IJE TRANSACTIONS B: Applications Vol. 34, No. 02, (February 2021) 470-479

International Journal of Engineering

Journal Homepage: www.ije.ir

# A Blood Supply Chain Network with Backup Facilities Considering Blood Groups and Expiration Date: A Real-world Application

M. Asadpour[a,b,c], O. Boyer[b], R. Tavakkoli-Moghaddam[*d]

[a] *Department of Information Systems and Operations Management, Business School, The University of Auckland, Auckland, New Zealand*
[b] *Department of Industrial Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[c] *Young Researchers and Elite Club, Najafabad Branch, Islamic Azad University, Najafabad, Iran*
[d] *School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran*

*PAPER INFO*

*Paper history:*
Received 21 September 2020
Received in revised form 08 October 2020
Accepted 30 October 2020

*Keywords*:
*Blood Supply Chain*
*Goal Programming*
*Blood Groups*
*Expiration Date*
*Backup Facilities*

*ABSTRACT*

The purpose of this paper is to design a green Blood Supply Chain (BSC) network regarding expiration date and backup facilities. The proposed model is a bi-objective Mixed Integer Programming (MIP) one. The two objective functions are to minimize the total cost and the detrimental environmental impacts of shipping between facilities and generated wastes in the network. A Goal Programming (GP) approach is used to convert the multi-objective model into a single one. Moreover, to meet the demand, blood groups and plasma expiration date are also investigated. Since it has been proven that plasma of the people who have fully recovered from COVID-19, can help other patients to recover from this insidious disease; therefore, the proposed BSC network can supply the needs of this particular category of patients as well. To examine the feasibility of the proposed model, some random examples with different dimensions are generated and solved using the CPLEX solver of GAMS software. Furthermore, a real-case problem in Esfahan (Iran) was investigated to illustrate the applicability of the proposed model, and the sensitivity analysis was performed as well. Results approved the applicability of the proposed model in a real situation.

***doi**: 10.5829/ije.2021.34.02b.19*

## 1. INTRODUCTION

Blood Supply Chains (BSCs) have been one of the most interesting areas in the literature of the healthcare systems in recent years. What distinguishes the BSC from the other supply chains is that blood is not an ordinary commodity. Also, unlike the business supply chains, which are profit-oriented, the BSC is service-oriented. Besides, lack of blood products can increase the mortality rate. Meanwhile, blood products are very perishable. These criteria make BSC more complicated [1, 2].

The first step in the BSC is collecting blood from donors. After that, testing and production of blood products in the labs and sending them to hospitals are other steps which form a BSC. One of the most critical challenges for managers of the BSC is a continuous increase in demand for blood products while the rate of donors decreases so that American Red Cross reported in 2014, just 10% of US residents are blood donors. In addition, costs of testing, production of blood products, shipping, storage, and distribution are significant for officials of the healthcare systems. It means that managers expect to have a BSC that concurrently meets the demands, reduces wastages, and minimizes costs. Nonetheless, the perishability of most of the blood products leads to constraints and considerable costs for this sophisticated supply chain. Obviously, without a particular decision support framework, managers of the BSC will not be able to meet the demands for most of these products in a timely manner [3].

In the literature of the BSC, there are a wide variety of papers designed a BSC network regarding their own features. However, in Table 1, we only summarized some of them due to the page limitation.

[*] Corresponding Author Email: *tavakoli@ut.ac.ir* (R. Tavakkoli-Moghaddam)

Please cite this article as: M. Asadpour, O. Boyer, R. Tavakkoli-Moghaddam, A Blood Supply Chain Network with Backup Facilities Considering Blood Groups and Expiration Date: A Real-world Application, International Journal of Engineering, Transactions B: Applications Vol. 34, No. 02, (2021) 470-479

**TABLE 1.** Selected papers of the BSC

| Reference No. | Type of problem | Simulation | Mathematical modelling | Single objective | Multi-objective | Back up facilities | Blood groups | Expiration date | Solution method | Case study |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | Network design | * | | | | | | | Taguchi method | Tehran/ Iran |
| [4] | Network design | | * | Cost minimization | | | | | Branch & Bound | Tehran/ Iran |
| [5] | Network design | | * | | Cost minimization; Transportation time minimization; Maximization of tests' reliability | | | | ε-constraint | Tehran/ Iran |
| [6] | Network design | | * | | Cost minimization; Transportation time minimization | | | | Max–Min; Utility function; Goal attainment; LP-metric; Goal Programming | Tehran/ Iran |
| [7] | Network design | | * | | Cost minimization; The average blood delivery time minimization | | | | ε-constraint; Lagrangian relaxation | |
| [8] | Location-Allocation | | * | Cost minimization | | * | | | Tabu search; Bayesian belief network | Jamshedpur/ India |
| [9] | Network design | * | * | Cost minimization | | | * | | Branch & Cut | Tehran/ Iran |
| [10] | Network design | | * | Cost minimization | | * | | | GAMS/CPLEX solver | Tehran/ Iran |
| [11] | Network design | | * | | Cost minimization; Shortage minimization | * | | | Goal Programming | Qaemshahr/ Iran |
| [12] | Network design | | * | | Cost minimization; Shortage minimization | * | * | | Fuzzy VIKOR; GAMS/CPLEX solver | Tehran/ Iran |
| [13] | Network design | | * | Cost minimization | | * | | | Lagrangian relaxation | |
| [14] | Allocation | | * | Shortage minimization | | | * | | Greedy heuristic | Wenchuan/ China |
| [15] | Location-Inventory | * | * | Cost minimization | | | * | | IBM ILOG CPLEX software | Sichuan/ China |
| [16] | Network design | | * | | Cost minimization; Shortage minimization | | * | | ε-constraint | |
| [17] | Network design | | * | Cost minimization | | | | | GAMS/MIP solver | Not clear |
| [18] | Network design | | * | Cost minimization | | * | | | Self-Adaptive Imperialist Competitive; Invasive Weed Optimization | Mazandaran/ Iran |
| [19] | Network design | | * | | Cost minimization; Detrimental environmental impacts minimization; Total social impacts maximization | * | | | ε-constraint; Simulated Annealing; Harmony Search | |
| Present study | Network design | | * | | Cost minimization; Detrimental environmental impacts minimization | * | * | * | Goal Programming | Esfahan/ Iran |

