



Re-design of a blood supply chain organization with mobile units

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Abstract

This research analyses the re-organization of a blood supply chain organization. Blood supply chain network design is a hard problem. Uncertainties of the blood supply and demand, perishability of blood over time and compatibility of blood types are some factors that make the problem difficult. This paper presents a novel multi-objective mixed-integer location-allocation model for a blood supply chain design problem. Unlike many studies on blood supply chain design in the literature, supply chain network consisting of mobile and permanent units is planned together effectively with our mixed-integer programming model. Multi-objective structure of the model minimizes distances between the blood supply chain elements and the length of the mobile unit routes. The objectives are prioritized by experts using the Analytical Hierarchical Process. Finally, the model is implemented on a real life case study using real data from the Eastern Anatolia region of Turkey for various supply demand scenarios. The solutions offered by the model are compared with the current situation in the region. It is shown that the proposed model gives at least %25 more effective solutions. Moreover, sensitivity analysis on the budget constraint is conducted, and robustness of the model is empirically illustrated.

Keywords Blood supply chain · Blood · Humanitarian supply chain management · Mixed-integer programming

1 Introduction

Blood is a vital fluid that can deteriorate quickly which makes the development of precise blood supply chains a fundamental issue. Blood supply chains are systems that carry out the activities of collecting blood from donors, processing in laboratories, producing, storing and distributing blood products to the people in need. In this regard, blood supply chains can be considered as a human supply chain. Uncertainties in demand and supply, and the fact that blood is a vital and perishable product, make it difficult to design and plan effective and efficient blood supply chains.

Blood supply chain organization design is actually a humanitarian supply chain management design. Issues such as pricing and decision effort management (Chen et al. (2017), Wang et al. (2020)), optimal contract design (Xiao et al. (2020)) are important in classical supply chain management. Unlike other classical supply chain management systems, the purpose of humanitarian supply chain management systems is to benefit humanity sustainably. For this reason, it is necessary to design blood supply chains effectively and efficiently. In the Republic of Turkey, blood supply chain management solely belongs to the Turkish Red Crescent. The Turkish Red Crescent has an existing blood supply chain in the country. However, it has not been questioned until now how effective and efficient the current system is. The question is, if the system had been designed with operations research techniques, how strong would it be compared to the current system? We are aiming to reply that question by this study and enlighten the way for the decision makers for the new investments in the blood supply chain. It is quite difficult and complex to design, establish and manage a blood supply chain system from scratch. Though, considering the new investments to be made in the current supply chain, the proposed model in

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the study can be useful and guide blood supply chain decision makers.

Turkish Red Crescent is an important and complementary part of the international health system. It is the only legal authority recognized by Republic of Turkey Ministry of Health for the collection, distribution, storage and production of blood and blood products. Figure 1 illustrates the supply chain structure of the Turkish Red Crescent, which is responsible for the Turkish Blood Supply Chain. Blood collected from donors through Mobile Blood Donation Vehicle (MBDV) or Blood Donation Center (BDC) is transported to the closest Regional Blood Center (RBC) they are connected to. RBCs process various laboratory operations, produce and stock blood products and the products obtained are transferred to demand points such as hospitals and health centers in amount of their demands. BDCs are units that are smaller compared to RBCs in terms of size, function and capacity, usually in the form of stores in city centers. Donors can donate blood within the relevant working hours. On the other hand, MBDVs travel to donors to collect the donated bloods. RBCs take blood collected by BDCs and MBDVs and undergo various medical laboratory procedures and produce blood products such as platelets, red blood cells and plasma.

Uncertainties in demand and supply in blood supply chains are handled mainly as stochastic optimization problems in Gunpinar and Centeno (2015), Ensafian et al. (2017), Dillon et al. (2017), Zahiri et al. (2018), Hamdan and Diabat (2020a, b) and as robust optimization problems

in Zahiri et al. (2015), Ramezani and Behboodi (2017), Ensafian and Yaghoubi (2017), Heidari-Fathian and Pashandideh (2018), Jafarkhan and Yaghoubi (2018), Diabat et al. (2019). In addition, the blood supply chain problem is in the form of fuzzy linear optimization in Zahiri and Pishvae (2017), Eskandari-Khanghahi et al. (2018), Samani and Hosseini-Motlagh (2019). In our study, demand and supply are estimated based on the historical data, and scenarios are created accordingly.

There are 6 goals that we aim to reach in this study for the design of the blood supply chain organization: (1) determining the number and locations of RBCs, (2) determining the demand points that RBCs will serve, (3) determining the number and positions of BDCs, (4) determining the assignment of BDCs to RBCs, (5) determining the number and route of MBDVs, (6) determining the assignment of MBDVs to RBCs. Thus, we develop a multi-objective mixed-integer mathematical model and we solve it for a real case study with different scenarios. We show that our approach is robust in the sense that the optimal solution remains the same for varying scenario parameters.

There are 5 sections in our study. In Sect. 1, the problem is introduced. In Sect. 2, there is a comprehensive literature research. The formal definition of the problem and the mathematical formulation of the proposed model are given in Sect. 3. In Sect. 4, the results of the mathematical model for the actual data obtained from East-Anatolian region of Turkey are explained. In the last section, the obtained results are evaluated and possible research aspects for future studies are discussed.

2 Literature survey

Blood supply chain management, which is a special area of humanitarian supply chain management, is increasingly becoming popular among researchers. There are 4 literature survey of the studies related to the blood supply chains. These are Nahmias (1982), Beliën and Forcé (2012), Osorio et al. (2015) and Pirabán et al. (2019). Nahmias (1982) does not take into account the blood supply and its components and elaborate the studies that take blood as a perishable product. Beliën and Forcé (2012)'s point of view focuses on inventory management, distribution and scheduling in the blood supply chain. Osorio et al. (2015) categorize the models of the studies based on operational processes and model parameters. The recent literature review by Pirabán et al. (2019) analyses the models and methods especially from the recent studies. The study reveals that 57.69% of the literature occurred after 2015, and the studies are categorized in a more detailed manner compared to the previous literature surveys.

