Location and Multi-Compartment Capacitated Vehicle Routing Problem for Blood Banking System

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Abstract- Blood banking is important for the healthcare system and blood products are vital needed for medical treatment, surgeries, and organ transplants. Delivery time becomes vital when a hospital needs a blood product emergently. Therefore, delivering blood products in the safest and fastest way is the main responsibility of blood banks. In this study, we aim to minimize total delivery times between depots and demand points over a time period. We propose a two-stage mathematical model to determine both location and vehicle delivery routes. This problem is defined as Location and Routing problem for blood bank operations. This study also investigates the effect of distributing blood products among multi-compartment along with routing decisions. The proposed models are tested on a real-world case data in order to demonstrate their effectiveness in producing optimal solutions. By the results the approach can minimize both delivery time and total cost. Furthermore, a computer program with a graphical user interface is developed to implement the proposed approach for different data sets.

Keywords Blood banks, location-routing problems, mathematical model.

1. Introduction

Public and private sector organizations face a continual increase in logistics costs and therefore, then need to improve the efficiency of logistics operations. The performance of these organizations depends on the location and distribution decisions based on their logistic network [4]. The location-routing problems have been critical for logistics experts [9]. These problems include both location and routing decisions.

People can die by inadequate blood needs nowadays [27]. Turkey's blood needs are provided by the Turkish Red Crescent. In 2008, Ministry of Health designated the Turkish Red Crescent Society as an only organization to collect and distribute blood and blood products.

In Turkey, the blood banking logistics system consists of three types of centers: blood donation centers, regional blood centers and transfusion centers. The blood is collected in blood donation centers, regional blood center tests the blood, and blood transfusion centers are distributed. Blood donation centers use fixed and mobile blood donation centers. The blood is brought to blood centers; the whole blood is separated into three products: erythrocytes, platelets and plasma. The requested products are transported to hospitals with vehicles.

In the literature, location routing problems are mostly solved together. However, in this study, the problem is divided into two stages. The reasons for this are as follows:

- Modeling of location routing problem is complex and requires expertise. The type and size of the problem can receive too much computer time.
- Location is strategic decision, routing is an operational decision, so these two decisions are difficult to think together.

Although this approach minimizes the total cost of the problems, in some cases, especially at health sector, cost minimization would not be the primary aim of the problem. Therefore, we propose a two stage approach to overcome the limitations. Locations of depots are selected according to minimizing direct service time of depots to each costumer. Number and location of the depots are decided with regard to keep installation and general expenses cost relatively low. In the second model routing cost which is not the primary aim of the problem is minimized according to located depots.

The main contributions of this study are two-folds: (i) proposed two-stage mathematical programming model considers distributing blood products to multi-compartments along with location of distribution centers and delivery routing, (ii) this study provides the proposed model is applied for a regional blood banking using a computer program.

We give literature work in Section 2. We present the problem description in Section 3. We provide the mathematical formulations in Section 4. In Section 5, an interface is proposed. We give a case study to illustrate the benefit of the models in Section 6. Discussion is presented in Section 7. A summary of the study and future directions are provided in Section 8.

2. Literature Review

2.1. Literature Review on Location and Routing Problem (LRP)

Many studies about location routing problem are conducted by many researchers. They use exact formulations or/and heuristic algorithms.

Some papers propose exact solutions for the problem. The problem is considered with capacity constraints, solved this problem with a branch and price algorithm [2]. A model for locating and routing dangerous waste with two objectives is presented. They present a mixed integer approach and apply this model with 92 nodes [3]. A branch-and-cut algorithm for at most 50 customers is developed [5]. A location routing industrial hazardous waste with two objectives including total cost minimization and transportation risk minimization is developed. In the study, a mathematical model is developed and application is tested in Markazi province in Iran [6].

A mathematical model for designing an internet access is proposed [15]. A branch-and-price-and-cut algorithm including prices, strengthening cuts, a heuristic for a generalized location and distribution problem is presented [7]. A locating routing problem with risks is considered. A mixed-integer programming formulation is formulated and a three-phase heuristic is designed to solve the problem [1]. Branch and cut algorithms are used to solve the problem [8].