With respect to the above-mentioned studies, we have not observed any research on the BSC investigating backup facilities, wastes, blood groups, and expiration date in satisfying demands simultaneously. Also, it seems that there has been no research on the BSC in Esfahan up to this time. Hence, regarding the importance and necessity of the subject and lack of any research on this area, the purpose of this paper is to design a green BSC network considering backup facilities, wastes, blood groups, and expiration date for Esfahan.

Similar to the classic supply chains, costs of establishing a BSC are important. Furthermore, there is the possibility of generating wastes because of blood contamination during the processes (because of pollution of test tubes or other devices), blood corruption due to inappropriate temperature conditions, leaking blood bags, etc. Therefore, minimizing the costs of establishing a BSC, along with minimizing the costs of waste and other detrimental environmental impacts, are significant for managers of Esfahan Blood Transfusion Organization (EBTO).

Consequently, the proposed model is a bi-objective MIP model, in which the first objective function is to minimize the total costs, whereas the second objective function is a green function, which investigates the environmental aspects of the problem. Also, regarding the experts' opinions of the EBTO, this study focuses on plasma product. While the proposed network is able to supply the patients' needs the plasma in Esfahan, with minimum costs and the minimum amount of waste, it can also involve recovered patients of COVID-19. In other words, since it has been proven that plasma of people who have fully recovered from COVID-19 can help other patients recover from COVID-19; therefore, the current network can supply the needs of this particular category of patients as well.

To summarize, the most contributions of the present research can be highlighted and listed below:

- ✓ To the best of our knowledge, it is the first BSC study considering backup facilities, blood groups, and expiration date simultaneously.
- ✓ With respect to the type of variables and objective functions, the proposed model is a green one, which actually is novel compared with the previous studies in the BSC literature.
- ✓ It is the first BSC network for EBTO so far that can efficiently supply required demands.
- ✓ Because of considering different scenarios in satisfying demands, the proposed model is flexible enough to cope with fluctuations in demands.
- ✓ With respect to the significance of plasma in treating COVID-19 patients, the proposed model can be invaluable from the perspective of the COVID-19 pandemic as well.

The rest of this paper is organized as follows:

In section 2, the problem and assumptions are defined and the proposed model is formulated. Also, the solution approach is explained. Section 3 examines the feasibility of the proposed model and results of solving the model for a real-case study along with a sensitivity analysis and practical recommendations to managers are presented. Finally, in section 4, the most important results and directions for future research are provided.

## 2. MODEL AND METHODS

In this paper, a BSC network considering blood groups and expiration date has been designed. Figure 1 shows the network of this problem. As illustrated in this figure, the network of this paper has three echelons, including blood collecting centers, laboratories for quality assurance and producing blood products, and demand centers (hospitals).

Donors refer to blood collecting centers. These centers receive blood from donors and transfer to labs. Blood labs send blood products to demand points (hospitals) after completing the required tests. Also, there are two types of facilities at all echelons of the network, i.e. permanent facilities and backup facilities.

The proposed model is a bi-objective MIP model. The first objective function minimizes total costs, including the establishment cost of facilities, cost of transportation, and cost of holding inventory by designing appropriate constraints and taking into account the level of demand at the hospitals regarding blood groups. The second objective function minimizes the detrimental environmental impacts of shipping between facilities and the amount of generated wastes in the network.

In the proposed model of this study, according to the experts' opinions of the EBTO, a blood product; namely, plasma has been considered.

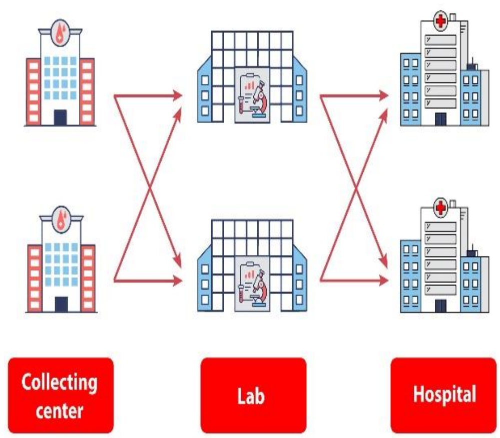


**Figure 1.** Proposed Blood Supply Chain Network

Moreover, in order to meet the demand, blood groups and plasma expiration date have also been investigated. The assumptions of the proposed model are as follows:

- The establishment cost of all facilities is deterministic and fixed.
- Operation and shipping costs are deterministic and fixed.
- The shipping and operation times are deterministic and fixed and are based on the "day" unit.
- All collected blood at collecting centers will transfer to labs.
- There is blood inventory neither in laboratories nor collecting centers. Inventory is kept just in hospitals.
- A blood product (plasma) is considered.
- There is a percentage of waste at the lab and hospital.

**2. 1. Indices** Let $I = (i, ib)$ be set of blood collecting centers, where $i$ is permanent blood collecting center while $ib$ indicates a backup blood collecting center. Also, $J = (j, jb)$ and $K = (k, kb)$ are set of labs and hospitals which similare to blood collceting centers, there are two types of labs and hospitals as well, i.e. permanent lab/hospital, and backup lab/hospital. Further, $G = \{g | g = 1, \ldots, 8\}$ denotes blood groups. Additionally, $V$ and $T$ are vehicle set and period set respectively. Besides, $S$ exhibit the set of scenarios as well.

