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Designing a bi-objective, multi-product supply chain network for blood supply

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A B S T R A C T

During the past few years, operations research applications in health care operation management have grown quickly. On the other hand blood as a perishable, valuable and lifesaving product is one important asset of any healthcare center. Therefore, designing a blood supply network comes to importance. It also should be noted that a blood supply chain comprises specific modifications. This study intends to locate blood bank components in a network, and to determine the allocations among the network components. The supply chain components considered in this study are donation sites, testing and processing labs, blood banks, and demand points. It is known that demand centers such as hospitals and clinics highly depend on blood products and any deficiency in procurement can even result in a person's death. Thus, in the last layer of the considered network a transshipment sub-network is considered between demand points. Most of the intricacies in problem formulation of blood supply chain are regarded in this study; cases such as blood wastage, blood product decomposition in lab facilities, and transshipments between demand points. Due to the fact that for such an important and lifesaving supply chain the aim would go beyond minimizing cost, another objective function is presented for the problem. Hence, to obtain a Pareto solution for both objective functions ϵ-constraint method is utilized. Finally, to demonstrate the applicability of the problem, the model is implemented on a number of problem sets.

1. Introduction

Decisions made in most of the supply chain network design problems comprise determining the optimal location and capacity of facilities in order to fulfill the market demand at the lowest cost. However, how a blood supply chain works and what is its difference with typical supply chains? The flow of blood products from donors to patients is a process that may look like its simple form in other supply chains for perishable products. However, it should be noticed that the importance of a blood supply chain is far further than ordinary perishable products. Pierskalla (2005) noted several characteristics of blood banking. For instance, firstly, blood is a highly perishable commodity with many components that each component has a different lifetime before being perished. Secondly, blood planning is very hard due to its variability in supplying. Thirdly, as Beliën and Forcé (2012)

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have also stated, the demands for blood components at demand points are extremely random variables and at least are stochastic. Other intricacies such as blood demand compatibility, blood wastage, blood product decomposition in lab facilities, and transshipments between demand points can also be characteristics unique for blood supply chains. Besides, blood planning is very difficult because of its variability in supplying. Based on Katsaliaki (2008) and Schreiber et al. (2006), only 5% of the eligible donor population actually donates.

This study integrates facility location and network design problems. In this paper, a capacitated facility location-network design problem (CFLNDP) is considered. Problems related to blood banking are not solved to satisfy just one issue. Subjects such as minimizing costs, minimizing distance traveled, maximizing availability and maximizing accessibility have been the center of attention in different studies. Thus, it is more reasonable to simultaneously consider multiple objectives for the problem. This matter can be found in many studies such as (Cetin & Sarul, 2009; Sapountzis, 1989; Kendall & Lee, 1980). The considered network in this paper has four layers. The layers are namely donation sites, testing and processing labs, blood centers or distribution centers as well as demand points. One of the assumptions in this study is that demand points and laboratories are positionally fixed in the network and other components are going to be located through the network.

Despite exhaustive modeling attempts in facility location modeling and supply chain design; exploring blood supply chains design has not been widely discussed. One of the earliest studies in regional blood banking is done by Or and Pierskalla (1979). A recent review of the literature on supply chain management for blood products is proposed by Beliën and Forcé (2012) that classifies the problems in blood supply chain management and reveals numerous research gaps existing in the strategic facility location decisions. Moreover, Pierskalla (2005) proposes an overview of models for allocating donor areas and transfusion centers to community blood centers. The aim of the modelling in Prieskalla's paper, or to be more precise book chapter is to determine the number of community blood centers in a region, locating these centers, and matching supply and demand. Daskin et al. (2002) formulated a non-linear integer programming model for distribution center (DC) location problem of supplying blood to hospitals. The model considered inventory decisions in a single-period model. They used Heuristic solution methods for solving the proposed models. Şahin et al. (2007) and Sha and Huang (2012) proposed practical blood supply chain models. They utilized median location-allocation problems. Şahin et al. (2007) model contained a single-period location-allocation problem in a hierarchical structure to regionalize blood services of the Turkish Red Crescent Society. On the other hand, Sha and Huang (2012) examined a blood scheduling model. They considered the supply of emergency blood after an earthquake occurrence in Beijing. In addition, Nagurney et al. (2012) proposed a network optimization to determine optimal capacities of supply chain network activities and allocation of resources to demand points. Finally, Jabbarzadeh et al (2014) proposed a dynamic supply chain network design for the supply of blood in disasters. In their paper they presented a robust network design model that was able to supply blood both during and after a disaster occurrence. They analyzed the robustness of their model in the existence potential earthquakes in Tehran, Iran as a real case.