A comprehensive framework for the LRP is proposed. Exact algorithms are intended to solve medium-scale instances. Therefore, some of the studies are focused on heuristic approaches [17]. A two-phase Tabu search for the LRP with capacitated routes and incapacitated depots for up to 200 customers is proposed [25]. Multi depot location routing problem with a clustering based heuristic is dealt [14]. A hybrid metaheuristic algorithm including Tabu search and neighborhood search heuristics for LRP is studied [16]. A two phase heuristic based on a Tabu search and ant colony algorithm for the location routing problem is developed [26]. Aa framework for depot location, fleet assignment and routing decisions using a Greedy Randomized Adaptive Search Procedure combined with an Evolutionary Local Search is proposed [11]. A mixed integer programming formulation for a multi depot location problem and also proposed a new algorithm and a heuristic within a simulated annealing method is developed [10]. A metaheuristic algorithm for location and routing is developed [24]. A heuristic for a combined maximal covering location problem is formulated [20]. The problem of locating and routing of unmanned aerial vehicles to maximize of the total score collected at points by flight routes of those vehicles is addressed. He formulates this problem as an integer linear program and develops a metaheuristic [28]. A metaheuristic approach for location and routing for the cross docks is provided [12].

2.2. Literature Review on LRP for the Blood Banking System

Location - routing on blood centers have been interested by some of the authors. The optimal number and locations of blood centers in Chicago is studied and thus system is intended to ensure adequacy to meet hospital demand Due to general structure of the problem is a complex, the problem is required to divide into two sub-problems [18]. Blood banking to minimize the biggest blood problems is studied. A linear programming model is developed about transfusion of blood units from the center to hospitals taking into account the characteristics of hospitals in order to ensure delivery [22]. Blood donation location problems in Quebec are examined [19]. Virginia blood products' collection, testing and distribution system is studied and established two models in order to improve. In the first model, the distance between collecting place of blood products and blood bank is tried to minimize. In the second model, the distance between hospital and the blood bank was tried to minimize. A p-median model is used to find a solution to the problem [13]. A blood bank system is introduced. They approach the problem in three stages. A median problem, set covering models are given in the problems [23]. Central Anatolia Region's problems by establishing distribution centers at various points are solved. In this system distribution centers are closer to the hospital, the time to reach the demand and the rate of elimination reduces. Hospitals that are assigned to distribution centers receive blood products once every day with their own vehicles in an emergency case to meet the needs [21]. Blood supply chain is designed for a disaster relief. The model is formulated by a fuzzy-stochastic mixed integer programming model. Total costs are tried to minimize for a real case [29]. A solution is proposed for a robust and flexible approach for red blood cells to prevent the shortage. Supply and demand of blood are considered as uncertain. Sensitivity analysis is conducted on four scenarios [30]. An other recent study is about fresh food location routing problem. The study considers environmental conditions such as carbon emissions. A heuristic algorithm is developed for this model. Carbon tax conditions are added to this model and this situation could reduce the carbon emissions for a clean environment [31]. A blood supply chain is investigated based on location, inventory, routing problems and uncertain data is considered. A meta-heuristic algorithm called Simulated Annealing and Harmony is proposed for larger cases [32].

The recent blood chain works generally uses metaheuristic approaches for larger problems and consider uncertain conditions, environmental policies.

3. Problem Definition

In this study, a new system is proposed to solve problems caused by the central structure. Some hospitals in the region are assigned as Distribution Center (DC) as an additional layer between Regional Blood Center (RBC) and hospitals to distribute blood products. The proposed model solves the optimum number and location of distribution centers, and routes from RBC to DC and from DC to hospitals. Delivery time of blood products at emergency cases is markedly decreased by new DCs. The system is shown on Figure 1.

