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Bi-objective optimization of a blood supply chain network with reliability of blood centers

Hassan Heidari-Fathian[1], Seyed Hamid Reza Pasandideh[1*]
[1]*Department of Industrial Engineering, Faculty of Engineering, Kharazmi University, Tehran, Iran*
std_fathian@khu.ac.ir, shr_pasandideh@khu.ac.ir

Abstract
This paper presents a multi-periodic, multi-echelon blood supply chain network consisting of blood donors, mobile collection units, local blood centers, main blood centers and demand points in which the local and main blood centers are subject to random failure in dispatching blood products to demand points. The problem has two objectives including minimization of the total chain costs and maximization of the reliability of the local and main blood centers by maximizing the average total number of blood products dispatched to demand points. The problem is first formulated as a mixed-integer linear mathematical model. Then, to solve the problem, three multi-objective decision-making (MODM) methods including Elastic Bounded Objective Method, Modified augmented ε-constraint method and LP-metric method are employed for the solution. Thirty different examples are solved to assess the performance of the solution methods and their results are compared statistically. Using ELECTRE method, the best solution method is selected. At the end, to determine the effect of the change in the main parameters of the problem on the objective functions values, sensitivity analysis is performed.
Keywords: Blood supply chain, perishable product, Reliability, MODM, Multiple comparisons, ELECTRE

1- Introduction

Like other supply chains, a blood supply chain network consists of several different echelons including blood donors, blood collection facilities, component labs, storage facilities, distribution centers and demand points (Nagurney et al. 2012). The management of perishable products is a considerable issue in Supply chain management. Human blood is a perishable and worthwhile resource that the life of human beings is strongly dependent on it and any untimely supply of this urgent product to demand points could cause irreparable damages and lives may be lost. Demand points receive blood products from blood centers. Blood centers are responsible for receiving, transfusing and finally dispatching blood products to demand points. There are some different types of blood centers that are divided into the two main categories: Dynamic blood centers and static blood centers.

*Corresponding author
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Dynamic blood centers are usually buses or coaches that are driven to locations accessible to donors. But static blood centers are facilities for blood donation in fixed or permanent locations with more donation capacities rather than dynamic blood centers. They receive whole blood from donors and also from dynamic blood centers and produce several different blood product from them: red blood cells, white blood cells, platelets, serum, and plasma. All of the produced components except for plasma have a limited shelf life and can become outdated. For example, platelet has a very short shelf life among them and becomes unusable after six days. For this reason, static blood centers have to be reliable to dispatch blood products to demand point. If a blood center is not able to service the demand points due to any reason in a period, a demand point may don't receive its demand and some of the patients may lose their life. On the other hand, the blood remained to the blood centers owing to the unreliability of blood centers to dispatch them to demand points, may become outdated.

This paper formulates the problem into a mixed-integer linear mathematical model with two conflicting objectives including minimization of the total chain costs and maximization of the reliability of the local and main blood centers by maximizing the average total number of blood dispatched to demand points. A probability distribution based on the exponential distribution is used for considering the issue of reliability in the proposed model. In the proposed model, a new assumption is considered for the sequence visits of the mobile collection units. For solving the proposed mathematical model, three multi-objective decision making (MODM) methods are employed and their applicability is evaluated statistically using Tukey method. Also, the ELECTRE method is used to select the best solution method.

The reminder of this paper is organized as follows. Section 2 reviews the related literature. The problem description and the mathematical model are given in section 3. Section 4 discusses the solution methods to solve the problem. The performance of the solution methods is evaluated in section 5. Section 6 contains sensitivity analysis on the effects of some input parameters on the objective functions values. Finally, conclusions and future researches come in Section7.

2- Literature review

Management of the perishable products in a supply chain network has received the considerable attention of many researchers for a number of years. For example, Niakan and Rahimi (2015) extended a multi-objective model for Routing Problem for of a medicinal drug distribution to healthcare facilities with considering perishability of drugs. Sarker et al. (2000) developed a supply chain model to determine an optimal ordering policy for deteriorating items under inflation. Blackburn and Scudder (2009) examined supply chain design strategies for a specific type of perishable product. Blood, as a perishable product is also an interesting field for researchers. But the majority of literature in the blood supply chain management is about individual echelons and does not consider relationships between the different stages. For example, Elston and Pickrel (1963) considered a simulation based study to ordering and usage policies for a hospital blood bank. Cumming et al. (1976) investigated a planning model to assist regional blood suppliers in diminishing seasonal imbalances between the supply of and demand for blood. Abdulwahab and Wahab (2014) introduced a model for the establishment of an inventory bank holding perishable blood platelets with a short shelf life. Their model considered a blood platelet bank with stochastic demand, stochastic supply, and formulated using approximate dynamic programming. Gunpinar and Centeno (2015) presented stochastic and deterministic models to minimize the total cost, shortage and wastage levels of blood products at a hospital within a planning horizon. Their focus was on the red blood cells and the platelet components of the whole blood. Gunpinar and Centeno (2016) proposed a vehicle routing problem for a blood center to identify the number of bloodmobiles to operate and minimize the distance traveled. Similar studies can also be found in Hemmelmayr et al. (2009), Bosnes et al. (2005), Pereira (2006), Lowalekar and Ravichandran (2015). Recently, publications have aimed to connect the echelons with each other by considering the whole of the supply chain. Osorio et al. (2015) reviewed the related works on modelling for the blood product supply chain. Sahin et al. (2007), formulated several mathematical problems to address the location–allocation aspects of regionalization of blood services of the Turkish Red Crescent Society. They assumed that demand for blood and blood products at a certain site is completely uncertain. Fahimnia et al. (2015) suggested a supply chain design model for the efficient and effective supply of blood in disasters. They considered different echelons including blood donors, mobile blood facilities, local and regional blood centers, and demand points. A similar problem is studied in Jabbarzadeh et al. (2014). Chaiwuttisak et al. (2016) developed a model for the blood supply chain of the Thailand Red Cross Society using low-cost collection and distribution centers. In another work, Zahiri et al. (2015) proposed a mixed integer linear programming model to make strategic as well as tactical decisions in a multi-echelon system over a multi-period planning horizon. They applied a robust possibilistic programming approach to cope with the epistemic uncertainty in the demand and supply data. Zahiri and Pishvaee (2017) considered compatibility of blood groups in their works by presenting a bi-objective mathematical model for simultaneous minimization of the total cost and the maximum unsatisfied demand.

Different types of solution methods have been implemented to solve the blood supply chain problems. Zahiri et al. (2015), Jabbarzadeh et al. (2014), Fahimnia et al. (2015), Sahin et al. (2007), Chaiwuttisak et al. (2016), Gunpinar and Centeno (2016), Nagurney et al. (2012) used integer programming in their works and Cohen et al. (1976), Blake (2009) used stochastic dynamic programming. In Kamp et al. (2010), Gregor et al. (1982), Michaels et al. (1993), Alfonso et al. (2012) simulation methods and in Pegels and Jelmert (1970), Kaspi and Perry (1983), Kopach (2008) queuing methods were used.

Regarding the literature review, the goal of the present work is to design a supply chain framework for management of blood as a vital resource with considering the economic aspects, uncertainty, and the perishability of the blood. The main contributions of this research are presented in the following:

- A new mathematical model is proposed to design a reliable blood supply chain network
- Different echelons of the blood supply chain network including blood donors, mobile collection units, local blood centers, main blood centers and hospitals are considered in the model
- A probability distribution based on the exponential distribution is used to consider the issue of reliability in the proposed model
- The model has two conflicting objective functions for minimization of the costs of the supply chain network and also maximization of the average total number of blood dispatched to demand points
- Shelf life of blood are considered in the problem and the model tries to minimize the wastage of blood in the cost objective function
- A new assumption is considered for the sequence visits of the mobile collection units from the candidate locations
- Three multi-objective decision making (MODM) methods are employed to solve the proposed mathematical model
- The solution methods are compared to each other using a statistical approach
- The ELECTRE method is applied to rank the solution methods.

3- Problem modeling

This section includes notations, problem description, and the mathematical model.

