International Journal of Industrial Engineering Computations 7 (2016) 535–554

Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

A robust optimization model for blood supply chain in emergency situations

Meysam Fereiduni* **and Kamran Shahanaghi**

Department of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran

C H R O N I C L E

Article history:
Received April 4 2016
Received in Revised Format April 27 2016
Accepted May 12 2016
Available online May 14 2016

Keywords:
Blood supply chain
Humanitarian logistics
Robust optimization
P-robust approach
Uncertainty programing

A B S T R A C T

In this paper, a multi-period model for blood supply chain in emergency situation is presented to optimize decisions related to locate blood facilities and distribute blood products after natural disasters. In disastrous situations, uncertainty is an inseparable part of humanitarian logistics and blood supply chain as well. This paper proposes a robust network to capture the uncertain nature of blood supply chain during and after disasters. This study considers donor points, blood facilities, processing and testing labs, and hospitals as the components of blood supply chain. In addition, this paper makes location and allocation decisions for multiple post disaster periods through real data. The study compares the performances of "p-robust optimization" approach and "robust optimization" approach and the results are discussed.

1. Introduction

Natural disasters like earthquake, flood, and famine cause many problems around the world annually. Indian Ocean earthquake and tsunami on December16, 2004, Yellow River flood in China, on July 10, 1931, Bam earthquake in Iran, on December 26, 2003 and prevalence of Ebola virus in Africa in 2014, are only a few examples of natural disasters. It is obvious that these disasters have an intense impact on the affected areas and create a huge volume of demands there. So, without a precise schematization, rescue operations are not efficient. One of the most useful applications in this respect is mathematical modeling approach that has helped affected countries' governments during natural disasters (Sheu, 2007). First of all, in disaster management, mathematical modeling approach was used for marine disasters in 1980s. After those achievements, researchers have gradually started using a mathematical approach for other emergency situations as a powerful method in disaster management nowadays (Beamon & Kotleba 2006).

Recent disasters have shown that blood supply chain and its effective operation services are affected by outer disruption (Jabbarzadeh et al., 2014). For example, for the case of Bam earthquake, because of

* Corresponding author. Tel: +98-937-798-6090
E-mail: meysamfereiduni@gmail.com (M. Fereiduni)

doi: 10.5267/j.ijiec.2016.5.002

improper blood supply chain only 23% of donated blood units were distributed to the affected areas (Abolghasemi et al., 2008). Similarly, Sichuan earthquake in China disrupted blood supply chain, in 2008 (Sha & Huang, 2012). Likewise, during Japan earthquake and tsunami in 2011, also called Great Sendai Earthquake, the blood management system of this country faced many problems (Nollet et al., 2013).
The above-mentioned instances demonstrate complexity of blood supply chains, so we need an ingenious design of blood supply chain during natural disasters, because shortage of blood in disasters always increases mortality rate (Pierskalla, 2005). Statistics show blood demand during disasters has unstable rate and dynamic behavior and demand for blood in necessary during the first hours of incidents. On one hand, this dynamic nature of blood demand absolutely increases complexity. On the other hand, because blood products have a short expiration date, and donation rate has a huge doze at the very early hours, special constrains on blood products should be considered and consequently, it results in more complexity (Delen et al., 2011; Tabatabaie et al., 2010).

Therefore, by considering aforesaid uncertain and dynamic nature of blood demand, this study develops a dynamic optimization model by using robust stochastic approach for determining the number and the location of blood facilities, and also specifying inventory levels in hospitals at the end of each period. Blood donors, blood facilities, processing and testing labs, and hospitals have been considered as the components of blood supply chain in this paper. Our objective function seeks to minimize the total cost in this network such as transportation cost, inventory cost and fix cost. While our model has considered real situations, it will help decision makers implement location and allocation decisions during disasters. This paper is organized as follows: The following section briefly reviews related literature. Section 3 presents the robust network model for blood supply during emergency situations. Also, this section defines basic assumptions of the proposed model. Finally, the p-robust model is proposed in the last part of this section. The computational experiments are proposed in section 4, also this section involves sensitivity analysis about proposed models and compares "robust" and "p-robust" models performance. And the last section presents concluding and remarks some directions for future researches in respect.

2. Literature Review

Despite the fact that there are a lot of studies about dynamic supply chain management and its related problems, blood supply chain has not been explored profoundly and there are numerous research gaps in this problem. Or and Pierskalla (1979) studied partial blood banking for the first time. A literature review paper by focusing on dynamic network analysis was performed by Beliën and Forcé (2012) which relegates blood supply chain's problems and exposes research gaps on the strategic facility location decisions. Also, a review of tactical and operational models focusing on blood gathering and allocated inventory to each hospital was proposed by Pierskalla (2005). This study also reviewed models for allocating donor areas and transfusion centers to community blood centers, specifying the number of community blood centers in a region, locating these centers, and matching supply and demand. Daskin, Coullard and Shen (2002) expanded an integrated approach to determine the location of distribution centers and the amount of allocated inventory to each center. A nonlinear integer programming model for locating the problem of blood supply chain was presented by Shen et al. (2003). This model also considered inventory decisions in a single-period. Cetin and Sarul (2009) developed a model for determining the number and location of blood banks by minimizing total cost and total distance traveled.

In practical blood supply chain area, Şahin et al. (2007), Sha and Huang (2012) and Nagurney et al. (2012) presented location-allocation models with real case study. Şahin et al. (2007) developed a hierarchical location-allocation model in single-period state for Turkish Red Crescent Society. Sha and Huang (2012) presented a deterministic and multi-period model to determine location-allocation decisions of blood facilities. Their case study was about blood supply chain in Beijing earthquake. Nagurney et al. (2012) developed a blood supply chain network for allocating decisions and determining optimal capacity of blood centers. Arvan et al. (2015) presented a bi-objective, multi-product for blood supply chain by using ϵ-constraint method, but their single-period model did not capture uncertainty in blood demand. Eventually, Jabbarzadeh et al. (2014) proposed a dynamic blood supply chain network in emergency situations. Their robust network analyzed existence of potential earthquakes in Tehran, Iran as a real case. This proposed network considered blood donor, blood facilities, and blood centers without processing and testing labs.

According to our study there are many different performance measures that researchers have used. Wastage, backorders, availability, transportation cost and shortage are the most prevalent classes of performance measures. Table 1 shows these categories. In addition, this table demonstrates that different studies have focused on transportation and delivery costs.

Table 1
Different performance measures in blood supply chain

Backorders and shortage	Pierskalla & Roach 1972; Brodheim et al., 1976; Kaspi & Perry, 1983; Katsaliaki, 2008; Erickson et al., 2008; Blake, 2009; Nagurney, et al. 2012; Jabbarzadeh et al., 2014
Transportation costs	Cohen et al., 1979; Prastacos & Brodheim, 1980; Federgruen, et al., 1986; Katsaliaki, 2008; Cetin & Sarul 2009; Pierskalla, 2005; Ghandforoush & Sen 2010; Hemmelmayr et al., 2010; Nagurney et al., 2012; Jabbarzadeh et al., 2014; Arvan et al., 2015
Availability and safety	Brodheim et al.,1975; Cumming et al., 1976; Friedman et al., 1982; Galloway et al., 2008; Kopach et al., 2008;
Wastage rate	Brodheim et al., 1975; Dumas & Rabinowitz 1977; Chapman & Cook 2002; Pierskalla, 2005; Hess, 2004; Heddle et al., 2009; Davis et al., 2009
Other measures	Frankfurter et al., 1974; Kahn et al., 1978;, Custer et al., 2004; Carden & DelliFraine 2006; Katsaliaki, 2008

Our contribution in this study is to present a dynamic blood supply chain network with a robust approach in disastrous situations. Also our proposed model considers main components in blood supply chain (Blood donors, blood facilities, processing and testing labs, and hospitals). None of the mentioned studies focuses on blood supply chain network design for emergency situations with these main components.

3. Model Formulation

Our blood supply chain network and basic assumptions are presented in this section. According to Fig. 1, donor points, blood facilities, processing and testing labs, and hospitals are components of this four-layer network. Fig. 1 shows the schematic form of blood supply chain network. Hospitals receive blood products in each period and help injuries during natural disasters. Processing and testing labs receive blood from blood facilities and record, test and process these blood samples and transport them to hospitals. In laboratories the donated bloods will be completely examined and the demand for them will be considered. Blood facilities are responsible for gathering blood from donors, in addition this layer should transport collected bloods to testing labs. Permanent facilities and mobile facilities are considered as two kinds of blood facilities in this model. Permanent facilities cannot move and have larger capacities than temporary facilities. The objective function of the proposed model is to minimize the total cost of blood supply chain under each scenario. By solving the model the following decisions are specified at each period by using a set of scenarios:

1. the number and the location of permanent and mobile facilities,
2. the allocation of facilities to donation points,
3. the allocation of hospitals to labs,
4. The blood inventory in each hospital.

This section is divided into two parts. First, we present a robust optimization formulation and its related model that incorporates different disaster scenarios for the values of critical input data and then, in the second part, we introduce the p-robust model which incorporates different scenarios for possible disruptions after earthquake occurrence.