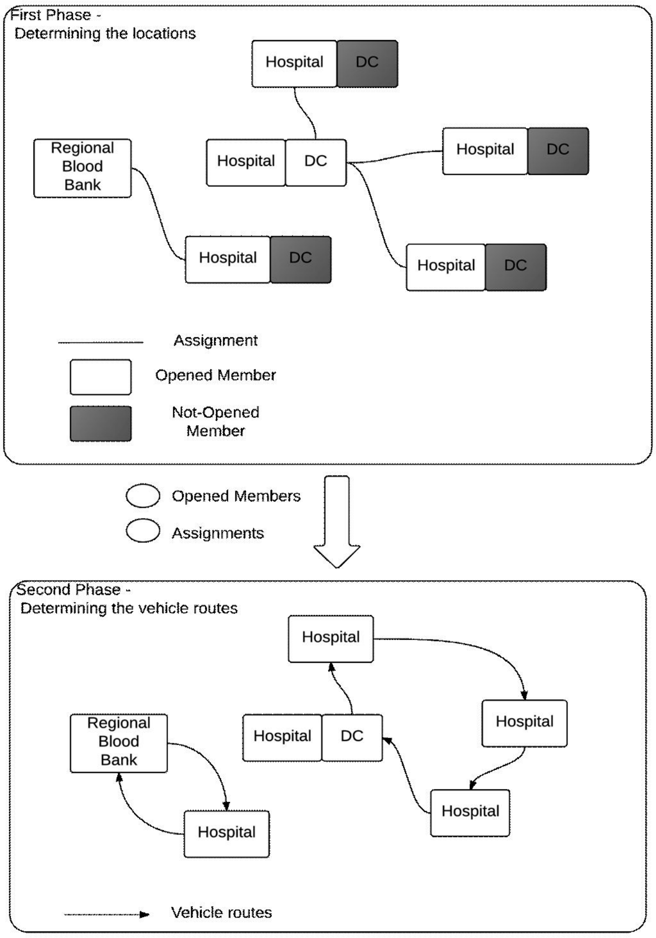


Fig. 1. Framework of the proposed system

In the problem, we have only one RCB which has no opening cost since the center is already available in the current system. All hospitals and the RBC can be authorized as DC. We assume that the system's costs are assumed for 10 years and net present value of the costs is found. The system is assumed to be installed at the start of the year. In the first model, the problem is considered as a two level problem: RBC to DC and DC to hospitals. The second model is considered as one level problem: DC to the hospitals. Blood demands of the hospitals are deterministic. Furthermore, we assume that there is no restriction on the number of DCs to be installed. The distribution vehicles have limited compartment capacities for each type of blood product, which are 180 unit products for erythrocytes, 30 unit products for platelets and 90 unit products for plasma. The total demand for each blood product type is partitioned between hospitals according to their patient capacities. Each DC is served one time in a week from RBC. Each hospital is served three times in a week from DC.

4. Mathematical Models

The model is a complex structure, thus problem is converted into two problems. The first problem is minimization of average distances between the regional blood bank - the distribution centers, the distribution centers - the hospitals, distribution center setup and general expenses. The second sub-problem aims to minimize periodic transportation costs between hospitals and distribution centers.

The notation used for mathematical modeling of the problem is as follows;

I,J,T represent the set of hospitals, candidate distribution centers and the time periods, respectively. d_{ij} is the distance between the distribution centers and the hospitals. ∂ is the percentage of emergency cases required by the hospitals. M is the maximum travelled distance of the vehicles. C is the transportation cost per km. B is the maximum budget to open distribution center. k is the interest rate. K_j is the setup cost at distribution center j and f is the yearly general expenses of the distribution centers. The decision variable is y_j 1 if a distribution center is at point j, 0 otherwise. The decision variable x_{ij} will be 1 if the i. hospital at is assigned to the distribution center at point j.

The objective function (1) minimizes the total costs including the initial investment cost of building a distribution center, annual operating costs for ten years and the delivery cost based on demand-weighted distances between the regional blood bank- the distribution centers and the distribution centers-the hospitals. The constraint (2) ensures that each hospital is assigned to only one distribution center.

