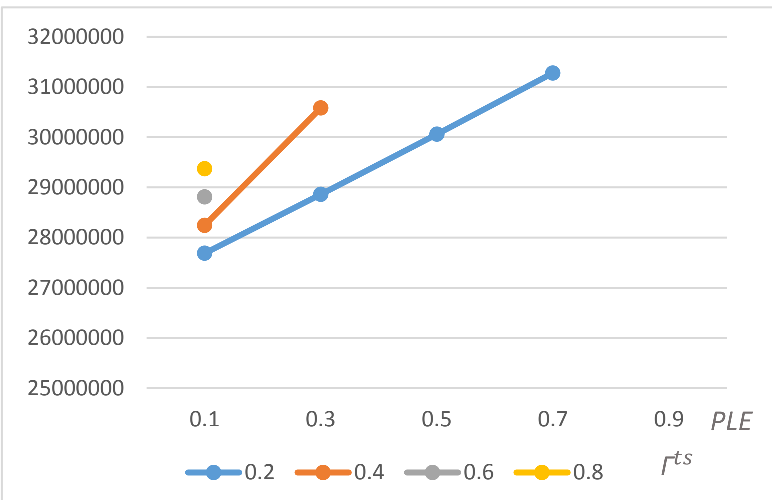

Figure 14. Amount of the objective function in earthquake magnitude 8-9 Richter

Tabel 21. Amount of the objective function in earthquake magnitude 8-9 Richter

SET SIZES	UNCERTAIN PARAMETER COEFFICIENT OF COSTS AND DEMAND ON B & S	UNCERTAIN COEFFICIENT OF NOMINAL VALUE INCLUDING DEMAND IN EACH PERIOD	OBJECTIVE FUNCTION
	PLE	Γ^{ts}	uncertain
$\|i\| * \|j\| * \|y\| * \|n\| * \|h\| * \|t\| * \|s\|$ 13*5*10*2*40*4*4	0.1	0.2	27685181.024
	0.3		28860519.9246
	0.5		30055593.5828
	0.7		31277282.2108
	0.9		Infeasible
	0.1	0.4	28242555.1506
	0.3		30578999.1837
	0.5		Infeasible
	0.1	0.6	28809519.9248
	0.3		Infeasible
	0.1	0.8	29369608.9774
	0.3		Infeasible

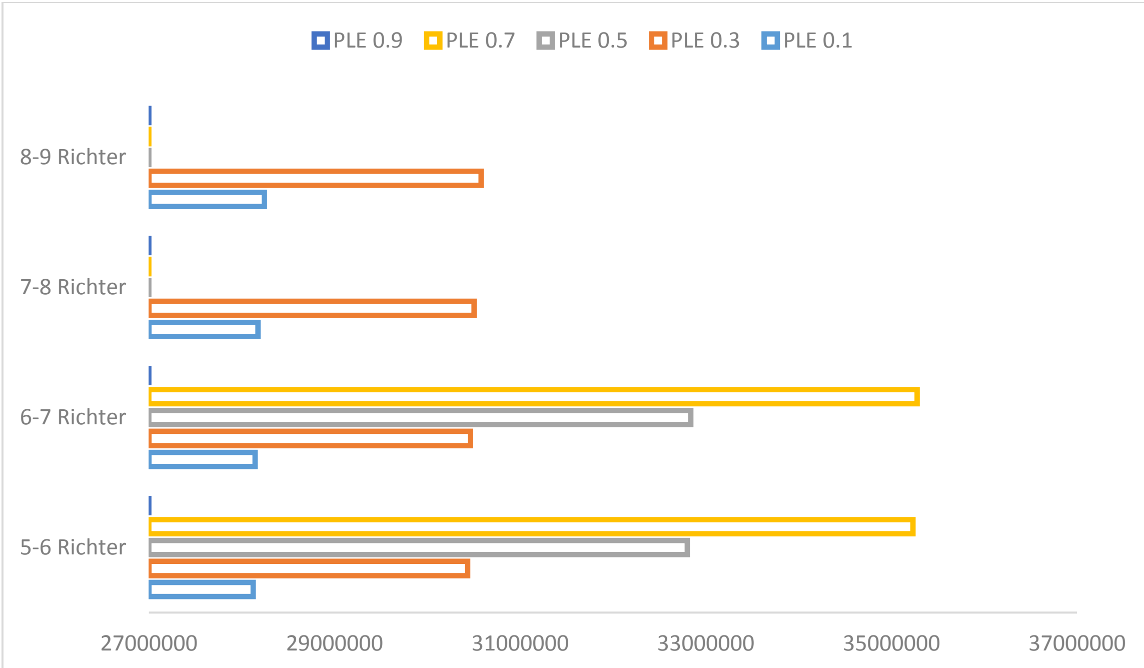

Figure 15. Comparison of the values of the objective function due to the magnitude of various earthquakes, with $\Gamma^{ts} = \mathbf{0.4}$