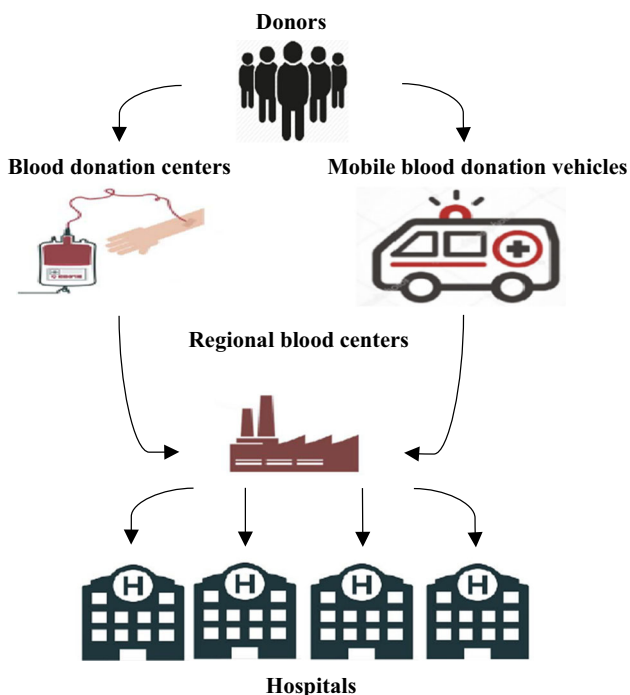


Fig. 1 Turkish Red Crescent Blood Supply Chain Framework

The blood supply chain literature focuses on inventory management and distribution of blood and/or blood products. The degradability of blood over time requires careful planning and control of blood inventory management. One of the oldest studies on this subject is done by Prastacos (1984). The study offers applying tools of operations research to blood inventory management theory and practice, and provides an insight into new areas of study for further research. In a similar study, Karaesmen et al. (2011) provide an overview of perishable products. The study accepts blood as a perishable product and elaborates studies on inventory management and points out possible future research topics. Various studies are related to the inventory management in blood banks and hospitals. For instance, Abdulwahab and Wahab (2014) develop a dynamic programming model for blood platelets with a short shelf life that takes into account ABO blood group compatibility for inventory in blood banks. Duan and Liao (2014) present a new simulation optimization approach that takes ABO blood group compatibility into consideration for red blood cells (erythrocytes) with a long shelf life. The authors determine near optimal inventory policies based on a new meta-heuristic optimization algorithm. Another study is due to Gunpinar and Centeno (2015) in which a stochastic programming model is proposed for the first time against the uncertainty inherent in the blood demand that minimizes the total cost, the absence of blood product, and the amount of idle blood product throughout a planning horizon. An inventory policy that reduces the amount of out-of-date products during the absence of blood product is proposed by Wang and Ma (2015). The age-related inventory policy of the developed product is analysed by several what-if scenarios and the sensitivity of various parameters are also analysed. A combined inventory policy based on age and stock is presented by Lowalekar and Ravichandran (2017). Dillon et al. (2017) contribute to blood product inventory management. They propose a two-stage stochastic programming model that takes into account uncertainty in demand and degradability of the product over time. Najafi et al. (2017) present a multi-objective mixed-integer programming model for blood inventory management in a hospital blood bank, while taking the uncertainty in demand and supply into account. The model minimizes the total cost, the absence of blood product and the amount of idle blood product throughout a planning horizon.

Inventory management for the flow of blood and/or blood products in the supply chain is another important subject study in the literature. Ensafian et al. (2017), Ensafian and Yaghoubi (2017), Osorio et al. (2017), Hosseinfard and Abbasi (2018), Clay et al. (2018), Hosseinfard et al. (2020) can be shown as recent examples. In addition, Ghandforoush and Sen (2010), Şahinyazan et al.

(2015), Blake et al. (2015), Gunpinar and Centeno (2016), Elalouf et al. (2018) focus on the logistics of blood products in the supply chain. The status of the blood supply chain network design and optimization after any disaster and emergency situations is also a sub-area. The changes in the supply chain after the disaster and the optimum strategies to be followed are examined in this sub-study area. Jabbarzadeh et al. (2014), Fahimnia et al. (2017), Samani et al. (2018), Glasgow et al. (2018), Diabat et al. (2019), Fazli-Khalaf et al. (2019), Sharma et al. (2019), Salehi et al. (2019), Rahmani (2019), Khalilpourazari and Khamseh (2019), Haghjoo et al. (2020), Hamdan and Diabat (2020a, b), Wang and Chen (2020) are current examples on this topic.

In this study, we address the blood supply chain network design and optimization problem. We analyse similar studies below. First, Or and Pierskalla (1979) are the pioneering research that addresses the problem of location-allocation in blood supply chain management. A model that minimizes total transportation and system costs is developed in the blood supply chain consisting of hospitals and blood banks. In his handbook, Pierskalla (2004) examines the blood supply chain management from a general perspective. He discusses the hierarchical structure of blood supply chains, inventory management and network design. One of the important studies that address the problem of location-allocation is due to Şahin et al. (2007) in which three mixed-integer mathematical sub-models are proposed. The pq-median location model minimizes the distance between the facilities. The second model keeps the facilities to be opened at a certain distance. The third model is for the homogeneous distribution of mobile units in the service areas. Another important example following this study is pursued by Çetin and Sarul (2009). A non-linear goal programming model is developed to determine the locations and number of blood banks to be placed between hospitals, minimizing the total distance to supply and demand points. Another important example that will be the key to current studies in the literature is due to Nagurney et al. (2012). In this study, unlike previous studies, blood perishability, waste/disposal costs, uncertainties in demand and costs arising from these uncertainties are taken into account. A significant part of the recent literature has followed this study. Zahiri et al. (2015) present a mixed-integer linear programming model by applying a robust probabilistic programming approach to eliminate the uncertainty in model parameters. A similar study is made by Arvan et al. (2015). In addition to cost minimization in the objective function of the proposed model, the time remaining before consumption in the supply chain of blood and blood products is minimized. Zahiri and Pishvae (2017), on the other hand, prepare a network design study considering the compatibility between blood groups. The

mathematical model proposed for network design consists of minimum cost with maximum demand satisfaction. Ramezani and Behboodi (2017) aim to eliminate uncertainty in supply chain parameters using the robust optimization approach. The study is the first article to investigate the role of blood donors on decision variables in blood supply chain design, according to the authors' claims. Masoumi et al. (2017) examine the merger of two different blood supply chain organizations, unlike the studies in the literature. With the mathematical model they propose, performance criteria such as cost efficiency, product absence and product excess are improved. Heidari-Fathian and Pasandideh (2018) work on green blood supply chain design and propose a Lagrange relaxation approach to solve the mixed-integer mathematical model they propose. Eskandari-Khanghahi et al. (2018) propose a multi-objective stochastic optimization model for a sustainable blood supply chain design. The solution for large-scale problems in the study is provided by simulated annealing. Zahiri et al. (2018), with their multi-objective mixed-integer programming model, offer a priority queue system for blood product congestion in each hospital and a new meta-heuristic solution is developed for large-scale problems. Bruno et al. (2019) reposition the supply chain facilities in a region of interest. They prove that their model can be used as a decision support system with several scenarios. Hamdan and Diabat (2019) design a blood supply chain with a two-step multi-objective stochastic optimization model. While the number of mobile units is determined in the first stage, inventory and production decisions are determined in the second stage. Hosseini-Motlagh et al. (2020) develop a bi-objective two-stage stochastic programming model for managing a red blood cells supply chain that observes blood group compatibility. The proposed model determines the optimum location-allocation and inventory management decisions and aims to minimize the total cost of the supply chain including fixed costs, operating costs, inventory holding costs, wastage costs and transportation costs along with minimizing the substitution levels to provide safer blood transfusion services. Finally, Hamdan and Diabat (2020a, b) propose a novel approach to deal with the issue of solving large operational stochastic optimization problems by using machine learning models.