3-1- Notations

The following notations including indices, parameters, and decision variables are used in the proposed model.

Indices:

i: index used for a donor group, $i=1,...,I$

y,j: index of candidate locations for mobile collection units, $y=1,...,Y$

p: index used for a mobile collection unit, $p=1,…,P$

l: index used for a local blood center, $l=1,...,L$

m: index used for a main blood center, $m=1,…,M$

h: index used for a demand point, $h=1,…,H$

t, t' : index used for a period with a fixed length of v , $t=1,\ldots,T$

Parameters:

U_{yjpt} : Cost of moving mobile collection unit p from location j to location y in period t

$MAXB_{it}$: Maximum blood supply of donor group i in period t

uc_{ypt} : Unit operational cost of mobile collection unit p at location y in period t

ulc_{lt} : Unit operational cost at local blood center l in period t

umc_{mt} : Unit operational cost at main blood center m in period t

cmm_{ypmt} : Unit transportation cost from mobile collection unit p located at location y to main blood center m in period t

clm_{lmt} : Unit transportation cost from local blood center l to main blood center m in period t

clh_{lht} : Unit transportation cost from local blood center l to hospital h in period t

cmh_{mht} : Unit transportation cost from main blood center m to hospital h in period t

hcl_{lt} : Unit holding cost at local blood center l in period t

hcm_{mt} : Unit holding cost at main blood center m in period t

sc_{ht} : Unit shortage cost at hospital h in period t

cap_p : The capacity of mobile collection unit p

cap_l : Storage capacity available for local blood center l to store blood in a period

cap_m : Storage capacity available for main blood center m to store blood in a period

dy_{iy} : Distance between donor i and location y

dl_{il} : Distance between donor i and local blood center l

cd : Coverage distance of blood facilities

r : Referral rate: the rate of processes that local blood centers can't fulfill and they have to direct them to main blood centers

$smh_{m,t}$: Shelf life of blood products that are sent from main blood center m to hospital h in period t

$slh_{l,t}$: Shelf life of blood products that are sent from local blood center l to hospital h in period t

M : A reasonably large number

ex_{ht} : Unit expiration cost of blood products at hospital h in period t

λ_{mt} : Failure rate of main blood center m to dispatch blood products to demand points in period t

λ_{lt} : Failure rate of local blood center l to dispatch blood products to demand points in period t

D_{ht} : Demand for blood product at hospital h in period t

Variables:

X_{yjpt} : 1, if mobile collection unit p travels from location j to location y in period t, 0 otherwise

O_{iyt} : 1, if location y is assigned to donor i in period t, 0 otherwise

G_{ilt} : 1, if local blood center l is assigned to donor i in period t under, 0 otherwise

LM_{lmt} : 1, if local blood center l is assigned to main blood center m in period t, 0 otherwise

NBM_{iypmt} : Quantity of blood collected at location y from donor i in period t by mobile collection unit p to dispatch to main blood center m

NBL_{ilt} : Quantity of blood collected at local blood center l from donor i in period t

NLM_{lmt} : Quantity of blood dispatched by local blood center l to main blood center m in period t

$NLH_{lhtt'}$: Quantity of transfused blood dispatched by local blood center l to hospital h in period t to be used in period t'

$NMH_{mhtt'}$: Quantity of transfused blood dispatched by main center m to hospital h in period t to be used in period t'

IL_{lt} : Inventory level of blood at local blood center l at the end of period t

IM_{mt} : Inventory level of blood at main blood center m at the end of period t

S_{ht} : Shortage quantity of blood at hospital i at the end of period t

3-2- Problem description

Consider a blood supply chain network shown in figure 1. This network consists of blood donors, mobile collection units, local blood centers, main blood centers and demand points (like hospitals). The main assumptions involved in this problem are:

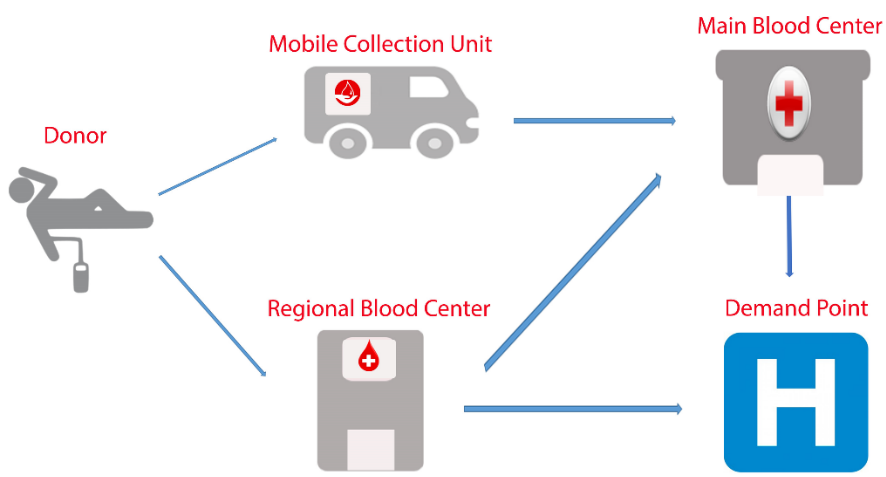

Fig. 1 The proposed blood supply chain network

- Blood donors can donate blood at either a local blood center or a mobile one within a certain geographical distance, but not at the main blood centers
- The mobile collection units are already purchased (the number of them is known) and their location could be changed over from one period to another. They transform the collected blood to main blood centers.
- All transfusion processes can be done at the main blood centers, but the local blood center can't fulfill a full range of transfusion processes and they may direct some of these processes to a pre-assigned main blood center.

- Mobile collection units aren't permitted to visit a location within a certain number of days after the previous visit. According to Sahinyazan et. al (2015), the number of donations significantly decreases on a second and third day of having the Mobile collection unit visiting the same location
- The blood products that are shipped from local and main blood centers to the demand points have a specific expiration date and will be unusable thereafter
- Shortage of blood products at the demand points are considered in the model
- Local and main blood centers do not operate perfectly all the time in term of dispatching blood products to demand point and they may fail to dispatch blood product to demand point in a period T_l (for local blood centers) and T_m (for main blood centers). This failing follows an exponential distribution with a mean of λ_{lt} (for local blood centers) and λ_{mt} (for main blood centers). Accordingly, the reliabilities of local blood center l, (R_l) and main blood center m, (R_m) in dispatching blood product to demand point in a period are:

$$R_l = P(T_l > v) = \mathrm{e}^{-\lambda_{lt} v} \ ; \ \forall l \in L \quad (1)$$

$$R_m = P(T_m > v) = \mathrm{e}^{-\lambda_{lm} v} \ ; \ \forall m \in M \quad (2)$$

Considering the above assumptions, the goal is to reach a compromise between two objective functions so that the total costs of supply chain are minimized and also the average total number of blood products dispatched to demand points be maximized.

3.3. The mathematical model

According to the above-mentioned assumptions, the mathematical model of the problem is a mixed-integer linear programming as follows:

$$\begin{aligned}
\min F_1 = & \sum_j \sum_y \sum_p \sum_t U_{yjpt} X_{yjpt} + \sum_i \sum_y \sum_p \sum_t uc_{iypt} (\sum_m NBM_{iypmt}) \\
& + \sum_l \sum_t ulc_{lt} (\sum_i NBL_{ilt}) \\
& + \sum_m \sum_t umc_{mt} (\sum_i \sum_y \sum_p NBM_{iypmt} + \sum_l NLM_{lmt}) \\
& + \sum_i \sum_y \sum_p \sum_m \sum_t cmm_{ypmt} NBM_{iypmt} + \sum_l \sum_m \sum_t clm_{lmt} NLM_{lmt} \\
& + \sum_l \sum_h \sum_t \sum_{t'} clh_{lht} NLH_{lhtt'} + \sum_m \sum_h \sum_t \sum_{t'} cmh_{mht} NMH_{mhtt'} \\
& + \sum_l \sum_t hcl_{lt} IL_{lt} + \sum_m \sum_t hcm_{mt} IM_{mt} + \sum_h \sum_t sc_{ht} S_{ht} \\
& + \sum_h \sum_t \mathrm{ex}_{ht} (\sum_m \sum_{t' > t + smh_{m,t}} NMH_{mhtt'} + \sum_l \sum_t \sum_{t' > t + slh_{l,t}} NLH_{lhtt'})
\end{aligned} \quad (3)$$