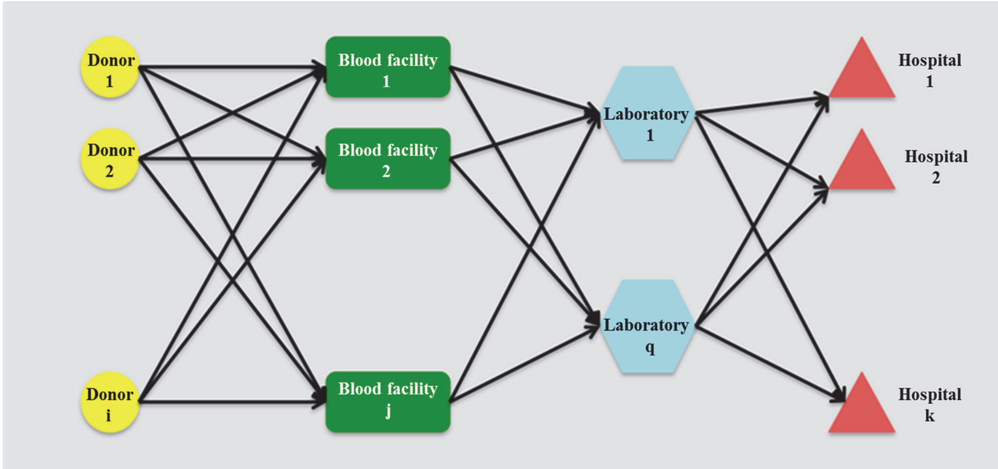

Fig. 1. Schematic form of blood supply chain network

3.1 Robust model

Mulvey et al. (1995) introduced a robust optimization due to the optimal design of supply chain in the real world and uncertain environments. By expressing the value of vital input data in a set of scenarios, robust optimization tries to approach the preferred risk aversion. This approach results in a series of solutions that are less sensitive to the model data from a scenario set. Two sets of variables act in this approach: control and design variables. The first ones are subject to adjustment once a specific realization of the data is obtained, while design variables are determined before realization of the uncertain parameters and cannot be adjusted once random parameters are observed. Constraints can be divided into two types as well: structural and control constraints. Structural constraints are typical linear programming constraints which are free of uncertain parameters, while the coefficients of control constraints are subject to uncertainty. Now we present our robust model.

Our decisions in this paper are made in two stages. Stage 1 specifies the location of permanent facilities for long periods of time before occurrence of a specific scenario. After that, stage 2 determines the mobile facilities' location and above decisions such as allocation and inventory decisions according to a specific scenario.

Notations

Following indicates, parameters, and decision variables are used for our robust model:

Indices

I	Set of donor points $i \in \{1, 2, ..., I\}$
J	Set of blood facilities points $j \in \{1, 2, ..., J\}$
P	Set of different blood products $p \in \{1, 2, ..., P\}$
Q	Set of lab points $q \in \{1, 2, ..., Q\}$
K	Set of hospital points $k \in \{1, 2, ..., K\}$
T	Set of time periods $t \in \{1, 2, ..., T\}$
S	Set of scenarios $s \in \{1, 2, ..., S\}$

Parameters

f_j	Fixed costs of locating a permanent blood facilities at point j
f'_q	Fixed costs of locating a lab at point j
v_{jl}^{ts}	Cost of moving mobile blood facility from point l to point j in period t under scenario s

O_{ij}^{ts}	Unit of operational costs of gathering blood at point *j* from donor *i* in period *t* under scenario *s*
$O_{jq}'^{ts}$	Unit of operational costs of gathering blood at lab *q* from point *j* in period *t* under scenario *s*
$O_{qk}''^{ts}$	Unit of operational costs of gathering blood at hospital *k* from lab *q* in period *t* under scenario *s*
W	Unit of transportation cost
r	Coverage radius of blood facilities
r'	Coverage radius of labs
r''	Coverage radius of hospitals
d_{ij}	Distance between point *j* and donor *i*
d_{qk}''	Distance between hospital *k* and lab *q*
d_{jq}'	Distance between lab *q* and point *j*
h_k	Unit of inventory cost at hospital *k*
m_i^{ts}	Maximum donation capacity of each donor *i* in period *t* under scenario *s*
u_{kp}	Total capacity of hospital *k* to hold blood product *p*
T_j	Duration which bloods remain in point *j*
T_q'	Duration which blood products remain in lab *q*
C_j^{ts}	Capacity of a permanent blood facility at point *j* in period *t* under scenario *s*
b_j^{ts}	Capacity of a mobile blood facility at point *j* in period *t* under scenario *s*
Cbb_q^{ts}	Capacity of lab *q* in period *t* under scenario *s*
p_s	Possibility of scenario *s* occurrence
TT	Maximum time that blood products should be arrived in hospitals
V	Average velocity of transportation vehicles
M	A very large number
D_{kp}^{ts}	Demand of blood product *p* at hospital *k* in period *t* under scenario s

Decision variables

X_j	If a permanent facility is located in point *j* equal to 1, otherwise 0
Y_q	If a lab is located in point *q* equal to equal to 1, otherwise 0
$y_{ij}'^{ts}$	If point *j* is assigned to donor *i* in period *t* under scenario *s* equal to 1, otherwise 0
$y_{jq}''^{ts}$	If lab *q* is assigned to point *j* in period *t* under scenario *s* equal to 1, otherwise 0
$y_{qk}'''^{ts}$	If hospital *k* is assigned to lab *q* in period *t* under scenario *s* equal to 1, otherwise 0
Z_{jl}^{ts}	If a mobile blood facility is located at point l in period *t*-1 and moves to point *j* in period *t* equal to 1, otherwise 0
Q_{ijq}^{ts}	Quantity of gathered blood at point *j* from donor *i* and transported to lab *q* in period *t* under scenario *s*
$Q_{qkp}'^{ts}$	Quantity of transported blood product *p* in lab *q* to hospital *k* in period *t* under scenario *s*
I_{kp}^{ts}	Quantity of blood product *p* in hospital *k* in period *t* under scenario *s*
δ_{kp}^{ts}	Unsatisfied demand of blood product *p* in hospital *k* in period *t* under scenario *s*

The robust model aims to minimize total costs of blood supply chain under each scenario. Total costs (TOTC) consist of fixed cost (FC), moving cost of mobile facilities, operational cost (OC), transportation cost (TC), and inventory cost (IC). These costs have been shown as follows:

$$FC_s = \sum_{j\in J} f_j x_j + \sum_{q\in Q} f'_q y_q$$

$$VC_s = \sum_{j\in J}\sum_{l\in L}\sum_{t\in T} v_{jl}^{ts} Z_{jl}^{ts}$$

$$OC_s = \sum_{i\in I}\sum_{j\in J}\sum_{q\in Q}\sum_{t\in t} O_{ij}^{ts} Q_{ijq}^{ts} + \sum_{i\in I}\sum_{j\in J}\sum_{q\in Q}\sum_{t\in T} O_{jq}'^{ts} Q_{ijq}^{ts} + \sum_{q\in Q}\sum_{k\in K}\sum_{p\in P}\sum_{t\in T} O_{qk}''^{ts} Q_{qkp}'^{ts}$$

$$TC_s = \sum_{i\in I}\sum_{j\in J}\sum_{q\in Q}\sum_{t\in T} Wd_{jq} Q_{ijq}^{ts} + \sum_{i\in I}\sum_{j\in J}\sum_{q\in Q}\sum_{t\in T} Wd_{qk} Q_{qkp}'^{ts}$$

$$IC_s = \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} h_k I_{kp}^{ts}$$

$$TOTC_s = FC_s + VC_s + OC_s + TC_s + IC_s$$

The mathematical model can be formulated as follows:

$$\min \sum_{s\in S} p_s (TOTC_s) + \lambda \sum_{s\in S} p_s [(TOTC_s) - \sum_{s'\in S} p_{s'} (TOTC_{s'}) + 2\theta_s] + \omega \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} p_s \delta_{kp}^{ts} \tag{1}$$

subject to:

$$x_j + \sum_{l\in J} Z_{jlt}^{t} \le 1 \quad \forall j\in J, \forall t\in T, \forall s\in S \tag{2}$$

$$\sum_{l\in J} Z_{lj}^{ts} \le \sum_{l\in J} Z_{jl}^{t-1s} \quad \forall j\in J, \forall t\in T, \forall s\in S \tag{3}$$

$$y_{ijt}'^{ts} \le x_j + \sum_{l\in J} Z_{jl}^{ts} \quad \forall i\in I, j\in J, \forall t\in T, \forall s\in S \tag{4}$$

$$d_{ij} y_{ij}'^{ts} \le r \quad \forall i\in I, j\in J, \forall t\in T, \forall s\in S \tag{5}$$

$$I_{kp}^{t-1s} - I_{kp}^{ts} + \delta_{kp}^{ts} + \sum_{j\in J} Q_{jkp}'^{ts} = D_{kp}^{ts} \quad \forall k\in K, \forall p\in P, \forall t\in T, \forall s\in S \tag{6}$$

$$Q_{ijq}^{ts} \le M\, y_{ij}'^{ts} \quad \forall i\in I, \forall j\in J, \forall q\in Q, \forall t\in T, \forall s\in S \tag{7}$$

$$Q_{ijq}^{ts} \le M\, y_{jq}''^{ts} \quad \forall i\in I, \forall j\in J, \forall q\in Q, \forall t\in T, \forall s\in S \tag{8}$$

$$\sum_{j\in J}\sum_{q\in Q} Q_{ijq}^{ts} \le m_i^{ts} \quad \forall i\in I, \forall s\in S \tag{9}$$

$$d'_{jq} y_{jq}''^{ts} \le r' \quad j\in J, \forall q\in Q, \forall t\in T, \forall s\in S \tag{10}$$