As a result of the general literature review, the contributions of our study to the literature can be summarized in the following;

- The blood supply chain we examine has 4 echelons. These are RBCs, BDCs, MBDVs and supply/demand points. RBCs perform all the duties of the laboratories, storage facilities and distribution centers in the supply chains (Nagurney et al. (2012) and Zahiri et al. (2015)). BDCs are fixed units that collect blood donations and are connected to RBCs. MBDVs are mobile units that collect blood in the supply chain and transfer the collected blood to RBCs. They serve at locations where RBCs and BDCs are not available or where capacity is not sufficient. Our aim is to determine the number and locations of facilities that can meet the needs of supply demand points.
- The proposed model is a multi-objective mixed-integer mathematical model. Unlike the objective function of the mathematical models in the literature, the objective function minimizes the distance of the supply chain components with each other, as well as the total length of the route of the mobile elements. Similar models in the literature generally deal with cost minimization as an objective function.
- We address the blood supply chain problem from an integrated perspective, not just a location-allocation problem or just a route planning of mobile units' problem. Therefore, as much as we are concerned with the positioning of the permanent units, we are also interested in the routes that mobile units should follow.
- Different purposes in the objective function are evaluated by experts using the Analytical Hierarchical Process (AHP) and their priority coefficients are determined. The objective function takes into account the minimum transport time, minimum cost directly and product shelf lives, indirectly.
- The model is tested for a real data set obtained from the East-Anatolian region of Turkey. It is shown that the efficiency of the existing blood supply chain can be improved significantly by the help of the offered model.
- By addressing the supply chain in a developing region, the model is intended to contribute to the new investments to be made. Theoretical and practical outputs are provided to supply chain decision makers for possible future investments.

3 Multi-objective mixed-integer mathematical model

In this section, the multi-objective mixed-integer mathematical model is explained. First of all, the problem specifications are given. Then, notation and formulation of the mathematical model are introduced.

3.1 Problem statement

The content of this problem includes locating RBCs, BDCs and MBDVs positions, determining the optimum number of units which is used and determining the allocations between them. As mentioned above, the model possesses a

holistic perspective. Namely, we minimize the distances between the units of the blood supply chain and at the same time, we minimize the travel lengths of the mobile units.

The assumptions we make about the problem specifications are as follows;

- The capacity of each RBC is known.
- The capacity of each BDC is known.
- The capacity of each MBDV is known.

These assumptions are made due to the fact that the RBCs, BDCs and MBDVs, which are in the supply chain of the Red Crescent, mostly have the same type and equal capacity and it is therefore natural to assume known capacities.

- Opening and operating costs of RBC, BDC and MBDV vary by location and they are all known.
- RBCs can be found in locations with a population of 400 thousand and above.
- BDCs can be found in locations with a population of 100 thousand and above.
- Each BDC that is opened is assigned to a single RBC.
- Each MBDV that is opened is assigned to a single RBC.

These assumptions comply with the cost/settlement structures of the real Red Crescent units that are already known in advance.

- Donors are distributed homogeneously in the population and bounded.
- Demands are distributed homogeneously in the population and bounded.

These two assumptions are commonly made in the literature (i.e., Ensafian and Yaghoubi (2017), Arvan et al. (2015), Şahinyazan et al. (2015), Jabbarzadeh et al. (2014)). Hence, we also resort to homogeneity assumptions. Moreover, studies reveal that imbalance between the different regions of Turkey tend to decrease in every aspect in recent years which can be seen as a justification for our usage of these assumptions.

3.2 Mathematical model

3.2.1 Model notation

The notation to be used in the proposed model is as follows;

3.2.2 The formulation

In the proposed model, the objective function takes into account three different sections. The first part of the objective function is the distance between BDCs and RBCs (A), the second part is the distance between RBCs and

demand points (B) and the third part is the length of the routes that MBDVs will follow for blood collection (C). However, the importance of these objectives is undoubtedly different from each other. In this regard, the goals are evaluated by three experts who have experience and knowledge on the subject. We choose Analytical Hierarchical Process (AHP) which is developed by Saaty (1990) as the evaluation method since it is simple and practical to use and still considered to be quite effective. AHP uses binary comparison matrices to determine weights, using a scale from 1 to 9 in these comparisons. It takes the value 9 if one goal is of much more important than the other, and 1 if it is of equal importance. However, depending on the degree of importance, intermediate values of 3, 5 and 7 can also be given by the decision maker. Binary comparison matrices are square matrices, their diagonal values are 1, and the comparison of goals is made exactly and mutually according to the degree of importance they have (Tables 1, 2 and 3).

After the goals included in the objective function are named as A, B, C, respectively, the decision makers are asked to evaluate them in the criterion of the “total cost that will create in the supply chain”. Table 4 is the binary comparison matrix of one of the decision makers. These comparison values are then normalized first by the column totals, and then, weights of the rows are calculated to find the weight values. The average of the weight values obtained from three decision makers in the decision making team are 0,409, 0,386 and 0,204, respectively. Minimizing the distance between the RBCs and demand points is represented by the decision-making team with the highest weight value. The RBC is very costly in terms of investment and investment decision is more important than other purposes since it is strategically important. The objective function is formulated accordingly. The mixed-integer linear programming formulation is given below:

$$\begin{aligned} \text{Min } & 0,409 \sum_{i \in I} \sum_{j \in J} (d_{ij}^1 u_{ij}^1) + 0,386 \sum_{j \in J} \sum_{k \in K} (d_{jk}^2 u_{jk}^2) \\ & + 0,204 \sum_{l \in L} \sum_{k \in K} \sum_{m \in K} (d_{km}^3 \beta_{lkm}) \end{aligned} \tag{1}$$

Subject to

Table 1 Sets and indices

Sets	Description
I/i	Set of BDC candidate points and its index
J/j	Set of RBC candidate points and its index
$K/k,m$	Set of supply/demand points and its indices
L/l	Set of MBDVs and its index