$$MaxF_2 = (\sum_m \sum_h \sum_t \sum_{t'} NMH_{mhtt'} \, \mathrm{e}^{-\lambda_{mt}\tau} + \sum_l \sum_h \sum_t \sum_{t'} NLH_{lhtt'} \, \mathrm{e}^{-\lambda_{lt}\tau}) \quad (4)$$

subject to:

$$\sum_{j\in J}\sum_{p\in P} X_{yjpt} \le 1 \qquad \forall y\in Y,\ \mathrm{t}\in T \tag{5}$$

$$\sum_{j\in Y}\sum_{p\in P} X_{jypt} \le \sum_{j\in Y}\sum_{p\in P} X_{yjpt-1} \qquad \forall y\in Y,\ \mathrm{t}\in T \tag{6}$$

$$O_{iyt} \le \sum_{j\in Y}\sum_{p\in P} X_{yjpt} \qquad \forall i\in I, y\in Y,\ \mathrm{t}\in T \tag{7}$$

$$\sum_{j\in Y}\sum_{p\in P}\sum_{t=a}^{a+n} X_{yjpt} \le 1 \qquad \forall y\in Y,\ a=1,2,\ldots,T-n \tag{8}$$

$$\sum_{j\in Y}\sum_{p\in P}\sum_{t=T-n+a}^{T} X_{yjpt} \le 1 \qquad \forall y\in Y,\ a=1,2,\ldots,n-1 \tag{9}$$

$$NBM_{iypmt} \le M.O_{iyt} \qquad \forall y\in Y, i\in I, p\in P, m\in M, t\in T \tag{10}$$

$$NBM_{iypmt} \le M.\sum_{j} X_{yjpt} \qquad \forall y\in Y, i\in I, p\in P, m\in M, t\in T \tag{11}$$

$$NBL_{ilt} \le M.G_{ilt} \qquad \forall i\in I, l\in L, t\in T \tag{12}$$

$$\sum_{y}\sum_{p}\sum_{m} NBM_{iypmt} + \sum_{l} NBL_{ilt} \le MAXB_{it} \qquad \forall\, \mathrm{i}, \mathrm{t} \tag{13}$$

$$\sum_{i}\sum_{y}\sum_{m} NBM_{iypmt} \le cap_{p} \qquad \forall\ \mathrm{p}\in P, t\in T \tag{14}$$

$$dy_{iy}.O_{iyt} \le cd \qquad \forall i\in I, y\in Y,\ \mathrm{t}\in T \tag{15}$$

$$dl_{il}.G_{ilt} \le cd \qquad \forall i\in I, l\in L,\ \mathrm{t}\in T \tag{16}$$

$$\sum_{m} LM_{lmt} \le 1 \qquad \forall l\in L, \mathrm{t}\in T \tag{17}$$

$$NLM_{lmt} \le M.LM_{lmt} \qquad \forall l\in L, m\in M,\ \mathrm{t}\in T \tag{18}$$

$$NLM_{lmt} \le r\sum_{i} NBL_{ilt} \qquad \forall l\in L, m\in M,\ \mathrm{t}\in T \tag{19}$$

$$IL_{lt} = IL_{lt-1} + (1-r)\sum_{i} NBL_{ilt} - \sum_{h}\sum_{t'} NLH_{lhtt'} \qquad \forall l\in L,\ \mathrm{t}\in T \tag{20}$$

$$IM_{mt} = IM_{mt-1} + \Big(\sum_{i}\sum_{y}\sum_{p} NBM_{iypmt} + \sum_{l} NLM_{lmt}\Big) - \sum_{h}\sum_{t'} NMH_{mhtt'} \qquad \forall m\in M,\ \mathrm{t}\in T \tag{21}$$

$$S_{\mathrm{h,t}} = S_{\mathrm{h},t-1} + D_{ht} - \Big(\sum_{l}\sum_{t-slh_{l,t'}\le t'\le t} NLH_{lht't} + \sum_{m}\sum_{t-smh_{m,t'}\le t'\le t} NMH_{mht't}\Big) \qquad \forall h\in H,\ \mathrm{t}\in T \tag{22}$$

$$IL_{lt} \le cap_{l} \qquad \forall l\in L,\ \mathrm{t}\in T \tag{23}$$

$$IM_{mt} \le cap_{m} \qquad \forall m\in M,\ \mathrm{t}\in T \tag{24}$$

$$NBM_{iypmt}, NBL_{ilt}, NLM_{lmt}, S_{ht}, NLH_{lhtt'}, NMH_{mhtt'}, IL_{lt}, IM_{mt} \ge 0 \tag{25}$$

$$X_{yjpt}, O_{iyt}, G_{ilt}, LM_{lmt} \in \{0,1\} \tag{26}$$

The first objective function shown in equation (3) aims to minimize the total cost of the blood supply chain network. The first term in the right hand side of equation (3) refers to the cost of moving mobile collection units from a location to another one. The rest of the terms in RHS of equation (3) refer respectively to the operational cost at mobile collection centers, operational cost at local blood centers, operational cost at main blood centers, transportation cost of bloods from mobile collection units to main blood centers, transportation cost of bloods from local blood centers to main blood centers, transportation cost of bloods from local blood centers to demand points, transportation cost of bloods from main blood centers to demand points, inventory holding cost of the bloods in local blood centers, inventory holding cost of the bloods in main blood centers, the shortage cost of demand points and finally the cost of expired bloods. The second objective function in equation (4) maximize the average total number of blood products dispatched from local and main blood centers to demand points. Equation (5) forces that in every period; at most one mobile collection unit can locate at each donation location. Equation (6) ensures that a mobile collection unit can't move from a donation location where no collection unit has been located. Equation (7) state that donor groups can't be assigned to vacant locations. Equations (8) and (9) specify that when a donation location is visited, the subsequent visit can't occur during next *n* days. Equation (10) eschews transporting blood from mobile collection units that are not assigned to that donor group. Equation (11) ensures the blood cannot be dispatched from the locations that don't exist any mobile collection unit in them. Equation (12) assures that local blood centers can't transport donated blood of a donor group when that donor group is not assigned to them. Equation (13) limits the capacity of blood donation of each donor group. Equation (14) guarantee that the total collected blood at each mobile collection unit cannot exceed its capacity. Equation (15) and (16) are for avoiding the assignment of donors to mobile collection units and local blood centers out of service area. Equation (17) enforces assigning no more than one local blood center to each main blood center. Equation (18) states that local blood centers can't transport blood to not assigned main blood centers. Equation (19) is related to the rate of processes that local blood centers can't fulfill and they have to direct them to main blood centers. The constraints in equations (20) and (21) are balance equations for blood inventory at local and main blood centers, respectively. Equation (22) is balance equation for shortages of the hospitals' demands. Equations (23) and (24) limit the capacity of blood holding at local and main blood centers, respectively. Equation (25) enforces the non-negativity restriction on the decision variables and finally equation (26) represents the binary variables.

4- Solution methods

The proposed model in the previous section is a bi-objective mixed integer linear programming for the blood supply chain problem. The objective functions of the model are in conflict with each other such that a feasible solution cannot optimize both of them simultaneously. One approach for solving multi-objective optimization problems is converting the objective functions into a single-objective and then solving the single-objective problem using some multi-criteria decision making (MCDM) methods (Hwang and Masud 1979). In most of the multi-objective problems, the objective functions are in conflict with each other such that one objective function cannot gain its optimal value without deterioration of at least one of the other objective functions. In this situations, the multi-criteria decision making (MCDM) methods are used to reach a win-win deal between the objective functions. There are various methods to solve multi-objective problems. In this paper, three multi-objective decision making techniques including Elastic Bounded objective method, Modified augmented ε-constraint method, and LP-metric method are employed to solve the proposed bi-objective optimization problem. The next subsections describe the selected solution methods.

