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The Integrated Problem of Locating, Allocating, and Routing Transportation Vehicles in the Blood Product Supply Chain During Crisis Conditions

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ABSTRACT

In this research, a multi-objective model has been developed to minimize costs, blood transfer time, and shortages, taking into account the blood supply chain in a crisis situation at three levels: supply, processing, and distribution, and whole blood and its derivatives. The scenarios examined in this issue pertain to the intensity of the earthquake (severe, moderate) and a 10-day time frame. In this research, inventory control is performed based on various scenarios, and by considering this aspect alongside the demand, the model determines whether a shortage will occur. If the establishment of centers is warranted, the proposed potential locations from the Isfahan crisis management headquarters will be utilized, and the optimal site for setting up the field hospital and mobile blood collection centers will be chosen. Furthermore, by providing a precise model that incorporates most real-world details, this model has proven effective in reducing costs and shortages of blood products. This model has been solved using GAMS software with the CPLEX solver, and the case study focuses on the city of Isfahan.

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1) Introduction

A crisis, as an inevitable reality in social life, is a situation that disrupts the order of the main system or parts of its subsystems and undermines its stability. In other words, a crisis is an event that occurs suddenly due to natural and human actions and events, causing damage to a human society that requires emergency measures to compensate for it. Crises vary in terms of type and severity. The occurrence of such events leads to widespread destruction and significant financial and human losses. After each crisis, there is an urgent need for water, food, shelter, medical equipment, and other basic necessities, including blood as a vital and scarce product (Hosseini & Cheraghi, 2018).

An earthquake is one of the most destructive natural disasters. The primary need of the injured following a devastating earthquake is blood and blood products. Blood is a perishable product, and to date, no substitute product has been found for it. Consequently, supplying the required blood for the injured is only possible through human donors. Blood shortage imposes irreparable costs on a country, as this shortage leads to the death of the injured (Piling et al., 2004).

One of the key components of a healthcare system is the blood supply chain, which accounts for a significant portion of the system's costs. This research aims to address location, routing, and inventory allocation problems in the blood supply chain, considering different conditions and states of the chain. To demonstrate the applicability of the proposed model, a case study in Isfahan is analyzed based on two scenarios.

The unique innovation of this research is the modeling and solving of the simultaneous optimization of location, allocation, distribution, and routing problems for blood products under crisis conditions, which has not been addressed in an integrated manner so far. Furthermore, simultaneously considering cost minimization, delivery times, and inventory shortages, as well as modeling the aforementioned problem as a multi-objective and multi-period problem, represents another innovation of this study.

The analysis of numerical results shows that the proposed model is effective regarding the location of mobile blood centers and field hospitals, as well as transportation and routing considering processing time constraints, and helps ensure that blood products are delivered in the shortest possible time.

2) Literature Review

In recent years, the blood supply chain has attracted the attention of many researchers. Below is a review of some research on the blood supply chain.

Hamdana and Diabat (2020), in their paper, presented a blood supply chain model that uses robust optimization and two-stage stochastic optimization techniques to reduce the effects of natural disasters on the blood supply chain. Yavari et al. (2020) investigated the multi-period location-inventory-routing problem of perishable products under route disruption in some periods and applied both dynamic and destructive pricing to manage demands along with location, inventory, and routing decisions. Wang and Chen (2019) considered a bi-objective integrated warehouse location and vehicle routing problem with time windows in a disaster response environment to ensure timely and cost-effective delivery of relief supplies. Tavana et al. (2017), in their paper, proposed a new multi-level logistics network with locating central warehouses, inventory planning and control, as well as routing of relief vehicles. Zhang et al. (2019) presented a two-stage mixed-integer location-allocation model to determine the position of mobile blood collection facilities. Armaghan et al. (2019) proposed a multi-level, multi-objective mathematical model over several periods based on minimizing the cost of the blood supply chain network and maximizing the reliability of selectable routes for blood transfusion. A Bayesian network-based two-stage stochastic programming model was proposed by Wang and Chen (2019) and Pourghasemi et al. (2026). Karadag et al. (2021) proposed a mathematical model for providing optimal network design and planning of the blood supply chain. Eskandari and Feil (2021) designed and modeled a location-routing-allocation problem in a blood supply chain network considering uncertainty and the perishable nature of blood. Shokohifar et al. (2022) designed a new inventory management model for managing the blood supply chain considering lateral transshipment between demand groups (hospitals). Erani et al. (2021) examined the concept of lateral resupply in the context of blood supply chain network

design. Ghahremani Nahr et al. (2021) designed and modeled a blood supply chain network considering uncertainty and the perishable nature of blood. Salehi et al. (2021) proposed a new two-stage stochastic model for designing a blood supply network following a disaster in Tehran. Farrokhizadeh et al. (2021), in their paper, presented a mathematical model to address the problem of blood supply in times of disaster under uncertainty, formulated for efficient and timely blood supply. Salehi et al. (2017) proposed a robust two-stage multi-period stochastic model for designing a blood supply network considering a probable natural disaster in Tehran, the capital of the Islamic Republic of Iran. Khalilpourazari et al. (2020), in this paper, designed a six-echelon blood supply chain. They also used various transportation vehicles with limited capacity and a limited number to transport collected blood to hospitals in the earthquake-affected region. Rezaei Kalaj et al. (2021) sought to develop a mixed-integer linear programming model for relief supply under crisis conditions. The model has two objectives: maximizing the amount of blood collected by blood devices and minimizing the time it takes for blood-collecting buses and a helicopter to reach the crisis-stricken city after consuming the collected blood. Khalilpourazari et al. (2017) developed a multi-objective mathematical model for designing a blood supply chain network in earthquakes, with objectives including minimizing total time and total cost in the blood supply chain. For the first time, the radius of earthquake destruction was considered in the mathematical model to design a robust supply chain during a severe earthquake. Chen et al. (2021), in their research, examined the blood supply chain decision-making problem considering the lifetime distribution of blood products under uncertain supply and demand environments (Bushehri et al., 2027). Khiyabani et al. (2024) stated that the main goal of this research is to present an optimization model for efficient blood distribution in critical situations to help vulnerable populations. In this paper, demand forecasting and inventory management are considered to optimally manage blood resources in emergencies to prevent blood shortages. Altunoglu and Didem (2024) stated that the main goal of this research is to minimize costs and maximize quality in the blood supply chain. This includes reducing establishment and transportation costs and increasing the quality of blood delivery to hospitals so that blood reaches healthcare centers on time and in the appropriate quantity. Hosseini et al. (2020) argue that optimal management of the blood supply chain under crisis conditions requires multi-objective approaches that can reduce costs, optimize delivery time, and increase reliability.

Shirdel and Rezapour (2020) studied the acceleration problem on the time-varying shortest path. This problem involves finding paths from a specified vertex (called the origin) to other vertices such that the cost of this path is minimized and the sum of traversal times and waiting times equals a maximum of T, where T is a given positive integer. Then, the acceleration problem for a shortest path problem is described. Abolghasemian et al. (2024), in their research, presented a mathematical modeling for determining efficient locations for dispatching support forces using data envelopment analysis. Additionally, a mixed-integer mathematical model for routing prioritized support items is presented. Nazemi et al. (2021) attempted to present a multi-objective model that, in addition to maximizing profit, enhances the quality of products transported along the supply chain and minimizes the final delivery time. Farrokhizadeh et al. (2021) used a hybrid solution method to solve the bi-objective integer mathematical model using the CPLEX solver in GAMS software. Salehi et al. (2019), in their paper, used GAMS software and the branch-and-cut method to solve the proposed model. Hosseini and Cheraghi et al. (2018) used GAMS software and the CPLEX solver to solve the proposed model. Ramezanian et al. (2017) in their paper examined the application of the proposed model using real data in Tehran in GAMS software with the CPLEX solver. Rezaei et al. (2021) examined a mixed-integer linear programming model using GAMS software and the CPLEX solver, bringing the data closer to real-life situations.