According to Tables 18, 19, 20 and 21 and Figures 11, 12, 13, 14 and 15, when uncertain parameters increase (PLE, Γ^{ts}), the degree of stringency grows, and as a result, the value of the objective function (total cost) increases. As a result of this, larger number of temporary and permanent facilities and field hospitals will be activated.

Based on the results, when there is no disruption risk or disaster, it is also necessary to establish a permanent facility in locations 7 and 10 (Table 22) in addition to the temporary facility in location 4 in district 13 (Samen) and the permanent facility in existing locations 1, 2, 3, 4, and 5. Also, the required blood is processed and distributed from blood centers 1 and 2 in districts 1 and 6, and there is no need to establish any potential hospitals before the disaster.

Table 22. Location of temporary and permanent facilities under various scenarios in a non-disturbing mode

	TEMPORARY FACILITY	PERMANENT FACILITY
ESTABLISHMENT	Location 4	Location 1, 2, 3, 4, 5, 7, 10

Well, if disruption and destruction occur as a result of an earthquake with a magnitude of 5-6 on the Richter scale, by considering the uncertain parameters of costs and demand in the Bertsimas and Sim model equal to 0.5 and uncertain coefficient of nominal value including demand equal to 0.6 per period, the location of the facilities changes as shown in Table 23.

Table 23. Location of temporary and permanent facilities and field hospitals under different scenarios with earthquake 5-6 Richter

		Temporary facility	Permanent facility	field hospital
New Establishment	Scenario 1	Location 3	Location 8, 9	Location 3, 5, 9, 10
	Scenario 2		Location 8, 9	Location 3, 4, 5, 9
	Scenario 3	Location 3	Location 8, 9	Location 5, 9, 10
	Scenario 4		Location 8, 9	Location 3, 5, 9
Disruption	Scenario 1		Location 7	

	Scenario 2		Location 4	
	Scenario 3	Location 4	Location 1, 3	
	Scenario 4		Location 10	

According to Table 24, the location of the facilities changes when an earthquake with a magnitude of 6-7 Richter is occurred, by considering the uncertain parameters of costs and demand in Bertsimas and Sim model equal to 0.5 and the uncertain coefficient of nominal value equal to 0.4.

Table 24. Location of temporary and permanent facilities and field hospitals under different scenarios with earthquake 6-7 Richter

		Temporary facility	Permanent facility	field hospital
New Establishment	Scenario 1		Location 8	Location 3, 9
	Scenario 2		Location 6, 8	Location 3, 5
	Scenario 3		Location 6, 8	
	Scenario 4		Location 8	
Disruption	Scenario 1		Location 7	
	Scenario 2		Location 4, 5	
	Scenario 3	Location 4	Location 1, 3	
	Scenario 4		Location 10	

Tables 25 and 26 also show changes in the location of facilities. In this table, we consider earthquakes with a magnitude of 7-8 and 8-9 Richter, the uncertain parameters of costs and demand in Bertsimas and Sim equal to 0.4 for 7-8 Richter and 0.3 for 8-9 Richter, and the uncertain coefficient of nominal value equal to 0.4.

Table 25. Location of temporary and permanent facilities and field hospitals under different scenarios with earthquake 7-8 Richter

		Temporary facility	Permanent facility	field hospital
New Establishment	Scenario 1		Location 8	Location 9
	Scenario 2	Location 2	Location 6, 8	Location 5
	Scenario 3	Location 1, 3	Location 8	
	Scenario 4		Location 8	
Disruption	Scenario 1		Location 7	
	Scenario 2		Location 2, 4, 5	
	Scenario 3	Location 4	Location 1, 3	
	Scenario 4		Location 10	

Table 26. Location of temporary and permanent facilities and field hospitals under different scenarios with earthquake 8-9 Richter

		Temporary facility	Permanent facility	field hospital
New Establishment	Scenario 1		Location 8	
	Scenario 2	Location 2	Location 6, 8	Location 5
	Scenario 3	Location 3	Location 8, 9	
	Scenario 4		Location 8, 9	
Disruption	Scenario 1		Location 7	
	Scenario 2		Location 2, 4, 5	
	Scenario 3	Location 4	Location 1, 3, 10	