4-1- Elastic Bounded Objective Method (BOM)

The Bounded Objective Method is one of the decision making methods to solve the multi-objective problems. In this method, one of the objective functions is optimized considering the other objective functions as the constraint with two-sided bounds. Elastic BOM method is an extended version of the

Mounded Objective Method that like the conventional form of BOM, optimizes one of the objective function and considers the other objective functions as the constraint. But its difference is that Elastic BOM involves all of the objective function in the created objective function by using an elastic factor as shown in below (Marler and Arora 2004), (Jabbarzadeh et al. 2017).

$$\text{Maximize } \{f_i(x) - \sum_{\substack{g=1 \\ g\neq r}}^{p} \mu_g k_g\}$$
$$\text{subject to :}$$
$$m_g - k_g \leq f_g \leq M_g + k_g \qquad g=1,...,p \quad g\neq i \tag{27}$$
$$x \in S, \; k_g \in R^+$$

Where, μ_g is a positive parameter that controls the values of variable k_g, $f_g(x)$ is the value of objective function g, S is the feasible space of the original problem, and m_g and M_g are lower and upper bounds for value of objective function g, that in this paper, are considered equal to lowest and highest values of the payoff table, respectively.

4-2- Modified augmented ε-constraint method

Recently, Esmaili et al. (2011) proposed the modified augmented ε-constraint that is a novel version of conventional ε-constraints, which was introduced by Haimes et al. (1971). Although ordinary ε-constraint method is considered among the most popular method to generate a set of Pareto solutions for multi-objective optimization problems, but in some cases, it can result in inefficient Pareto solutions that this new version has remedied this problem by considering the slack variables into the objective function constraints and putting them as a second term in the objective function. Also Modified augmented ε-constraint method, considers the relative importance of the objective functions in generating the Pareto solutions. The mathematical form of the modified augmented e-constraint method is as follows:

$$\text{Maximize } \{f_i(x) + r_i \times (\sum_{\substack{g=1 \\ g\neq i}}^{p} \frac{w_g}{w_i} \times s_g / r_g)\}$$
$$\text{subject to :}$$
$$f_g(x) = e_g + s_g \quad \forall \; g=1,...,p \;, g\neq i \tag{28}$$
$$x \in S, \quad s_g \in R^+$$

Where S is the feasible space of the original problem, $f_g(x)$ is the value of objective function g, s_g is slack variables of *gth* constrained objective function, r_g is range of *gth* constrained objective function obtained from the payoff table such that $r_g = f_g^{max} - f_g^{min}$, w_i is the weight factor of the *ith* objective function such that $\sum_{g=1}^{p} w_g = 1$ and e_g is an upper bound for $f_g(x)$ that are obtained using the individual optimization method.

4-3- LP-metric method

The LP-metric method is one of the popular methods for solving multi-objective problems with inconsistent objective functions. The goal in this method is to find a solution that minimizes digression between the objective functions $(f_g; g = 1,2, \dots, p)$ and their ideal solution $(f_g^*; g = 1,2, \dots, p)$ that are obtained using the individual optimization method. The following mathematical problem is solved by this method.

$$Min\,D = \left(\sum_{g=1}^{p} \left(\frac{f_g^* - f_g}{f_g^*} \right)^r \right)^{1/r} \tag{29}$$

In this research, r is chosen 1.

5- Performance evaluation and comparison

In order to demonstrate the applicability and to assess the performances of the above-mentioned solution methods in terms of the objective functions values and required CPU time, thirty different hypothetical examples are employed in this section. The sizes of the generated problems are given in table 1. These examples are generated randomly and are solved on a laptop with core (TM) i5, 2.40 GHz, RAM 4 Mb using GAMS 24.7.3 software and making use of the CPLEX solver. Consider a blood supply chain problem that aims to optimize the platelet's chain. The shelf life of the platelets dispatched from local and main blood centers to demand's points are randomly generated based on a uniform distribution between 4 and 6 days. The referral rate r considered 0.3. Also, the failure rates of the local and main blood centers to dispatch blood products to demand points are randomly generated based on a uniform distribution between 0.02 and 0.05. The other main parameters of the mathematical model are randomly generated using uniform distributions presented in table 2. Furthermore, the initial data required in the solution methods are w_1=0.4, w_2=0.6, and $\mu = 10$. The results of the local optimum feasible solutions (Z1 & Z2) and their CPU times for thirty different examples obtained by GAMS are summarized in table 3. The results present the Pareto optimal solutions that consider all of the objective functions and try to satisfy all of the objectives of decision makers. If the decision makers want to simultaneously reach to all of the objectives in their optimal values, it is impossible. Because the objective functions are in conflict with each other and an optimal value of an objective function cannot be reached without deteriorating another objective function. Thus, if the decision makers want to reach to the entire objective functions in their near to optimal values, the results of the solution methods can help them. Otherwise, they cannot gain a logical result to reach their objectives.

Table1. Generated problems

problem code	i	p	y	l	m	h	t
5-3-5-3-2-6-30	5	3	5	3	2	6	30
8-4-9-4-1-6-30	8	4	9	4	1	6	30
10-5-10-5-2-10-60	10	5	10	5	2	0	60
8-3-9-3-2-13-41	8	3	9	3	3	13	41
13-6-10-3-2-11-30	13	6	10	3	2	11	30
12-6-12-4-1-14-52	12	6	12	4	1	14	52
11-7-10-4-1-10-50	11	7	10	4	1	10	50
7-3-15-5-3-16-45	7	3	15	5	3	16	45
10-6-9-3-1-15-58	10	6	9	3	1	15	58
8-4-8-6-2-17-59	8	4	8	6	2	17	59
13-5-9-3-1-15-43	13	5	9	3	1	15	43
11-8-12-3-2-16-51	11	8	12	3	2	16	51
9-5-16-3-1-16-34	9	5	16	3	1	16	34
10-2-8-6-2-6-80	10	2	8	6	2	6	80
8-3-14-5-1-13-52	8	3	14	5	1	13	52
11-4-11-3-3-10-36	11	4	11	3	3	10	36
12-5-15-3-1-14-38	12	5	15	3	1	14	38
11-5-8-3-2-8-30	11	5	8	3	2	8	30
9-6-8-5-3-7-33	9	6	8	5	3	7	33
11-7-9-4-2-11-60	11	7	9	4	2	11	60
12-3-15-5-2-16-47	12	3	15	5	2	16	47
9-6-15-5-2-12-32	9	6	15	5	2	12	32
9-5-11-3-3-15-33	9	5	11	3	3	15	33
14-3-9-4-2-10-55	14	3	9	4	2	10	55
13-8-15-5-2-8-47	13	8	15	5	2	8	47
8-3-14-4-2-8-38	8	3	14	4	2	8	38
9-3-16-3-2-11-30	9	3	16	3	2	11	30
13-7-10-6-2-10-50	13	7	10	6	2	10	50
8-4-10-4-2-19-46	8	4	10	4	2	19	46
11-6-12-4-1-12-60	11	6	12	4	1	12	60

Table 2: Parameters values

parameter	value	parameter	value
U_{yjpt}	Uniform (500,900)	ex_{ht}	Uniform (6,9)
$MAXB_{lt}$	Uniform (100,400)	hcl_{lt}	Uniform (1.5,2.5)
uc_{ypt}	Uniform (3,6)	hcm_{mt}	Uniform (1.5,3)
ulc_{lt}	Uniform (3,10)	D_{ht}	Uniform(100,700)
umc_{mt}	Uniform (3,14)	cap_{p}	Uniform (300,500)
cmm_{ypmt}	Uniform (1,3)	cap_{l}	Uniform(1000,2000)
clm_{lmt}	Uniform (1,5)	cap_{m}	Uniform(1500,3000)
clh_{lht}	Uniform (2,6)	dy_{iy}	Uniform (50,500)
cmh_{mht}	Uniform (2,7)	dl_{il}	Uniform (50,500)
sc_{ht}	Uniform (6,9)	cd	Uniform (50,300)