$$\sum_{i\in I}\sum_{q\in Q} Q_{ijq}^{ts} \le c_j^{ts} x_j + b_j^{ts} \sum_{l\in J} Z_{jl}^{ts} \quad \forall j\in J, \forall t\in T, \forall s\in S \tag{11}$$

$$y_{jq}'^{ts} \le y_q^{s} \quad \forall j\in J, \forall q\in Q, \forall t\in T, \forall s\in S \tag{12}$$

$$\sum_{i\in I}\sum_{j\in J} Q_{ijq}^{ts} \ge \sum_{j\in J}\sum_{k\in K}\sum_{p\in P} Q_{jqkp}'^{ts} \quad \forall q\in Q, \forall t\in T, \forall s\in S \tag{13}$$

$$d''_{qk} y_{qk}'''^{ts} \le r'' \quad \forall q\in Q, \forall k\in K, \forall t\in T, \forall s\in S \tag{14}$$

$$Q_{qkp}'^{ts} \le M y_{qk}'''^{ts} \quad \forall q\in Q, \forall k\in K, \forall p\in P, \forall t\in T, \forall s\in S \tag{15}$$

$$\sum_{q\in Q} Q_{qkp}'^{ts} = 1 \quad \forall k\in K, \forall p\in P, \forall t\in T, \forall s\in S \tag{16}$$

$$T_j(x_j + \sum_{l \in J} Z_{jl}^{ts}) + T'_q y_q + \frac{d'_{jq} y''^{ts}_{jq}}{V} + \frac{d''_{qk} y'''^{ts}_{qk}}{V} \le TT \quad (17)$$
$$\forall j \in J, \forall q \in Q, \forall k \in K, \forall t \in T, \forall s \in S$$

$$I_{kp}^{ts} \le u_{kp} \quad \forall k \in K, \forall p \in P, \forall t \in T, \forall s \in S \quad (18)$$

$$\sum_{i \in I} \sum_{j \in J} Q_{ijq}^{ts} + \sum_{i \in I} \sum_{j \in J} Q_{ijq}^{t-1s} - \sum_{k \in K} \sum_{p \in P} Q'^{ts}_{qkp} \le Cbb_q^{ts} y_q \quad \forall q \in Q, \forall t \in T, \forall s \in S \quad (19)$$

$$(TOTC_s) - \sum_{s' \in S} p_{s'}(TOTC_{s'}) + \theta_s \ge 0 \quad (20)$$

$$x_j \in \{0,1\} \quad \forall j \in J$$
$$y_q \in \{0,1\} \quad \forall q \in Q$$
$$y'^{ts}_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in J, \forall t \in T, \forall s \in S$$
$$y''^{ts}_{jq} \in \{0,1\} \quad \forall j \in J, \forall q \in Q, \forall t \in T, \forall s \in S$$
$$y'''^{ts}_{qk} \in \{0,1\} \quad \forall q \in Q, \forall k \in K, \forall t \in T, \forall s \in S$$
$$z_{jl}^{ts} \in \{0,1\} \quad \forall j \in I, \forall l \in J, \forall t \in T, \forall s \in S \quad (21)$$
$$Q_{ijq}^{ts} \ge 0 \quad \forall i \in I, \forall j \in J, \forall q \in Q, \forall t \in T, \forall s \in S$$
$$Q'^{ts}_{qkp} \ge 0 \quad \forall q \in Q, \forall k \in K, \forall p \in P, \forall t \in T, \forall s \in S$$
$$I_{kp}^{ts} \ge 0 \quad \forall k \in K, \forall p \in P, \forall t \in T, \forall s \in S$$
$$\delta_{kp}^{ts} \ge 0 \quad \forall k \in K, \forall p \in P, \forall t \in T, \forall s \in S$$

Eq. (1) shows the objective function that minimizes total costs. As it has been stated above, this objective function consists of fixed cost, moving cost, operational cost, transportation cost, and inventory cost. Eq. (2) prevents locating more than one facility at each point. Eq. (3) shows that a mobile facility cannot move from a point where no facility has been located in its previous period. Eq. (4) enforces donors cannot be assigned to unopened facilities. Eq. (5), Eq. (10), and Eq. (14) clarify coverage radius restriction. Eq. (6) determines inventory level and also unsatisfied demand for each product at hospitals. Eq. (7), Eq. (8), and Eq. (15) ensure blood and its products can be transported according to correct assignment. Eq. (9) shows the capacity of each donor. Eq. (11) clarifies maximum capacity of mobile and permanent facilities. Eq. (12) asserts a lab can be assign to a hospital if this lab is located. Eq. (13) balances input bloods and output products. Eq. (16) expresses each demand product of each hospital, at least partially, should be satisfied. Eq. (17) limits transportation time of blood supply. Eq. (18) illustrates maximum capacity of each hospital for each product. Eq. (19) explains capacity of each lab to hold donation bloods. Eq. (20) is an auxiliary equation based on what Yu and li (2000) have proposed. Eq. (21) defines binary and positive decision variables.

3.2 p-Robust model

The proposed model in the previous part determines location and allocation decisions for preparedness phase in disaster management. Location decisions consist of specifying mobile and permanent facilities and processing labs. Allocation decisions involve assignment of blood facilities to donor points, processing labs to blood facilities, and hospitals to processing labs. Here we complete this model to be more practical in real world. As it is stated in the previous section many studies such as (Jabbarzadeh et al. 2014) assumed facilities, labs, and hospitals remain unaffected during disasters, however, it is obvious these sites may be located on the faults and consequently may be affected during an earthquake. So we used Mont-Carlo simulation to generate scenarios and p-robust method to solve these problems for respond phase in disaster management. We assume two different events can occur after an earthquake:

blood facilities or processing labs disruption. The method of generating scenarios for affected sites has been shown in Fig. 2.

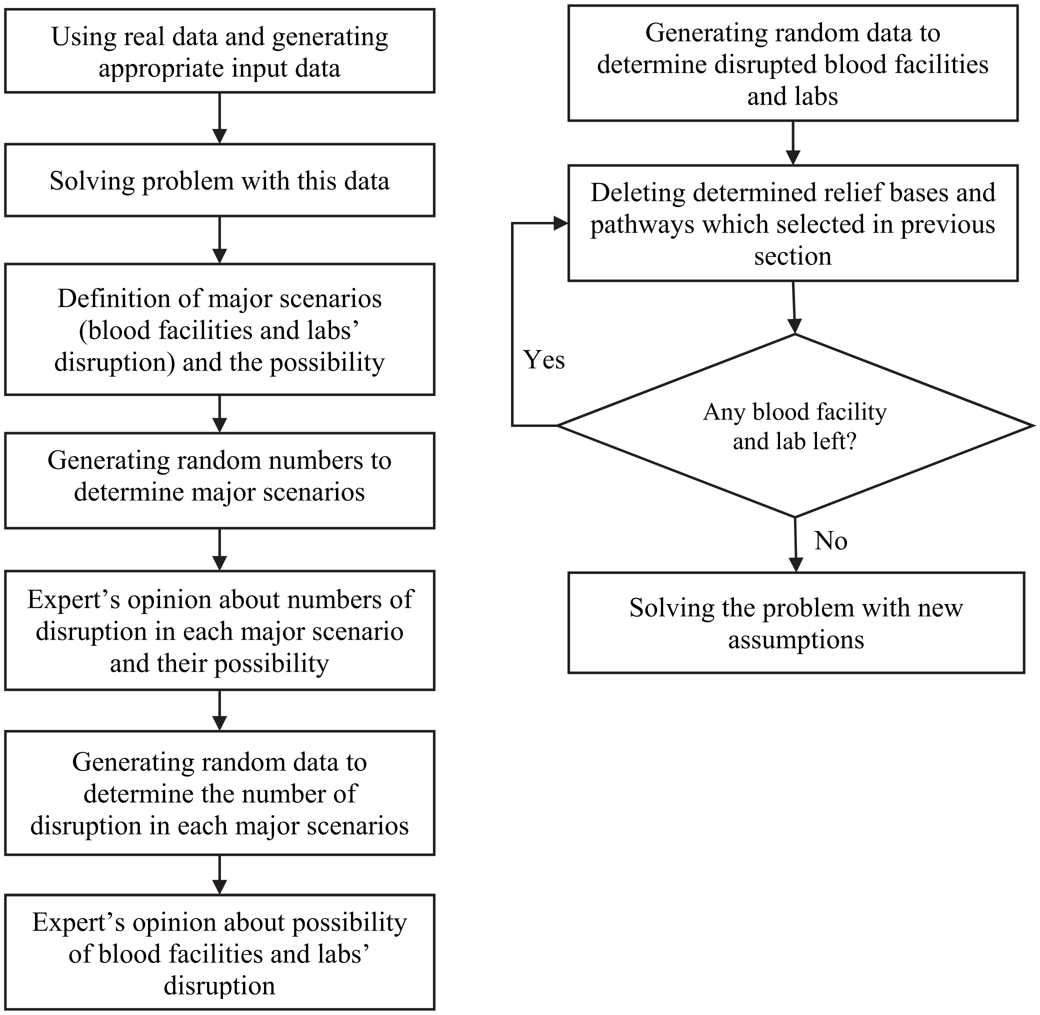

Fig. 2 Simulation flow chart to generate input parameters

To introduce the robustness measure we use in this paper, let E be a set of scenarios. Let (P_e) be a deterministic (i.e., single-scenario) minimization problem, indexed by the scenario index e. (That is, for each scenario e ∈ E, there is a different problem (P_e)). The structure of these problems is identical; only the data is different. For each e, let z^*_e be the optimal objective value for (P_s); we assume $z^*_e > 0$ for each e. The notion of p-robustness was first introduced in the context of facility layout (Kouvelis et al., 1992) and used subsequently in the context of an international sourcing problem (Gutierrez and Kouvelis 1995) and a network design problem (Gutiérrez et al., 1996).