Table 2 Parameters

Parameters	Description
A_k	Supply of point k
D_k	Demand of point k
c_i^1	Capacity of BDC to be opened at point i
c_l^2	Capacity of the l^{th} MBDV
c_j^3	Capacity of RBC to be opened at point j
d_{ij}^1	Distance between BDC at point i and RBC at point j
d_{jk}^2	Distance between RBC at point j and demand point k
d_{km}^3	Distance between demand/supply point k and demand/supply point m
d_{ki}^4	Distance between demand/supply point k and BDC at point i
F	Total allocated budget
f_i^1	Total cost of locating a BDC at point i
f_j^2	Total cost of locating an RBC at point j
f_l^3	Total operating cost of operating l^{th} MBDV
γ_k	1 if k demand point is also an RBC point, otherwise 0
φ_k	1 if k supply point is also an BDC point, otherwise 0

Table 3 Decision variables

Variables	Description
p_i	1 if an BDC is opened at point i , otherwise 0
r_j	1 if an RBC is opened at point j , otherwise 0
s_l	1 if l th MBDV is used, otherwise 0
u_{ij}^1	1 if BDC at point i is assigned to RBC at point j , otherwise 0
u_{jk}^2	1 if demand/supply point k is assigned to RBC at point j , otherwise 0
u_{ij}^3	1 if l th MBDV is assigned to RBC at point j , otherwise 0
u_{ki}^4	1 if demand point k is assigned to BDC at point i , otherwise 0
x_k^1	Amount of blood collected at BDC from supply point k
x_{kl}^2	Amount of blood collected from l th MVDV from supply point k
y_{ij}^1	Amount of the supply transferred from BDC at point i to RBC at point j
y_{ij}^2	Amount of the supply transferred from l th MBDV to RBC at point j
z_{jk}	Amount of blood transferred to demand point k by RBC at point j
θ_{kl}	1 if k demand point takes service from l th MBDV, otherwise 0
β_{lkm}	1 if l th MBDV goes from demand point k to demand point m , otherwise 0
v_{kl}	The order of the arrival of l th MBDV to the demand point k

Table 4 Binary Comparison matrix

	A	B	C	Weight
A	1,000	5,000	0,333	0,574
B	0,200	1,000	3,000	0,286
C	3,000	0,333	1,000	0,140

$$\sum_{j=1}^J u_{ij}^1 = p_i \quad i \in I \tag{2}$$

$$u_{ij}^1 \leq r_j \quad i \in I, j \in J \tag{3}$$

$$\sum_{j=1}^J u_{jk}^2 = 1 \quad k \in K \tag{4}$$

$$u_{jk}^2 \leq r_j \quad j \in J, k \in K \tag{5}$$

$$\sum_{j=1}^J u_{ij}^3 = s_l \quad l \in L \tag{6}$$

$$u_{ij}^3 \leq r_j \quad j \in J, l \in L \tag{7}$$

$$\sum_{i=1}^I p_i f_i^1 + \sum_{j=1}^J r_j f_j^2 + \sum_{l=1}^L s_l f_l^3 \leq F \tag{8}$$

$$\theta_{kl} = \sum_{m \in K} \beta_{lkm} \quad k \in K, l \in L \tag{9}$$

$$\sum_{k \in K} \beta_{ljk} = u_{ij}^3 \quad j \in J, l \in L \tag{10}$$

$$\sum_{k \in K} \beta_{lkj} = u_{ij}^3 \quad j \in J, l \in L \tag{11}$$

$$\sum_{k \in K} \sum_{m \in K} \beta_{lkm} \leq s_l |K|^2 \quad l \in L \tag{12}$$

$$\sum_{k \in K} \beta_{lkm} = \sum_{k \in K} \beta_{lmk} \quad l \in L, m \in K \tag{13}$$

$$v_{kl} - v_{ml} + |K| \beta_{lkm} \leq |K| - 1 \tag{14}$$

$k \in K, l \in L, m \in K : \gamma_k \neq 1, \gamma_m \neq 1, k \neq m$

$$x_k^1 + \sum_{l=1}^L x_{kl}^2 \leq A_k \quad k \in K \tag{15}$$

$$x_k^1 \leq c_k^1 p_k \quad k \in K : \varphi_k = 1 \tag{16}$$

$$\sum_{k=1}^K x_{kl}^2 \leq c_l^2 \quad l \in L \tag{17}$$

$$x_{kl}^2 \leq c_l^2 \theta_{kl} \quad k \in K, l \in L \tag{18}$$

$$\sum_{i \in I} y_{ij}^1 + \sum_{l \in L} y_{lj}^2 \leq c_j^3 \quad j \in J \tag{19}$$

$$y_{ij}^1 \leq u_{ij}^1 c_j^3 \quad i \in I, j \in J \tag{20}$$

$$y_{lj}^2 \leq u_{lj}^2 c_j^3 \quad j \in J, l \in L \tag{21}$$

$$x_k^1 = \sum_{j=1}^J y_{kj}^1 \quad k \in K : \varphi_k = 1 \tag{22}$$

$$\sum_{k=1}^K x_{kl}^2 = \sum_{j=1}^J y_{lj}^2 \quad l \in L \tag{23}$$

$$\sum_{j=1}^J z_{jk} = D_k \quad k \in K \tag{24}$$

$$z_{jk} \leq u_{jk}^2 D_k \quad j \in J, k \in K \tag{25}$$

$$\sum_{i=1}^I y_{ij}^1 + \sum_{l=1}^L y_{lj}^2 \geq \sum_{k=1}^K z_{jk} \quad j \in J \tag{26}$$

$$p_i, r_j, s_l, u_{ij}^1, u_{jk}^2, u_{ij}^3, u_{ki}^4, \theta_{kl}, \beta_{lkm} \in \{0, 1\} \tag{27}$$