The rest of this paper is organized as follows. The following section discusses the problem and the proposed mathematical modeling. Section 3 presents the computational experiments related to it. Moreover, to cope with the multi-objective problem, an augmented ∊-constraint method is described in this section and also a sensitivity analysis is performed in the model. Finally, concluding remarks as well as directions for further research in the area are presented in Section 4.

2. Problem description and model formulation

This section discusses the blood supply chain design problem, network optimization model, and mathematical programming of the proposed model. The considered network in this study is a four-layer. The network layers are donation point, laboratory, central blood bank, and demand points. The illustrated form of this network is demonstrated in Fig. 1. It should be noted that there is a sub-network in the last layer of the main network that links some hospitals together in order to satisfy the demand in a more reliable form. This assumption about sub-network makes it possible for the hospitals to send blood products to each other whenever there is a shortage of supply that cannot be satisfied by central blood banks linked to a given hospital or the time to satisfy this demand from blood banks is inappropriately long. In addition, the supply chain is considered to be multi-product. The products considered in the proposed problem are plasma, platelet, red blood cells, and whole blood. These products have different rates of perishability. Besides, the demand for these products is noticeably different.

It should be noted that modeling the decomposition procedure that happens in laboratories needs intricate considerations. In laboratories the donated bloods are completely examined and considering the demand for them, they can be decomposed into three blood products namely plasma, platelet, and red blood cells. If the blood taken from donors remains without decomposition, that would be called whole blood cell. A pack of whole blood cell (about 450 ml) can be decomposed to 3 packs of plasma, platelet, and red blood cells.

The procedure of the blood network can be explained as below. Blood products are shipped from donation points to laboratories to be examined for disease, including HBV, HCV, HIV and Syphilis and blood type identification. After that, the products are shipped to demand points through central blood banks.

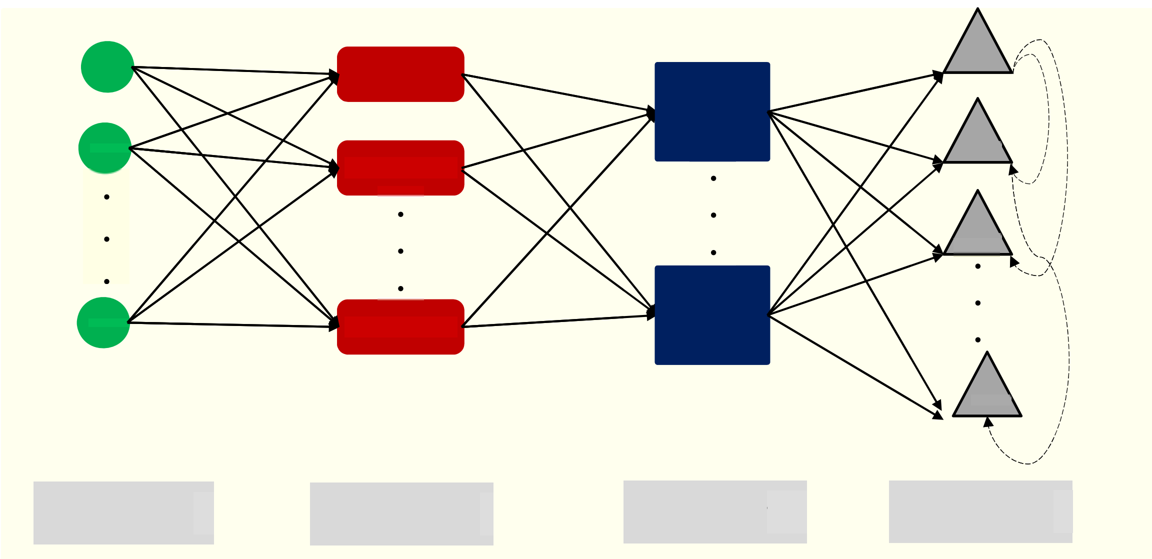

Fig. 1. Schematic illustration of blood supply chain network

In this study, we have assumed that the capacities of donation points and blood banks for different blood products are deterministic and known, the demand of demand centers are known and deterministic, the operating cost of opening a donation point or a central blood bank is known, the cost of transportation per blood product on the network is known, interest rate, and the wastage rate at laboratories are known in advance. Moreover the Potential locations for blood banks and donation points are known.