Let $p \geq 0$ be a constant. Let X be a feasible solution to (P_s) for all e ∈ E, and let $z^*_e(X)$ be the objective value of problem (P_s) under solution x. x is called p-robust if for all e ∈ E,

$$Z_e^*(X) - Z_e^* \leq (1+p)Z_e^* \quad (22)$$

The left-hand side of the Equation above is the relative regret for scenario e; the absolute regret is given by $z^*_e(X) - z^*_e$ (Snyder & Daskin 2006).

According to the explanation given and because of uncertainty some variables must be changed as bellow:

y'^{tse}_{ij}	If point j is assigned to donor i in period t under scenario s and scenario e equal to 1, otherwise 0
y''^{tse}_{jq}	If lab q is assigned to point j in period t under scenario s and scenario e equal to 1, otherwise 0
y'''^{tse}_{qk}	If hospital k is assigned to lab q in period t under scenario s and scenario e equal to 1, otherwise 0
Z^{tse}_{jl}	If a mobile blood facility is located at point l in period t-1 and moves to point j in period t under scenario s and scenario e equal to 1, otherwise 0
Q^{tse}_{ijq}	Quantity of gathered blood at point j from donor i and transported to lab q in period t under scenario s and scenario e.
Q'^{tse}_{qkp}	Quantity of transported blood product p in lab q to hospital k in period t under scenario s and scenario e.
I^{tse}_{kp}	Quantity of blood product p in hospital k in period t under scenario s and scenario e.
δ^{tse}_{kp}	Unsatisfied demand of blood product p in hospital k in period t under scenario s and scenario e.

For each scenario (E) the optimum value of the objective function regarding model 2 must be calculated. Model 2 is described as follows:

$$\min \sum_{s\in S} p_s(TOTC_{se}) + \lambda \sum_{s\in S} p_s[(TOTC_{se}) - \sum_{s'\in S} p_{s'}(TOTC_{s'e}) + 2\theta_{se}] + \omega \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} p_s \delta^{tse}_{kp} \tag{23}$$

subject to:

$$Eq.(2)\,to\,Eq.(21) \qquad \forall e \in E \tag{32}$$

The constraints of the above model are the same as the robust model's constraints, however, based on new definition on some variable, these constraints consider each scenario $e \in E$.

Model 2 is solved for each scenario and the optimum value of the objective functions named Z^*_e. According to p-robust method, the effect of each scenario must be involved in the optimum structure of the blood supply network. So Model 3 is used to build the network.

$$\min \sum_{s\in S} p_s(TOTC_{s0}) + \lambda \sum_{s\in S} p_s[(TOTC_{s0}) - \sum_{s'\in S} p_{s'}(TOTC_{s'0}) + 2\theta_s] + \omega \sum_{k}\sum_{p}\sum_{t} p_s \delta^{ts0}_{kp} \tag{33}$$

subject to:

Eq. (32) (35)

$$\sum_{s\in S} p_s(TOTC_{se}) + \lambda \sum_{s\in S} p_s[(TOTC_{se}) - \sum_{s'\in S} p_{s'}(TOTC_{s'e}) + 2\theta_{se}] + \omega \sum_{k}\sum_{p}\sum_{t} p_s \delta^{tse}_{kp} \le (1+\alpha)Z^*_e \quad \forall e \in E/\{0\} \tag{36}$$

Eq. (33) is the p-robust model's objective function which considers all scenarios $e \in E$. Eq. (36) enforces, for each scenario, the costs cannot be more than 100(p +1) % of its optimal costs Z^*_e (value of p is related to the necessity of its scenario). Other constraints are the same as model 1 and 2.

4. Computational Result and Discussion

Because of the strategic and geographical location of Iran, and owing to the fact that 90 percent of Iran is located on faults, earthquakes have always been the most devastating disaster in the country among other natural disasters. Tehran, as a strategic city in Iran, has always been exposed to such disasters.

Regarding earthquakes, Tehran is considered a dangerous region (8 to 10 Mercalli scales). The fault in the north of Tehran is the biggest fault of the city located in the south foothill of Alborz ranges and in the north of Tehran. This fault starts in Lashkarak and Sohanak, continues in Farahzad and Hesarak, and continues towards the west. This fault encompasses Niavaran, Tajrish, Zaferanieh, Elahieh, and Farmanieh on its way.

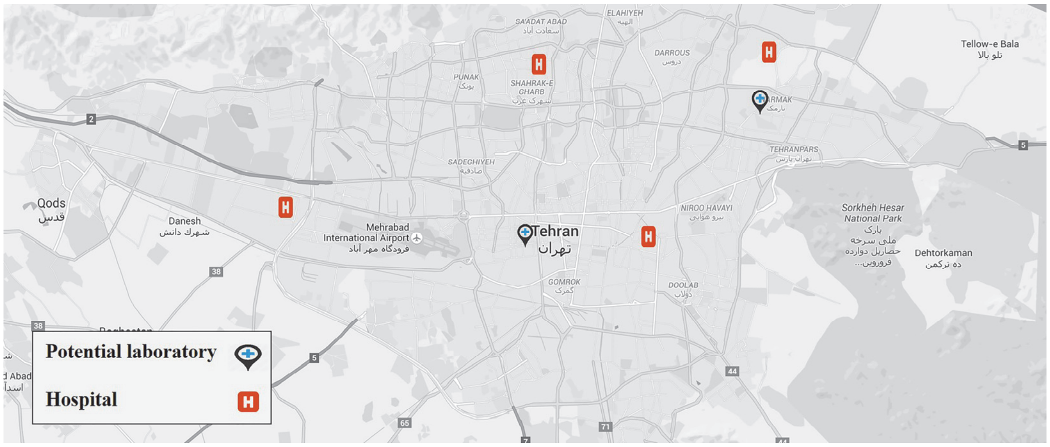

Fig. 3. Districts of Tehran and potential sites of processing labs

The necessity of paying attention to crisis management is an obvious issue regarding the dangerous and risky situation of Tehran (Sabzehchian et al. 2006). Fig. 3 shows 22 districts in Tehran which also shows donors' locations in this large city. By using the population of each district and the average blood donation rate of 22.05 unit per 1000 population, donation capacity of each district (m_i) can be estimated (Torghabeh et al., 2006). Centers of districts have been considered as potential sites for permanent blood facilities. The information about districts' location and their donation capacity is derived from Jabbarzadeh et al. (2014). Potential locations of processing labs are shown in Fig. 3. These potential sites are in districts of 2, 4, 9 and 14. According to Jabbarzadeh et al. (2014) the fixed cost of permanent facilities in Tehran is about $1518.23; in addition, the unit of operational cost of blood products is about $ 0.07 and finally, the capacity of permanent and mobile facilities are 2500 and 700. The cost of moving in of the temporary facilities in the first period is about $ 322.98 and the moving cost of the second period is derived from (Jabbarzadeh et al., 2014). According to Daskin et al. (2002) the unit of inventory cost of blood is about $1. Unit of blood transportation cost between facilities and labs and hospitals is $2.35. Coverage radius for blood facilities, labs, and hospitals are 9, 15, and 21 kilo meters.

The fixed cost for processing labs is $1990. In addition, we assume the average velocity for transporter vehicles is 60 km/h. The maximum capacity for each blood product in each lab is 550. The time that blood remains in each facility is 10 hours and the time that blood products detain in labs is 32 hours. The time window for blood supply is 70 hours.

According to Tabatabaie et al. (2010) and Jabbarzadeh et al. (2014) and generating numbers, we define earthquake scenarios and estimate the demand for blood products for each hospital in two periods. These demands have been shown in Table 2. We assume during an earthquake that, the first period demand for blood products is more than the second one, also we suppose all scenarios have equal possibilities.

Latitude and longitude of hospitals are shown in Table 3. Distance between the two points can be calculated by the following equation.

$$d_{ij} = 6371.1 \times \arccos[\sin(LAT_i) \times \sin(LAT_j) + \cos(LAT_i) \times \cos(LAT_j) \times \cos(LONG_j - LONG_i)]$$