The parameters and variables used in this model are presented as follows:

| | |
|---|---|
| $M$ | A very large number |
| $a_i$ | Operation time at the blood collecting center for each unit of blood |
| $a_j$ | Operation time at the lab for each unit of blood |
| $a_k$ | Operation time at the hospital for each unit of blood |
| $toi$ | Total operation time at the blood collecting center |
| $toj$ | Total operation time at the lab |
| $tok$ | Total operation time at the hospital |
| $d_{kgst}$ | Blood demand of hospital *k* in period *t* for blood group *g* under scenario *s* |
| $cap_{igt}$ | Capacity of blood collecting center *i* in period *t* for blood group *g* |
| $h_{kgt}$ | Holding cost in hospital *k* in period *t* for blood group *g* |
| $scj_{jgt}$ | Capacity of lab *j* in period t for blood group g |
| $sck_{kgt}$ | Capacity of hospital *k* in period *t* for blood group *g* |
| $c_{igt}$ | Operation cost of blood collecting center *i* in period *t* for blood group *g* |
| $c'_{jgt}$ | Operation cost of lab *j* in period *t* for blood group *g* |
| $c''_{kgt}$ | Operation cost of hospital *k* in period *t* for blood group *g* |
| $cq_{ij}$ | Fixed cost of using arc between *i* and *j* |
| $cq'_{jk}$ | Fixed cost of using arc between *j* and *k* |
| $fi_i$ | Fixed cost of collecting center establishment |
| $fib_{ib}$ | Fixed cost of backup collecting center establishment |
| $fj_j$ | Fixed cost of lab establishment |
| $fjb_{jb}$ | Fixed cost of backup lab establishment |
| $fk_k$ | Fixed cost of hospital establishment |
| $fkb_{kb}$ | Fixed cost of backup hospital establishment |
| $tti_{ij}$ | Transportation time from the blood collecting center *i* to the lab *j* |
| $tti_{jk}$ | Transportation time from the lab *j* to the hospital *k* |
| $scv_v$ | Capacity of vehicle |
| $cv_v$ | Setup cost of vehicle |
| $T_{gmax}$ | Expiration date |
| $EIij_{ij}$ | Environmental impacts of shipping between nodes *i* and *j* |
| $EIjk_{jk}$ | Environmental impacts of shipping between nodes *j* and *k* |
| $DC$ | Cost caused by generating each unit of waste |
| $l_j$ | Waste percentage of lab |
| $l_k$ | Waste percentage of hospital |
| $x_{ijgst}$ | Amount of blood transported of group *g* from the blood collecting center *i* to the lab *j* in period *t* under scenario *s* |
| $y_{jkgst}$ | Amount of plasma transported of group $g$ from the lab *j* to the hospital *k* in period *t* under scenario *s* |
| $inv_{kgst}$ | Amount of plasma inventory of group $g$ in hospital *k* in period *t* under scenario *s* |
| $wi_i$ | A binary variable which will be 1 if a collecting center is established at node *i*; 0, otherwise |
| $wib_{ib}$ | A binary variable that will be 1 if a backup collecting center is established at node *i*; 0, otherwise |
| $wj_j$ | A binary variable that will be 1 if a lab is established at node *j*; 0, otherwise |
| $wk_k$ | A binary variable that will be 1 if a hospital is established at node *k*; 0, otherwise |
| $wkb_{kb}$ | A binary variable that will be 1 if a backup hospital is established at node *k*; 0, otherwise |
| $vh_v$ | A binary variable that will be 1 if a vehicle *v* is used; 0, otherwise |
| $q_{ij}$ | A binary variable that will be 1 if arc between *i* and *j* is used; 0, otherwise |
| $q'_{jk}$ | A binary variable that will be 1 if arc between *j* and *k* is used; 0, otherwise |
| $HP_t$ | Amount of waste at period *t* |

**2. 2. Model Formulation**

$$\begin{aligned}\text{Min } Z_1 = & \sum_i \sum_j \sum_g \sum_s \sum_t c_{igt} \,.\, x_{ijgst} + \\ & \sum_i \sum_j \sum_g \sum_s \sum_t c'_{jgt} \,.\, x_{ijgst} + \\ & \sum_j \sum_k \sum_g \sum_s \sum_t c''_{kgt} \,.\, y_{jkgst} + \\ & \sum_k \sum_g \sum_s \sum_t h_{kgt}.\, inv_{kgst} + \sum_i fi_i.\, wi_i + \\ & \sum_j fj_j.\, wj_j + \sum_k fk_k.\, wk_k + \sum_{ib} fib_{ib}.\, wib_{ib} + \\ & \sum_{jb} fjb_{jb}.\, wjb_{jb} + \sum_{kb} fkb_{kb}.\, wkb_{kb} + \\ & \sum_i \sum_j cq_{ij}.\, q_{ij} + \sum_j \sum_k cq'_{jk}.\, q'_{jk} + \sum_v cv_v.\, vh_v\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Min } Z_2 = & \sum_i \sum_j EIij_{ij}.\, q_{ij} + \sum_j \sum_k EIjk_{jk}.\, q'_{jk} + \\ & \sum_t DC.\, HP_t\end{aligned} \tag{2}$$

s.t.