According to the literature review conducted in the field of modeling and solving similar problems, conventional and reliable methods, such as Mixed-Integer Linear Programming (MILP) in GAMS software, have often been used. Furthermore, in most of these studies, problem-solving has been performed using the powerful CPLEX solver. The prevalence and widespread application of these approaches indicate that these methods typically provide accurate and reliable solutions, and there is no need for independent validation with other methods. Accordingly, the present work also uses this same

approach, as the reliability and validity of this method have been proven, and the results obtained from it are trustworthy and valid.

3) Proposed Model

In this section, the mathematical model of the problem and its required descriptions are explained.

1-3) Problem Assumptions

The aim is to present a model for the supply, processing, and distribution of blood and its products during crises with the following characteristics:

- Presenting a three-objective model to minimize the costs of the supply chain network, minimize the duration of blood collection and delivery, and also decrease the total shortage of blood products at demand points.
- Considering different scenarios to represent the intensity and dimensions of the crisis.
- Considering different time periods for planning and increasing efficiency.
- Considering three levels including supply, processing, and distribution.
- Categorizing all collected blood units and their separated components into existing blood groups.
- Considering blood donor groups to supply the required blood to meet existing demand.
- The potential location of mobile facilities is known, but the location for establishing mobile facilities will be determined after solving the model.
- Collection facilities are divided into two categories: permanent and mobile. Other network facilities include main blood centers, hospitals, and field hospitals as demand points.
- Considering a coverage radius for allocating blood donors to the nearest collection facility.
- All facilities and transportation vehicles have limited and specific capacity for storage and transport.
- Due to the presence of various blood-borne diseases, including hepatitis, AIDS, and other infectious diseases (after conducting tests at main blood centers), a percentage of the total collected blood units are considered unusable.

2-3) Problem Statement

The blood supply chain network investigated in this research is a four-level network including donors, fixed and mobile blood collection facilities, main blood centers, and demand points including hospitals and field hospitals. The location of mobile facilities can vary from one period to another.

Blood units donated by blood donors are collected at permanent and mobile blood collection centers, and blood group categorization operations are performed at all blood collection facilities. Blood collection centers are of two types: permanent such as clinics, healthcare centers, and other medical facilities, and temporary mobile centers such as tents, portable cabins, buses, etc., which can be relocated in different periods if needed to increase the efficiency and flexibility of the supply chain network.

All collected blood units at blood collection centers will be transported by vehicles to main blood centers for medical testing to confirm safety or for disposal of contaminated blood. The portion of blood units confirmed as safe will be separated into whole blood and blood products at those same centers.

In this problem, two types of trips are considered for transporting collected blood units, grouped in the set F = {st, nd}. The first type of trips is called st and the second type is called nd. First-type trips start from the blood transfusion center at time t_st0v > 0 and end at the blood center at time t_st(u+1), v. The service starts time t_stjv at node j ∈ w ∪ {u+1} is at least the service start time of the previous node i ∈ w ∪ {0} in the trip plus the service time o_i at node i plus the travel time c_ij between nodes i and j. Each blood collection center is visited at most once by first-type trips. The first-type trip must comply with the processing time constraint. It must be supplied by whole blood units with a maximum

age a_max, which represents the processing time constraint. Then, the age a_i of whole blood units collected at collection site i ∈ w by transportation vehicle v ∈ V upon arrival at the blood center at time t_st(u+1), f must be at most a_max. It is assumed that age a_i begins counting at the start of activities at the collection site: a_i = t_st(u+1), f - o_i ≤ a_max.

Second-type trips receive the remaining blood from blood collection centers. The second-type trip of vehicle v ∈ V starts from the blood center at time t_nd0v greater than the end of its first-type trip and ends at the blood center at time t_nd(u+1), v. Each collection site is visited at most once by second-type trips. According to the explanations given, each blood collection center must receive either a first-type or second-type trip at a time greater than or equal to its activity end time to deliver all collected blood. Additionally, second-type trips must deliver whole blood units to the blood transfusion center regardless of the center's closing time.

Once the safety of collected blood is confirmed and it is separated into whole blood and blood products, the distribution planning of blood from main blood centers to demand points, including hospitals and field hospitals, is carried out.

3-3) Sets and Parameters

Table 1 shows the sets, parameters, and decision variables that will be used in the mathematical model.

Table 1. Model Symbols

Sets		
J	Permanent facilities	j=1, ... , J
Z	Mobile facilities	z=1, ... , Z
L	Main blood centers	l= 1, ... , L
V	Vehicle modes	v = v_1 , v_2
G	Blood groups	g = 1, ... , G
k	Blood components	k = 1, ... , K
A	Blood donors	a = 1, ... , A
H	Hospitals	h = 1, ... , H
D	Field hospitals	d = 1, ... , D
T	Time periods	t = 1, ... , T
S	Scenarios	s = 1, ... , S
N	Sets of hospitals and field hospitals	
W	Permanent and mobile sites for blood donation	w = 1, ... , W
W’	Sets of blood donation sites and major blood centers	
C	Arcs and routes	$c=\{(i.j)\|i.j\in w'.i\neq j\}$
F	Types of trips performed by each vehicle	$F=\{st,nd\}$
Q	Urgency levels	q = 1, ... , Q
Parameters:		
$Capv_v$	Capacity of vehicle v	
CV_v	The cost of utilizing transportation vehicle *v*	
CV'_v	The cost of utilizing auxiliary transportation vehicle *v*	
Num_v	Number of owned vehicles	
Num'_v	Number of auxiliary vehicles	
CM^s_{zpt}	Fixed cost of establishment mobile blood collection center *z* in location *p* in period *t* under scenario *s*	
DM_{PL}	Distance between mobile blood collection center *p* and blood center *l*	
DP_{jL}	Distance between permanent blood collection center *j* and blood center *l*	
DH_{Lh}	Distance between demand point *h* and blood center *l*	
DD_{Ld}	Distance between demand point *d* and blood center *l*	
$CapM^s_z$	Capacity of mobile blood collection center *z* under scenario *s*	
$CapP^s_j$	Capacity of permanent blood collection center *j* under scenario *s*	

Sets	
$CapB^s_L$	Capacity of blood center *l* under scenario *s*
C^s_{zipt}	Transportation cost of mobile blood collection center z form point *i* to point *p* in period *t* under scenario *s*
$DisM_{ap}$	Distance between donor *a* and mobile blood collection center *p*
$DisP_{aj}$	Distance between donor *a* and permanent blood collection center *j*
OCM^s_{pzgt}	The operational cost of mobile blood collection center *z* stationed at location *p* in period *t* under scenario *s* for collecting a blood unit and determining blood group *g*
OCP^s_{jgt}	The operational cost of permanent blood collection center *j* in period *t* under scenario *s* for collecting a blood unit and determining blood group *g*
OCB^s_{kgLt}	The operational cost of blood center *l* in period *t* under scenario *s* for collecting blood and processing blood into blood products *k* and determining blood group *g*
OCW^s_{gLt}	The operational cost of whole blood with blood group *g* at blood center *l* in period t under scenario *s*
IW^s_{gLt}	The holding cost of whole blood with blood group *g* at blood center *l* in period *t* under scenario *s*
IC^s_{gkLt}	The holding cost of blood product *k* with blood group *g* at blood center *l* in period *t* under scenario *s*
$DemC^s_{gkt}$	The demand for blood product *k* with blood group *g* in period *t* under scenario *s*
Dem^s_{gt}	The demand for whole blood with blood group *g* in period *t* under scenario *s*
TVM_{pL}	Travel time between *p* and *l* locations
TVP_{jL}	Travel time between *j* and *l* locations
TVH_{hL}	Travel time between *h* and *l* locations
TVD_{dl}	Travel time between *d* and *l* locations
Cd	Coverage area
$^s\pi$	Probability of scenario *s* occurrence
B_t	Percentage of unusable blood in period *t*
$_k\alpha$	Proportion of blood product *k* in one unit of blood
M	Big number
U	Number of blood collection centers
O_i	Start time of activities at location *i*
R_i	Service time at location *i*
C_i	End time of activities at location *i*
a^{max}	Processing time constraint
W^d	Delay cost per unit time
U^s_{hgt}	The demand level for whole blood with blood group *g* at hospital *h* in period *t* under scenario *s*
U^s_{hkgt}	The demand level for blood with blood group *g* that has been processed into component *k* at hospital *h* in period *t* under scenario *s*
U^s_{dgt}	The demand level for whole blood with blood group *g* at field hospital *d* in period *t* under scenario *s*
U^s_{dkgt}	The demand level for blood with blood group *g* that has been processed into component *k* at field hospital *d* in period *t* under scenario *s*
Cap_h	Capacity of hospital *h*
Cap_d	Capacity of hospital *d*
Decision Variables:	
EB_L	1 if blood center is stablished at *l*, otherwise 0
EP_j	1 if permanent blood collection center is stablished at j, otherwise 0
LM^s_{zpt}	1 if in period *t* under scenario *s* mobile blood collection center is stablished at *p*, otherwise 0
TM^s_{zipt}	1 if mobile blood collection center *z* is relocated from *i* to location *p* in period *t* under scenario *s*, otherwise 0
W^s_{apzt}	1 if donor a is assigned to mobile blood collection center *z* stationed at location *p* in period *t* under scenario *s*, otherwise 0