Table 2
Earthquake scenarios and their relevant demands

			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Hospital 4	Period1	P1	123	231	124	240	237	247	227	247	290	247	271	300	281	271	320
		P2	239	250	235	560	536	542	536	542	600	542	592	610	592	592	630
		P3	89	100	88	160	145	168	145	168	201	168	190	210	195	190	210
		P4	135	142	129	790	694	700	684	700	750	700	721	760	721	721	760
	Period2	P1	120	210	119	236	210	214	210	214	230	214	230	250	230	230	257
		P2	220	230	224	542	531	539	531	539	550	539	600	653	630	600	653
		P3	50	85	56	145	110	129	110	129	140	129	132	140	135	132	145
		P4	123	140	129	657	632	649	632	649	700	649	693	730	699	693	737
Hospital 5	Period1	P1	123	231	124	240	237	247	227	247	290	247	271	300	281	271	320
		P2	239	250	235	560	536	542	536	542	600	542	592	610	592	592	630
		P3	89	100	88	160	145	168	145	168	201	168	190	210	195	190	210
		P4	135	142	129	790	694	700	684	700	750	700	721	760	721	721	760
	Period2	P1	120	210	119	236	210	214	210	214	230	214	230	250	230	230	257
		P2	220	230	224	542	531	539	531	539	550	539	600	653	630	600	653
		P3	50	85	56	145	110	129	110	129	140	129	132	140	135	132	145
		P4	123	140	129	657	632	649	632	649	700	649	693	730	699	693	737
Hospital 12	Period1	P1	123	231	124	240	237	247	227	247	290	247	271	300	281	271	320
		P2	239	250	235	560	536	542	536	542	600	542	592	610	592	592	630
		P3	89	100	88	160	145	168	145	168	201	168	190	210	195	190	210
		P4	135	142	129	790	694	700	684	700	750	700	721	760	721	721	760
	Period2	P1	120	210	119	236	210	214	210	214	230	214	230	250	230	230	257
		P2	220	230	224	542	531	539	531	539	550	539	600	653	630	600	653
		P3	50	85	56	145	110	129	110	129	140	129	132	140	135	132	145
		P4	123	140	129	657	632	649	632	649	700	649	693	730	699	693	737
Hospital 18	Period1	P1	123	231	124	240	237	247	227	247	290	247	271	300	281	271	320
		P2	239	250	235	560	536	542	536	542	600	542	592	610	592	592	630
		P3	89	100	88	160	145	168	145	168	201	168	190	210	195	190	210
		P4	135	142	129	790	694	700	684	700	750	700	721	760	721	721	760
	Period2	P1	120	210	119	236	210	214	210	214	230	214	230	250	230	230	257
		P2	220	230	224	542	531	539	531	539	550	539	600	653	630	600	653
		P3	50	85	56	145	110	129	110	129	140	129	132	140	135	132	145
		P4	123	140	129	657	632	649	632	649	700	649	693	730	699	693	737
Hospital 21	Period1	P1	123	231	124	240	237	247	227	247	290	247	271	300	281	271	320
		P2	239	250	235	560	536	542	536	542	600	542	592	610	592	592	630
		P3	89	100	88	160	145	168	145	168	201	168	190	210	195	190	210
		P4	135	142	129	790	694	700	684	700	750	700	721	760	721	721	760
	Period2	P1	120	210	119	236	210	214	210	214	230	214	230	250	230	230	257
		P2	220	230	224	542	531	539	531	539	550	539	600	653	630	600	653
		P3	50	85	56	145	110	129	110	129	140	129	132	140	135	132	145
		P4	123	140	129	657	632	649	632	649	700	649	693	730	699	693	737

Table 3
Geographic coordination of hospitals

	Hospital 4	Hospital 5	Hospital 12	Hospital 18	Hospital 21
Longitude	51.49124	51.30091	51.42611	51.29289	51.25790
Latitude	35.74183	35.74879	35.68102	35.65207	35.69101

This robust model has been coded in GAMS on a laptop with Intel Core i2, 2.8 GHz and 8GB of RAM. Fig. 4 sums up numerical example results at ω=50. The location of permanent facilities and processing labs are shown on Fig. 4 and it is evident these facilities and processing labs tend to be located near hospitals. Optimal decision variables are provided in Table 4-9 under each scenario in each period. Table 4 shows allocated facilities to donors, according to this table, it is possible that different blood facilities be allocated in first and second periods. Table 4 demonstrates located mobile facilities under each scenario in first and second period. This Table, also, consists of mobile facilities located only in stronger earthquake scenarios.

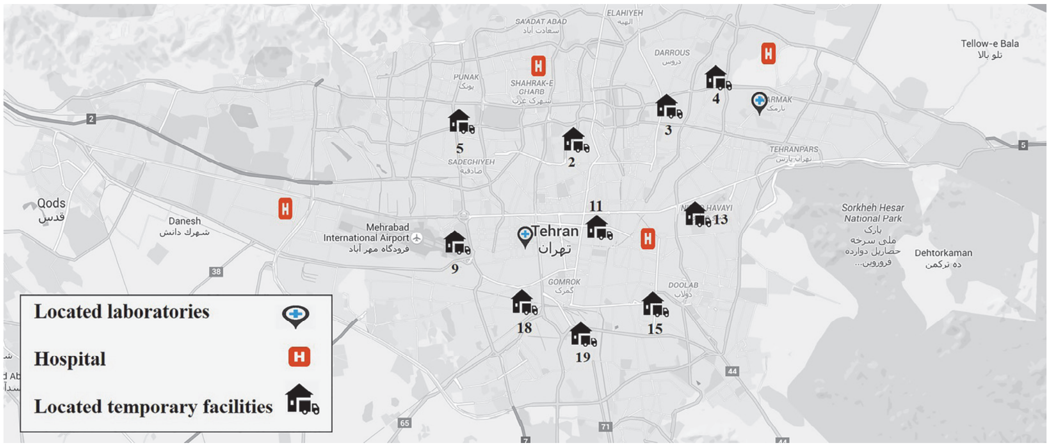

Fig. 4. Selected permanent blood facilities and laboratories

Table 4
Selected mobile facilities under each scenario at each period

Mobile facilities	Period 1	Period 2
F1	S12, S13	
F6	S9, S12, S15	S12, S15
F7	S9, S12, S13	S9, S13
F8	S15	S15
F10	S12, S15	S15
F12		
F14	S9, S12, S13	S9, S13
F16	S15	
F17	S15	S15
F20		
F21	S12, S13, S15	S13, S15
F22	S15	S15

Table 5 shows allocation of donors to mobile and temporary facilities under each scenario at each period. This table demonstrates one donor can be assigned to more than one facility. In addition, it has been concluded the number of located facilities in the first period are more than the second one.

Table 5
Allocated donors to mobile and permanent facilities

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
D1								2					1		2
D2	3	3, 4	3, 4	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5	1, 3, 4, 5	3, 4, 5	3, 4, 5	3, 4, 5
D3	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4	3, 4
D4												6	1, 2		22, 21
D5			5	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2	5, 2
D6		2	2, 5	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9	2, 5, 9
D7						18		11	7, 2	18		7, 10	7	2	7, 8
D8					11					11, 4	7, 11			13, 2	11, 15
D9				9	9, 11	9	9	9	9	9	9	9	9, 14	9	9
D10									14		2	2, 5		11, 18	2, 6, 10
D11	3	3	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5	3, 5
D12													21		11, 18
D13	4	3, 4	3, 4	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9	3, 5, 9
D14	4	4	4	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9	4, 9
D15												14			15
D16				19	19	19	19	19	19	19	19	19	19	19	19, 2
D17									6						17
D18												21	21, 14	11, 18	9, 8, 17
D19															21, 17
D20														15	15
D21															
D22															19

Table 6 shows gathered blood from donor points at first period in each mobile and permanent facilities. Table 7 describes quantity of bloods that is transported from blood facilities to processing labs at first period under each scenario.

Table 6
Quantity of gathered bloods in each facility at first period under each scenario

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
F1												500	500		
F2		500	500	1000	1000	500	1000	1710	600	1085	1550	1500	2500	700	1000
F3	1930	751	640	2500	1500	1500	1750	1000	1500	1500	1600	1000	1500	1000	900
F4	1000	2400	1000	1500	2000	1500	1500	750	2500	1500	1500	500	1750	1300	1000
F5			740	1500	1500	1500	2060	1000	2000	1250	1350	1000	1250	1500	700
F6									500			500			500
F7									500			500	500		450
F8															550
F9				2000	1300	2000	750	1575		1500	1570	1700			700
F10												500			500
F11					500			2000		750	1000			1500	600
F12															
F13															
F14									500			400	500		
F15														870	1000
F16															300
F17															200
F18						700				500				750	700
F19				250	260	500	900	250	1000	200	300	300		1250	
F20															
F21												500	445		500
F22															500

Table 7
Quantity of gathered bloods in each processing lab at each period under each scenario

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
First period	Lab 4	1904	2349	1872	5687	5239	5385	5174	5385	5983	5385	5765	6110	5814	5765	6240
	Lab 9	1025	1265	1008	3062	2821	2899	2786	2899	3221	2899	3104	3290	3130	3104	3360
Second period	Lab 4	1667	2161	1716	5135	4819	4975	4819	4975	5265	4975	5378	5762	5505	5378	5824
	Lab 9	897	1163	924	2765	2595	2679	2595	2679	2835	2679	2896	3102	2964	2896	3136

Table 8
Quantity of blood products transported from lab4 to each hospital at each period under each scenario