$$x_k^1, x_{kl}^2, y_{ij}^1, y_{lj}^2, z_{jk}, v_{kl} \geq 0 \tag{28}$$

- Constraint (2) connects each BDC to an RBC that is if a BDC is opened at point i , p_i will be 1 on the right hand side of the equation, sum of all RBC connection variables is equated to 1.
- Constraint (3) is the link between RBC j and BDC i , if an RBC is opened at point j , r_j will be 1 and the corresponding variable providing the connection between RBC and BDC which is u_{ij}^1 may be 1, otherwise the connection is not provided.
- Constraint (4) connects each demand point to one RBC; the sum of all RBC connections that is connected to the demand point must be 1.
- Constraint (5) is the link between RBC j and k demand point, if an RBC is opened at point j , r_j will be 1 and on the left hand side of the equation the corresponding variable providing the connection between RBC and k demand point may be 1, otherwise the connection is not provided.
- Constraint (6) connects each used MBDV to one RBC, that is if l th MBDV is used, s_l will be 1 and it is assigned to a single RBC as the summation of the assignment variables are equated to 1.
- Constraint (7) is the link between RBC j and the l th MBDV, if an RBC is opened at point j , r_j will be 1 and on the left hand side of the equation, the corresponding variable providing the connection between RBC and l th MBDV may be 1, otherwise the connection is not provided.
- Constraint (8) is the budget constraint. The costs of total opening and operating RBCs, BDCs and the MBDVs cannot exceed the total budget allocated by the Turkish Red Crescent.
- Constraint (9) checks whether l th MBDV has visited point k or not.
- Constraints (10) and (11) should be examined together. If l th MBDV is assigned to the RBC at point j , then l th MBDV is forced to start its tour from point j and to return to point j by these constraints.
- Constraint (12) prevents movement of l th MBDV if the related variable s_l is 0, and vice versa.
- Constraint (13) ensures that l th MBDV leaves the point that it enters.
- Constraint (14) prevents the formation of sub-tours.
- Constraint (15) guarantees that the total supply collected by the assigned BDC and MBDVs are less than the supply amounts for all points.
- Constraint (16) ensures that the supply transferred to the BDC at point k does not exceed the capacity of the BDC.

- Constraint (17) ensures that the supply transferred to l th MBDV by the supply points does not exceed the capacity.
 - Constraint (18) provides the link between supply point k and l th MBDV. The θ_{kl} variable will be 1 if supply point k is visited by the l th MBDV so this will create a connection between these units.
 - Constraint (19) ensures that the amount coming from the BDCs and MBDVs does not exceed the capacity of the RBC at point j .
 - Constraint (20) provides the connection between the BDC at point i and the RBC at point j , namely the u_{ij}^1 variable will be 1 if there is a connection between the BDC point i and the RBC at point j . Otherwise, there is no connection.
 - Constraint (21) provides the connection between the l th MBDV and the RBC at point j . The u_{ij}^3 variable will be 1 if there is a connection between the l th MBDV and the RBC at point j . Otherwise, there is no connection.
- Constraint (22) ensures that the amount of donations collected by BDC at point k is equal to the amount transferred it to the RBCs.
- Constraint (23) ensures that the amount of donations collected by l th MBDV is equal to the amount transferred from it to the RBCs.
 - Constraint (24) ensures that the RBCs transmit the quantity to the demand points as much as the demands of them.
 - Constraint (25) provides the connection between RBCs and the demand points so that the demand point k can be served from the RBC at point j . The u_{jk}^2 variable will be 1 if there is a connection between the demand point k and the RBC at point j . Otherwise, there is no connection.
 - Constraint (26) ensures that the amount transmitted from the RBC at point j is less than the amount that is collected and transferred to it.
 - Constraint (27) and constraint (28) define the type of decision variables.

4 Re-design of a real blood supply chain

This section is devoted to the application of our model to a real life problem from the Eastern Anatolia region of Turkey. Eastern Anatolia region is located in the eastern part of Turkey. Although it is the largest region occupying 21% of the total area of the country, it is in the last place in terms of population density. Stockbreeding is the major income for the local economy. Agriculture is very limited to wheat, barley, cotton and tobacco. The region has the

highest unemployment rate in Turkey. The lowest investments and elements of the Turkish Red Crescent blood supply chain are located in this region. Therefore, it is more appropriate to compare the current system in this region with the proposed model and to evaluate the new investments to be made by blood supply chain decision makers. In the Eastern Anatolia Region of Turkey, there are 14 cities and a total of 122 settlements. The total population is 6,058,529 as of 2018. 4 RBCs candidate points, 14 BDCs candidate points, 15 MBDVs, 122 supply/demand points are determined in the region. Figure 2 shows the cities in the region. The red dots in the figure indicate RBC candidate points, blue dots indicate BDC candidate points and green dots indicate some of the demand points.

The Red Crescent data of the city centers in the Eastern Anatolia Region are summarized in Table 5. The latest data available in the region to the Turkish Red Crescent belong to 2018. According to Table 5, Red Crescent provides continuous service in 7 cities in the region. Red Crescent does not actively collect blood from other cities and settlements of the region. We will call the cities that Red Crescent actively serves as the active cities and the rest of the cities as the passive cities in the sequel. In addition, due to the lack of data and information, passive cities and settlements have no recorded demand values. The only data available regarding the demand can be deducted from the total amount of products offered by RBCs in the region (Fig. 3).

In order to compare the current situation of the supply chain with the supply chains the model offers for different scenarios, the data for the passive cities and settlements must be generated. Based on the assumption that donors are homogeneously located in the settlements of the region and are directly proportional to the population, we determined these missing demand and supply values. First, we find supply coefficients by dividing the supply amounts in the active cities of the region by the populations of the cities. We apply these supply coefficients for the passive cities and settlements assuming that the passive city and settlements have the same blood donation structure with the closest active city. Thus, the potential total supply in the entire region is calculated. We also determine the demand coefficients by dividing the total population of the cities served by each RBC to the total demand of these cities. We apply these demand coefficients for the passive cities and settlements. Thus, potential total demand values in the region for the passive cities/settlements are also calculated according to the closest active city criteria.

In order to evaluate the current situation and to be able to compare it with the supply chains the model offers, we fix the RBC, BDC location variables (p , r) and MBDV usage variables (s) according to the real data obtained from the region. The routes of MBDVs are not known and they

Fig. 2 Eastern Anatolia Region of Turkey

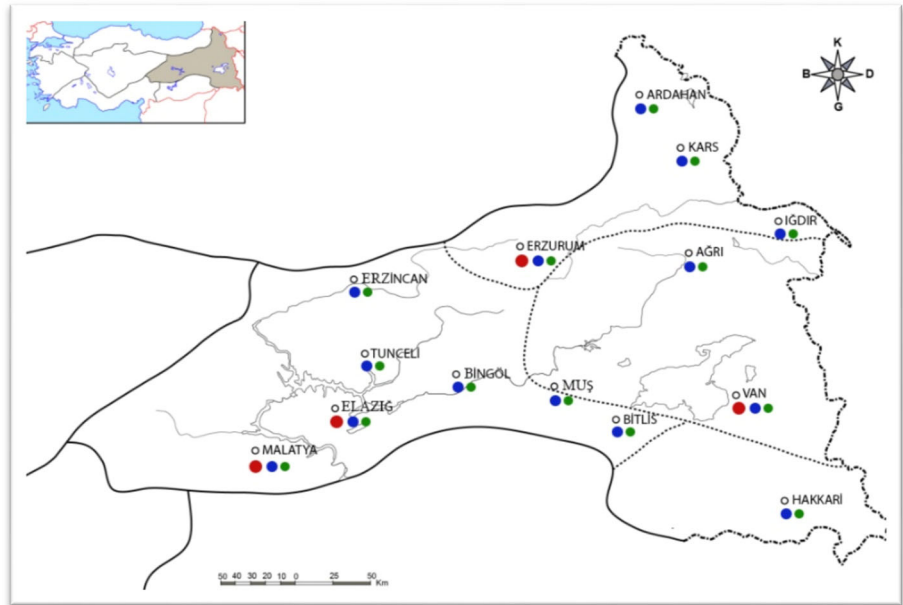


Table 5 Blood Supply Chain Data for Eastern Anatolia Region Cities (2018)