Sets	
D^s_{ajt}	1 if donor *a* is assigned to permanent blood collection center *j* in period *t* under scenario *s*, otherwise 0
X^s_h	1 if hospital *h* is open, otherwise 0
F^s_d	1 if field hospital *d* is open, otherwise 0
X^s_{ijvF}	1 if arc (*i, j*) is traversed by vehicle *v* on trip type *F* under scenario *s*, otherwise 0
$Ymfh^s_{Ldqt}$	1 if main blood center *l* is assigned to field hospital *d* with casualty urgency level *q* in time period *t* under scenario *s*, otherwise 0
Ymh^s_{Lhqt}	1 if main blood center *l* is assigned to hospital *h* with casualty urgency level *q* in time period *t* under scenario *s*, otherwise 0
t^s_{ivF}	Service start time at node *i* for vehicle *v* on trip type *F* under scenario *s*
$QM^s_{agvzpLt}$	The volume of blood collected from donor *a* at mobile blood collection center *z* with blood group *g* at location *p*, transported by vehicle *v* to blood center *l* in period *t* under scenario *s*
QP^s_{agvjLt}	The volume of blood collected from donor *a* at permanent blood collection center *j* with blood group *g*, transported by vehicle *v* to blood center *l* in period *t* under scenario *s*
QC^s_{kgLt}	The volume of blood collected at blood center *l* with blood group *g* that has been processed into component *k* in period *t* under scenario *s*
QCH^s_{gkLvht}	The volume of blood transported by vehicle *v* from blood center *l* with blood group *g* that has been processed into component *k* to hospital *h* in period *t* under scenario *s*
QWH^s_{gLvht}	The volume of whole blood with blood group *g* transported from blood center *l* to hospital *h* by vehicle *v* in period *t* under scenario *s*
QD^s_{gLvdt}	The volume of whole blood with blood group *g* transported from blood center *l* to field hospital *d* by vehicle *v* in period *t* under scenario *s*
QD^s_{kgvLdt}	The volume of blood transported by vehicle *v* from blood center *l* with blood group *g* that has been processed into component *k* to field hospital *d* in period *t* under scenario *s*
QW^s_{gLt}	The volume of processed whole blood with blood group *g* at blood center *l* in period *t* under scenario *s*
Q^s_{gLt}	The volume of processed blood with blood group *g* at blood center *l* in period *t* under scenario *s*
Inv^s_{gLt}	The inventory level of whole blood with blood group *g* at blood center *l* in period *t* under scenario *s*
Inl^s_{kgLt}	The inventory level of blood with blood group *g* that has been processed into component *k* at blood center *l* in period *t* under scenario *s*
Inv^s_{ght}	The inventory level of whole blood with blood group *g* at hospital *h* in period *t* under scenario *s*
Inl^s_{kght}	The inventory level of blood with blood group *g* that has been processed into component *k* at hospital *h* in period *t* under scenario *s*
Inv^s_{gdt}	The inventory level of whole blood with blood group *g* at field hospital *d* in period *t* under scenario *s*
Inl^s_{kgdt}	The inventory level of blood with blood group *g* that has been processed into component *k* at field hospital *d* in period *t* under scenario *s*
BSC^s_{gkt}	The shortage volume of blood with blood group *g* that has been processed into component *k* in period *t* under scenario *s*
BSW^s_{gt}	The shortage volume of required whole blood with blood group *g* in period *t* under scenario *s*
TH^s_{Lnt}	The volume of blood transported from blood center l to hospitals and field hospitals in period *t* under scenario *s*
Ih^s_{ghtq}	The list of blood groups *g* at hospital *h* in time period *t* under scenario *s*
Ih^s_{kghtq}	The list of blood groups *g* processed into component *k* at hospital *h* in time period *t* under scenario *s*
Im^s_{gLt}	The list of blood groups *g* at blood center *l* in time period *t* under scenario *s*
Im^s_{kgLt}	The list of blood groups *g* processed into component *k* at blood center *l* in time period *t* under scenario *s*
β^s_{ivF}	Delay at node *i* for transportation vehicle *v* on trip type *F* under scenario *s*

Sets	
δ_{vF}^{s}	Maximum delay of transportation vehicle v on trip type F at blood collection points under scenario s

The mathematical model is as follow.

$$\min F_1 = LC_s + TC_s + TCH_s + OC_s + IC_s \quad (1)$$

$$LC_S = \sum_S \pi_S \left(\sum_Z \sum_P \sum_t CM^s_{zpt} LM^s_{zpt} \right) \quad (1\text{-}1)$$

$$\mathrm{TC_s} = \sum_{\mathrm{S}} \mathrm{p_s} \left(\sum_{\mathrm{Z}} \sum_{\mathrm{i}} \sum_{\mathrm{p}} \sum_{\mathrm{t}} \mathbf{C}^{\mathrm{s}}_{\mathrm{zipt}} \mathbf{TM}^{\mathrm{s}}_{\mathrm{zipt}} + \sum_v \sum_t CV_V \left(\sum_p \sum_z \sum_a \sum_L DM_{PL} \times \left[\frac{\sum_g QM^s_{agvzpLt}}{CaPV_v} \right] \right. \right.$$

$$+ \sum_j \sum_L \sum_a DP_{jL} \times \left[\frac{\sum_g QP^s_{agvjLt}}{CaPV_v} \right] + \sum_L \sum_h \sum_a DH_{Lh} \times \left[\frac{\sum_g \sum_k QCH^s_{kgvLht} + \sum_g QWH^s_{gvLht}}{CaPV_V} \right] + \sum_L \sum_d \sum_a DD_{Ld}$$

$$\left. \left. \times \left[\frac{\sum_g \sum_k QDF^s_{gLvdtk} + \sum_g QD^s_{gLvdt}}{CaPV_V} \right] \right) \right) \quad (1\text{-}2)$$

$$TCH_s = \sum_v \sum_t CV'_V \left(\sum_P \sum_Z \sum_a \sum_L DM_{PL} \times \left[\frac{\sum_g QM^s_{agvzpLt}}{CaPV_V} \right] + \sum_j \sum_L \sum_a DP_{jL} \times \left[\frac{\sum_g QP^s_{agvjLt}}{CaPV_v} \right] + \sum_L \sum_h \sum_a DH_{Lh} \right.$$