Minimize:

$$\sum_{j=1}^{J} y_j K_j + \sum_{j=1}^{J}\sum_{t=1}^{T} f y_j \left(1+k\right)^{-t} + \sum_{j=1}^{J} C d_{0j} y_j + \sum_{i=1}^{I}\sum_{j=1}^{J} \partial C d_{ij} x_{ij} \quad (1)$$

$$\sum_{j\epsilon J} x_{ij} = 1 \qquad i\in I \qquad (2)$$

$$x_{ij} \leq y_j \qquad i\in I, j\in J \qquad (3)$$

$$\sum_{i} x_{ii} * f \leq B \qquad (4)$$

$$x_{ij} * d_{ij} \leq M \qquad i\in I, j\in J \qquad (5)$$

$$y_j = (0,1) \qquad j\in J \qquad (6)$$

$$x_{ij}=(0,1) \qquad i\in I, j\in J \qquad (7)$$

The constraint (3) ensures that each hospital is assigned to itself if the hospital is opened as a distribution center. The constraint (4) allows to open the distribution center within the scope of a given budget criteria. The constraint (5) ensures the distance between distribution centers and hospitals, should be within the scope of a given maximum distance constraints. Constraints (6) and (7) are binary. (D_{0j}) is taken as the distances between the regional blood center and the distribution centers, (D_{ij}) is taken as the distances between the distribution centers and hospitals, and (M) is taken as the maximum distance that limits the distance between opened distribution center and hospital. The second sub-problem is formulated as a classical vehicle routing problem. I, J, K, P represent the set of hospitals, distribution centers, vehicles and blood products, respectively. d_{ij} is the distance between the distribution centers and the hospitals. ∂ is the number of weekly referrals. Q_{pk} is compartment capacity of blood product p by vehicle k. C is the transportation cost per km. D_{ip} is the demand of the blood product p by hospital i. F is the annual operating cost of the vehicles. H is the number of hospitals. The decision variable Z_{ijk} will be 1 if the vehicle k travels from point i to point j directly, 0 otherwise. The decision variable v_k will be 1 if the vehicle k is used. The decision variable T_{ipk} will be 1 if the hospital at point i is distributed the blood product p by the vehicle k, 0 otherwise. W_{mk} is the auxiliary variable for the sub-tour elimination constraint. Min:

$$\sum_{k\epsilon K} F * v(k) + \sum_{i\epsilon U}\sum_{j\epsilon U}\sum_{k\epsilon K}(C * d_{ij} * Z_{ijk} * \alpha) \qquad (8)$$

Constraints:

$$\sum_{i\epsilon I} D_{ip} * T_{ipk} \leq Q_{pk} * \imath \qquad \forall k\in K\ \forall p\in P \qquad (9)$$

$$\sum_{i\epsilon U} Z_{ijk} - \sum_{i\epsilon U} Z_{jik} = 0 \qquad \forall j\in U\ \forall k\in K \qquad (10)$$

$$\sum_{i\epsilon U} Z_{i0k} \leq v_k \qquad \forall j\in U\ \forall k\in K \qquad (11)$$

$$\sum_{i\epsilon U} Z_{0ik} \leq v_k \qquad \forall j\in U\ \forall k\in K \qquad (12)$$

$$T_{ipk} \leq \sum_{i\epsilon U} Z_{ijk} \qquad \forall p\in P\ \forall i\in I\ \forall k\in K \qquad (13)$$

$$\sum_{k\epsilon K} T_{ipk} = 1 \qquad \forall i\in I\ \forall p\in P \qquad (14)$$

$$\sum_{i\epsilon U}\sum_{k\in K} Z_{ijk} = 1 \qquad \forall j\in U, \qquad (15)$$

$$W_{mk} - W_{ik} + H * Z_{jik} \leq H - 1 \qquad \forall c,i\in I, \forall k\in K \qquad (16)$$

$$T_{ipk} = (0,1) \qquad \forall p\in P\ \forall k\in K\ \forall i,j\in U \qquad (17)$$

$$Z_{ijk} = (0,1),$$

$$v_k = (0,1)$$

$$W_{ik} \geq 0$$

The objective function (8) minimizes the annual operating cost of the vehicle and the cost of demand-weighted distances between the distribution centers and the hospitals. The constraint (9) ensures total product demand of hospitals in the route of the vehicle, must not be more than the capacity of the vehicle compartment. The constraint (10) ensures that the vehicle returns to start point. The constraints (11) and (12) show the start and end of the route. The constraint (13) ensures p product is delivered to the hospital by the vehicle if the hospital is on the route from the distribution center to the hospital. The constraint (14) allows that a product is carried by only one vehicle and to only one hospital. The constraint (15) shows that each blood product ordered by a hospital is delivered by one vehicle. The constraint (16) is sub tour elimination constraint. The last constraint (17) is binary constraint.