Table 3: The results obtained by the solution methods

problem code	Lp-metric			Elastic BOM			Modified epsilon-constraint		
i-p-y-l-m-h-t	**z1**	**z2**	**cpu time(s)**	**z1**	**z2**	**cpu time(s)**	**z1**	**z2**	**cpu time(s)**
5-3-5-3-2-6-30	7799075	3951	1.137	7794253	3353	1.033	7814749	3703	1.057
8-4-9-4-1-6-30	2399371	55217	1.584	2379322	54918	1.547	2543548	55548	1.556
10-5-10-5-2-10-60	28743360	121123	16.757	28096140	119810	11.020	28841680	120960	11.069
8-3-9-3-2-13-41	26444340	37193	7.114	26416860	35773	4.032	26777040	37449	7.999
13-6-10-3-2-11-30	11374440	40307	26.505	11396660	37434	8.111	11359800	40506	12.704
12-6-12-4-1-14-52	52214630	37924	10.909	51992650	34277	7.938	52027300	34359	7.680
11-7-10-4-1-10-50	14783070	130918	124.003	15797020	122155	7.583	14833460	128854	17.230
7-3-15-5-3-16-45	40277670	57787	1006.709	41420800	47301	26.626	40594520	51210	57.275
10-6-9-3-1-15-58	43321640	93198	80.228	42832040	90838	21.475	43012190	92850	36.825
8-4-8-6-2-17-59	64992390	112433	14.853	63187460	111894	11.402	63749920	113167	10.935
13-5-9-3-1-15-43	34554250	47815	6.568	34838950	44649	5.332	34535120	46130	5.200
11-8-12-3-2-16-51	39412040	133293	198.815	38339090	133026	16.099	38341530	133033	15.434
9-5-16-3-1-16-34	119305200	12152	12.956	119563500	9983	12.662	119563600	10027	12.762
10-2-8-6-2-6-80	10894690	156425	42.257	10797580	154067	24.241	14728450	158320	30.664
8-3-14-5-1-13-52	34547540	96494	7.700	33835380	96436	6.417	34254630	97185	6.115
11-4-11-3-3-10-36	7639785	89050	1003.476	7570895	88698	44.280	8003258	89839	1003.684
12-5-15-3-1-14-38	14628710	107865	5.961	14334660	107874	5.778	14748440	108503	5.628
11-5-8-3-2-8-30	5366930	52745	15.644	5326427	51650	5.740	5684550	53174	7.121
9-6-8-5-3-7-33	9353089	21751	9.182	9406150	20456	3.459	9285299	21745	4.774
11-7-9-4-2-11-60	32908920	110288	205.366	32797870	105476	34.691	32130080	108924	66.738
12-3-15-5-2-16-47	29939820	136834	46.073	30294540	128159	11.837	30311490	128298	11.603
9-6-15-5-2-12-32	11081910	65639	40.697	11195350	62604	7.306	10886070	65717	20.288
9-5-11-3-3-15-33	22597420	112111	11.049	21863130	111468	8.812	22360820	112899	8.565
14-3-9-4-2-10-55	11216590	164470	37.727	11318970	162149	12.282	12531920	166128	30.797
13-8-15-5-2-8-47	1727034	144474	91.674	1736178	143590	13.469	2565572	147892	77.587
8-3-14-4-2-8-38	1727034	144474	92.628	1736178	143590	14.002	2565572	147892	78.725
9-3-16-3-2-11-30	8711086	59811	67.770	9112921	54375	9.929	8864646	56504	27.093
13-7-10-6-2-10-50	8912509	155960	22.962	8814511	155787	16.275	10362810	157604	68.829
8-4-10-4-2-19-46	52583610	53721	17.902	52587960	49943	7.917	52451170	51199	9.645
11-6-12-4-1-12-60	30832580	149031	52.429	30964480	144645	22.779	31798030	150586	58.271

5-1- Comparison

In this section, the Tukey method is employed to analyze and compare the results of the solution methods with each other. This method is a useful test when there are more than two means being compared. It compares the difference between each pair of means with appropriate adjustment for multiple testing (Montgomery, 2009). By considering 0.05 Significance level (α), the null hypothesis H_0 declare that the means of the objective functions values and required CPU time in all three proposed solution methods are the same and alternative hypothesis H_1 state that at least one mean is different. The result of performing the Tukey test using MINITAB17.3.1 software are shown in ANOVA tables 4-6 and figures 2-4 .According to this results:

- As shown in ANOVA tables (4) and (5), given that the amounts of P-values for both objective functions are more than the significance level (0.999 > 0.05 for first objective function, and 0.976 > 0.05 for second objective function), the null hypothesis for both objective functions values are accepted, and there is not any significant difference between the result of the three proposed method in terms of objective functions values.
- The null hypothesis for required CPU time is rejected. According to ANOVA table (6), the amount of P-value in this comparison is 0.045 that is less than the significance level (0.05).
- The Tukey simultaneously control limits graph, is a graph that shows control limits of the difference of means for all pairs in multiple comparisons and if an interval does not contain zero, it means that the corresponding means are significantly different. Figures 2 and 3 are the Tukey simultaneously control limits graphs for the values of first and second objective functions, respectively. Considering these graphs, there is not any significant difference between the results of the three proposed method in terms of objective functions values for all pairwise comparisons. But figure 4 shows that the means of LP-metric and Elastic BOM methods are significantly different in term of required CPU time value and it causes the rejection of null hypothesis for required CPU time.

Table 4: ANOVA results for first objective value

SOURCE	DF	SS	MS	P-VALUE
TREATMENT	2	1.71632E+12	8.58160E+11	0.999
ERROR	87	5.16418E+16	5.93584E+14	
TOTAL	89	5.16435E+16		

Table 5: ANOVA results for second objective value

SOURCE	DF	SS	MS	P-VALUE
TREATMENT	2	115246272	57623136	0.976
ERROR	87	2.02275E+11	2324997591	
TOTAL	89	2.02390E+11		

Table 6: ANOVA results for required CPU time

SOURCE	DF	SS	MS	P-VALUE
TREATMENT	2	200433	100217	0.045
ERROR	87	2703854	31079	
TOTAL	89	2904287		

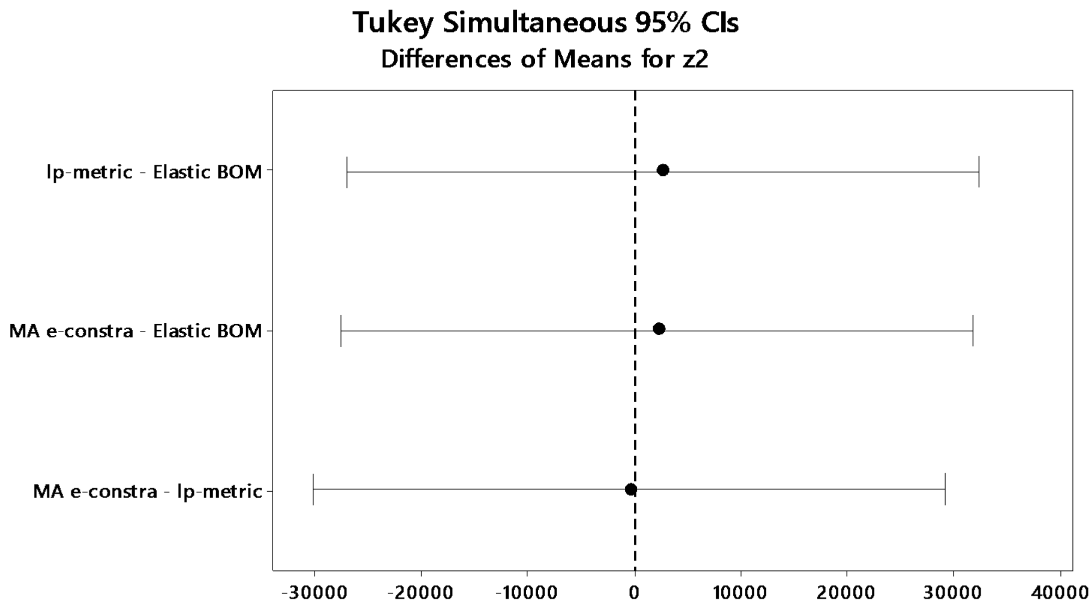

Fig. 2 Tukey's simultaneous 95 percent intervals for first objective function value comparison