$$\left. \times \left[\frac{\sum_g \sum_k QCH^s_{kgvLht} + \sum_g QWH^s_{gvLht}}{CaPV_V} \right] + \sum_L \sum_d \sum_a DD_{Ld} \times \left[\frac{\sum_g \sum_k QDF^s_{gLvdtk} + \sum_g QD^s_{gLvdt}}{CaPV_V} \right] \right) \quad (1\text{-}3)$$

$$OC_S = \sum_S \pi_S \left(\sum_P \sum_Z \sum_a \sum_g \sum_L \sum_t \sum_v QM^s_{agvzpLt} OCM^s_{pzgt} \right.$$

$$+ \sum_j \sum_g \sum_t \sum_a \sum_L \sum_v QP^s_{agvjLt} OCP^s_{jgt} + \sum_k \sum_g \sum_L \sum_t QC^s_{kgLt} OCB^s_{kgLt} \quad (1\text{-}4)$$

$$\left. + \sum_g \sum_L \sum_t OCW^s_{gLt} \left(Q^s_{gLt} + QW^s_{gLt} \right) \right)$$

$$IC_S = \sum_S \pi_S \left(\sum_L \sum_g \sum_t IW^S_{Lgt} + \sum_k \sum_g \sum_L \sum_t IC^s_{kgLt} InL^s_{kgLt} \right) \quad (1\text{-}5)$$

$$\min F_2 = TCB_s + TBH_s + TBD_s \quad (2)$$

$$TCB_S = \sum_s \pi_s \left(\sum_a \sum_g \sum_z \sum_p \sum_L \sum_t \sum_v QM^s_{agvzpLt} TVM_{pL} + \sum_j \sum_g \sum_t \sum_a \sum_L \sum_v QP^s_{agvjLt} TVP_{jL} \right) \quad (2\text{-}1)$$

$$TBH_S = \sum_s \pi_s \left(\sum_k \sum_g \sum_L \sum_h \sum_t \sum_v QCH^s_{kgvLht} TVH_{Lh} + \sum_g \sum_L \sum_h \sum_t \sum_v QWH^s_{gvLht} \right) \quad (2\text{-}2)$$

$$TBD_s = \sum_s \pi_s \left(\sum_k \sum_g \sum_L \sum_d \sum_t \sum_v QDF^s_{kgvLdt} TVD_{dL} + \sum_g \sum_L \sum_d \sum_t \sum_v QD^s_{gLvdt} \right) \quad (2\text{-}3)$$

$$\min F_3 = \sum_s \pi_s \left(\sum_g \sum_k \sum_t BSC^s_{gkt} + \sum_g \sum_t BSW^s_{gt} \right) \quad (3)$$

S.T

$$\sum_{i \in p} TM^s_{zipt} = LM^s_{zpt} \qquad \forall z \in Z, \forall t \in T, \forall p \in P, \forall s \in S \quad (4)$$

$$\sum_z LM^s_{zpt} \le 1 \qquad \forall p \in P, \forall t \in T, \forall s \in S \quad (5)$$

$$\sum_{t\in p} TM^{s}_{zpit} \le \sum_{t\in p} TM^{s}_{zip\cdot t-1} \qquad \forall z\in Z,\forall t\in T,\forall p\in P,\forall s\in S \qquad 6$$

$$y^{s}_{apzt} \le LM^{s}_{zpt} \qquad \forall a\in A,\forall z\in Z,\forall p\in P,\forall t\in T,\forall s\in S \qquad 7$$

$$D^{s}_{ajt} \le EP_{j} \qquad \forall a\in A,\forall j\in J,\forall t\in T,\forall s\in S \qquad 8$$

$$QM^{s}_{agvzpLt} \le M\cdot W^{s}_{apzt} \qquad \forall a\in A,\forall g\in G,\forall v\in V,\forall z\in Z,\forall p\in P,\forall l\in L,\forall t\in T,\forall s\in S \qquad 9$$

$$QP^{s}_{agvjLt} \le M\cdot D^{s}_{ajt} \qquad \forall a\in A,\forall g\in G,\forall v\in V,\forall j\in J,\forall l\in L,\forall t\in T,\forall s\in S \qquad 10$$

$$DisM_{ap}\cdot W^{s}_{apzt} \le cd \qquad \forall a\in A,\forall z\in Z,\forall p\in P,\forall t\in T,\forall s\in S \qquad 11$$

$$DisP_{aj}\cdot D^{s}_{ajt} \le cd \qquad \forall a\in A,\forall j\in J,\forall t\in T,\forall s\in S \qquad 12$$

$$\sum_{a}\sum_{g}\sum_{t} QM^{s}_{agvzpLt} \le M\cdot EB_{L} \qquad \forall v\in V,\forall z\in Z,\forall p\in P,\forall l\in L,\forall s\in S \qquad 13$$

$$\sum_{a}\sum_{g}\sum_{t} QP^{s}_{agvjLt} \le M\cdot EB_{L} \qquad \forall v\in V,\forall j\in J,\forall l\in L,\forall s\in S \qquad 14$$

$$\sum_{a}\sum_{g}\sum_{v} QM^{s}_{agvzpLt} \le CaPM^{s}_{z}\cdot LM^{s}_{zpt} \qquad \forall z\in Z,\forall p\in P,\forall l\in L,\forall t\in T,\forall s\in S \qquad 15$$

$$\sum_{a}\sum_{g}\sum_{v} QP^{s}_{agvjLt} \le CaPP^{s}_{j}\cdot EP_{j} \qquad \forall j\in J,\forall l\in L,\forall t\in T,\forall s\in S \qquad 16$$

$$\sum_{g} InV^{s}_{gLt} + \sum_{k}\sum_{g} InL^{s}_{kgLt} \le CaPB_{L}\cdot EB_{L} \qquad \forall l\in L,\forall t\in T,\forall s\in S \qquad 17$$

$$Q^{s}_{gLt} + QW^{s}_{gLt} = (1-\beta_{t})\left(\sum_{a}\sum_{p}\sum_{z}\sum_{v} QM^{s}_{agvzpLt} + \sum_{a}\sum_{j}\sum_{v} QP^{s}_{agvjLt}\right) \qquad \forall l\in L,\forall t\in T,\forall s\in S \qquad 18$$

$$QC^{s}_{kgLt} = \alpha_{K}\cdot Q^{S}_{gLT} \qquad \forall k\in K,\forall g\in G,\forall l\in L,\forall t\in T,\forall s\in S \qquad 19$$

$$\left[\frac{\sum_{a}\sum_{g}\sum_{z}\sum_{p}\sum_{L} QM^{s}_{agvzpLt}}{CaPV_{v}}\right] + \left[\frac{\sum_{a}\sum_{g}\sum_{j}\sum_{L} QP^{s}_{agvjLt}}{CaPV_{V}}\right] + \left[\frac{\sum_{g}\sum_{L}\sum_{h} QW^{s}_{gLht} + \sum_{k}\sum_{g}\sum_{L}\sum_{h} Qc^{s}_{kgLt}}{CaPV_{V}}\right] \le num_{v} + num'_{v} \qquad \forall v\in V,\forall t\in T,\forall s\in S \qquad 20$$

$$InV^{s}_{gLt} = InV^{s}_{gL\cdot t-1} + QW^{s}_{gLt} - \sum_{v}\sum_{h} QWH^{s}_{gvLht} \qquad \forall g\in G,\forall l\in L,\forall t\in T,\forall s\in S \qquad 21$$

$$InL^{s}_{kgLt} = InL^{s}_{kgL\cdot t-1} + QC^{s}_{kgLt} - \sum_{v}\sum_{h} QCH^{s}_{kgvLht} \qquad \forall k\in K,\forall g\in G,\forall l\in L,\forall t\in T,\forall s\in S \qquad 22$$

$$TH^{s}_{Lnt} \le M\times X^{s}_{h} \qquad \forall l\in L,\forall n\in N,\forall h\in H,\forall t\in T,\forall s\in S \qquad 23$$