$$\sum_j y_{jkgst} - HP_t = d_{kgst} + inv_{kgst} - inv_{kgst-1} \quad \forall k, g, s, \tag{3}$$

$$\sum_j x_{ijgst} \le cap_{igt}.wi_i \quad \forall i, g, s, t \tag{4}$$

$$\sum_i x_{ijgst} \ge \sum_k y_{jkgst} \quad \forall j, g, s, t \tag{5}$$

$$\sum_i x_{ijgst} \le scj_{jgt}.wj_j \quad \forall j, g, s, t \tag{6}$$

$$\sum_j y_{jkgst} \le sck_{kgt}.wk_k \quad \forall k, g, s, t \tag{7}$$

$$\sum_{ib} wib_{ib} \ge 1 \tag{8}$$

$$\sum_{jb} wjb_{jb} \ge 1 \tag{9}$$

$$\sum_{kb} wkb_{kb} \ge 1 \tag{10}$$

$$\sum_i \sum_g x_{ijgst} \le \sum_v scv_v.vh_v \quad \forall j, s, t \tag{11}$$

$$\sum_j \sum_g y_{jkgst} \le \sum_v scv_v.vh_v \quad \forall k, s, t \tag{12}$$

$$(tti_{ij}.q_{ij}) + (tti_{jk}.q'_{jk}) + (toi.wi_i) + (toj.wj_j) + (tok.wk_k) \le T_{gmax} \quad \forall i, j, k \tag{13}$$

$$a_i.\sum_j \sum_g \sum_s \sum_t x_{ijgst} \le toi \quad \forall i \tag{14}$$

$$a_j.\sum_k \sum_g \sum_s \sum_t y_{jkgst} \le toj \quad \forall j \tag{15}$$

$$a_k.\sum_k \sum_g \sum_s \sum_t d_{kgst} \le tok \quad \forall k \tag{16}$$

$$\sum_g \sum_s \sum_t x_{ijgst} \le M.q_{ij} \quad \forall i, j \tag{17}$$

$$\sum_g \sum_s \sum_t y_{jkgst} \le M.q'_{jk} \quad \forall j, k \tag{18}$$

$$\sum_g \sum_s \sum_t x_{ijgst} \ge M.(1 - q_{ij}) \quad \forall i, j \tag{19}$$

$$\sum_g \sum_s \sum_t y_{jkgst} \ge M.(1 - q'_{jk}) \quad \forall j, k \tag{20}$$

$$HP_t = \sum_j \sum_g \sum_s l_j.y_{jkgst} + \sum_g \sum_s l_k.inv_{kgst} \quad \forall k, t \tag{21}$$

$$x_{ijgst}, y_{jkgst}, inv_{kgst}, HP_t \ge 0 \tag{22}$$

$$wi_i, wj_j, wk_k, wib_{ib}, wjb_{jb}, wkb_{kb}, vh_v, q_{ij}, q'_{jk} \in \{0,1\} \tag{23}$$

The objective function (1) minimizes the total cost of the network, including transportation costs, holding inventory cost, and the establishment cost of centers. The objective function (2) minimizes the amount of generated wastes and the detrimental environmental impacts of shipping between facilities.

Constraint (3) ensures that each hospital's demand is met. Constraint (4) states that the amount of the sent blood from each collecting center should not be greater than the capacity of that center. Constraint (5) states that the amount of plasma that is transferred from the lab to the hospital cannot exceed the amount of blood that is sent from the collecting center to the lab. Constraint (6) states that the amount of the sent blood to the lab should not exceed the capacity of the lab. Constraint (7) states that the amount of the sent plasma to each hospital should not exceed the hospital's capacity. Constraints (8) to (10) assure the establishment of backup facilities in each echelon of the network. Constraints (11) and (12) state that the transferred blood from the collecting center to the lab, and the transferred plasma from the lab to the hospital should not exceed the vehicle capacity.

Constraint (13) provides the maximum allowed time for consuming the plasma. Constraint (14) relates to the operation time at the collecting center and indicates that the operation time at the collecting center should not exceed a certain limit. Constraint (15) relates to the operation time in the lab and indicates that the operation time of the lab should not exceed a certain limit. Constraint (16) relates to the operation time at the hospital and indicates that the operation time at the hospital should not exceed a certain limit. Constraints (17) to (20) relate to using arcs between collecting centers and labs, and arcs between labs and hospitals. Constraint (21) specifies the amount of the generated wastes in each period in the laboratory and hospital. Eventually, constraints (22) and (23) define the domains of the decision variables.

**2. 3. Solution Approach** Multi-objective problems are problems that have more than a single objective function. These objectives usually are not compatible. In fact, optimizing one of the objectives can lead to a non-optimal solution for others. In such a situation, some methods make a trade-off among all objectives' solutions [11, 20, 21].

Goal Programming (GP) is one of these methods, which have been deployed in this research. In this paper, we use the GP approach for solving the bi-objective problem. The method is based on determining goals for all objectives and then minimizing the deviations from these goals. In this procedure, we should use deviation variables. There are two types of deviation variables. The $d_i^+$ means the amount of objective is more than the goal while $d_i^-$ means the amount of objective is less than the goal. The GP model minimizes the sum of these deviations [11].

The following GP approach is employed in the current research for solving the bi-objective problem:

$$\mathbf{Min} \sum_{i=1}^{n} \boldsymbol{W_i}(\boldsymbol{d_i^+} + \boldsymbol{d_i^-}) \tag{24}$$

s.t.

$$\boldsymbol{h_k(X) = or \le or \ge 0} \qquad \boldsymbol{k = 1, 2, \ldots, q} \tag{25}$$

$$\boldsymbol{f_i(X) - d_i^+ + d_i^- = g_i} \qquad \boldsymbol{i = 1, 2, \dots, n} \tag{26}$$

$$\boldsymbol{d_i^+, d_i^- \geq 0} \qquad \boldsymbol{i = 1, 2, \dots, n} \tag{27}$$

where $d_i^+$ and $d_i^-$ will be calculated using Equations (28) and (29):

$$\boldsymbol{d_i^+} = \begin{cases} \boldsymbol{f_i(X) - g_i} & \textbf{if } \boldsymbol{f_i(X) > g_i} \\ \boldsymbol{0} & \textbf{otherwise} \end{cases} \tag{28}$$

$$\boldsymbol{d_i^-} = \begin{cases} \boldsymbol{g_i - f_i(X)} & \textbf{if } \boldsymbol{f_i(X) < g_i} \\ \boldsymbol{0} & \textbf{otherwise} \end{cases} \tag{29}$$

It should be noted that the sum of weights should be 1.

$$\sum_{i=1}^{n} W_i = 1 \tag{30}$$

The solution steps of the problem are as follows:

I. The problem is solved for each objective function separately to determine the value of goals.
II. The value of its goal is used as the right-hand side for each objective function and by adding deviation variables, the equation is considered as a new constraint in the initial model.
III. Pareto solutions are calculated by using different weights of objective functions.
IV. Based on experts' opinions, the best answer is selected among the dominant solutions.