Scenario 4	Location 3, 10

6. Conclusion

For the sake of the vital role and unique characteristics of blood and due to uncertainty in times of disasters, it is challenging to manage and plan an efficient blood supply chain and avoid possible shortages in addition to mitigate wastage. Moreover, deciding on locating and allocating limited available resources becomes more complicated in such critical circumstances due to dealing with human health. In this paper, a location-allocation model is proposed to achieve an optimized allocation of temporary and permanent facilities for blood collection and find suitable locations for field hospitals after a disaster. On the other hand, disruption in the location of temporary and permanent blood donation facilities and their unavailability in times of disaster, dependent on the intensity and magnitude of the earthquake, can make an adverse impact on the chain's performance. Thus, locating temporary and permanent facilities was initially carried out in the first phase using the Data Envelopment Analysis (DEA) approach to minimize the probability of destruction. This model aimed to minimize costs, including the cost of establishment and opening facilities, the cost of testing and processing of blood, inventory costs, and collection and shortage costs.

To become closer to reality, uncertainty in designing and planning the blood supply chain network is inevitable, especially during the earthquake disaster. In order to tackle `the uncertainty, we have applied a scenario-based robust optimization approach in which two models, called P-Robust and Bertsimas & Sim models, are considered. Then, the validity of the model was evaluated by utilizing a real-life case study of Mashhad, Iran, and the implementation results were scrutinized and discussed. The results showed that the demand for blood in times of disaster could timely be satisfied by spending reasonable costs, establishing sufficient various facilities in proper locations and optimal allocation.

The presented model of this study can be developed in various aspects. Instead of modeling only one product (whole blood), other blood components, such as erythrocytes (red blood cells), leukocytes (white blood cells), and the thrombocytes (platelets), or different blood groups can be considered in the model. In addition to robust optimization approach, other uncertainty programming approaches, such as stochastic, fuzzy [51] or fuzzy-robust approaches can be utilized to cope with the uncertain nature of such a supply chain. Moreover, essential environmental and social factors can be taken into account in order to prevent the endangerment of nature and society. To solve the model in the large scales [52], exact problem-solving methods, heuristic or meta-heuristic algorithms can be utilized. Besides, various objective functions can be merged in the model, such as minimizing the blood delivery time to patients by utilizing routing models and minimizing the number of obsoleted units.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Jabbarzadeh, A., B. Fahimnia, and S. Seuring, *Dynamic supply chain network design for the supply of blood in disasters: A robust model with real world application.* Transportation research part E: logistics and transportation review, 2014. **70**: p. 225-244.
2. *Iranian Blood Transfusion Organisation (IBTO)*. 2017; Available from: https://en.ibto.ir/.
3. Torrado, A.S. and A. Barbosa-Póvoa, *Towards an Optimized and Sustainable Blood Supply Chain Network under Uncertainty: A Literature Review.* Cleaner Logistics and Supply Chain, 2022: p. 100028.
4. *Disaster operations handbook-Hospital.*, in *American Association of Blood banks.* 2008, AABB Pub. Co., New York. : Chapter 3.
5. Shen, Z.-J.M., R.L. Zhan, and J. Zhang, *The reliable facility location problem: Formulations, heuristics, and approximation algorithms.* INFORMS Journal on Computing, 2011. **23**(3): p. 470-482.
6. Ghandforoush, P. and T.K. Sen, *A DSS to manage platelet production supply chain for regional blood centers.* Decision Support Systems, 2010. **50**(1): p. 32-42.
7. Nagurney, A., A.H. Masoumi, and M. Yu, *Supply chain network operations management of a blood banking system with cost and risk minimization.* Computational management science, 2012. **9**(2): p. 205-231.
8. Duan, Q. and T.W. Liao, *Optimization of blood supply chain with shortened shelf lives and ABO compatibility*. International Journal of Production Economics, 2014. **153**: p. 113-129.
9. Hsieh, C.-L. *An evolutionary-based optimization for a multi-objective blood banking supply chain model*. in *International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems*. 2014. Springer.
10. Abdulwahab, U. and M. Wahab, *Approximate dynamic programming modeling for a typical blood platelet bank.* Computers & Industrial Engineering, 2014. **78**: p. 259-270.
11. Arvan, M., R. Tavakkoli-Moghaddam, and M. Abdollahi, *Designing a bi-objective and multi-product supply chain network for the supply of blood.* Uncertain Supply Chain Management, 2015. **3**(1): p. 57-68.
12. Zahraee, S.M., J.M. Rohani, A. Firouzi, and A. Shahpanah, *Efficiency improvement of blood supply chain system using Taguchi method and dynamic simulation.* Procedia Manufacturing, 2015. **2**: p. 1-5.
13. Hosseinifard, Z. and B. Abbasi, *The inventory centralization impacts on sustainability of the blood supply chain.* Computers & Operations Research, 2018. **89**: p. 206-212.
14. Fahimnia, B., A. Jabbarzadeh, A. Ghavamifar, and M. Bell, *Supply chain design for efficient and effective blood supply in disasters.* International Journal of Production Economics, 2017. **183**: p. 700-709.
15. Salehi, F., M. Mahootchi, and S.M.M. Husseini, *Developing a robust stochastic model for designing a blood supply chain network in a crisis: A possible earthquake in Tehran.* Annals of Operations Research, 2019. **283**(1): p. 679-703.
16. Zahiri, B. and M.S. Pishvaee, *Blood supply chain network design considering blood group compatibility under uncertainty.* International Journal of Production Research, 2017. **55**(7): p. 2013-2033.
17. Salem, R.W. and M. Haouari, *A simulation-optimisation approach for supply chain network design under supply and demand uncertainties.* International Journal of Production Research, 2017. **55**(7): p. 1845-1861.