$$TH^{s}_{Lnt} \le M\times F^{s}_{d} \qquad \forall l\in L,\forall n\in N,\forall d\in D,\forall t\in T,\forall s\in S \qquad 24$$

$$DEM^{s}_{gt} - \sum_{V}\sum_{L}\sum_{h} QWH^{s}_{gvLht} - \sum_{V}\sum_{L}\sum_{d} QD^{s}_{gLvdt} = BSW^{s}_{gt} \qquad \forall g\in G,\forall t\in T,\forall s\in S \qquad 25$$

$$DEMC^{s}_{gt} - \sum_{V}\sum_{L}\sum_{h} QCH^{s}_{kgvLht} - \sum_{V}\sum_{L}\sum_{d} QDF^{s}_{kgLvdt} = BSC^{s}_{kgt} \qquad \forall k\in K,\forall g\in G,\forall t\in T,\forall s\in S \qquad 26$$

$$\sum_{j\in w} X^{s}_{0jvf} = \sum_{i\in w} X^{s}_{i(u+1)vf} \le 1 \qquad \forall v\in V,\forall f\in F,\forall s\in S \qquad 27$$

$$\sum_{i=0}^{u} X^{s}_{ijvf} = \sum_{i=1}^{u+1} X^{s}_{jivk} \qquad \forall j\in W,\forall v\in V,\forall f\in F,\forall s\in S \qquad 28$$

$$\sum_{i=0}^{u}\sum_{v=1}^{num_{v}} X^{s}_{ijvf} \le 1 \qquad \forall j\in W,\forall f\in F,\forall s\in S \qquad 29$$

$$t^s_{ivf} + R_i + C_{ij} - M\left(1 - X^s_{ijvf}\right) \le t^s_{ivf} \qquad \forall j \in W, \forall f \in F, \forall s \in S \qquad 30$$

$$t^s_{ivst} \ge O_i \sum_{j=1}^{u+1} X^s_{ijvfst} \qquad \forall (i,j) \in C, \forall v \in V, \forall f \in F, \forall s \in S \qquad 31$$

$$t^s_{(u+1)vst} - O_i - M\left(2 - \sum_{j=1}^{u+1} X^s_{ijvst} - \sum_{j=1}^{u} X^s_{j(u+1)vst}\right) \le a^{\max} \qquad \forall i \in W' \setminus \{n+1\}, \forall v \in V, \forall s \in S \qquad 32$$

$$t^s_{ivnd} \ge C_i \sum_{j=1}^{u+1} X^s_{ijvnd} \qquad \forall i \in w, \forall v \in V, \forall s \in S \qquad 33$$

$$t^s_{ivnd} \ge C_i \sum_{j=1}^{u+1} X^s_{ijvnd} \qquad \forall i \in w, \forall v \in V, \forall s \in S \qquad 34$$

$$t^s_{0vnd} \ge t^s_{(u+1)vst} + R_{u+1} - M + M \sum_{i \in w} X^s_{i(u+1)vst} \qquad \forall v \in V, \forall s \in S \qquad 35$$

$$t^s_{0vnd} \ge O_0 \sum_{j \in w} X^s_{0jvnd} \qquad \forall v \in V, \forall s \in S \qquad 36$$

$$t^s_{ivf} - \beta^s_{ivf} \le C_i + M - M \sum_{j=0}^{u} X^k_{jivf} \qquad \forall i \in W' \setminus \{0\}, \forall v \in V, \forall f \in F, \forall s \in S \qquad 37$$

$$\delta^s_{vf} \ge \beta^s_{ivf} \qquad \forall i \in w, \forall v \in V, \forall f \in F, \forall s \in S \qquad 38$$

$$INV^s_{ght} = INV^s_{ght-1} + \sum_v \sum_h QWH^s_{glvht} - U^s_{hgt-1} \qquad \forall g \in G, \forall l \in L, \forall t \in T, \forall s \in S, \forall h \in H \qquad 39$$

$$INL^s_{kght} = INL^s_{kght-1} + \sum_v \sum_h QCH^s_{kglvht} - U^s_{hkgt-1} \qquad \forall k \in K, \forall g \in G, \forall l \in L, \forall t \in T, \forall s \in S, \forall h \in H \qquad 40$$

$$INV^s_{gdt} = INV^s_{gdt-1} + \sum_v \sum_h QD^s_{glvdt} - U^s_{dgt-1} \qquad \forall g \in G, \forall l \in L, \forall t \in T, \forall s \in S, \forall d \in D \qquad 41$$

$$INL^s_{kgdt} = INL^s_{kgdt-1} + \sum_v \sum_h QDF^s_{kglvdt} - U^s_{dkgt-1} \qquad \forall k \in K, \forall g \in G, \forall l \in L, \forall t \in T, \forall s \in S, \forall d \in D \qquad 42$$

$$\sum_L \sum_g QWH^s_{gLvht} + \sum_L \sum_k \sum_g QCH^s_{kgvLht} + \sum_g Ih^s_{gh,t-1} \sum_k \sum_g Ih^s_{gkh,t-1} \le CaP_h \qquad \forall v \in V, \forall h \in H, \forall s \in S, \forall t \succ 1 \qquad 43$$

$$\sum_L \sum_g QD^s_{gLvdt} + \sum_L \sum_k \sum_g QDF^s_{kgvLdt} \le CaP_d \qquad \forall v \in V, \forall d \in D, \forall s \in S, \forall t \in T \qquad 44$$

$$\sum_g \mathrm{Im}^s_{gLt} + \sum_k \sum_g \mathrm{Im}^s_{kgLt} \le CaPB^s_L \qquad \forall s \in S, \forall l \in L, \forall t \in T \qquad 45$$

$$\sum_g \sum_q Ih^s_{ghqt} + \sum_k \sum_g \sum_q \mathrm{I}\, h^s_{kghqt} \le CaP_h \qquad \forall s \in S, \forall h \in H, \forall t \in T \qquad 46$$

$$EP_j, EB_L, LM^S{}_{ZPt}, TM^S{}_{zipt}, W^s{}_{apzt}, D^s{}_{ajt}, X^s{}_h, F^s{}_d, X^s{}_{ijf}, ymfh^s{}_{Ldqt}, ymh^s{}_{Lhqt} \in \{0,1\} \qquad \forall a \in A, \forall g \in G, \forall h \in H, \forall z \in Z, \forall u \in U, \forall p \in P, \forall l \in L, \forall t \in T, \forall s \in S, \forall d \in D \qquad 47$$

$$QM^s{}_{agvzpLt}, QP^s{}_{agvjLt}, QC^s{}_{kgLt}, QCH^s{}_{kgvLht}, QWH^s{}_{gLvht}, QD^s{}_{gLvdt}, QDF^s{}_{kgvLdt}, QW^s{}_{gLt}, Q^s{}_{gLt}, InV^s{}_{gLt}, InL^s{}_{kgLt}, InV^s{}_{ght}, InL^s{}_{kght}, InV^s{}_{gdt}, InL^s{}_{kgdt}, BSC^s{}_{ght}, BSW^s{}_{gt}, TH^s{}_{Lnt}, t^s{}_{ivf}, Ih^s{}_{ghtq}, Ih^s{}_{kghtq}, Im^S{}_{gLt}, Im^s{}_{kgLt}, \beta^s{}_{ivf}, \delta^s{}_{vf} \ge 0 \qquad \forall a \in A, \forall g \in G, \forall h \in H, \forall z \in Z, \forall k \in K, \forall v \in V, \forall p \in P, \forall l \in L, \forall t \in T, \forall s \in S, \forall d \in D, \forall q \in Q, \forall f \in F, i \in w' \qquad 48$$