## 3. RESULTS AND FINDINGS

To approve the accuracy and feasibility of the proposed model, the model is implemented for sample problems with different dimensions that are generated randomly. All computations are done using CPLEX solver of GAMS software on a laptop with Intel Core i5, 2.5 GHz and 4 GB of RAM. Tables 2 and 3 depict dimensions of the sample problems and values of input parameters respectively. Also, results of solving sample problems are presented in Table 4.

After solving the sample problems and validating the proposed model, to verify the applicability of the proposed model, a real problem is investigated in Esfahan, a metropolitan city in Iran with about 2,000,000 residents according to the last census in 2016. Tables 5 and 6 show the parameters of the case study. Moreover, demands with respect to different blood groups in each scenario have been presented in Tables 7 to 9.

After solving the problem for Esfahan, Pareto solutions are obtained and Table 10 includes these values. It should be noted that for more convenience, all values in this table are divided into 10,000,000.

**TABLE 2.** Dimensions of sample problems

| Problem No. | Collecting center No. | Lab No. | Hospital No. | Blood group No. | Period No. | Vehicle No. | Scenario No. |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 2 | 3 | 2 | 1 | 1 | 2 |
| 2 | 4 | 4 | 6 | 4 | 2 | 4 | 2 |
| 3 | 10 | 8 | 12 | 8 | 4 | 4 | 2 |
| 4 | 20 | 12 | 25 | 8 | 4 | 8 | 4 |
| 5 | 25 | 15 | 30 | 8 | 7 | 12 | 4 |

**TABLE 3.** Distribution of input parameters

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| $fi_i$ | uniform(150,250) | $fib_{ib}$ | uniform(30, 50) |
| $fj_j$ | uniform(250,350) | $fjb_{jb}$ | uniform(50, 75) |
| $fk_k$ | uniform(300,500) | $fkb_{kb}$ | uniform(80, 100) |
| $d_{kgs1t}$ | uniform(1,3) | $d_{kgs2t}$ | uniform(3,6) |
| $EIjk_{jk}$ | uniform(1,10) | $EIij_{ij}$ | uniform(1,10) |
| $tti_{ij}$ | uniform(0.3,0.5) | $tti_{jk}$ | uniform(0.3,0.5) |
| $c_{igt}$ | uniform(2,9) | $c'_{jgt}$ | uniform(4,18) |
| $c''_{kgt}$ | uniform(2,9) | $cq_{ij}$ | uniform(1,5) |
| $cq'_{jk}$ | uniform(1,5) | $h_{kgt}$ | uniform(3,8) |

**TABLE 4.** Objective values of sample problems

| Problem No. | Objective functions | Objective values |
|---|---|---|
| 1 | f1 | 6477 |
| | f2 | 75 |
| 2 | f1 | 11728 |
| | f2 | 527 |
| 3 | f1 | 28780 |
| | f2 | 923 |
| 4 | f1 | 63976 |
| | f2 | 2290 |
| 5 | f1 | 89518 |
| | f2 | 3173 |

**TABLE 5.** Establishment costs of facilities

| Parameter | Values(IRR) | Parameter | Values(IRR) |
|---|---|---|---|
| $fi_i$ | 8500 | $fib_{ib}$ | 180 |
| $fj_j$ | 20500 | $fjb_{jb}$ | 630 |
| $fk_k$ | 76000 | $fkb_{kb}$ | 3000 |

**TABLE 6.** Capacities of facilities

| Parameter | Values | Parameter | Values |
|---|---|---|---|
| $cap_{igt}$ | 1000 | $scj_{jgt}$ | 1000 |
| $scv_v$ | 600 | $sck_{kgt}$ | 5000 |

**TABLE 7.** Demands in the first Scenario

| Blood Group | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| $A^+$ | 194 | 227 | 274 | 299 |
| $B^+$ | 214 | 233 | 248 | 276 |
| $AB^+$ | 221 | 242 | 245 | 290 |
| $O^+$ | 235 | 284 | 341 | 360 |
| $A^-$ | 28 | 31 | 34 | 41 |
| $B^-$ | 31 | 49 | 57 | 63 |
| $AB^-$ | 39 | 45 | 50 | 53 |
| $O^-$ | 15 | 17 | 26 | 29 |

**TABLE 8.** Demands in the second Scenario

| Blood Group | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| $A^+$ | 386 | 418 | 475 | 519 |
| $B^+$ | 331 | 339 | 364 | 387 |
| $AB^+$ | 315 | 328 | 336 | 394 |
| $O^+$ | 451 | 490 | 549 | 588 |
| $A^-$ | 48 | 55 | 59 | 67 |
| $B^-$ | 65 | 69 | 71 | 77 |
| $AB^-$ | 58 | 61 | 64 | 69 |
| $O^-$ | 34 | 41 | 48 | 51 |