The first objective function of the proposed model minimizes the total cost of the supply chain. The second objective function considers minimizing the sum of the times that blood products remain in the network before being consumed.

By solving the model the following decisions are made:

- Quantity of each kind of blood product to be shipped from each node to other nodes in the network.
- Number and location of donation points.
- Number and location of central blood banks.
- Allocation of demand points to central banks.
- Allocation of donation points to laboratories.

The indices used for different blood products are listed in the Table 1.

Table 1
Indices for different products

Blood product	Index
Red blood cell	f_1
Plasma	f_2
Platelet	f_3
Whole blood	f_4

The sets, parameters, and decision variables are as follows:

Sets

I	Set of candidate donation points, $i \in \{1,2,\ldots,I\}$
J	Set of laboratories, $j \in \{1,2,\ldots,J\}$
K	Set of candidate CBBs, $k \in \{1,2,\ldots,K\}$
L	Set of demand points, $l,m \in \{1,2,\ldots,L\}$
F	Set of different blood products, $f \in \{1,2,\ldots,F\}$

Parameters

dc_i	Donation point *i* capacity
lc_i	Laboratory *j* capacity
cbb_k	Central blood bank *k* capacity
hc_l	Demand point *l* capacity (i.e. Hospital capacity)
d_l^f	The demand of demand point *l* for blood product *f*
T^f	The maximum time that blood product *f* can be used before perishing
t_{ij}	The time of traveling link *(i, j)*
t_{jk}	The time of traveling link *(j, k)*
t_{kl}	The time of traveling link *(k, l)*
t_{lm}	The time of traveling link *(l, m)*
t_i	Time of processing blood in donor *i*
t_l^f	Time of processing blood in Hospital *l* for blood product *f*
g_i	Fixed cost of opening a donation point on node *i*
g'_k	Fixed cost of opening a CBB on node *k*
c_{ij}	Travel cost per unit flow on link *(i, j)* for blood product
c_{jk}	Travel cost per unit flow on link *(j,k)*
c_{kl}	Travel cost per unit flow on link *(k,l)*
c_{lm}	Travel cost per unit flow on link *(l,m)*
ρ_{ij}	Fixed cost of constructing a link *(i, j)*
ρ_{jk}	Fixed cost of constructing a link *(j,k)*
ρ_{kl}	Fixed cost of constructing a link *(k,l)*
ρ_{lm}	Fixed cost of constructing a link *(l,m)*
f_i	Operating cost of opened donation point on node *i*
f_k	Operating cost of opened CBB on node *k*

h_{ij}	Operating cost of constructed link on *(i, j)*
h_{jk}	Operating cost of constructed link on *(j,k)*
h_{kl}	Operating cost of constructed link on *(k,l)*
h_{lm}	Operating cost of constructed link on *(l,m)*
α	Percentage of donated blood that waste

Decision Variables

y_i	If donor *i* is open (1), otherwise (0)
y'_k	If CBB *k* is open (1), otherwise (0)
x_{ij}	The amount of blood product traveling from donor *i* to laboratory *j*
x^f_{jk}	The amount of blood product *f* traveling from donor *j* to laboratory *k*
x^f_{kl}	The amount of blood product *f* traveling from donor *k* to laboratory *l*
x^f_{lm}	The amount of blood product *f* traveling from hospital *l* to hospital *m*
z_{ij}	If link *(i,j)* is open (1), otherwise (0)
z_{jk}	If link *(j,k)* is open (1), otherwise (0)
z_{kl}	If link *(k,l)* is open (1), otherwise (0)
z_{lm}	If link *(l,m)* is open (1), otherwise (0)

Therefore, the model can be formulated as bellow:

$$\min\ TC=\sum_{i\in I}(g_i+f_i)y_i+\sum_{k\in K}(g'_k+f'_k)y'_k+\sum_{i\in I}\sum_{j\in J}(\rho_{ij}+h_{ij})z_{ij}+\sum_{j\in J}\sum_{k\in K}(\rho_{jk}+h_{jk})z_{jk}+\sum_{k\in K}\sum_{l\in L}(\rho_{kl}+h_{kl})z_{kl}$$
$$+\sum_{l\in L}\sum_{m\in L}(\rho_{lm}+h_{lm})z_{lm}+\sum_{i\in I}\sum_{j\in J}c_{ij}x_{ij}+\sum_{f\in F}\sum_{j\in J}\sum_{k\in K}c_{jk}x^f_{jk}+\sum_{f\in F}\sum_{k\in K}\sum_{l\in L}c_{kl}x^f_{kl}+\sum_{f\in F}\sum_{l\in L}\sum_{m\in L}c_{lm}x^f_{lm}+M\times\sum_f\sum_l slack^f_l \quad (1)$$