			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Hospital 4	Period 1	P1	80	129	81	134	154	138	148	138	189	138	176	168	183	152	208
		P2	155	140	153	314	348	304	348	304	390	304	385	342	385	332	410
		P3	58	56	57	90	94	94	94	94	131	94	124	118	127	106	137
		P4	88	80	84	442	451	392	445	392	488	392	469	426	469	404	494
	Period 2	P1	78	118	77	132	137	120	137	120	150	120	150	140	150	129	167
		P2	143	129	146	304	345	302	345	302	358	302	390	366	410	336	424
		P3	33	48	36	81	72	72	72	72	91	72	86	78	88	74	94
		P4	80	78	84	368	411	363	411	363	455	363	450	409	454	388	479
Hospital 5	Period 1	P1	80	129	81	134	154	138	148	138	189	138	176	168	183	152	208
		P2	155	140	153	314	348	304	348	304	390	304	385	342	385	332	410
		P3	58	56	57	90	94	94	94	94	131	94	124	118	127	106	137
		P4	88	80	84	442	451	392	445	392	488	392	469	426	469	404	494
	Period 2	P1	78	118	77	132	137	120	137	120	150	120	150	140	150	129	167
		P2	143	129	146	304	345	302	345	302	358	302	390	366	410	336	424
		P3	33	48	36	81	72	72	72	72	91	72	86	78	88	74	94
		P4	80	78	84	368	411	363	411	363	455	363	450	409	454	388	479
Hospital 12	Period 1	P1	80	129	81	134	154	138	148	138	189	138	176	168	183	152	208
		P2	155	140	153	314	348	304	348	304	390	304	385	342	385	332	410
		P3	58	56	57	90	94	94	94	94	131	94	124	118	127	106	137
		P4	88	80	84	442	451	392	445	392	488	392	469	426	469	404	494
	Period 2	P1	78	118	77	132	137	120	137	120	150	120	150	140	150	129	167
		P2	143	129	146	304	345	302	345	302	358	302	390	366	410	336	424
		P3	33	48	36	81	72	72	72	72	91	72	86	78	88	74	94
		P4	80	78	84	368	411	363	411	363	455	363	450	409	454	388	479
Hospital 18	Period 1	P1	80	129	81	134	154	138	148	138	189	138	176	168	183	152	208
		P2	155	140	153	314	348	304	348	304	390	304	385	342	385	332	410
		P3	58	56	57	90	94	94	94	94	131	94	124	118	127	106	137
		P4	88	80	84	442	451	392	445	392	488	392	469	426	469	404	494
	Period 2	P1	78	118	77	132	137	120	137	120	150	120	150	140	150	129	167
		P2	143	129	146	304	345	302	345	302	358	302	390	366	410	336	424
		P3	33	48	36	81	72	72	72	72	91	72	86	78	88	74	94
		P4	80	78	84	368	411	363	411	363	455	363	450	409	454	388	479
Hospital 21	Period 1	P1	80	129	81	134	154	138	148	138	189	138	176	168	183	152	208
		P2	155	140	153	314	348	304	348	304	390	304	385	342	385	332	410
		P3	58	56	57	90	94	94	94	94	131	94	124	118	127	106	137
		P4	88	80	84	442	451	392	445	392	488	392	469	426	469	404	494
	Period 2	P1	78	118	77	132	137	120	137	120	150	120	150	140	150	129	167
		P2	143	129	146	304	345	302	345	302	358	302	390	366	410	336	424
		P3	33	48	36	81	72	72	72	72	91	72	86	78	88	74	94
		P4	80	78	84	368	411	363	411	363	455	363	450	409	454	388	479

Finally, Table 8 and Table 9 show the quantity of blood products transported from lab4 and lab9 to each hospital at each period under each scenario. Unsatisfied demand can be calculated from Table 8.

Table 9

Quantity of blood products transported from lab4 and lab9 to each hospital at each period under each scenario

			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Hospital 4	**Period 1**	P1	43	81	43	84	83	86	79	86	102	86	95	105	98	95	112
		P2	84	88	82	196	188	190	188	190	210	190	207	214	207	207	221
		P3	31	35	31	56	51	59	51	59	70	59	67	74	68	67	74
		P4	47	50	45	277	243	245	239	245	263	245	252	266	252	252	266
	Period 2	P1	42	74	42	83	74	75	74	75	81	75	81	88	81	81	90
		P2	77	81	78	190	186	189	186	189	193	189	210	229	221	210	229
		P3	18	30	20	51	39	45	39	45	49	45	46	49	47	46	51
		P4	43	49	45	230	221	227	221	227	245	227	243	256	245	243	258
Hospital 5	**Period 1**	P1	43	81	43	84	83	86	79	86	102	86	95	105	98	95	112
		P2	84	88	82	196	188	190	188	190	210	190	207	214	207	207	221
		P3	31	35	31	56	51	59	51	59	70	59	67	74	68	67	74
		P4	47	50	45	277	243	245	239	245	263	245	252	266	252	252	266
	Period 2	P1	42	74	42	83	74	75	74	75	81	75	81	88	81	81	90
		P2	77	81	78	190	186	189	186	189	193	189	210	229	221	210	229
		P3	18	30	20	51	39	45	39	45	49	45	46	49	47	46	51
		P4	43	49	45	230	221	227	221	227	245	227	243	256	245	243	258
Hospital 12	**Period 1**	P1	43	81	43	84	83	86	79	86	102	86	95	105	98	95	112
		P2	84	88	82	196	188	190	188	190	210	190	207	214	207	207	221
		P3	31	35	31	56	51	59	51	59	70	59	67	74	68	67	74
		P4	47	50	45	277	243	245	239	245	263	245	252	266	252	252	266
	Period 2	P1	42	74	42	83	74	75	74	75	81	75	81	88	81	81	90
		P2	77	81	78	190	186	189	186	189	193	189	210	229	221	210	229
		P3	18	30	20	51	39	45	39	45	49	45	46	49	47	46	51
		P4	43	49	45	230	221	227	221	227	245	227	243	256	245	243	258
Hospital 18	**Period 1**	P1	43	81	43	84	83	86	79	86	102	86	95	105	98	95	112
		P2	84	88	82	196	188	190	188	190	210	190	207	214	207	207	221
		P3	31	35	31	56	51	59	51	59	70	59	67	74	68	67	74
		P4	47	50	45	277	243	245	239	245	263	245	252	266	252	252	266
	Period 2	P1	42	74	42	83	74	75	74	75	81	75	81	88	81	81	90
		P2	77	81	78	190	186	189	186	189	193	189	210	229	221	210	229
		P3	18	30	20	51	39	45	39	45	49	45	46	49	47	46	51
		P4	43	49	45	230	221	227	221	227	245	227	243	256	245	243	258
Hospital 21	**Period 1**	P1	43	81	43	84	83	86	79	86	102	86	95	105	98	95	112
		P2	84	88	82	196	188	190	188	190	210	190	207	214	207	207	221
		P3	31	35	31	56	51	59	51	59	70	59	67	74	68	67	74
		P4	47	50	45	277	243	245	239	245	263	245	252	266	252	252	266
	Period 2	P1	42	74	42	83	74	75	74	75	81	75	81	88	81	81	90
		P2	77	81	78	190	186	189	186	189	193	189	210	229	221	210	229
		P3	18	30	20	51	39	45	39	45	49	45	46	49	47	46	51
		P4	43	49	45	230	221	227	221	227	245	227	243	256	245	243	258

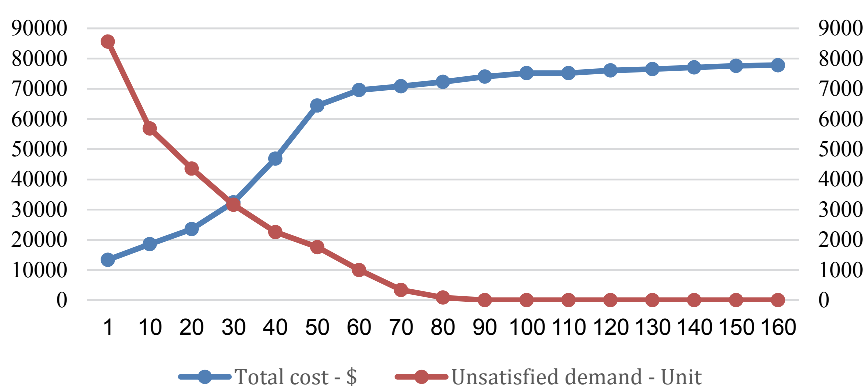

Fig. 5. Tradeoff between minimizing total costs' objective and maximizing satisfied demands

In this section, we explored a trade-off between minimizing total costs' objective and maximizing satisfied demand by changing in ω parameter. A decision maker who risks the shortage of blood likes a higher value of ω because of a lower cost. However, another decision maker who doesn't risk the shortage of blood prefers a lower value of ω. Fig. 5 helps decision makers find the best decision by choosing their favorite ω. With the increase in value of ω, total costs will increase and unsatisfied demands will decrease. For example at ω=50 total cost is $64431. At ω=100 total cost is increased to $75176 because reduction in unsatisfied demands.

This section proposes a sensitivity analysis of the vital parameters for deterministic models. The first parameter for this purpose is the demand of blood product *p* at hospital *k* in period *t*, that is shown by D_{pk}^{t}. Based on Arvan et al. (2015) blood demand depends on diverse factors such as population, age, gender, unpredictable events and so on. Table 10 shows a uniform distribution used in sensitivity analysis of demand for each product. Fig. 6 demonstrates the variation of the objective function in the deterministic model by changing the amount of blood demand product *p* at hospital *k* in period *t*. This figure shows a sudden increase in the mentioned objective function. By increasing the blood demand the model is unable to satisfy all demands. Consequently, shortage cost promotes noticeably and results in this sudden increase.

Table 10
Uniform distribution used in sensitivity analysis of demand for each product

No	Uniform distribution
1	~ Uniform (50, 70)
2	~ Uniform (35, 110)
3	~ Uniform (60, 140)
4	~ Uniform (90, 180)
5	~ Uniform (110, 210)
6	~ Uniform (190, 240)
7	~ Uniform (200, 300)

The maximum donation capacity of each donor is the second parameter that is used for sensitivity analysis. Donation capacity is a random variable because it depends on different elements such as population and this means it could have a noxious impact on the blood supply during disasters. So, being attentive to this parameter's changes would be advantageous for decision makers. To analyze these changes the uniform distributions of donation capacity have been proposed in Table 11. Fig. 7 displays the changes of objective function of deterministic model by variation in the donation capacity. Abrupt increase in this figure can be explained by the same reason that was mentioned for blood demand.