**TABLE 9.** Demands in the third Scenario

| Blood Group | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| $A^+$ | 523 | 560 | 616 | 639 |
| $B^+$ | 418 | 441 | 499 | 521 |
| $AB^+$ | 429 | 456 | 484 | 510 |
| $O^+$ | 751 | 805 | 838 | 895 |
| $A^-$ | 75 | 81 | 86 | 93 |
| $B^-$ | 89 | 93 | 94 | 102 |
| $AB^-$ | 76 | 88 | 96 | 97 |
| $O^-$ | 55 | 55 | 63 | 71 |

Furhtermore, Figure 2 presents a Pareto frontier of the case study problem and clearly reveales conflicting between objcetive functions. Since the cost of the first objective function is sharply higher than the second one, experts of EBTO selected the 11th Pareto solution as the best possible solution for the network. Therefore, the objective values are 25,182,674,000,000 IRR for the first objective function, and 20,160,000,000 IRR for the second objective function. Accordingly, the network

**TABLE 10.** Pareto solutions

| Weight of $Z_1$ (W1) | Weight of $Z_2$ (W2) | Pareto solution No. | $Z_1$ value (IRR) | $Z_2$ value (IRR) |
|---|---|---|---|---|
| 1 | 0 | 1 | 6,378,300.000 | 240.862 |
| 0.9 | 0.1 | 2 | 5,974,800.000 | 275.600 |
| 0.8 | 0.2 | 3 | 5,690,600.000 | 326.900 |
| 0.7 | 0.3 | 4 | 5,149,100.000 | 443.300 |
| 0.6 | 0.4 | 5 | 4,486,700.000 | 663.100 |
| 0.5 | 0.5 | 6 | 4,087,200.000 | 822.000 |
| 0.4 | 0.6 | 7 | 3,716,300.000 | 1,016.600 |
| 0.3 | 0.7 | 8 | 3,427,800.000 | 1,201.400 |
| 0.2 | 0.8 | 9 | 3,138,500.000 | 1,372.900 |
| 0.1 | 0.9 | 10 | 2,657,700.000 | 1,813.700 |
| 0 | 1 | 11 | 2,518,267.400 | 2,016.000 |

includes 10 blood collecting centers, eight labs, 10 hospitals, and four vehicles. Figure 3 shows the established BSC network for Esfahan. Also, as a sample, in Tables 11 and 12, the flow between two collecting center and lab, and lab and hospital are presented according to the first scenario.

### 3. 1. Sensitivity Analysis

In this section, a sensitivity analysis is performed for the $a_j$; namely, operation time at the lab for each unit of blood based on experts' opinions. The range of parameter variations is examined from a 50% decrease to a 200% increase.

Table 13 depicts the results of these changes. Also, Figure 4 illustrates the changes in the first objective function as well. It should be noted that for more convenience, all values in Table 13 and Figure 4 have been divided into 10,000,000.

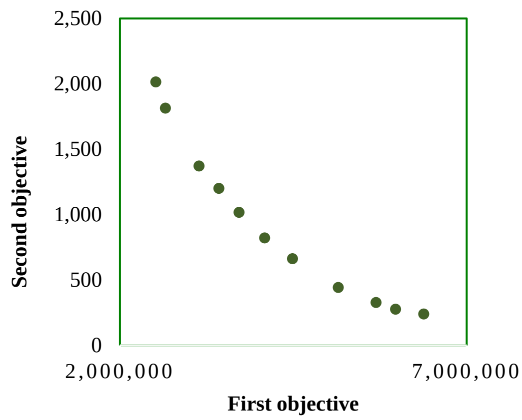


**Figure 2.** Pareto frontier of case study

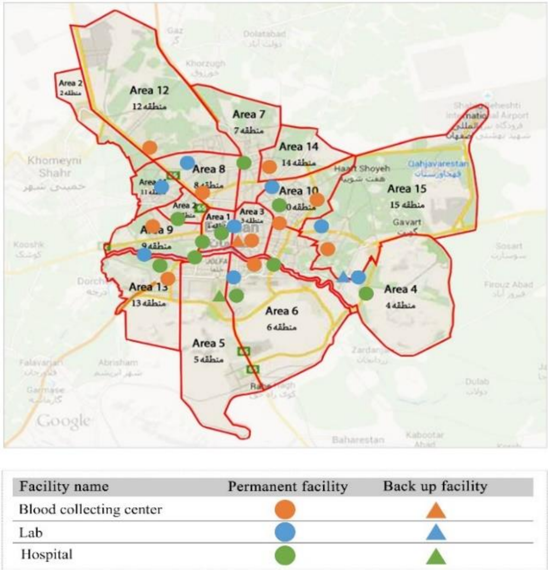


**Figure 3.** BSC Network for Esfahan

**TABLE 11.** Blood flow between Collecting center 1 & Lab 1

| Blood Group | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| $A^+$ | 15 | | 34 | 28 |
| $B^+$ | | 27 | 32 | |
| $AB^+$ | 32 | 25 | | 29 |
| $O^+$ | 37 | 24 | 35 | 15 |
| $A^-$ | | | 7 | 11 |
| $B^-$ | 6 | 13 | | 5 |
| $AB^-$ | 8 | 7 | 11 | |
| $O^-$ | 3 | | 2 | 5 |

**TABLE 12.** Product flow between Lab 1 & Hospital 1

| Blood Group | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|
| $A^+$ | 32 | 45 | | 57 |
| $B^+$ | 66 | | 46 | |
| $AB^+$ | 40 | 59 | 27 | 35 |
| $O^+$ | 52 | 55 | 38 | 73 |
| $A^-$ | | 6 | 7 | 11 |
| $B^-$ | 8 | | | 8 |
| $AB^-$ | 3 | 5 | 5 | |
| $O^-$ | 4 | 2 | 5 | 6 |

As shown in Figure 4, the value of the first objective function goes down with any drop in $a_j$. Whereas the difference between values of the first objective function regarding 10 and 25% decrease in $a_j$ is not very significant, by 50% reduction in $a_j$, the value of first objective function declines noticeably. Also, the first objective function is infeasible for either 10% or higher growth in $a_j$. Further, the second objective function is not sensitive to changes in $a_j$. Additionally, similar to the first objective function, the second objective function is infeasible for a 10% or higher rise in $a_j$. Hence, EBTO managers should be aware of the critical time of operation in the lab, and it may be advisable that by increasing the capacity (in the form of either expanding existing labs or establishing new labs) provides an amount of float for $a_j$.