$$\min\sum_f T^f \quad (2)$$

subject to

$$(1-\alpha)\sum_{i\in I}x_{ij}\geq\sum_{k\in K}x^4_{jk}+\max\{x^f_{jk}\mid f\leq 3\} \qquad \forall f\in F-\{4\},\forall j\in J \quad (3)$$

$$\sum_{j\in J}x^f_{jk}\geq\sum_{l\in L}x^f_{kl} \qquad \forall f\in F\ ,\ \forall k\in K \quad (4)$$

$$\sum_{k\in K}x^f_{kl}\geq\sum_{m\in L}x^f_{lm} \qquad \forall f\in F\ ,\ \forall l\in L \quad (5)$$

$$\sum_{j\in J}x_{ij}\leq dc_i\times y_i \qquad \forall i\in I\ , \quad (6)$$

$$\sum_{f\in F}\sum_{k\in K}x^f_{jk}\leq lc_j \qquad \forall j\in J \quad (7)$$

$$\sum_{f\in F}\sum_{l\in L}x^f_{kl}\leq cbb_k\times y'_k \qquad \forall k\in K \quad (8)$$

$$\sum_{f\in F}\sum_{k\in K}x^f_{kl}+\sum_{f\in F}\sum_{m\in L}x^f_{ml}\leq hc_l \qquad \forall l\in L \quad (9)$$

$$\sum_{k\in K}x'^f_{kl}+\sum_{m\in L}(x'^f_{ml}-x'^f_{lm})+slack^f_l=d^f_l \qquad \forall f\in F,\forall l\in L \quad (10)$$

$$t_{ij}z_{ij}+t_{jk}z_{jk}+t_{kl}z_{kl}+t_iy_i+t^f_j+t^f_ky_k+(t_{lm}+t^f_l)\times z_{lm}\leq T^f \qquad \forall f\in F\ ,\forall i\in I\ ,\forall j\in J\ , \forall k\in K\ ,\forall l\in L\ ,\forall m\in L \quad (11)$$

$$T^f\leq T^f_{\max} \qquad \forall f\in F \quad (12)$$

$$x_{ij}\leq My_i \qquad \forall i\in I\ ,\forall j\in J \quad (13)$$

$$x^{f}_{jk} \le My'_{k} \qquad \forall f \in F, \forall j \in J, \forall k \in K \qquad (14)$$

$$x^{f}_{kl} \le My'_{k} \qquad \forall f \in F, \forall k \in K, \forall l \in L \qquad (15)$$

$$x_{ij} \le Mz_{ij} \qquad \forall i \in I, \forall j \in J \qquad (16)$$

$$x^{f}_{jk} \le Mz_{jk} \qquad \forall f \in F, \forall j \in J, \forall k \in K \qquad (17)$$

$$x^{f}_{kl} \le Mz_{kl} \qquad \forall f \in F, \forall k \in K, \forall l \in L \qquad (18)$$

$$x^{f}_{lm} \le Mz_{lm} \qquad \forall f \in F, \forall l \in L, \forall m \in L \qquad (19)$$

$$x_{ij}, x^{f}_{jk}, x^{f}_{kl}, x^{f}_{lm} \ge 0 \qquad \forall f \in F, \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L, \forall m \in L \qquad (20)$$

$$z_{ij}, z_{jk}, z_{kl}, z_{lm}, y_{i}, y_{k} \in \{0,1\} \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall l \in L, \forall m \in L \qquad (21)$$

The objective function in Eq. (1) minimizes the total cost (fixed + variable). It is consisted of setting up the donation points and blood banks; operating the network costs such shipping costs, cost of building a link between two nodes of the network, etc. Moreover a big coefficient (M) is considered for unsatisfied demands that forces the network to satisfy as much as demand that is possible. This is due to the crucial importance and life and death matter of satisfying the demands. The second objective function minimizes the sum of times that blood products remain in the network.