5. Blood Location Allocation and Routing Planner GUI

The location routing problem discussed as a two stage should be solved again according to the problem structure. This structure should be able to run again for the next planning period by the end of the planning period. In order to respond quickly to the end user and ensure the ease of provision in practice, an interface called Blood Location Allocation and Routing has been proposed.

In Figure 2, a login screen of Blood Location and Routing planner is shown. In this screen, the number of blood centers, the number of distribution centers and hospitals and periods are determined and receiving the data from the Excel file is available.

In Figure 3, location assignment model which is the first stage of the location routing problem is solved. By the output of this model, hospitals (red circle) are assigned to the blood centers (black square) and the distribution centers (red square). According to the distribution center data obtained, the routing problem is solved.

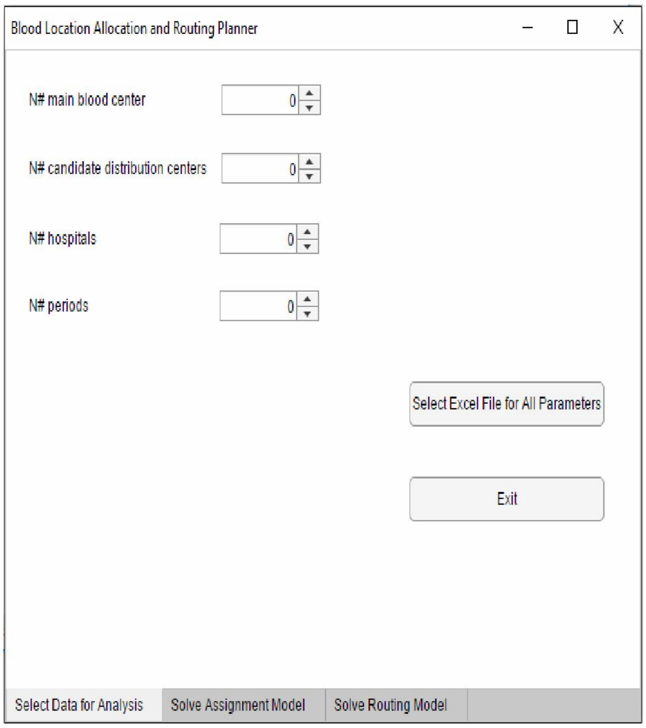


Fig. 2. Login screen of Blood Location and Routing planner

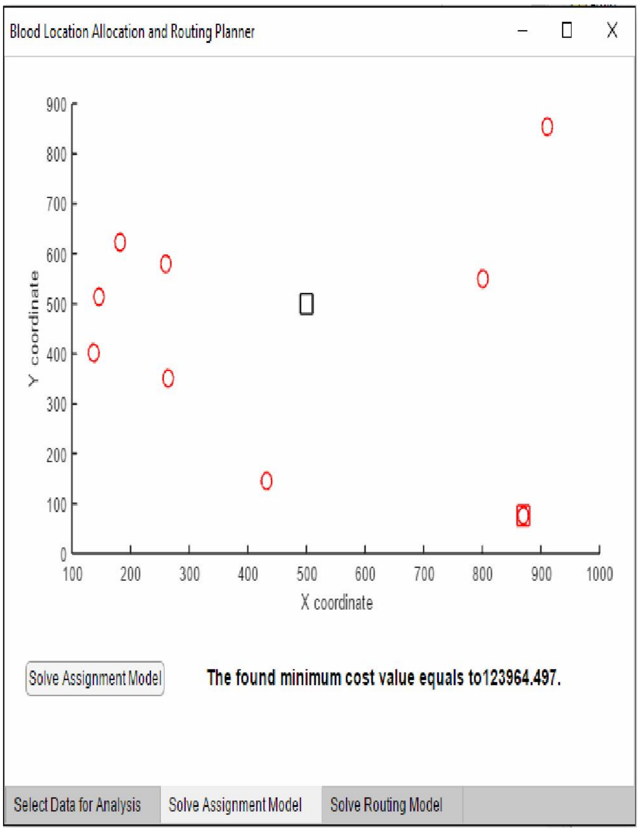


Fig. 3. Location assignment model

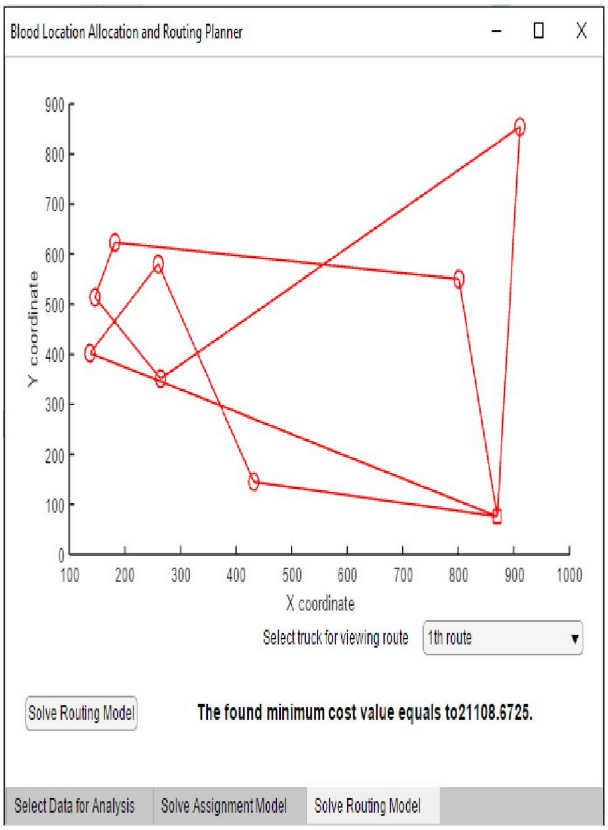


Fig. 4. Routing model

In Figure 4, routing model which is the second stage of the location routing problem is solved. By this model, the routes for carrying the products from the distribution centers to the demand points (hospitals) are determined. Each route is showed graphically.