## 3. 2. Managerial Insight

In this research, a BSC for Esfahan is designed, whose results are helpful for the managers of EBTO in some certain aspects. In particular, we have formulated a BSC regarding specific features and constraints of EBTO that can satisfy the demands in a timely manner. While in real situations, demand can be affected by unexpected occurrences (e.g. disaster), we deployed different scenarios to better capture demand fluctuations. However, the managers of EBTO are advised to monitor the status of demands periodically and once they see a trend (usually ascending trend) immediately take required decisions to be ready for

**TABLE 13.** Results of the sensitivity analysis in $a_j$

| $a_j$ (%) | -50 | -25 | -10 | 0 | 10 | 25 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|---|---|
| **First objective function** | 2509481.4 | 2516524.4 | 2516535.4 | 2518267.4 | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible |
| **Second objective function** | 2016 | 2016 | 2016 | 2016 | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible |

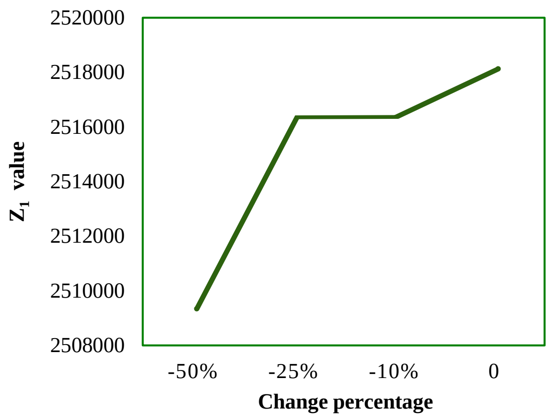


**Figure 4.** First objective function values based on changes in operation time in the lab

satisfying the possible increasing demand. Furthermore, results of the sensitivity analysis revealed that the situation in the lab (from the operation time perspective) is somehow fragile. Thus, the EBTO managers should consider possible alternatives to prevent network disruption due to forming a bottleneck in the lab (test and production echelon).

## 4. CONCLUSION AND FUTURE RESEARCH

In this paper, a BSC network considering backup facilities, blood groups, and expiration date has been designed. The proposed model is a bi-objective location-allocation-inventory model that, by designing appropriate constraints and considering inventory at the demand points, not only minimizes total costs but also satisfies hospitals' demand. Furthermore, demands have been met with regard to blood groups. Also, the proposed network can involve recovered patients of COVID-19. More specifically, since it has been proven that plasma of people who have fully recovered from COVID-19, can help other patients recover from COVID-19. Therefore, the proposed BSC network can supply the needs of this particular category of patients as well. A Goal Programming approach has been applied to solve the bi-objective problem and has been examined in a real case in Esfahan, Iran. Besides, a sensitivity analysis has been performed to provide additional managerial suggestions for the decision-makers in EBTO.

In future research, researchers can investigate the possibility of storing inventory at all echelons of the BSC network. Additionally, designing and modeling a multi-product BSC network under assumptions of this paper, applying a robust approach for facing uncertain parameters, considering wastes for collecting centers, and developing heuristic and meta-heuristic techniques for solving problems in large scales would be interesting for future studies.

## 5. REFERENCES

1. Zahraee, S. M., Rohani, J. M., Firouzi, A., and Shahpanah, A., "Efficiency improvement of blood supply chain system using Taguchi method and dynamic simulation", ***Procedia Manufacturing***, Vol. 2, (2015), 1-5. doi: 10.1016/j.promfg.2015.07.001.

2. Samani, M. R. G., Torabi, S. A., and Hosseini-Motlagh, S. M., "Integrated blood supply chain planning for disaster relief", ***International Journal of Disaster Risk Reduction***, Vol. 27, (2018), 168-188. doi:10.1016/j.ijdrr.2017.10.005.

3. Osorio, A. F., Brailsford, S. C., and Smith, H. K., "A structured review of quantitative models in the blood supply chain: a taxonomic framework for decision-making", ***International Journal of Production Research***, Vol. 53, No. 24, (2015), 7191-7212. doi:10.1080/00207543.2015.1005766.

4. Jabbarzadeh, A., Fahimnia, B., and Seuring, S., "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***, Vol. 70, (2014), 225-244. doi:10.1016/j.tre.2014.06.003.

5. Fazli-Khalaf, M., Khalilpourazari, S., and Mohammadi, M., "Mixed robust possibilistic flexible chance constraint optimization model for emergency blood supply chain network design", ***Annals of Operations Research***, Vol. 283, No. 1, (2019), 1079-1109. doi:10.1007/s10479-017-2729-3.

6. Khalilpourazari, S., and Khamseh, A. A., "Bi-objective emergency blood supply chain network design in earthquake considering earthquake magnitude: a comprehensive study with real world application", ***Annals of Operations Research***, Vol. 283, No. 1, (2019), 355-393. doi:10.1007/s10479-017-2588-y.

7. Fahimnia, B., Jabbarzadeh, A., Ghavamifar, A., and Bell, M. "Supply chain design for efficient and effective blood supply in disasters", ***International Journal of Production Economics***, Vol. 183, (2017), 700-709. doi:10.1016/j.ijpe.2015.11.007.