Constraints in Eq. (3) are for blood decomposition at laboratories. Some of these bloods remain as the whole blood and others decompose into three different products that are platelets, plasmas, and red blood cells. This decomposition happens based on maximum demand for these three products. Parameter α in these equations represents the wastage rate. Constraints in Eq. (4) and Eq. (5) Clarify the flow balance among labs, blood banks, and hospitals. Eqs. (6-9) are capacity constraints on donation points, labs, blood banks, and demand points respectively. Constrains in Eq. (10) guarantee the demand for all customers is considered. Based on these equations, demand can be fulfilled either by a blood bank or other hospitals. Constrains in Eq. (11) and Eq. (12) ensure the total time that each blood product type is in the system doesn't exceed its related expiration time. Constrains in Eqs. (13-15) relate that no product passes the donation points and CBBs that are not open. Constraints in Eqs. (16-19) enforce that product shipment between layers happens only when the link is built. Finally, the constraints (20) and (21) are positivity and binary constraints.

Linearization

Eq. (3) makes the proposed model a nonlinear one. It is known that nonlinear models are harder to solve and it takes more time for a nonlinear model to give a solution set. Therefore, to tackle this problem, this equation is transformed to a linear one as follows by replacing x''^{f}_{ij} with $\max\{x^{f}_{jk} \mid f \le 3\}$. Consequently constraints in Eq. (22) and Eq. (23) are added to the model.

$$(1-\alpha)\sum_{i\in I} x_{ij} \ge \sum_{k\in K} x^{4}_{jk} + x''^{f}_{ij} \qquad \forall f \in F-\{4\}, \forall j \in J \qquad (22)$$

$$x''^{f}_{ij} \ge x^{f}_{jk} \qquad \forall f \in F-\{4\}, \forall j \in J \qquad (23)$$

3. Computational experiments

To demonstrate the validity of the proposed model several numerical experiments are implemented and the related results are reported in this section. All computational experiments are conducted on a Pentium core i5 CPU, M460, 2.53 GHz laptop with 4 GB RAM. The parameters used in the computational experiments are generated based on uniform distributions. Tables 2 lists the parameters used in the computations. In this table, different products have different demand and supply rate.

Table 2
Parameter values used in computational results.

Parameter	Corresponding random distribution	Unit
d_l^f	~ Uniform (25,60)	Cells
$t_{ij} t_{jk} t_{kl} t_{lm}$	~ Uniform (1,4)	Hours
t_i	~ Uniform (0.5,10)	Hours
t^f_l	~ Uniform (5,48)	Hours
t^f_k	~ Uniform (24,72)	Hours
t^f_j	~ Uniform (12,72)	Hours
$c_{jk} c_{ij} c_{kl} c_{lm}$	~ Uniform (200,850)	Cost unit
$h_{jk} h_{ij} h_{lm} h_{kl}$	~ Uniform (500,1650)	Cost unit
$\rho_{ij} \rho_{lm} \rho_{jk} \rho_{kl}$	~ Uniform (1000,2450)	Cost unit
$f_i\ f_k$	~ Uniform (2000,5000)	Cost unit
α	0.1	
lc_j	~ Uniform (400,900)	Unit
cbb_k	~ Uniform (1000,2500)	Unit
hc_l	~ Uniform (350,450)	Unit
dc_i	~ Uniform (30,80)	Whole Blood Cells
T^f_{max}	1008, 8760, 120, 840	Hours
g_i	~ Uniform (20000,60000)	Cost unit
g'_k	~ Uniform (150000,350000)	Cost unit

Moreover, Table 3 summarizes the results of implementing the proposed model on several problem sets with different sizes. In Table 3, the sizes of the problem, the amount of both objective functions and the computational time is listed. It should be noted that the objective functions has been computed separately. In the next section Pareto solution of objective functions is proposed.

Table 3
Summary of test results

Problem set No	Objective Function No	Problem Size *i/j/k/l*	Objective function values	Computational time (s)
Problem set No 1	Objective Function No 1	3/2/2/3	3.1482E+5	*[1]
	Objective Function No 2	3/2/2/3	49(h)	*[2]
Problem set No 2	Objective Function No 1	8/3/4/12	2.7425E+7	48
	Objective Function No 2	8/3/4/17	87 (h)	84
Problem set No 3	Objective Function No 1	12/4/5/17	5.4920E+10	264
	Objective Function No 2	12/4/5/17	98 (h)	463
Problem set No 4	Objective Function No 1	18/6/7/25	1.1496E+12	1049
	Objective Function No 2	18/6/7/25	101 (h)	1267

[1] Computational time is insignificant.