City	Active/Passive	Population	Supply (Units)	Demand (Units)	Number of RBC	Number of BDC	Number of MBDV
Malatya	Active	600,660	32,638	102,210	1	1	3
Van	Active	472,766	30,159	84,300	1	1	2
Erzurum	Active	422,164	38,011	48,813	1	1	4
Elazığ	Active	421,726	20,018	–	0	1	2
Muş	Active	193,394	8786	–	0	1	0
Bingöl	Passive	160,165	–	–	0	0	0
Erzincan	Active	157,452	14,524	–	0	1	2
Ağrı	Passive	149,188	–	–	0	0	0
Iğdır	Passive	137,613	–	–	0	0	0
Kars	Active	115,891	10,017	–	0	1	2
Hakkari	Passive	81,424	–	–	0	0	0
Bitlis	Passive	71,501	–	–	0	0	0
Ardahan	Passive	42,226	–	–	0	0	0
Tunceli	Passive	38,504	–	–	0	0	0
Total		3 064 674	154,123	235,323	3	7	15

are taken as decision variables in the model, while the other relevant decision variables are fixed according to the real data. For instance, as there is an RBC at Malatya the relevant r_j variable related to Malatya is fixed as 1 and as there is no RBC located at Erzincan, the relevant r_j variable related to Erzincan is fixed to 0. Similarly, all the p , r and s variables and the assignment variables between these units are fixed. Only binary variables that are unknown are related to the routes of the mobile units and this is why they are taken as free decision variables in the model. The values of the current situation are summarized in Table 6.

The current supply chain objective function value is about 25% higher than the objective function value obtained by the proposed model in scenario 1. In addition, the blood supply chain in scenario 1 serves with fewer units. Besides, while the solutions for scenarios are obtained in 3 h by the commercial solver Gurobi, it runs for 6 h to obtain the current situation solution. The effectiveness of the proposed model can be proved when the objective function values obtained in other scenarios are examined. Scenario 1 is our basic scenario where we determine the expected supply and demand amount

Fig. 3 Flow chart of the proposed supply chain design

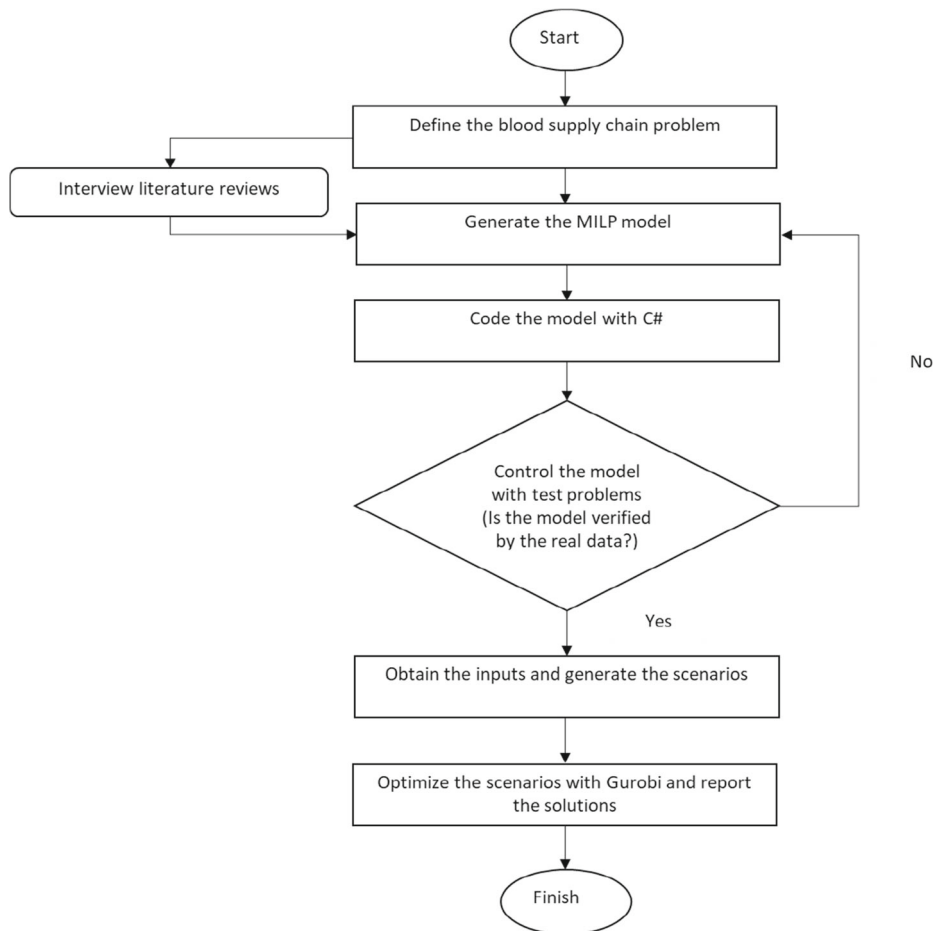


Table 6 The structure of the current supply chain

Objective function value (1)	13,507,016			
Total supply (2)	390,778			
Total demand (3)	336,560			
RBCs and their locations (4)	3	Malatya	Van	Erzurum
BDCs and their locations (5)	7	Malatya, Elazığ	Van, Kars, Mus	Erzurum, Erzincan
MBDVs shares (6)	15	5 MBDV	4 MBDV	6 MBDV

(detailed above) as if Red Crescent actively serves the entire region. Scenario 1 is actually the same with the current situation except that the values of the decision variables are not fixed according to real data. The supply and demand values are changed and different scenarios are created as shown in Table 7. Thus, supply and demand, which are the most important uncertainty sources in the model, are tried to be eliminated with the scenarios created. Scenario 2, 3, 4, 5 and 6 examine the results of the model in case the supply and demand values increase by 20%, 40%, 60%, 80% and 100% with respect to Scenario 1, respectively. Supply and demand values can increase together in

disasters such as earthquakes and floods where social sensitivity is at a high level, and in extraordinary situations such as war. Scenarios 7, 8 and 9 examine the results of the model when supply and demand values are reduced by 20%, 40% and 60%, respectively. Supply and demand may decrease together, where there is no social sensitivity and interest, pandemics (i.e., COVID-19) and where the region emigrates. In scenario 10, while supply increased by 20% compared to scenario 1, demand values decreased at the same rate.