8. Sharma, B., Ramkumar, M., Subramanian, N., and Malhotra, B., "Dynamic temporary blood facility location-allocation during and post-disaster periods", ***Annals of Operations Research***, Vol. 283, No. 1, (2019), 705-736. doi:10.1007/s10479-017-2680-3.

9. Salehi, F., Mahootchi, M., and Husseini, S. M. M., "Developing a robust stochastic model for designing a blood supply chain network in a crisis: A possible earthquake in Tehran", ***Annals of Operations Research***, Vol. 283, No. 1-2, (2019), 679-703. doi:10.1007/s10479-017-2533-0.

10. Cheraghi, S., and Hosseini-Motlagh, S. M., "Optimal blood transportation in disaster relief considering facility disruption and route reliability under uncertainty", ***International Journal of Transportation Engineering***, Vol. 4, No. 3, (2017), 225-254. doi:10.22119/IJTE.2017.43838.

11. Habibi-Kouchaksaraei, M., Paydar, M. M., and Asadi-Gangraj, E., "Designing a bi-objective multi-echelon robust blood supply chain in a disaster", ***Applied Mathematical Modelling***, Vol. 55, (2018), 583-599. doi:10.1016/j.apm.2017.11.004.

12. Cheraghi, S., and Hosseini-Motlagh, S. M., "Responsive and reliable injured-oriented blood supply chain for disaster relief: a real case study", ***Annals of Operations Research***, (2018), 1-39. doi:10.1007/s10479-018-3050-5.

13. Rahmani, D., "Designing a robust and dynamic network for the emergency blood supply chain with the risk of disruptions", ***Annals of Operations Research***, Vol. 283, No. 1, (2019), 613-641. doi:10.1007/s10479-018-2960-6.

14. Ma, Z. J., Wang, K. M., and Dai, Y., "An emergency blood allocation approach considering blood group compatibility in disaster relief operations", ***International Journal of Disaster Risk Science***, Vol. 10, No. 1, (2019), 74-88. doi:10.1007/s13753-018-0212-7.

15. Chen, S., and Wang, C., "Incorporating a Bayesian Network into Two-Stage Stochastic Programming for Blood Bank Location-Inventory Problem in Case of Disasters", ***Discrete Dynamics in Nature and Society***, (2019). doi:10.1155/2019/7214907.

16. Naghipour, M., and Bashiri, M., "Designing a Bi-Objective Stochastic Blood Supply Chain Network in a Disaster", In 15th Iran International Industrial Engineering Conference (IIIEC), (2019), 171-177. doi: 10.1109/IIIEC.2019.8720727.

17. Ghasemi, S., "The Location Allocation Problem of After Disaster Blood Supply Chain", In 15th Iran International Industrial

Engineering Conference (IIIEC), (2019), 127-131. doi:10.1109/IIIEC.2019.8720635.

18. Haghjoo, N., Tavakkoli-Moghaddam, R., Shahmoradi-Moghadam, H., and Rahimi, Y., “Reliable blood supply chain network design with facility disruption: A real-world application”, ***Engineering Applications of Artificial Intelligence***, Vol. 90, (2020), 103493. doi: 10.1016/j.engappai.2020.103493.
19. Eskandari-Khanghahi, M., Tavakkoli-Moghaddam, R., Taleizadeh, A. A., and Amin, S. H., “Designing and optimizing a sustainable supply chain network for a blood platelet bank under uncertainty”, ***Engineering Applications of Artificial Intelligence***, Vol. 71, (2018), 236-250. doi: 10.1016/j.engappai.2018.03.004.
20. Saeidi-Mobarakeh, Z., Tavakkoli-Moghaddam, R., Navabakhsh, M., and Amoozad-Khalili, H., “A Bi-level Meta-heuristic Approach for a Hazardous Waste Management Problem”, ***International Journal of Engineering, Transactions A: Basics***, Vol. 33, No. 7, (2020), 1304-1310. doi:10.5829/IJE.2020.33.07A.17.
21. Akbarpour, N., Hajiaghaei-Keshteli, M., and Tavakkoli-Moghaddam, R., “New Approaches in Meta-heuristics to Schedule Purposeful Inspections of Workshops in Manufacturing Supply Chains”, ***International Journal of Engineering, Transactions B: Applications***, Vol. 33, No. 5, (2020), 833-840. doi:10.5829/IJE.2020.33.05A.15.

## Persian Abstract

**چکیده**

هدف مقاله حاضر طراحی شبکه سبز زنجیره تامین خون با توجه به تاریخ انقضا و تسهیلات پشتیبان است. مدل پیشنهادی یک مدل سبز چند هدفه برنامه ریزی مختلط عدد صحیح است. تابع هدف اول، حداقل سازی هزینه کل است و تابع هدف دوم، اثرات مخرب زیست محیطی ناشی از حمل و نقل و پسماندهای تولید شده در شبکه را به حداقل می رساند. برای حل مدل چندهدفه پیشنهادی از یک رویکرد برنامه ریزی آرمانی استفاده شده است. علاوه بر این ، تامین تقاضا با توجه به گروههای خونی و تاریخ انقضا پلاسما صورت می گیرد. از آنجا که ثابت شده است که پلاسمای افرادی که به طور کامل از بیماری COVID-19 بهبود یافته اند می تواند به بهبودی بیماران دیگر کمک نماید، بنابراین، شبکه پیشنهادی می تواند نیاز این دسته از بیماران را نیز تأمین کند. به منظور اعتبارسنجی مدل پیشنهادی مسائل تصادفی در ابعاد مختلف ایجاد و با استفاده از نرم افزار GAMS حل شده اند. همچنین مدل پیشنهادی برای یک مساله واقعی در اصفهان حل و بر روی نتایج به دست آمده تحلیل حساسیت انجام گرفته است. نتایج، کارایی مدل پیشنهادی در شرایط واقعی را تأیید می کند.