The first objective function minimizes the total cost of the supply chain network, which includes the establishment and deployment costs of mobile facilities, transportation costs, auxiliary transportation costs, operational costs, and inventory holding costs. The second objective function, considering the perishable nature of blood, aims to reduce the average transportation time of blood from collection facilities to blood centers and from blood centers to hospitals. The third objective function is concerned with minimizing the total shortage of blood products at demand points. Constraint (4) states that a mobile facility z, after being relocated from location i to location p in period t under scenario s, will be deployed at location p. Constraint (5) ensures that at most one mobile facility can be located at each candidate site. Constraint (6) indicates that relocating a mobile facility from a location where it has not been deployed is not feasible. Constraint (7) specifies that blood donor groups can be assigned to a mobile facility only if that mobile facility is deployed. Constraint (8) states that blood donor groups can be assigned to a permanent facility only if that permanent facility is open. Constraints (9) and (10) ensure that mobile and permanent facilities cannot collect blood from donor groups that are not assigned to them. Constraints (11) and (12) indicate that donor groups cannot be assigned to mobile or permanent facilities that are located outside their coverage radius. The constraints further imply that samples collected at both mobile and permanent facilities must be transported to the main blood centers. Constraints (13) and (14) ensure that the total volume of blood collected at mobile and permanent facilities is transferred to the main blood centers.

Constraints (15) to (17) state that collection facilities, including both mobile and permanent facilities, as well as main blood centers, have limited and predefined capacities. Constraint (18) specifies that a certain proportion of the total blood collected from collection facilities will be identified as healthy after laboratory testing at the main blood centers. Constraint (19) indicates that each blood derivative exists in a fixed proportion within a unit of whole blood. Constraint (20) states that the number of vehicles available for transporting blood and blood products from collection facilities to blood centers and from blood centers to hospitals is limited and predefined.

Constraints (21) and (22) represent the inventory balance of whole blood and blood derivatives at the main blood centers, respectively. Constraints (23) and (24) ensure that blood can be transported from blood centers to hospitals and field hospitals only if these facilities are deployed and operational. Constraints (25) and (26) calculate the shortage levels at demand points.

Constraint (27) guarantees that if a shuttle departs from node 0, it must terminate at node u+1. Constraint (28) enforces flow conservation for each trip. Constraint (29) states that each blood collection location can be visited at most once by each type of trip. Constraint (30) defines the visiting time at each node. Constraints (31) and (32) ensure compliance with time window constraints for Type-1 trips, while Constraints (33) to (35) enforce time window constraints for Type-2 trips. Constraint (36) calculates delays, and Constraint (37) regulates the maximum delay of each trip while accounting for delays at blood collection locations.

Constraints (38) to (41) ensure inventory balance at each hospital. Constraints (42) and (43) indicate that the total volume of blood that can be transferred from all main blood centers to each hospital and field hospital cannot exceed the capacity of that hospital or field hospital. Constraints (44) to (46) state that the inventory level at each main blood center and each hospital must be less than or equal to their respective capacities. Finally, Constraints (47) and (48) define the admissible domains of the decision variables.

4) Research Findings

Based on the conducted investigations and the information obtained from the Isfahan Crisis Management Organization, the results of the project commissioned by the Isfahan Municipality—conducted by the University of Isfahan under the title Comprehensive Earthquake micro zonation and Seismic Risk Management Plan for the City of Isfahan—indicate that analyses based on the Iranian Seismic Design Standard No. 2800 demonstrate a relatively conservative standard response spectrum. In other words, the spectrum defined in this standard tends to be on the safer side compared to alternative formulations. Furthermore, the identification of active faults within a radius of 100 kilometers from the

city of Isfahan highlights the increasing necessity of paying greater attention to earthquake hazards in this city (Safaie & Tajmir Riahi, 2011).

Table 2. Main Faults of Isfahan City

Fault Name	Average maximum magnitude of probable earthquake	**Extent of vulnerable areas (by region)**	**Affected population size**
Three	7.09	2,7,12,14	**10136.7**
North east of Isfahan	7.34	7,10,14,15	**12830.88**
Airport	7.23	3,4,7,10,14,15	**17549.8**
Najaf-abad	7.34	1,2,8,9,11,12,13	**15131.7**
Harand	7.23	3,4,6,10,14,15	**16.809.24**
South of Isfahan	7.34	4,5,6,13	**10382.6**

In response to the request of the Blood Transfusion Organization, all considered blood centers were identified and mapped across Isfahan Province using GIS software. Subsequently, the GIS-based fault maps of the city of Isfahan were obtained from the Crisis Management Organization and overlaid with the locations of the blood centers. This overlay analysis enabled the identification of the spatial positions of blood centers relative to active fault lines (Alikhani and Ghiyasi, 2025).

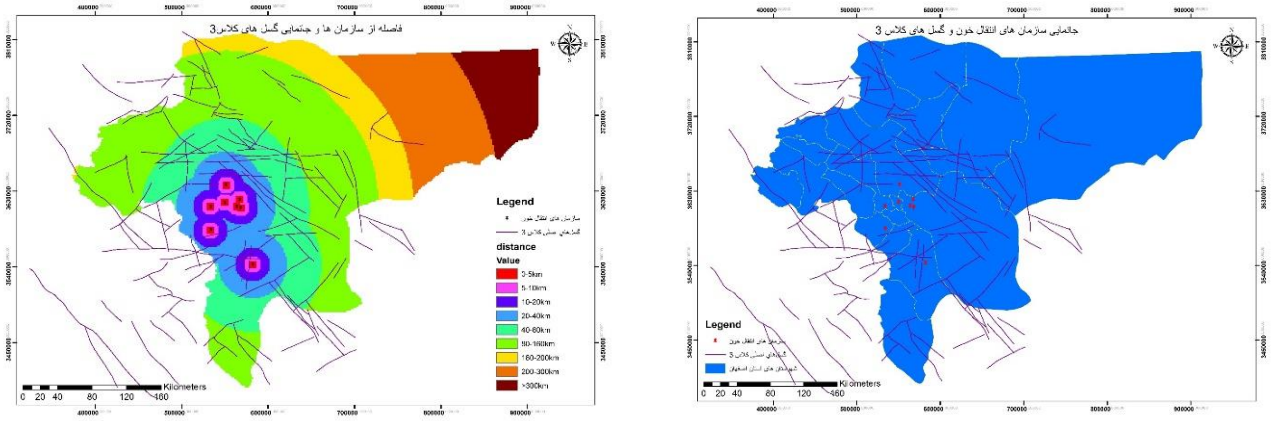

Figure 1. Location of Blood Transfusion Organizations and Class 1 Faults, and the Distance Between Organizations and the Location of Class 1 Faults

It is worth noting that, given the critical importance of the problem, most of the required data and information were obtained through consultations with experts from the Blood Transfusion Organization and the Isfahan Crisis Management Organization, as well as from relevant studies in the literature. A planning horizon of 10 days, consisting of two five-day periods, was considered. Two earthquake intensity scenarios—moderate and severe—were taken into account, with equal occurrence probabilities assigned to each scenario (0.5).

Each blood center is assumed to serve a limited number of donors in each period. Mobile collection facilities are capable of serving up to 70 donors, while each permanent blood center can serve a maximum of 300 donors for blood donation. Since each donor corresponds to the donation of one unit (bag) of blood, the blood collection capacity of each facility was defined accordingly. The operating hours were assumed to be from 7:00 a.m. to 8:00 p.m.

According to experts from the Blood Transfusion Organization, the maximum number of hospitals requesting blood under crisis conditions is 32. The blood demand of these 32 hospitals in Isfahan over a five-day period, disaggregated by blood type, is presented in the following table. These data were obtained directly from experts at the Isfahan Blood Transfusion Organization.