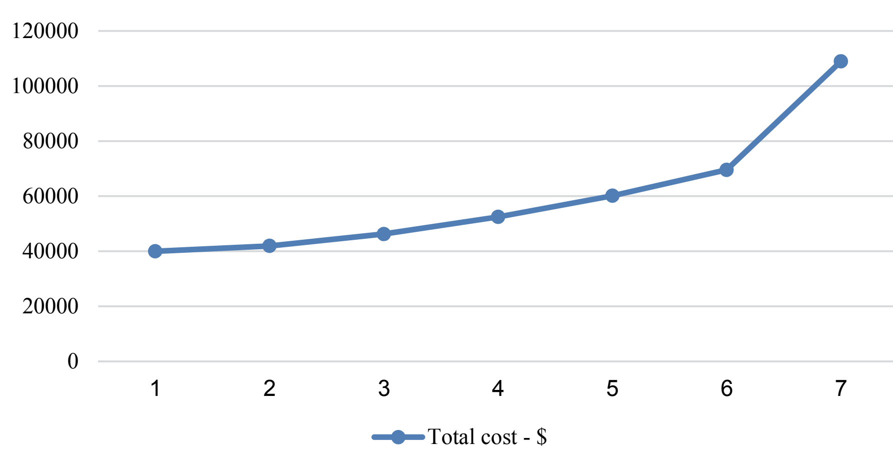

Fig. 6. Sensitivity of total costs by variation the blood demand

Table 11
Uniform distribution used in sensitivity analysis of donation capacity

No	Uniform distribution
1	~ Uniform (90, 110)
2	~ Uniform (80, 100)
3	~ Uniform (70, 90)
4	~ Uniform (65, 80)
5	~ Uniform (40, 70)
6	~ Uniform (20, 45)
7	~ Uniform (10, 25)

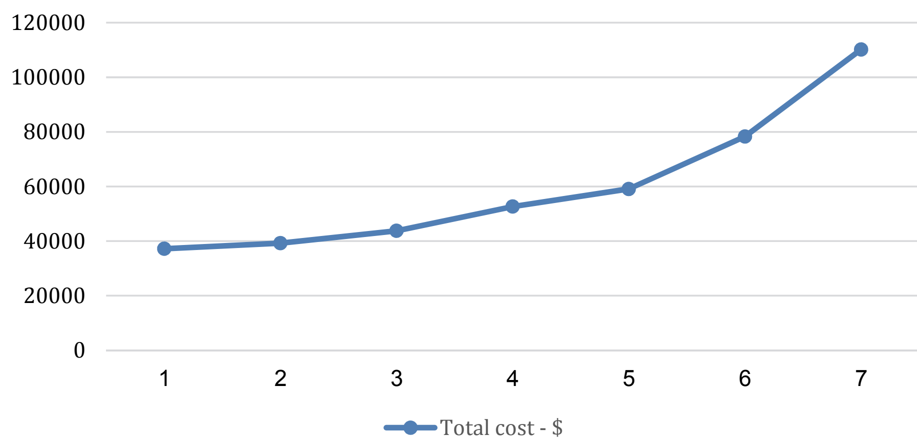

Fig. 7. Sensitivity of total costs by variation the donation capacity

Based on the proposed flowchart in Fig. 2, three permanent facilities will be down during earthquake, these facilities for special scenario are: F2, F9, and F15. Values of the objective functions for four scenarios are seen in Table 12. As stated before, these values go into the p-robust model as Ze* parameter. According to these scenarios and Table 5-10 the objective function of the third model is $69034.

Table 12
Values of the objective functions for four scenarios

	Ze* - $
Scenario 1	68995
Scenario 2	80301
Scenario 3	84510
Scenario 4	73450

To evaluate both the p-robust and robust models two performance measures are used: the mean and the standard deviation of the objective function under random realizations. Additionally, we vary the p-robust parameter between [0 1] and calculate mean and standard deviation for p-robust and robust models. The results show the p-robust model gained the solutions with both higher quality and lower standard deviation than robust model for fixed, moving, operational, transportation and inventory costs. In most problems, the p-robust approach dominates the robust model with respect to the mean of the cost objective function value and its standard deviation. These results are seen in Table 13. However, because of simulation in two cases the mean of the robust model is better than the p-robust model which are shown with a different color. The results imply that the p-robust strategy has a better performance in low values for p-robust parameters. As seen in Fig. 6, when p-robust parameter increases the mean of the objective function of p-robust model is closer to this objective in robust model. To determine the sensitivity of the objective functions' value to variations in robust parameter, sensitivity analysis experiment is performed. Fig. 8 shows the sensitivity of the proposed model's objective functions to variations in robust parameter. Based on the proposed model with increasing robust parameter, feasible region increases. Therefore, we expect that the increasing of the mentioned parameter improves both objective functions.

Table 13
Summary of test results of the second objective function value and the standard deviation of both models

problem size |I|*|J|*|Q|*|K|* |P|*|T|*|S|	P-robust parameter (α)	Mean of objective function values under realizations		Standard deviation of objective function values under realizations	
		Robust	P-Robust	Robust	P-Robust
9*9*2*2* 4*2*15	0.0	37457	37341	110	54
	0.4	37005	36899	1340	120
	0.8	36874	36561	2510	490
	1.0	36541	36530	2050	560
15*15*3*2* 4*2*15	0.0	50745	50604	1430	43
	0.4	50548	50012	2390	320
	0.8	49865	50131	1980	480
	1.0	49341	49212	3200	980
17*17*4*5* 4*2*15	0.0	62679	62851	4050	190
	0.4	62457	62310	2980	370
	0.8	61980	61760	3500	590
	1.0	61340	61215	5140	860
22*22*4*5* 4*2*15	0.0	75890	75490	4900	710
	0.4	75123	75111	6780	840
	0.8	74896	74549	3750	980
	1.0	74876	74020	5360	1120

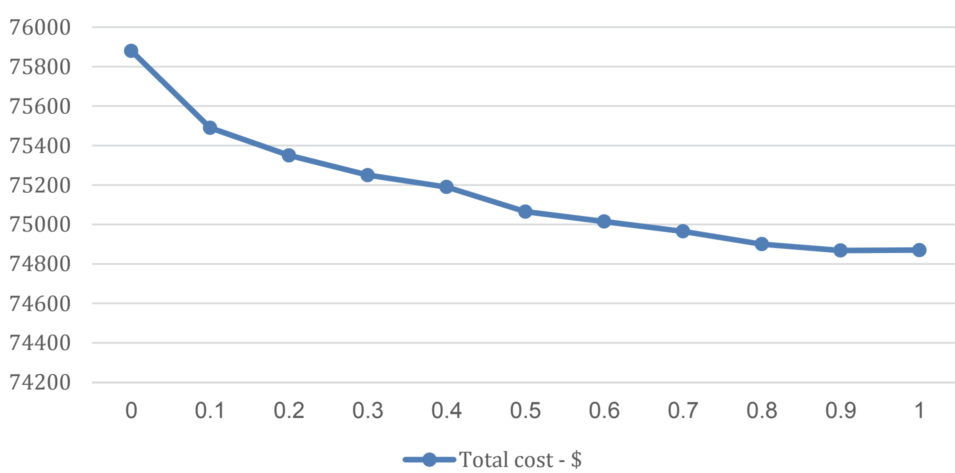

Fig. 8. Sensitivity of the proposed model to variations in robust parameter

5. Conclusion and Future Research

In this paper a robust model for blood supply chain was presented in emergency situations to minimize total cost. This model determined location and distribution decisions for an uncertain environment and a multi-period network. The location decisions consist of the number and location of temporary and permanent blood facilities, and the number and location of laboratories. Distribution decisions involve the quantity of transported blood between the components. In order to improve the application of the model against unforeseen events and possible disruption among routes, a p-robust approach was used.

To evaluate the application of the robust model, real data was applied and location-allocation decisions were determined. We presented different sensitivity analysis experiments from which important implications were drawn. For example, we demonstrated how the total cost of the supply chain can be balanced against unsatisfied demands. In addition, we showed how donation capacity and demand rate effect the objective function. In the last part of our numerical example, we compared the "robust" and "p-robust" models' performance by their objective functions' mean and standard deviation. The results explained that "p-robust" model dominated the "robust" model. This comparison also showed "p-robust" model performance is far better in lower levels of the p-robust parameter.

In brief, our contributions can be summarized as follows:

1. We developed a multi-period robust model for blood supply chain which captured uncertainty in the value of some input data.
2. The proposed model consists of all components in a given blood supply chain which are donors, blood facilities, laboratories, and hospitals.
3. We developed a p-robust model to consider possible damages among routes after earthquake occurrences.

Like other studies our paper is not without any defection. In this paper we just considered one decision maker which controlled the whole supply chain, in the real world, however, different Decision Makers paly roles in such a supply chain which has different goals. Future research can study this situation by using multi-level programming. Also, presenting a new solution technique which can solve the model within a reasonable length of time, can be a logical set point for future researches. Finally, considering more objective functions will be advantageous for this blood supply chain. Because of the emergency situation, considered in this paper, a reliable network is important. Developing a model which increases the reliability of the model helps decision makers more.

References

Abolghasemi, H., Radfar, M. H., Tabatabaee, M., Hosseini-Divkolayee, N. S., & Burkle, F. M. (2008). Revisiting blood transfusion preparedness: experience from the Bam earthquake response. *Prehospital and disaster medicine*,*23*(05), 391-394.