6. Case study and numerical analysis

In this part the results for the models are revealed. Central Mediterranean Regional Blood Center (CMRBC) established in Adana in 2010 has fed the hospitals from a single center. Hospitals which are located in Adana, Mersin, Hatay and Osmaniye cities (Figure 5) demand blood products (erythrocytes, platelets and plasma) from this center. There are 77 hospitals and 8 vehicles in the system.

6.1. Output of the first model

As a result of the first model, distance constraint shows that at 25- 50- 75 km restrictions, total cost are significantly increased due to the initial investment of DCs. At 100- 125- 150 km restrictions, the total cost shows little differences, the results are presented in table 1.

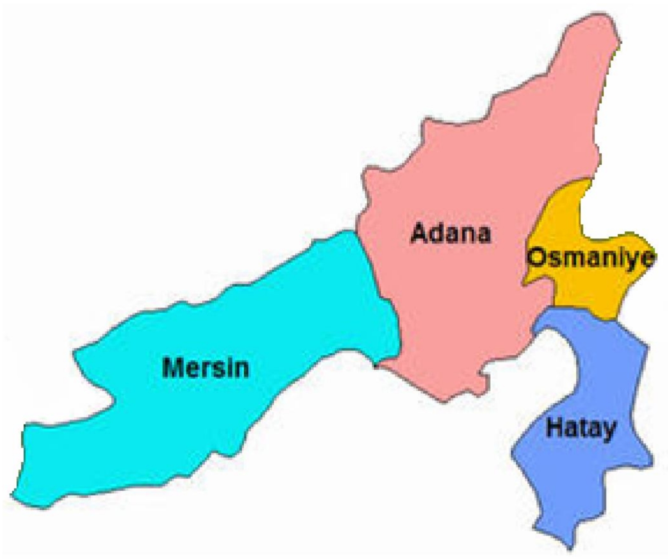


Fig. 5. Locations of Adana, Mersin, Hatay and Osmaniye

In Osmaniye and Hatay, only one DC is enough to cover all hospitals within 100 km since the area is not large and opening the second DC is costly. As Mersin has large area, two hospitals are assigned as DC. Adana has a different situation than other ones. The reason of that is, CMRBC already exists within the city, so it needs any installation cost. This causes the CMRBC is selected as one of the DCs in Adana. A hospital, which is too far from all other hospitals, is also opened as a DC and assigned only to itself.