Table 3. Five-Day Demand Level of Isfahan Hospitals

	O	A	B	AB
Red blood cells	615	470	410	115
Platelets	345	270	225	70
Plasma	285	220	185	60

Based on the information obtained from experts at the Isfahan Blood Transfusion Organization, under normal conditions, 50% of the total blood demand is concentrated in four hospitals, namely Omid Hospital (30%), Al-Zahra Hospital (12%), and Milad and Chamran Hospitals (8%).

Drawing on the studies by Entezari-Sara (2020) and Elmira Farokhzadeh et al. (2021), the blood demand of a hospital experiencing a high number of casualties under crisis conditions was estimated according to the intensity of the earthquake. These estimates, stratified by earthquake severity, are presented in the following tables.

Table 4. Demand Level of Whole Blood and Blood Products in the First Period

		Hospital (1st Period)				Field Hospital (1st Period)			
		Red blood cells	Platelets	Plasma	Whole blood	Red blood cells	Platelets	Plasma	Whole blood
Moderate earthquake	O	184	120	79	4	18	12	7	2
	A	282	86	66	4	28	8	6	2
	B	246	67	55	2	24	6	5	0
	AB	161	35	26	2	16	3	2	0
Severe earthquake	O	368	240	158	5	36	24	15	2
	A	564	172	132	5	56	17	13	2
	B	492	134	110	2	49	13	11	0
	AB	322	70	52	2	32	7	5	0

Since the demand of injured individuals is higher in the initial days following an earthquake and gradually decreases over time, based on expert opinions, the demand in the second period is assumed to be reduced by 30% compared to the first period. In this study, four blood products are considered, namely whole blood, platelets, plasma, and red blood cells.

The cost parameters used in this study were derived from the study by Entezari-Sara (2020), which reports cost data for the Yazd Blood Transfusion Center, subsequently adjusted based on the inflation rate. In addition, supplementary cost-related information was obtained from the Isfahan Blood Transfusion Organization.

Table 5. Costs Related to the Blood Supply Chain

Activity	Cost (Rials)
Cost of utilizing transportation vehicle	126217500
Cost of utilizing auxiliary transportation vehicle	252435000
Fixed cost of establishing a mobile blood collection center	1347104500
Relocation cost of a mobile blood collection center	13645905
Operational cost of a mobile blood collection center per bag	6000000
Operational cost of a permanent blood collection center per bag	6000000
Operational cost of producing blood products at the main blood center	20417245
Operational cost of producing whole blood at the main blood center	4072900
Holding cost of whole blood at the main blood center	6645564
Holding cost of blood products at the main blood center	6645564

Delay cost per unit time	34574150

To calculate the distances between different facilities, the shortest distance among the main routes was considered, and Google Maps was used for this purpose. As mentioned earlier, the proposed model was implemented using the GAMS software, and the CPLEX solver was employed to obtain optimal solutions.

Multi-Objective Solution Approach (Pareto Frontier)

The problem under study is a multi-objective optimization problem. Based on the conducted analyses and expert opinions, the cost objective function is considered to be more important than the other two objectives. Accordingly, the epsilon-constraint method is applied in this section. In this approach, the best and worst values of the objective functions are first determined. The interval between these two values is then divided into a predefined number of segments, each of which is considered as an epsilon value. By systematically varying the epsilon values within the optimization software, Pareto-optimal solutions can be obtained.

As stated earlier, due to its higher priority, the cost objective function is selected as the primary objective, while the other two objective functions are incorporated into the model as constraints. Finally, by obtaining the set of Pareto-optimal solutions, the Pareto frontier can be constructed.

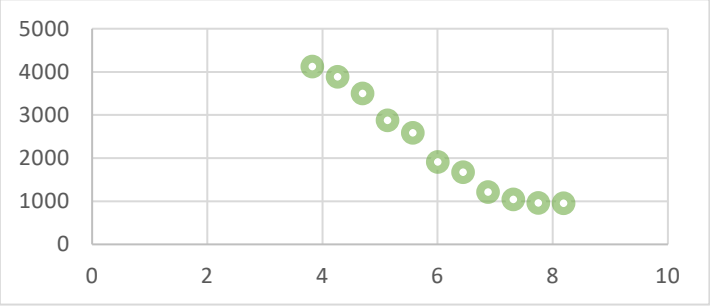

Figure 2. Relationship between the First and Second Objective Functions

As illustrated in the above figure, the trade-off between the two objective functions is clearly demonstrated. Given the perishable nature of blood and the critical importance of timely supply for saving lives, the time-related objective plays a crucial role. As shown in the figure, reducing the blood transportation time from donors to end users leads to an increase in the overall supply chain costs. Based on the graphical representation and the corresponding analysis, it can be concluded that achieving shorter delivery times requires higher costs. In other words, rapid blood delivery cannot be attained without incurring additional costs.

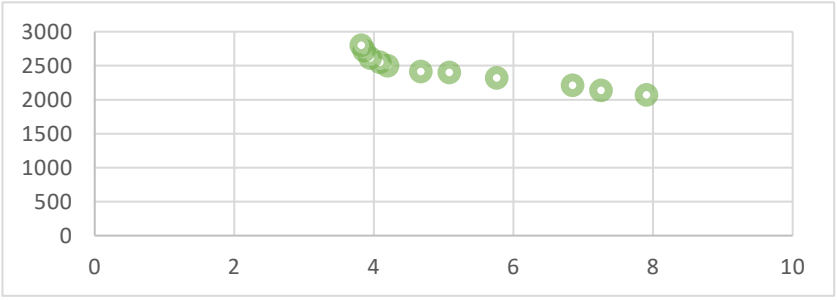

Figure 3. Relationship between the First and Third Objective Functions

As shown in the above figure, the conflict between the two objective functions is evident. As can be observed, an increase in the value of the first objective function leads to a decrease in the value of

the third objective function, and vice versa. In fact, it can be concluded that higher expenditures across all components of the supply chain result in the collection and delivery of a larger volume of blood, which consequently reduces the level of shortages at demand points.

5) Analysis of Findings

This section examines the sensitivity of the model to key parameters, including vehicle capacity, the number of vehicles, the number of permanent blood collection centers, the fixed establishment cost of mobile blood collection facilities, and variations in demand levels.

Vehicle Capacity

In this part, the impact of changes in vehicle capacity for blood transportation—ranging from a 30% decrease to a 20% increase—was investigated. As expected, and as reported in Table 6, increasing vehicle capacity leads to an increase in the value of objective function F1, while reducing the values of objective functions F2 and F3. Moreover, higher vehicle capacity has a positive effect on reducing blood transportation time and accelerating the fulfillment of demand.

Table 6. Sensitivity Analysis of Transportation Vehicle Capacity

Rate of change	Vehicle capacity	Objective function F1	Objective function F2	Objective function F3
+ 20 %	84	4.79261E+11	3540.653	2607.700
0	70	3.82456E+١١	4120.899	2802.500
- 30 %	49	3.39795E+11	5860.752	3210.400

Number of Vehicles

This section examines the impact of increasing and decreasing the number of transportation vehicles. As shown in Table 8, an increase in the number of vehicles leads to higher costs while reducing transportation time. This is because a larger fleet increases the number of trips, shortens travel times, and enables faster transfer of collected blood, thereby accelerating the response to demand.

Table 7. Sensitivity Analysis of the Number of Blood Transport Vehicles

Rate of change	Number of Vehicles	Objective function F1	Objective function F2	Objective function F3
+ 20 %	5	4.23761E+11	3960.533	2504.300
0	4	3.82456E+11	4120.899	2802.500
- 30 %	3	3.49844E+11	4850.476	3010.800

Number of Permanent Blood Collection Centers

In this section, variations in the number of permanent blood collection centers are analyzed. As reported in Table 8, increasing the number of permanent centers leads to an increase in the value of the cost objective function F1, mainly due to higher establishment costs, inventory holding costs, and operational expenses. Meanwhile, objective functions F2 and F3 decrease. Furthermore, reducing the number of permanent centers while increasing the number of mobile centers also increases F1; however, the resulting cost increase is lower than that observed when expanding the number of permanent centers.