3.1 ε-constraint method

The ε-constraint method is applied to the model to overcome its bi-objectivity. The applicability of this method is revealed from its vast use in different studies. In bellow the way this model works is presented. Consider the following multi objective model:

$$\begin{aligned}&\min(f_1(x), f_2(x), \dots, f_p(x))\\&\text{subject to}\\&x \in S\end{aligned} \tag{24}$$

Where x is the vector of decision variables, $f_1(x)$, $f_2(x)$, ... , $f_p(x)$ are objective functions and S is the feasible region. In this method, one of the objective functions is optimized while the other objective function is set as a constraint:

$$\begin{aligned}&\min f_1(x)\\&\text{subject to}\\&f_2(x) \le e_2\\&f_3(x) \le e_3\\&\dots\\&f_p(x) \le e_p\\&x \in S\end{aligned} \tag{25}$$

Changing the parameter in the right hand side of these constraints (e_i) leads to alternative solutions. To avoid trapping in infeasible solutions that result in increasing computational time augmented ε-constraint method introduced by Mavrotas (2009) is utilized. This method changes the parameters so that the feasible region expands.

$$\begin{aligned}&\min(f_1(x) - \delta \times ({}^{s_2}/_{r_2} + {}^{s_3}/_{r_3} + \dots + {}^{s_p}/_{r_p}))\\&\text{subject to}\\&f_2(x) + s_2 = e_i\\&f_3(x) + s_3 = e_3\\&\vdots\\&f_p(x) + s_p = e_p\\&x \in S, s_i \in R^+\end{aligned} \tag{26}$$

To generate a Pareto - optimal solution in this study, initially the first objective function is optimized in a loop, and then some ε values are defined for the second objective function. A payoff table is used for determining the ε value in each loop. Table 4 demonstrates the payoff table that has been obtained by solving the problem set 2.

Table 4
Payoff table

z_1	z_2
4.3179E+7	87
2.7425E+7	692

Then e_2 vector can be shaped as $e_2 = (87, 188, 289, 390, 491, 592, 692)$. Number 87 comes from solving the problem set 2 with objective function 2. Then we put this objective function in the constraints and solve the problem with objective function 1. Therefore, the value of objective function 2 becomes 692. The interval between these two numbers is divided to six and other values are gained. Then the following model is solved for each grid point in e_2 in order to gain the second objective functions:

$$\min Z_1 - \delta\left(\frac{s_2}{r_2}\right) \tag{27}$$

Subject to:

$$Z_2 + s_2 = e_2 \tag{28}$$

Constraints (4)-(23)

The objective functions' values are calculated as below:

y_N ={(4.3179E+7,87), (3.9214E+7,188), (3.5980E+7,289), (3.3169E+7,390), (3.1726E+7,491), (2.9549E+7, 592), (2.7425E+7,692)}. By running the problem for the intervals of the second objective function, the Pareto frontier can be obtained. The Pareto frontier of this case is presented in Fig. 2.