In the scenarios, we use the parameters of the distance between settlements from Turkey Highways government

agencies. According to data obtained from Turkish Red Crescent, all RBCs have the same capacity. Similarly, all BDCs capacities and MBDVs capacities are alike. However, the total investment and operating costs of an RBC, a BDC and an MBDV in the region are calculated and the total allocated budget by the Turkish Red Crescent is determined by considering all the supply chain units in the region. The budget parameter F is determined in this way.

In order to obtain the results of the model according to the scenarios, the model algorithm has been coded in C # programming language in Microsoft Visual Studio 2017 environment and it has been solved on the desktop computer with Intel (R) Core (TM) i7-4770 CPU 3.40 GHz processor with the help of Gurobi81.NET solver (Gurobi Optimization (2019)). In general, all the commercial MILP solvers employ Mathematical Programming and Operations Research tools such as branch and bound, generate valid inequalities to add them to branch and bound tree in order to convert it into a branch and cut scheme, etc. However, the exact structure of the branch and cut schemes they use, the valid inequalities they generate are kept hidden due to the commercial concerns. Nonetheless, we still add a flow chart that summarizes our solution approach in a step by step manner below.

The results for the scenarios are summarized in Tables 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 given below.

As the scenarios are examined, and the following results will be clearly seen. The objective function values are given in (1). Total supply (2) and total demand (3) amounts are the values obtained from the scenarios created. RBCs and their locations (4) show at which of the candidate points the model open or does not open RBCs. In all scenarios, RBCs are located in Malatya, Van, Erzurum and Elazığ cities. Consequently, RBC should be opened to Elazığ city in addition to the Malatya, Van and Erzurum which are real RBC places. BDCs and their locations are shown by (5). According to the results, cities with RBC should also have a BDC. These BDCs serve depending on RBCs in their cities. MBDVs and their locations (6) show which of the total mobile units determined will serve on which RBCs. MBDVs are positioned with different shares

according to the scenarios. As an example, 4 mobile units are assigned to RBC in Erzurum in scenario 1, while 3 mobile units are assigned to Erzurum in scenario 3. This situation also results in the differentiation of routes to be, followed by MBDVs according to the changing supply/demand structure. According to the scenarios, the route that each MBDV will follow is not given here and can be extracted from the detailed examination of the scenario results. For example, in scenario 1, mobile units visit 117 settlements, while in scenario 2, 111 settlements are visited. The model also reveals in which position each mobile unit should be located. However, the summary results do not include routes.

In Fig. 4, the objective function values of the scenarios are shown against the total units used in the supply chains. It can be seen that the more supply and demand in the system, the more mobile units need to travel or new BDCs need to be opened (i.e., scenario 4 and 6), and these affect the objective function. When we move from scenario 1 to scenario 2, total supply and demand increases by 20%. Although more MBDV units are used in Scenario 2, the objective function value decreases slightly due to the settlements with a higher supply of closer locations. Similarly, when we move from scenario 3 to scenario 4, we see that the objective function value decreases. This may be because of the new opened BDC in the system. We observe a similar situation when we move from scenario 5 to scenario 6 as well. In scenarios where there is a decrease in total supply and demand in the system (scenario 7, scenario 8 and scenario 9), the number of used MBDV units also decrease. Meanwhile, in all scenario results, it is seen that RBCs are opened in the same cities. The results possess a robust structure in this regard. Therefore, it may be suggested to Turkish Red Crescent to open RBC to Elazığ city. When BDC locations are examined, it is also mostly seen that they are opened in the same cities. Hence, the results are robust with respect to RBC opening decisions as well. However, in only one scenario, which is scenario 6, BDC distribution turns out to be different probably because of very high supply/demand values as we double them in that scenario. MBDVs are assigned with different combinations

Table 7 Scenarios

Scenarios	Total Supply (Units)	Total Demand (Units)	Scenarios	Total Supply (Units)	Total Demand (Units)
Scenario 1	390,778	336,560	Scenario 6	781,556	673,121
Scenario 2	468,993	403,872	Scenario 7	312,622	269,248
Scenario 3	547,089	471,184	Scenario 8	234,467	201,936
Scenario 4	625,245	538,497	Scenario 9	156,311	134,624
Scenario 5	703,400	605,809	Scenario 10	468,933	269,248

Table 8 Scenario 1 results

Objective function value (1)	10,791,432				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	9	1 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 9 Scenario 2 results

Objective function value (1)	10,288,368				
Total supply (2)	468,933				
Total demand (3)	403,872				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	12	2 MBDV	5 MBDV	3 MBDV	2 MBDV

Table 10 Scenario 3 results

Objective function value (1)	11,388,948				
Total supply (2)	547,089				
Total demand (3)	471,184				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	13	2 MBDV	5 MBDV	3 MBDV	3 MBDV

Table 11 Scenario 4 results

Objective function value (1)	10,921,775				
Total supply (2)	625,245				
Total demand (3)	538,497				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	5	Malatya	Van	Erzurum, Erzincan	Elazığ
MBDVs shares (6)	13	2 MBDV	6 MBDV	2 MBDV	3 MBDV

Table 12 Scenario 5 results

Objective function value (1)	12,212,402				
Total supply (2)	703,400				
Total demand (3)	605,809				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	14	2 MBDV	6 MBDV	3 MBDV	3 MBDV

according to the scenarios. Each different assignment combination brings with it different sub-scheduling problems.

4.1 Sensitivity analysis

In order to verify the robustness of the solutions provided by the proposed model, we perform a sensitivity analysis

Table 13 Scenario 6 results

Objective function value (1)	10,408,228				
Total supply (2)	781,556				
Total demand (3)	673,121				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	7	Malatya	Van, Erciş, Edremit	Erzurum, Erzincan	Elazığ
MBDVs shares (6)	14	2 MBDV	5 MBDV	4 MBDV	3 MBDV

Table 14 Scenario 7 results

Objective function value (1)	10,287,552				
Total supply (2)	312,622				
Total demand (3)	269,248				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	9	1 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 15 Scenario 8 results

Objective function value (1)	11,558,268				
Total supply (2)	234,467				
Total demand (3)	201,936				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	7	2 MBDV	3 MBDV	1 MBDV	1 MBDV