18. Masoumi, A.H., M. Yu, and A. Nagurney, *Mergers and acquisitions in blood banking systems: A supply chain network approach.* International Journal of Production Economics, 2017. **193**: p. 406-421.
19. Osorio, A.F., S.C. Brailsford, H.K. Smith, and J. Blake, *Designing the blood supply chain: how much, how and where?* Vox sanguinis, 2018. **113**(8): p. 760-769.
20. Rahmani, D., *Designing a robust and dynamic network for the emergency blood supply chain with the risk of disruptions.* Annals of Operations Research, 2019. **283**(1): p. 613-641.
21. Zahiri, B., S.A. Torabi, M. Mohammadi, and M. Aghabegloo, *A multi-stage stochastic programming approach for blood supply chain planning.* Computers & Industrial Engineering, 2018. **122**: p. 1-14.
22. Heidari-Fathian, H. and S.H.R. Pasandideh, *Green-blood supply chain network design: Robust optimization, bounded objective function & Lagrangian relaxation.* Computers & Industrial Engineering, 2018. **122**: p. 95-105.
23. Khalilpourazari, S. and A. Arshadi Khamseh, *Bi-objective emergency blood supply chain network design in earthquake considering earthquake magnitude: a comprehensive study with real world application.* Annals of Operations Research, 2019. **283**(1): p. 355-393.
24. Fazli-Khalaf, M., S. Khalilpourazari, and M. Mohammadi, *Mixed robust possibilistic flexible chance constraint optimization model for emergency blood supply chain network design.* Annals of Operations Research, 2019. **283**(1): p. 1079-1109.
25. Özener, O.Ö., A. Ekici, and E. Çoban, *Improving blood products supply through donation tailoring.* Computers & Operations Research, 2019. **102**: p. 10-21.
26. Rajendran, S. and A.R. Ravindran, *Inventory management of platelets along blood supply chain to minimize wastage and shortage.* Computers & Industrial Engineering, 2019. **130**: p. 714-730.
27. Hamdan, B. and A. Diabat, *A two-stage multi-echelon stochastic blood supply chain problem.* Computers & Operations Research, 2019. **101**: p. 130-143.
28. Rajendran, S. and S. Srinivas, *Hybrid ordering policies for platelet inventory management under demand uncertainty.* IISE Transactions on Healthcare Systems Engineering, 2020. **10**(2): p. 113-126.
29. Hamdan, B. and A. Diabat, *Robust design of blood supply chains under risk of disruptions using Lagrangian relaxation.* Transportation Research Part E: Logistics and Transportation Review, 2020. **134**: p. 101764.
30. Haghjoo, N., R. Tavakkoli-Moghaddam, H. Shahmoradi-Moghadam, and Y. Rahimi, *Reliable blood supply chain network design with facility disruption: A real-world application.* Engineering Applications of Artificial Intelligence, 2020. **90**: p. 103493.
31. Razavi, N., H. Gholizadeh, S. Nayeri, and T.A. Ashrafi, *A robust optimization model of the field hospitals in the sustainable blood supply chain in crisis logistics.* Journal of the Operational Research Society, 2021. **72**(12): p. 2804-2828.
32. Meneses, M., I. Marques, and A. Barbosa-Póvoa, *Blood inventory management: Ordering policies for hospital blood banks under uncertainty.* International Transactions in Operational Research, 2021.
33. Dehghani, M., B. Abbasi, and F. Oliveira, *Proactive transshipment in the blood supply chain: A stochastic programming approach.* Omega, 2021. **98**: p. 102112.
34. Zhou, Y., T. Zou, C. Liu, H. Yu, L. Chen, and J. Su, *Blood supply chain operation considering lifetime and transshipment under uncertain environment.* Applied Soft Computing, 2021. **106**: p. 107364.
35. Kamyabniya, A., Z. Noormohammadzadeh, A. Sauré, and J. Patrick, *A robust integrated logistics model for age-based multi-group platelets in disaster relief operations.* Transportation Research Part E: Logistics and Transportation Review, 2021. **152**: p. 102371.
36. Pouraliakbari-Mamaghani, M., A. Ghodratnama, S.H.R. Pasandideh, and A. Saif, *A robust possibilistic programming approach for blood supply chain network design in disaster relief considering congestion.* Operational Research, 2022. **22**(3): p. 1987-2032.