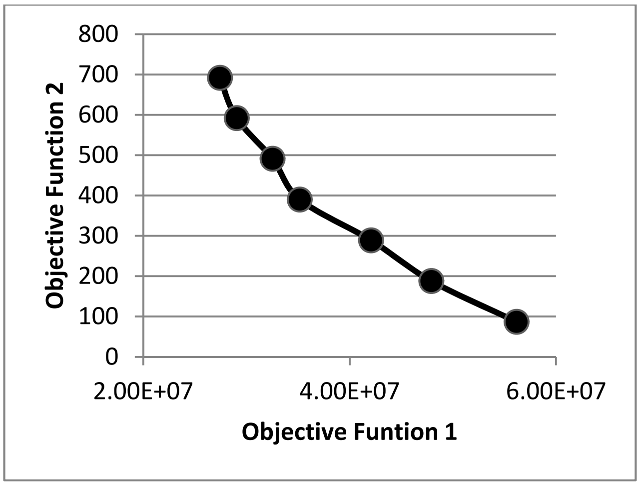

Fig. 2. Pareto frontier for problem set No 1

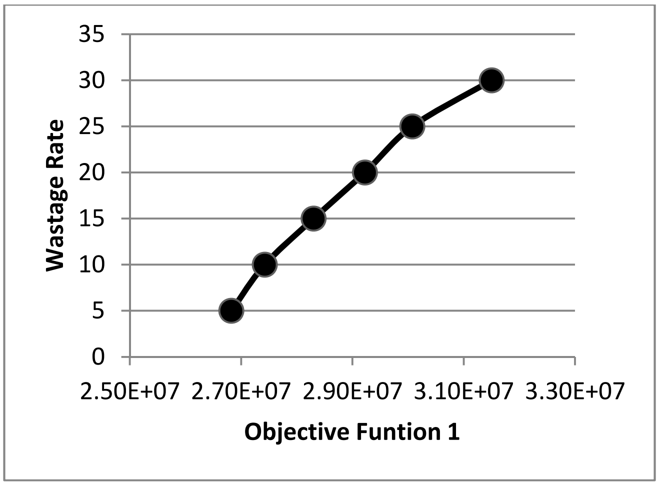

Fig. 3. Sensitivity of objective function 1 by changing the wastage rate

The same procedure can be done for other problem sets and their corresponding Pareto frontier can be gained.

3.2 Sensitivity analysis

This section presents a sensitivity analysis of the important parameters. All sensitivity analyses in this section are implemented on problem set 2. The first parameter that we consider for this purpose is the rate of blood wastage at laboratories that is shown by α. Blood wastage may occur for a number of reasons, including time expiry, wasted imports, blood medically or surgically ordered, but not used, stock time expired, hemolysis, or miscellaneous reasons. Based on Far et al. (2014) approximately 77.9% of wasted blood units are wasted for the reason of time expiry. Blood wastage in hospitals is reported to range from 1.93% to 30.7%. Therefor the exact rate of blood wastage is hard to be measured. In this paper we have considered α to be 10 percent. Figure 3 demonstrates the changes in objective functions 1 by changing α. In this Figure α changes by a rate of 5% from 5% to 30 %.

Fig. 2 demonstrates that increasing the blood wastage rate at laboratories can affect the total cost in an incremental manner. The second parameter that is considered in sensitivity analysis is the supply of blood at donation points. It is known that the donation rate is an extremely random variable and comparably small pool of active donors actually donate. This issue may adversely affect the blood supply chain; therefore, being aware of the changes that this parameter yields, is crucially important. To analyze this matter, we have determined six different uniform distributions that the donation rate may follow. These uniform distributions are listed in Table 5. Then the problem set 2 is solved using these six distributions and the results are shown in Fig. 3.

Table 5
Uniform distributions used in sensitivity analysis of donation rate

No	Uniform distribution
1	~ Uniform (10,30)
2	~ Uniform (10,40)
3	~ Uniform (20,50)
4	~ Uniform (20,70)
5	~ Uniform (30,80)
6	~ Uniform (50,100)

Fig. 3 reveals a sudden increase in the objective function that might be due to considering the big M in the objective function. This value that is a large number has been considered in the objective function in order to satisfy all demands in demand points. Actually, this value works as a compensation for not fulfilling the demand. By decreasing the rate of donation in donation point the model is unable to satisfy all demands and the $slack_l^f$ variable increases and results in this sudden increase.