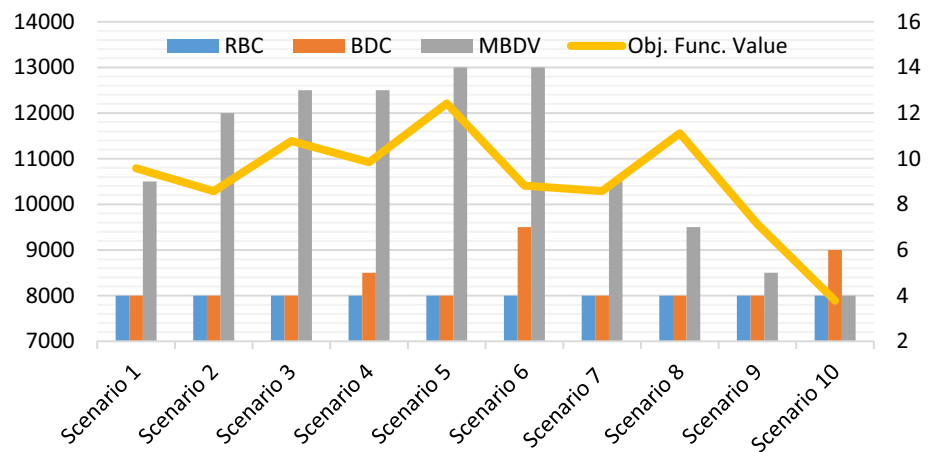
Table 16 Scenario 9 results

Objective function value (1)	9570,084				
Total supply (2)	156,311				
Total demand (3)	134,624				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	5	1 MBDV	2 MBDV	1 MBDV	1 MBDV

Table 17 Scenario 10 results

Objective function value (1)	7889,564				
Total supply (2)	468,933				
Total demand (3)	269,248				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	6	Malatya, Kars	Van, Ağrı	Erzurum	Elazığ
MBDVs shares (6)	4	–	2 MBDV	1 MBDV	1 MBDV

Fig. 4 Obj. function value according to scenarios



on the basic scenario (scenario 1). For this purpose, the budget constraint (9) of the model is examined. The budget constraint ensures that the annual total operating costs of the facilities opened do not exceed the budget allocated by the Turkish Red Crescent for this region. In our study, the total operating costs (f) that we consider according to each facility include installation costs, operating costs and all related costs associated with the facility. The total allocated budget by the Turkish Red Crescent is determined by considering all investment and operation costs of RBCs, BDCs and MBDVs in the region. This budget value is naturally an estimate and its real value may be slightly different.

If the Turkish Red Crescent's budget (F) that we consider in our main scenario decreases or increases, we would like to analyse the changes in the results. To this end, the total budget has been reduced by 10%, 20%, 30% and increased by 10%, 20%, 30%, and the results are reported below. (Tables 18, 19, 20, 21, 22 and 23).

When the results obtained in the above tables and scenario 1 results are compared, it is seen that increasing the total budget does not cause any significant changes in the supply chain management system. Unlike the scenario 1 results, only one more MBDV unit is used. Responsiveness of the objective function to the budget decrease may also be attributed to the solver's performance in the limited computation time. Table 22 also indicates a slight increase in the objective function as a result of an increase in the budget level which is a contradiction and can only be attributed to the solver's performance. Therefore, an %100 accurate and more detailed sensitivity analysis is not possible as the performance of the solver is limited. At this point, alternatives obtained and reported in Tables 18, 19, 20, 21, 22 and 23 can be offered to the Red Crescent and the managers who is in charge may use them for comparison purposes, while deciding the investments. In addition, with the savings to be obtained from the current budget, more and different investment proposals can be made. We

also observe from tables that decreasing the budget gradually forces the supply chain to reach and serve more cities and settlements using MBDVs. This is because MBDVs are shared between RBCs in a different combination and they travel more for blood donations while the positions of RBCs and BDCs remain the same. This implies that while the affordability of demand is 100%, a more effective structure emerges. It should not be forgotten that all these variations may vary according to the estimated supply and demand amount. For example, COVID-19 pandemic has caused 30% reduction in blood donation in 2020. Therefore, the Red Crescent's supply chain management should have an agile and harmonious structure in order to response possible rapid changes in supply and demand values. Our sensitivity analysis indicates that the model offered in this study may help Red Crescent to construct a more robust blood supply chain that is capable of adapting changes in design parameters.

5 Conclusions

The collection, processing and distribution of blood and/or blood products effectively and efficiently are very important functions performed by the blood supply chains in the health system. In this study, a mathematical model is proposed to provide optimal network design and planning of the blood supply chain. As in many similar studies in the literature, the blood supply chain examined does not consist solely of blood banks and transfusion centers (hospitals, health institutions, etc.). The supply chain we examine belongs to the Turkish Red Crescent, and it has four echelons; RBCs, BDCs, MBDVs and supply/demand points. In this complex structure, important decisions such as determining the location of the facilities, determining the route that mobile units should follow are to be made.

In the proposed model, the objective function is designed to minimize the lengths between the units that

Table 18 Results of the total budget was reduced by %10

Objective function value (1)	10,118,844				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	10	2 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 19 Results of the total budget was reduced by %20

Objective function value (1)	10,118,844				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	10	2 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 20 Results of the total budget was reduced by %30

Objective function value (1)	10,118,844				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	10	2 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 21 Results of the total budget was increased by %10

Objective function value (1)	9784,08				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	10	2 MBDV	4 MBDV	2 MBDV	2 MBDV

Table 22 Results of the total budget was increased by %20

Objective function value (1)	11,104,164				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	10	1 MBDV	4 MBDV	3 MBDV	2 MBDV

make up the blood supply chain and the length of the mobile unit routes. The objective function indirectly minimizes the transport time and cost, and indirectly improves the blood products' shelf lives. These goals are combined

in an objective function by multiplying different priority coefficients found by the help of analytical hierarchy process.

Table 23 Results of the total budget was increased by %30

Objective function value (1)	9251,232				
Total supply (2)	390,778				
Total demand (3)	336,560				
RBCs and their locations (4)	4	Malatya	Van	Erzurum	Elazığ
BDCs and their locations (5)	4	Malatya	Van	Erzurum	Elazığ
MBDVs shares (6)	9	1 MBDV	4 MBDV	2 MBDV	2 MBDV

The Turkish Red Crescent blood supply chain in the Eastern region of Turkey is discussed. For this purpose, in order to measure the effectiveness of the current system, the relevant variables in the proposed model are fixed by the ones from the existing scenario. One may observe that the offered model produces more effective supply chains than the existing ones.

In future studies, we will examine the situation of blood supply chain for Turkey as a whole. Thus, the size of the problem will increase. It will probably consume an excessive amount of the time and a meta-heuristic algorithm will probably be required for its solution. Hence a more efficient blood supply chain design will be targeted for the whole country. Another future research direction is to extend the model to take varying shelf lives of the blood products and inventory decisions of the blood products into account.

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Compliance with ethical standards

Conflict of interest Authors İlker Karadağ, M. Emre Keskin and Vecihi Yiğit declare that they have no conflict of interest.

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