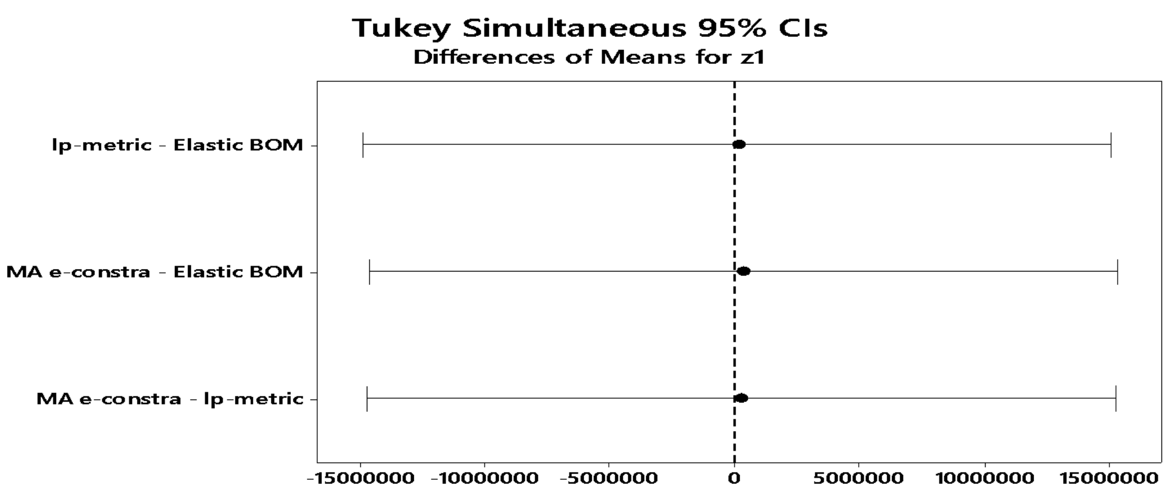

Fig. 3 Tukey's simultaneous 95 percent intervals for second objective function value comparison

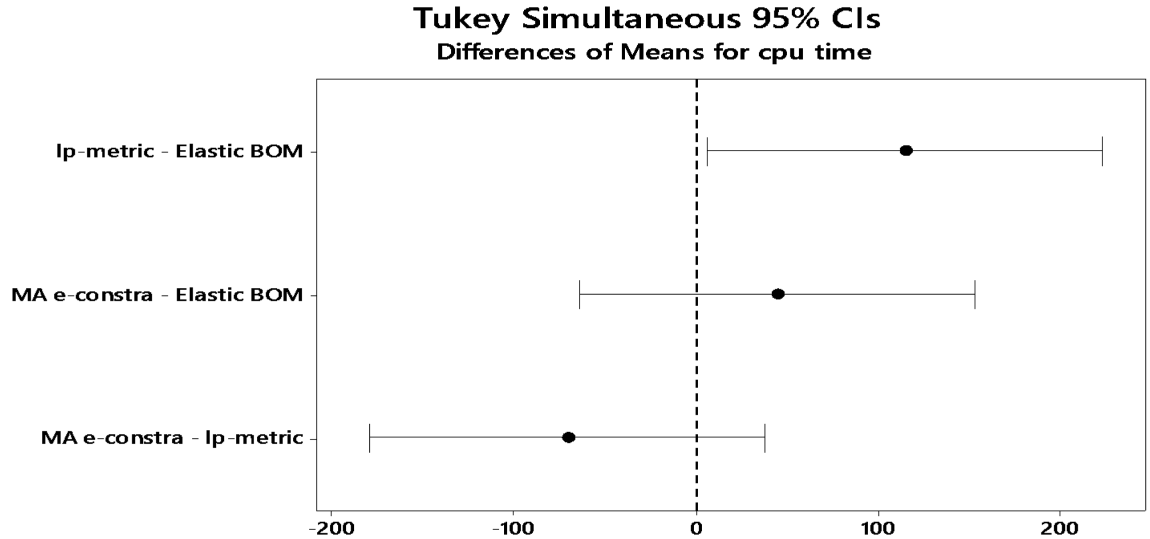

Fig. 4 Tukey's simultaneous 95 percent intervals for CPU time comparison

5-2- The Best solution method

The ELECTRE method is used in order to rank and choose the best solution method among the three proposed MODM methods. The acronym ELECTRE stands for "ELimination Et Choix Traduisant laREalité" and is the most widely used outranking methods for multiple criteria decision analysis (Greco et al. 2011). This method is based on the outranking relations. The construction of an outranking relation is based on the concordance and the discordance concepts. The concordance concept consists of the verification of the existence of a criteria's concordance in favor of the assertion that an alternative is as good as another one. The discordance concept consists of the verification of the inexistence of a strong discordance among the score values that may reject the previous assertion (Vahdani and Hadipour, 2011).

Considering the result of the numerical examples of section 4.1, Elastic BOM method selected as the best solution method among the three proposed methods by performing ELECTRE. Also there is not any preference between LP-metric and Modified augmented ε-constraint methods based on the results of ELECTRE.

6- Sensitivity analysis

In this section, sensitivity analysis is performed to determine the effects of the changes in some main parameters of the model on the objective functions values. For this purpose, main parameters of the model are selected. Given that the Elastic BOM method is the best method based on the result of the previous section; this method is used to perform the sensitivity analysis. The results are presented in figures 5-9.

6-1- Change in objective functions values by the changes in parameters $MAXB_i$, cd, cap_p, r

The result of increases (at +5% to +40% rates) in these parameters on the objective functions values are shown in figures 5 and 6. The results indicate that:

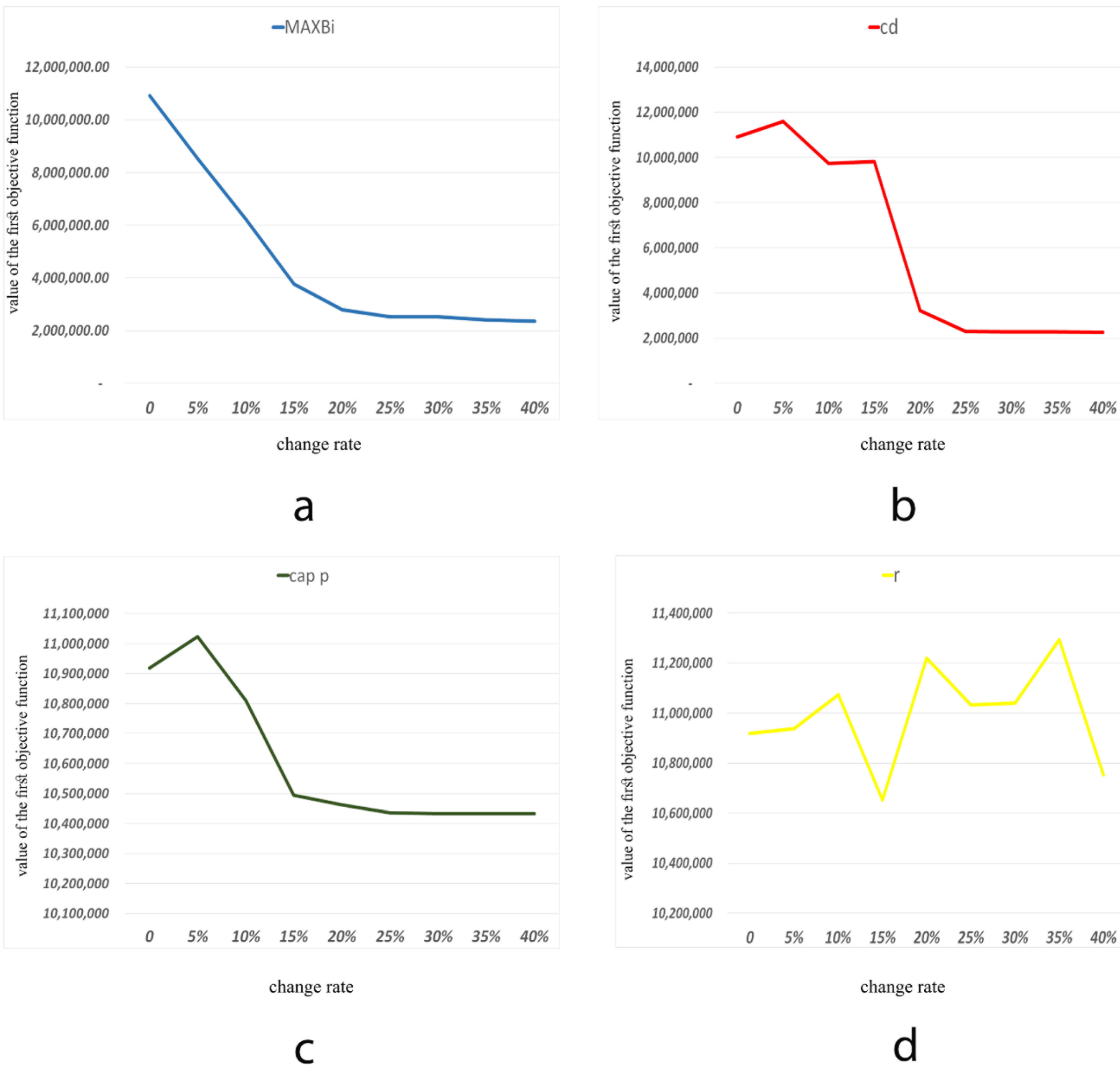

Fig. 5 Change in first objective function value by the changes in parameters *MAXBi*, *cd*, cap_p, *r*

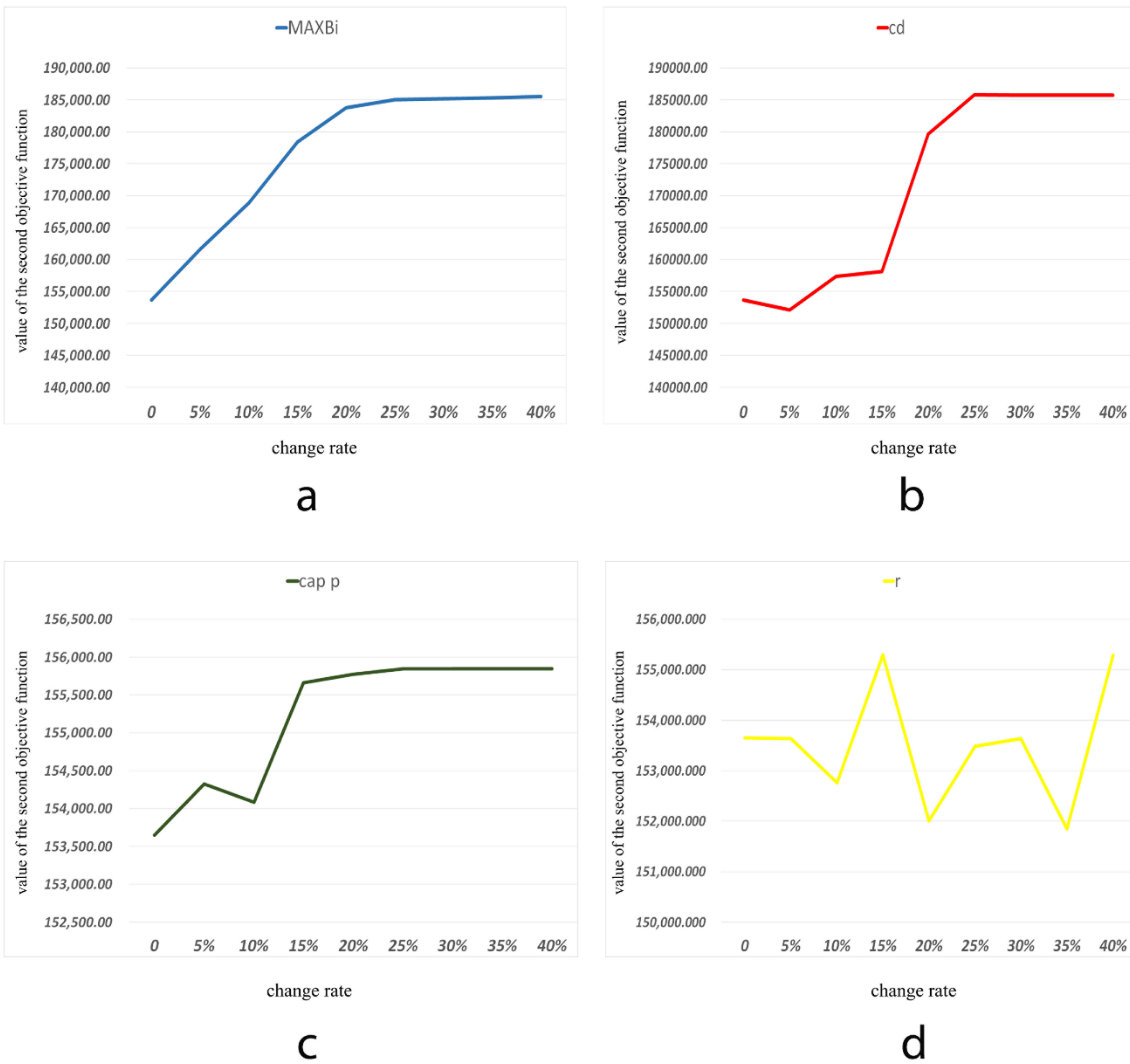

Fig. 6 Change in second objective function value by the changes in parameters *MAXBi*, *cd*, cap_p, *r*

a. The increase in the value of parameter $MAXB_i$ at all of the rates, results in the decrease in the first objective function value and increase in the second objective function value
b. The increase in the value of parameter *cd* at +5% rate, results in the increase in the first objective function value and decrease in the second objective function value. but for the other rates, it results in the decrease in the first objective function value and increase in the second objective function value
c. The increase in the value of parameter cap_p at +5% rate, results in the increase in the first objective function value. But for the other rates, it results in the decrease in the first objective function value. Also increase in the value of this parameter at all of the rates, results in the increase in the second objective function value
d. The increase in the value of parameter *r* at +15% and +40% rates, results in the decrease in the first objective function value and increase in the second objective function value. But for the other rates,

it results in the increase in the first objective function value and decrease in the second objective function value.

6-2- Change in objective functions values by simultaneous changes in parameters

In the following, the effect of the simultaneous changes in parameters *r* and cap_p on the objective functions values are analyzed. The results of simultaneous increases (at +5% to +40% rates) are presented in figure 7. Based on these results, the simultaneous increase in the values of parameters *r* and cap_p at +5% rate, results in the increase in the first objective function value. But for the other rates, it results in the decrease in the first objective function value. Also, the simultaneous increase in the value of these parameters at all of the rates results in the increase in the second objective function value.