6.2. Output of the second model

Second model answers the vehicle routes and vehicle numbers by the outputs of the first model.

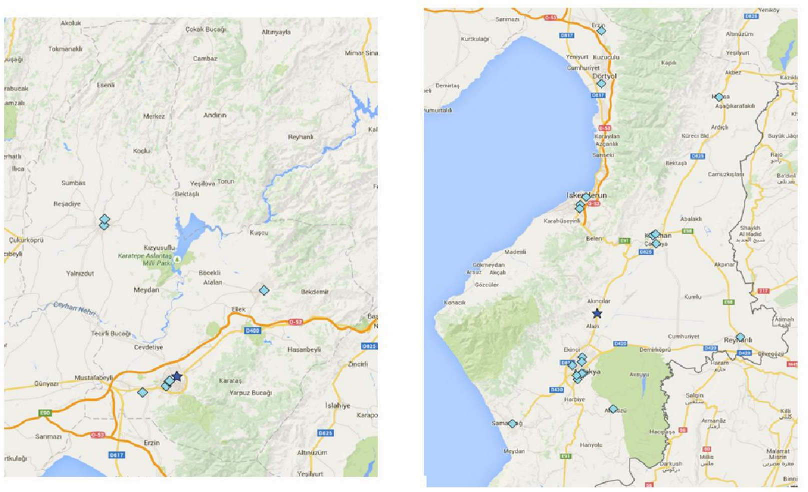
Osmaniye and Hatay have small geographic areas, thus, only one route is able to give optimum results (Figure 6). In Mersin, there are two routes starts from each DC (Figure 7(a)). As it can be seen in Figure 7(a), two vehicles should be used for meeting the total blood products, which are demanded from CMRBC. On the other hand, other DC in Adana (Figure 7(b)) is not assigned to any hospital, thus there is no route starting from the hospital. But a vehicle is assigned to the DC in case of emergent blood product demand.

Furthermore, in the proposed model, 7 vehicles are enough for delivery of blood products, whereas the number is 8 in the current system. Except CMRBC, only one vehicle is assigned to each DC. Total demands of hospitals that are assigned to CMRBC are more than the capacity of a distribution vehicle so; two vehicles have to be assigned to the center.

7. Discussion

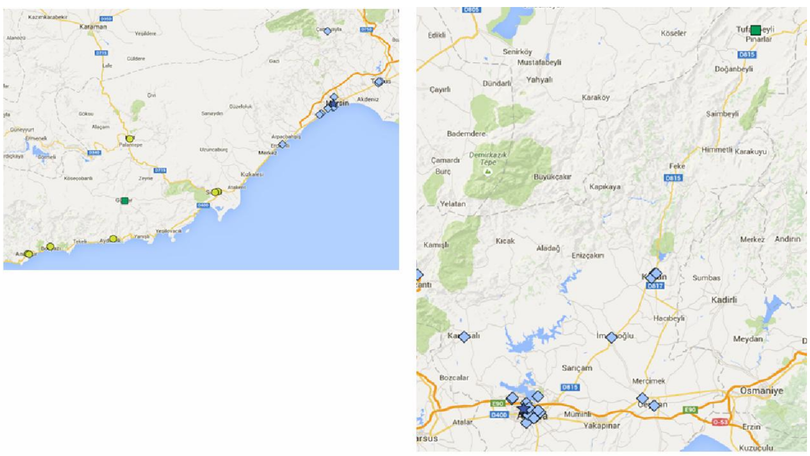
A comparison of the current system and the proposed system may be summarized as follows.

With newly opened DCs, the service time is significantly decreased for periodic distribution and emergent blood products demand. The results show that the proposed model compensates the initial investment in 10 years. The routing and emergency service times of current and propose models' results are shown in Table 2. And cost comparison of the current and proposed systems for 10 years are presented in Table 3.