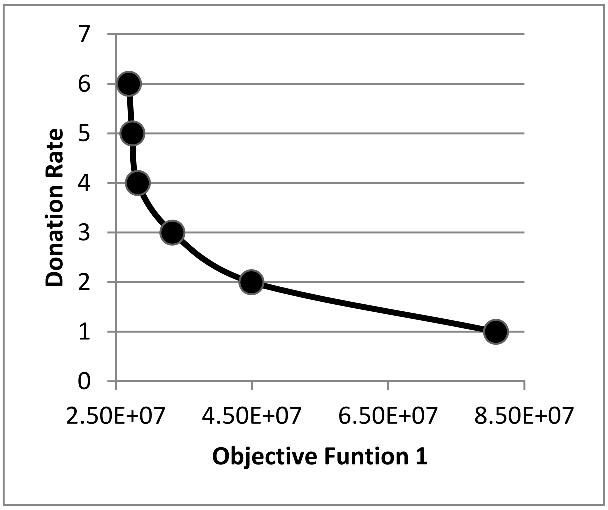

Fig. 4. Sensitivity of objective function 1 by changing the donation rate

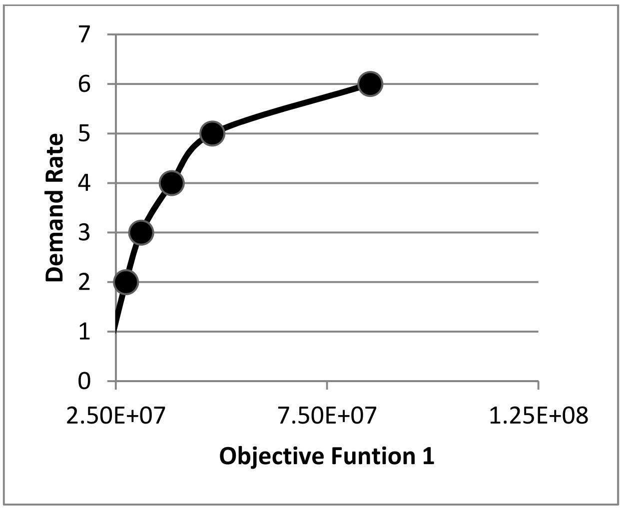

Fig. 5. Sensitivity of objective function 1 by changing the amount of demand

The last sensitivity analysis is performed on the amount of demand. Blood demand depends on numerous elements such as population of demand area, age, gender, accident and unpredictable event rates and so on. Therefore, forecasting blood demand requires a big deal of effort and might not be reliable enough. The analysis on demand is conducted similar to sensitivity analysis of donation rate. Notice that demand in here means demand for each product, but for donation points the supply was only for whole blood that is taken from donors. Table 6 lists the uniform distribution related to demand at demand centers. Figure 5 shows the changes of objective function 1 by changing the amount of demand at demand points. The same sudden increase can also be seen in this figure that is derived from the same reason that was for donation rate.

Table 6
Uniform distributions used in sensitivity analysis of demand

No	Uniform distribution
1	~ Uniform (15,40)
2	~ Uniform (25,60)
3	~ Uniform (40,80)
4	~ Uniform (65,100)
5	~ Uniform (80,115)
6	~ Uniform (100,130)

4. Conclusion

This paper presented a mixed integer linear programming for the location and allocation of facilities of a human blood supply chain. The network of the considered supply chain consisted of four layers, namely donation centers, laboratories, blood banks, and demand points. The main aim of this study is twofold: (1) to determine the locations of donation point and central blood banks within the network (2) to decide on the amount of product that is shipped among the facilities. Intricacies such as blood wastage, blood product decomposition in lab facilities, considering multi-products, transshipments between demand points are taken into account in the mathematical modeling of the problem. The proposed model is a bi-objective. The first objective function of the model is minimizing the total cost of the network and the second one minimizes the time that blood products remain in the network. CPLEX solver is utilized to solve the above stated problem and the model is applied on a real case in order to demonstrate the applicability and reliability of the modeling framework.

Future studies can combine other problems such as inventory and routing decisions to obtain more comprehensive models. Considering the combination of discrete and continuous facility location problems to formulate the model can be another step toward maturing this research area. Another direction for future research in this area can be incorporation of blood compatibility issue into the model. In addition, since there are numerous activities in the laboratories, this part of the network can be looked in a more detailed way. Considering queue systems, resource allocation, and failure rate are issues that can be considered in laboratories. Finally, presenting a dynamic model that considers mobile donation points can be a good hint for future studies.

References

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

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

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.

Far, R. M., Rad, F. S., Abdolazimi, Z., & Kohan, M. M. D. (2014). Determination of Rate and Causes of Wastage of Blood and Blood Products in Iranian Hospitals. *Turkish Journal of Hematology*, *31*(2), 161.

Jabbarzadeh, A., Fahimnia, B., & Seuring, S. (2014). Dynamic supply chain network designfor the supplyofblood in disasters:A robust modelwithreal world application. *Transportation Research Part E.* 70, 244-255.

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

Kendall, K. E. & Lee, S. M. (1980). Formulating blood rotation policies with multiple objectives. *Management Science,* 26**,** 1145-1157.

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

Mavrotas, G. (2009). Effective implementation of the ε-constraint method in Multi-Objective Mathematical Programming problems. *Applied Mathematics and Computation,* 213**,** 455-465.

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**,** 205-231.

Pierskalla, W. (2005). Supply chain management of blood banks. *Operations Research and Health Care***,** 103-145.

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

Sapountzis, C. (1989). Allocating blood to hospitals. *Journal of the Operational Research Society***,** 443-449.

Schreiber, G. B., Schlumpf, K. S., Glynn, S. A., Wright, D. J., Tu, Y., King, M. R., Higgins, M. J., Kessler, D., Gilcher, R. & Nass, C. C. (2006). Convenience, the bane of our existence, and other barriers to donating. *Transfusion,* 46**,** 545-553.

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