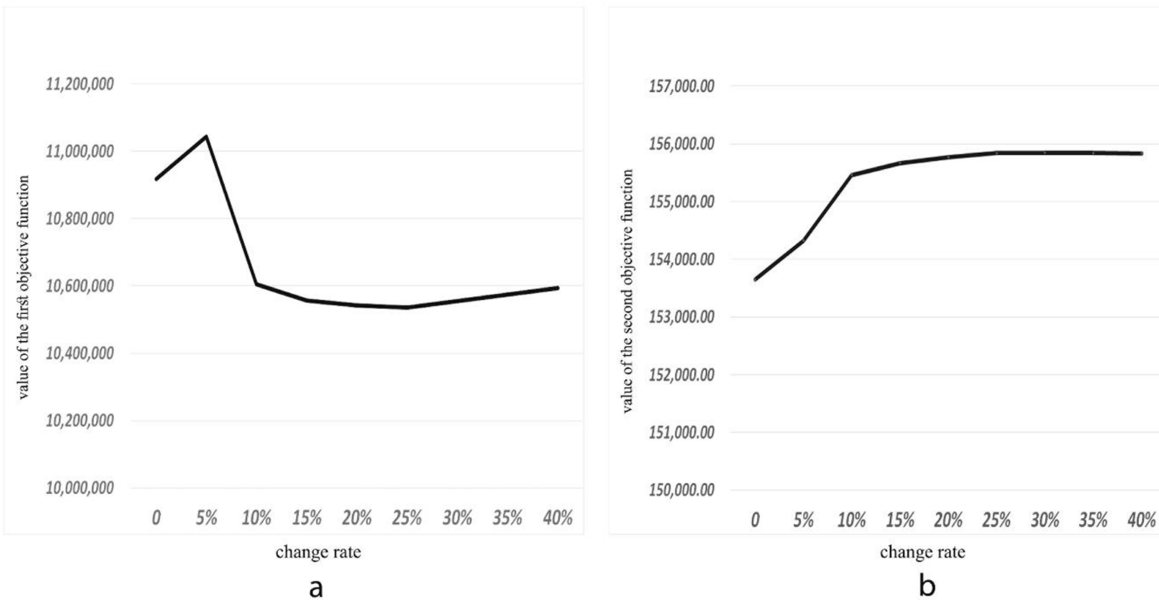

Fig. 7 Change in objective functions values by simultaneous changes in parameters *r and* cap_p

6-3- Change in objective functions values by the changes in parameter *n*

In order to analyze the effect of the number of days in between visits on the objective function values, different values of the *n* are employed. The results of figure 8 show that the increase in the number of days in between visits, results in the increase in the first objective function value and decrease in the second objective function value.

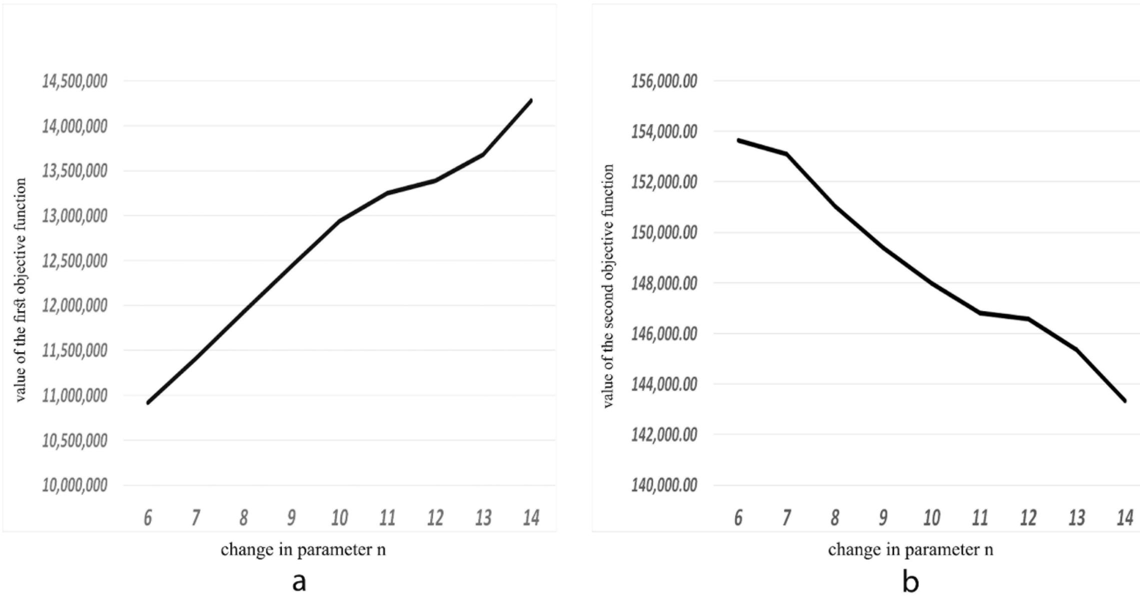

Fig. 8 Change in objective functions values by the changes in parameter *n*

6-4- Change in objective functions values by the changes in the parameter of Elastic BOM

A sensitivity analysis is performed to examine the effect of the different values of parameter µ on the objective function values. As presented in figure 9, the increase in the value of parameter μ results in the increase in the first objective function value except at $\mu=30$ rate that the best value of the first objective function is obtained at that rate. Also increase in the value of parameter µ, results in the decrease in the second objective function value and the best value of it is obtained at $\mu=10$ rate.

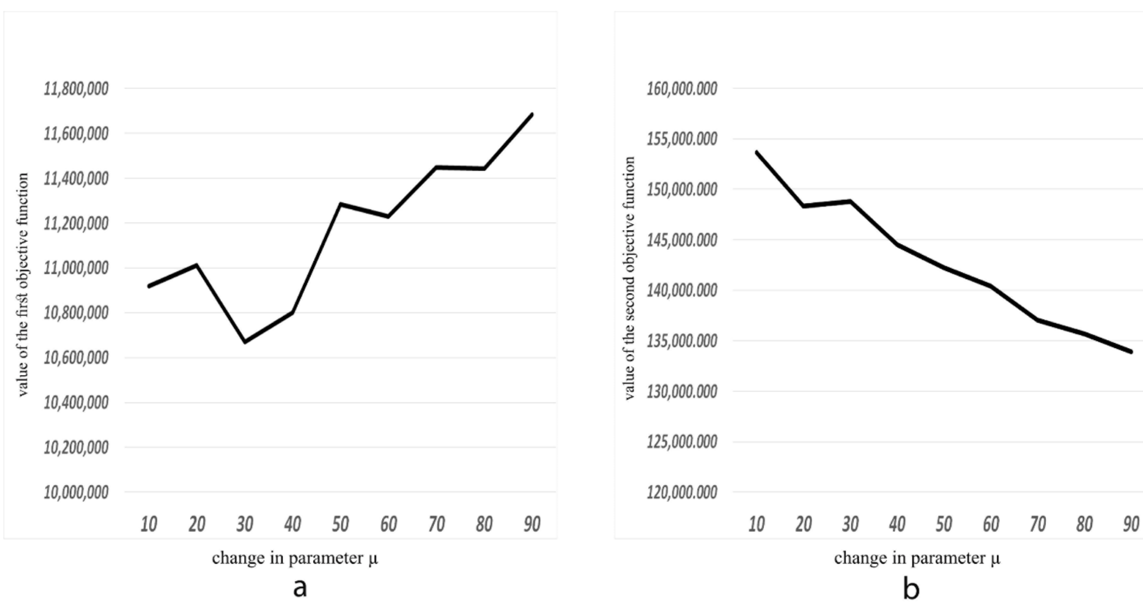

Fig. 9 Change in objective functions values by the changes in parameter μ

7- Conclusion

In this paper, a novel mathematical formulation for a blood supply chain network consisting of blood donors, mobile collection units, local blood centers, main blood centers and demand points was proposed in which the local and main blood centers were subject to random failure in dispatching blood products to demand points. The problem was first formulated into a mixed-integer linear model with two conflicting objectives including minimization of the total chain costs and maximization of the reliability of the local and main blood centers. Then, three MODM methods including LP- metric, Elastic BOM and modified augmented ε-constraint methods were developed to solve the mathematical model of the problem. In order to evaluate the efficacy of the solution methods in terms of the objective functions values and required CPU time, thirty different hypothetical examples were employed. The results of the solution methods were compared with each other using Tukey's multiple comparison tests. This comparison illustrated a significant difference between the results of the three proposed methods in terms of CPU time. Also, ELECTRE method was employed to rank and choose the best solution method among the three proposed MODM methods. The results demonstrated the better performance of the Elastic BOM method in terms of the objective functions values and required CPU time. Some sensitivity analysis was performed at the end to distinguish the effects of the changes in the main parameters of the model on the objective functions values.

As guidance for future research, one can consider uncertainty in some main parameters of the model like uncertainty in demand for blood products or uncertainty in the donation of blood. Also, other probability distributions can be developed to model the reliability of blood centers, instead of the exponential distribution. The proposed exact methods aren't capable of solving large scale problems in a reasonable time. Hence, developing meta-heuristic algorithms to solve the model would be worthwhile.

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