Arvan, M., Tavakkoli-Moghaddam, R., & Abdollahi, M. (2015). Designing a bi-objective and multi-product supply chain network for the supply of blood. *Uncertain Supply Chain Management*, *3*(1), 57-68.

Beamon, B. M., & Kotleba, S. A. (2006). Inventory modelling for complex emergencies in humanitarian relief operations. *International Journal of Logistics: Research and Applications*, *9*(1), 1-18.

Beliën, J., & Forcé, H. (2012). Supply chain management of blood products: A literature review. *European Journal of Operational Research*, *217*(1), 1-16.

Blake, J. T. (2009). On the use of Operational Research for managing platelet inventory and ordering. *Transfusion*, *49*(3), 396-401.

Brodheim, E., Derman, C., & Prastacos, G. (1975). On the evaluation of a class of inventory policies for perishable products such as blood. *Management Science*, *21*(11), 1320-1325.

Brodheim, E., Hirsch, R., & Prastacos, G. (1976). Setting inventory levels for hospital blood banks. *Transfusion*, *16*(1), 63-70.

Carden, R., & DelliFraine, J. L. (2006). An examination of blood center structure and hospital customer satisfaction: what can centralized and decentralized blood centers learn from each other?. *Health marketing quarterly*, *22*(3), 21-42.

Cetin, E., & Sarul, L. S. (2009). A blood bank location model: A multi objective approach. *European Journal of Pure and Applied Mathematics*, *2*(1), 112-124.

Chapman, J. F., & Cook, R. (2002). The Blood Stocks Management Scheme, a partnership venture between the National Blood Service of England and North Wales and participating hospitals for maximizing blood supply chain management. *Vox Sanguinis*, *83*(3), 239-246.

Cohen, M. A., Pierskalla, W. P., Sassetti, R. J., & Consolo, J. (1979). An overview of a hierarchy of planning models for regional blood bank management. *Transfusion*, *19*(5), 526-534.

Cumming, P. D., Kendall, K. E., Pegels, C. C., Seagle, J. P., & Shubsda, J. F. (1976). A collections planning model for regional blood suppliers: description and validation. *Management Science*, *22*(9), 962-971.

Custer, B., Johnson, E. S., Sullivan, S. D., Hazlet, T. K., Ramsey, S. D., Hirschler, N. V., ... & Busch, M. P. (2004). Quantifying losses to the donated blood supply due to donor deferral and miscollection. *Transfusion*, *44*(10), 1417-1426.

Daskin, M. S., Coullard, C. R., & Shen, Z. J. M. (2002). An inventory-location model: Formulation, solution algorithm and computational results. *Annals of operations research*, *110*(1-4), 83-106.

Davis, R., Geiger, B., Gutierrez, A., Heaser, J., & Veeramani, D. (2009). Tracking blood products in blood centers using radio frequency identification: a comprehensive assessment. *Vox sanguinis*, *97*(1), 50-60.

Delen, D., Erraguntla, M., Mayer, R. J., & Wu, C. N. (2011). Better management of blood supply-chain with GIS-based analytics. *Annals of Operations Research*, *185*(1), 181-193.

Dumas, M. B., & Rabinowitz, M. (1977). Policies for reducing blood wastage in hospital blood banks. *Management Science*, *23*(10), 1124-1132.

Erickson, M. L., Champion, M. H., Klein, R., Ross, R. L., Neal, Z. M., & Snyder, E. L. (2008). Management of blood shortages in a tertiary care academic medical center: the Yale-New Haven Hospital frozen blood reserve. *Transfusion*, *48*(10), 2252-2263.

Federgruen, A., Prastacos, G., & Zipkin, P. H. (1986). An allocation and distribution model for perishable products. *Operations Research*, *34*(1), 75-82.

Frankfurter, G. M., Kendall, K. E., & Pegels, C. C. (1974). Management control of blood through a short-term supply-demand forecast system. *Management Science*, *21*(4), 444-452.

Friedman, B. A., Abbott, R. D., & Williams, G. W. (1982). A blood ordering strategy for hospital blood banks derived from a computer simulation. *American Journal of clinical pathology*, *78*(2), 154-160.

Galloway, M. J., Jane, G., Sudlow, L., Trattles, J., & Watson, J. (2008). A tabletop exercise to assess a hospital emergency blood management contingency plan in a simulated acute blood shortage. *Transfusion Medicine*,*18*(5), 302-307.

Ghandforoush, P., & Sen, T. K. (2010). A DSS to manage platelet production supply chain for regional blood centers. *Decision Support Systems*, *50*(1), 32-42.

Gutierrez, G. J., & Kouvelis, P. (1995). A robustness approach to international sourcing. *Annals of Operations Research*, *59*(1), 165-193.

Gutiérrez, G. J., Kouvelis, P., & Kurawarwala, A. A. (1996). A robustness approach to incapacitated network design problems. *European Journal of Operational Research*, *94*(2), 362-376.

Heddle, N. M., Liu, Y., Barty, R., Webert, K. E., Whittaker, S., Gagliardi, K. & Owens, W. (2009). Factors affecting the frequency of red blood cell outdates: an approach to establish benchmarking targets. *Transfusion*, *49*(2), 219-226.

Hemmelmayr, V., Doerner, K. F., Hartl, R. F., & Savelsbergh, M. W. (2010). Vendor managed inventory for environments with stochastic product usage. *European Journal of Operational Research*, *202*(3), 686-695.

Hess, J. R. (2004). Red cell freezing and its impact on the supply chain. *Transfusion Medicine*, *14*(1), 1-8.

Jabbarzadeh, A., Fahimnia, B., & Seuring, S. (2014). 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*, *70*, 225-244.

Kahn, R. A., McDonough, B., Rowe, A., Ellis, F. R., & Pino, B. (1978). The impact of converting to an all frozen blood system in a large regional blood center. *Transfusion*, *18*(3), 304-311.

Kaspi, H., & Perry, D. (1983). Inventory systems of perishable commodities. *Advances in Applied Probability*, 674-685.

Katsaliaki, K. (2008). Cost-effective practices in the blood service sector. *Health policy*, *86*(2), 276-287.

Kopach, R., Balcıoğlu, B., & Carter, M. (2008). Tutorial on constructing a red blood cell inventory management system with two demand rates. *European Journal of Operational Research*, *185*(3), 1051-1059.

Kouvelis, P., Kurawarwala, A. A., & Gutierrez, G. J. (1992). Algorithms for robust single and multiple period layout planning for manufacturing systems. *European journal of operational research*, *63*(2), 287-303.

Mulvey, J. M., Vanderbei, R. J., & Zenios, S. A. (1995). Robust optimization of large-scale systems. *Operations research*, *43*(2), 264-281.

Nagurney, A., Masoumi, A. H., & Yu, M. (2012). Supply chain network operations management of a blood banking system with cost and risk minimization. *Computational Management Science*, *9*(2), 205-231.

Nollet, K. E., Ohto, H., Yasuda, H., & Hasegawa, A. (2013). The great East Japan earthquake of March 11, 2011, from the vantage point of blood banking and transfusion medicine. *Transfusion medicine reviews*, *27*(1), 29-35.

Or, I., & Pierskalla, W. P. (1979). A transportation location-allocation model for regional blood banking. *AIIE transactions*, *11*(2), 86-95.

Pierskalla, W. (2005). Supply chain management of blood banks. *Operations research and health care*, 103-145.

Pierskalla, W. P., & Roach, C. D. (1972). Optimal issuing policies for perishable inventory. *Management Science*, *18*(11), 603-614.

Prastacos, G. P., & Brodheim, E. (1980). PBDS: a decision support system for regional blood management. *Management Science*, *26*(5), 451-463.

Sabzehchian, M., Abolghasemi, H., Radfar, M. H., Jonaidi-Jafari, N., Ghasemzadeh, H., & Burkle, F. M. (2006). Pediatric trauma at tertiary-level hospitals in the aftermath of the Bam, Iran Earthquake. *Prehospital and disaster medicine*, *21*(05), 336-339.

Şahin, G., Süral, H., & Meral, S. (2007). Locational analysis for regionalization of Turkish Red Crescent blood services. *Computers & Operations Research*, *34*(3), 692-704.

Sha, Y., & Huang, J. (2012). The multi-period location-allocation problem of engineering emergency blood supply systems. *Systems Engineering Procedia*, *5*, 21-28.

Shen, Z. J. M., Coullard, C., & Daskin, M. S. (2003). A joint location-inventory model. *Transportation science*, *37*(1), 40-55.

Sheu, J. B. (2007). An emergency logistics distribution approach for quick response to urgent relief demand in disasters. *Transportation Research Part E: Logistics and Transportation Review*, *43*(6), 687-709.

Snyder, L. V., & Daskin, M. S. (2006). Stochastic p-robust location problems. *IIE Transactions*, *38*(11), 971-985.

Tabatabaie, M., Ardalan, A., Abolghasemi, H., Holakouie Naieni, K., Pourmalek, F., Ahmadi, B., & Shokouhi, M. (2010). Estimating blood transfusion requirements in preparation for a major earthquake: the Tehran, Iran study. *Prehosp Disaster Med*, *25*(3), 246-252.

Torghabeh, H. M., Pourfathollah, A., Shooshtari, M. M., & Yazdi, Z. R. (2006). Relation of Factor VIII and IX Inhibitors with ABO Blood Groups in 150 Patients with Hemophilia A and B. *Iranian Journal of Allergy, Asthma and Immunology*, *5*(1), 33-34.