Table 8. Sensitivity Analysis of the Number of Permanent Blood Collection Centers

Rate of change	Number of blood collection centers		Objective function F1	Weighted sum
	permanent centers	Mobile centers		
+ 20 %	9	0	4.90606E+11	1900232.8
0	7	0	3.49844E+11	1871255.8

- 30 %	5	2	3.79425E+11	1987432.3

Fixed Establishment Cost of Mobile Blood Collection Centers

In this part, the fixed establishment cost of mobile blood collection centers is varied. Based on the model solutions obtained using GAMS, mobile facilities need to be established during the first time period (the first five days) under Scenario 2 (severe earthquake). Reducing the establishment cost enables the deployment of a larger number of mobile facilities, which in turn increases the proportion of satisfied demand and reduces blood shortages.

Table 9. Cost Changes of Mobile Blood Collection Centers

Rate of change	Number of blood collection centers s_2t_1		Objective function F1	Weighted Sum
	Permanent centers	Mobile centers		
+ 20 %	7	2	3.92456E+11	1871255.8
0	7	3	3.49844E+11	1839851.8
- 30 %	7	4	3.23677E+11	1812568.3

Demand Variations

This section investigates the effects of a ±10% change in demand on the objective functions and shortage levels. As observed, blood shortages persist in all three demand scenarios under Scenario S2t1. Based on consultations with blood transfusion experts and considering the distances of blood collection centers from the city of Isfahan, only 7 out of the 9 existing centers were initially considered in the analysis.

Given the existing shortages, the two remaining centers located in Khansar (168 minutes to the main blood center) and Kashan (158 minutes to the main blood center) should also be incorporated into the network. These two centers can supply up to 600 units of blood based on their capacities. However, due to their long distances and processing time constraints, their integration poses operational challenges and necessitates an increase in the number of transportation vehicles. Even after including these two centers, the shortage cannot be fully eliminated.

Therefore, additional blood supply must be sourced from neighboring provinces, such as Chaharmahal and Bakhtiari Province. The main blood center in Shahrekord is located approximately 102 minutes from the main blood center of Isfahan, which is significantly closer than the centers in Khansar and Kashan. Moreover, blood supplied from this province is already processed into blood products, which accelerates the response to demand, whereas blood transported from Kashan and Khansar requires further testing and processing. If demand exceeds the examined levels, shortages must be compensated by sourcing blood from other neighboring provinces, such as Qom.

Table 10. Sensitivity Analysis of Demand Level

Rate of change	Objective functions			Shortage	
	F1	F2	F3	S_1t_1	S_2t_1
+ 10 %	9.94385E+11	11126427	5324.75	150	1482
0	3.82456E+11	4120899	2802.5	0	1195
- 10 %	1.47098E+11	1526258	1475	0	908

As previously stated, sensitivity analysis helps provide a deeper understanding of the performance of a proposed system by examining the effects of variations in key input parameters. Based on the results reported in the tables and figures related to changes in vehicle capacity for blood transportation, it is observed that when collection capacity decreases, the value of the cost objective function F1 does not significantly decline. This is mainly because the number of trips increases, and if the available number of vehicles is insufficient, a larger number of auxiliary vehicles must be utilized.

In contrast, increasing vehicle capacity leads to a reduction in objective functions F2 and F3, as a larger volume of blood can be transported to the main blood center in each trip. Increasing the number of permanent blood collection centers results in a substantial reduction in shortages and significantly improves demand responsiveness, which is particularly critical during crisis situations.

Reducing the establishment cost of mobile blood collection centers allows for the deployment of additional mobile facilities, which slightly increases the total cost; however, this increase is not substantial. Moreover, increasing the number of mobile centers does not have a pronounced effect on shortage reduction or response speed, primarily due to the limited capacity for collecting blood from donors.

Given the inherent uncertainty in blood demand and donation rates during crisis conditions, shortages may arise when supply decreases or demand increases. Therefore, various scenarios must be anticipated. While expanding permanent blood collection centers effectively reduces shortages, under increased demand levels, the current case study still experiences unmet demand. Consequently, shortages can be compensated by sourcing blood from neighboring provinces such as Qom and Chaharmahal and Bakhtiari.

6) Conclusions

Natural disasters occur worldwide each year with increasing frequency and varying intensity, exerting severe and adverse impacts on human lives. Under crisis conditions, the location of mobile blood collection centers and the routing of blood transportation to main blood centers—while accounting for blood perishability—are of paramount importance.

In this study, a four-echelon blood supply chain consisting of donors, blood collection centers (permanent and mobile), a main blood center, and demand points (hospitals and field hospitals) was proposed and analyzed under three objective functions. The first objective function minimizes the total cost of the blood supply chain network to ensure that the demand of injured individuals is satisfied at the lowest possible cost. The second objective function focuses on minimizing blood transportation time from permanent and mobile collection centers to the main blood center and from the main blood center to demand points, considering the perishable nature of blood. The third objective function aims to minimize the total shortage of blood products at demand points.

Blood collection centers operate in both permanent and mobile forms, with mobile centers being relocatable based on operational needs and conditions. Permanent and mobile collection centers, as well as the main blood center, are subject to limited and predefined capacities. Blood collected from donors is transported to the main blood center, where it undergoes laboratory testing and is then processed into blood products, including red blood cells, platelets, and plasma, before being distributed to hospitals according to demand levels.

Transportation vehicles used for blood transfer to the main blood center are limited in number and capacity. In the routing component, the model addresses a multi-trip routing problem while satisfying processing time constraints, with a maximum allowable processing time of six hours. The considered scenarios are defined based on earthquake severity (moderate and severe) over a 10-day planning horizon, divided into two consecutive five-day periods. Depending on the scenario and time period, the number of casualties and blood demand varies, and the model determines whether the establishment of field hospitals and mobile blood collection centers is required.

When such facilities are deemed necessary, potential locations proposed by the Isfahan Crisis Management Organization—considering infrastructure damage—are evaluated, and optimal locations for field hospitals and mobile blood collection centers are selected (Talebian et al., 2025).

6-1) Future Research Directions

Given the importance of the problem and the need to extend the current study while addressing existing gaps in the literature—particularly those encountered in real-world implementation—further research in this area is strongly recommended. Potential directions for future studies include:

- Modeling simultaneous and parallel crises, such as floods, earthquakes, and humanitarian emergencies, and investigating management strategies under multi-hazard conditions, especially in cities like Isfahan through which a river flows (Manshour and Lehmann, 2026).
- Incorporating damage caused by liquefaction and fine-grained sediment layers along riverbanks into future scenario analyses.
- Considering blood sharing among hospitals and the substitution of compatible blood groups.
- Focusing on the strategic location of backup blood storage facilities and warehouses at varying distances to reduce response times.
- Prioritizing patients based on injury severity in the allocation of blood products.
- From a practical perspective, organizations can leverage sensitivity analysis results to develop strategies that simultaneously control costs and ensure rapid and effective responses to demand. Accordingly, the following managerial recommendations are proposed:

It is recommended that the number and capacity of blood transportation vehicles be jointly and systematically evaluated and increased in a balanced manner. Any expansion should be coordinated and proportionate to avoid unnecessary and unsustainable costs while improving efficiency, reducing transportation time, and enhancing demand responsiveness.

Given that increased demand leads to shortages and considering that Isfahan Province has nine blood centers—two of which operate under limitations due to long distances and difficulties in timely blood transportation during crises—expert evaluations should be conducted to assess optimal facility locations and the feasibility of establishing new centers. A balanced policy is suggested in which the number of permanent and mobile centers is optimally adjusted based on regional demand patterns and transportation capacity. For instance, establishing permanent centers in high-traffic areas while expanding mobile centers in low-traffic regions may represent an effective strategy.

Overall, these recommendations contribute to improving the operational performance of the real-world blood supply system.

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