37. Matin, R.K., M. Azadi, and R.F. Saen, *Measuring the sustainability and resilience of blood supply chains.* Decision Support Systems, 2022. **161**: p. 113629.
38. Kenan, N. and A. Diabat, *The supply chain of blood products in the wake of the COVID-19 pandemic: appointment scheduling and other restrictions.* Transportation Research Part E: Logistics and Transportation Review, 2022. **159**: p. 102576.
39. Khalilpourazari, S. and H. Hashemi Doulabi, *A flexible robust model for blood supply chain network design problem.* Annals of operations research, 2022: p. 1-26.
40. Fallahi, A., S.A. Mousavian Anaraki, H. Mokhtari, and S.T.A. Niaki, *Blood plasma supply chain planning to respond COVID-19 pandemic: a case study.* Environment, Development and Sustainability, 2022: p. 1-52.
41. Aghsami, A., Y. Samimi, and A. Aghaie, *A combined continuous-time Markov chain and queueing-inventory model for a blood transfusion network considering ABO/Rh substitution priority and unreliable screening laboratory.* Expert Systems with Applications, 2022: p. 119360.
42. Asadpour, M., T.L. Olsen, and O. Boyer, *An updated review on blood supply chain quantitative models: A disaster perspective.* Transportation Research Part E: Logistics and Transportation Review, 2022. **158**: p. 102583.
43. Meneses, M., D. Santos, and A. Barbosa-Póvoa, *Modelling the Blood Supply Chain–From Strategic to Tactical Decisions.* European Journal of Operational Research, 2022.
44. Charnes, A., W.W. Cooper, and E. Rhodes, *Measuring the efficiency of decision making units.* European journal of operational research, 1978. **2**(6): p. 429-444.
45. Banker, R.D., A. Charnes, and W.W. Cooper, *Some models for estimating technical and scale inefficiencies in data envelopment analysis.* Management science, 1984. **30**(9): p. 1078-1092.
46. Charnes, A., W. Cooper, A.Y. Lewin, and L.M. Seiford, *Data envelopment analysis theory, methodology and applications.* Journal of the Operational Research society, 1997. **48**(3): p. 332-333.
47. Rahimian, H. and S. Mehrotra, *Distributionally robust optimization: A review.* arXiv preprint arXiv:1908.05659, 2019.
48. Snyder, L.V. and M.S. Daskin, *Stochastic p-robust location problems.* Iie Transactions, 2006. **38**(11): p. 971-985.
49. Bertsimas, D., D. Pachamanova, and M. Sim, *Robust linear optimization under general norms.* Operations Research Letters, 2004. **32**(6): p. 510-516.
50. *National Seismic Center (NSC)*. 2017; Available from: Http://irsc.ut.ac.ir
51. Avila-Torres, P., R. Caballero, I. Litvinchev, F. Lopez-Irarragorri, and P. Vasant, *The urban transport planning with uncertainty in demand and travel time: a comparison of two defuzzification methods.* Journal of Ambient Intelligence and Humanized Computing, 2018. **9**(3): p. 843-856.
52. Zhang, D.-g., *A new approach and system for attentive mobile learning based on seamless migration.* Applied Intelligence, 2012. **36**(1): p. 75-89.