[α] "★" indicates the location of DC, "◆" indicates the location of hospitals

Fig. 6. The result of the routing (a) for Osmaniye (b) for Hatay [α]



[α] "★" indicates the location of DC at first route , "◆" indicates the location of hospitals at first route

[β] "■" indicates the location of DC at second route , "●" indicates the location of hospitals at second route

Fig. 7. The result of the routing for Mersin (a) for Adana (b) [α,β]

Table 1. The number of opened distribution center, number of vehicle and total cost of the system versus distance

Name of the city	Distance Constraint	Number of opened distribution center	Number of vehicle	Costs (TL)
Osmaniye	25	3	3	4.736.456,7
	50	1	1	1.663.285,3
	75	1	1	1.663.285,3
	100	1	1	1.663.285,3
	125	1	1	1.663.285,3
	150	1	1	1.663.285,3
Hatay	25	5	5	8.108.274,3
	50	2	2	3.361.227,9
	75	2	2	3.361.227,9
	100	1	1	1.839.690,4
	125	1	1	1.839.690,4
	150	1	1	1.839.690,4
Mersin	25	9	9	14.397.446,6
	50	5	5	8.133.824,6
	75	3	3	5.150.581,8
	100	2	2	3.566.485,9
	125	2	2	3.566.485,9
	150	2	2	3.559.108,2
Adana	25	6	6	7.982.666
	50	4	4	4.956.703
	75	4	4	4.949.876
	100	2	2	2.025.530
	125	2	2	2.005.964
	150	2	2	1.997.884

As noted in Table 1, number of opened distribution center and number of vehicles decreases by increasing the distance constraint and also the total costs. Number of tours decreases by increasing the distance constraint. The significant cost differences are in Hatay by 77 % , in Mersin 75%, in Adana 74% and in Osmaniye 65%, consecutively. In the context of the costs, for the all provinces, the significant cost reduction occurs by increasing the distance constraint from twenty five to fifty. As a result, the distance constraints affect the results directly.

Table 2. Results for the routing and emergency service times of all cities

	Total Routing Times		Total Emergency Service Time	
	Curren t System (min)	Proposed System (min)	Current System (min)	Proposed System (min)
Osmaniye	253	128	695	119
Hatay	432	296	2933	545
Mersin	573	518	2614	617
Adana	572	364	728	558

Delivery time becomes vital when a hospital requires a blood product. As seen in Figure 8 and Table 2, total routing times and total emergency service times decrease comparing to the previous system, but especially total emergency service times are reduced as required for the demands in the proposed system.

As it can be compared from table 3, at the proposed system, there is not a significant difference about the total costs; the difference is at routing costs. The current system has a route that starts at Regional Blood Center and finishes the tour after visiting all hospitals in need. The proposed system's advantage is that the route starts at every distribution centers, visits the near hospitals and finishes the tour at the same distribution center.

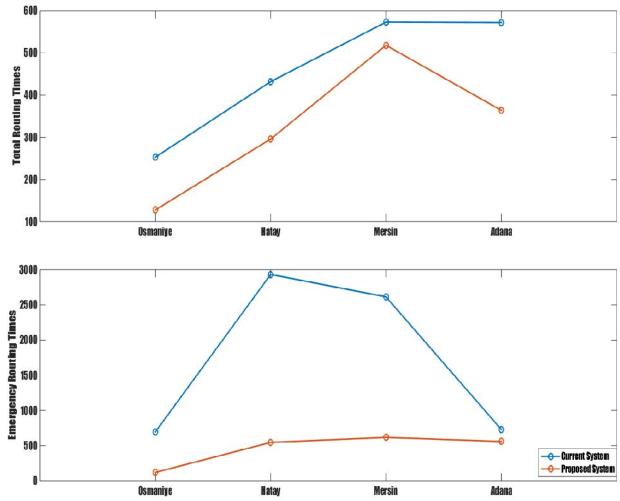


Fig. 8. Comparisons of delivery times between the current system and the proposed system

Table 3. Comparison of the current and proposed systems

	Current System	Proposed System
Routing	1.862.091 TL	1.278.987,1 TL
Vehicle cost	480.000 TL	420.000 TL
Fixed costs	31.840.974,4 TL	32.003.111,7 TL
Installation	0	480.000 TL
Total costs for ten years	34.183.065,4 TL	34.182.098,8 TL

However, to meet the needs in time improvements are observed in Osmaniye, Hatay and Mersin. This case shows effectiveness of the new system. Regional Blood Center continues to serve as the distribution center for hospitals in Adana, and so the times to meet the urgent for blood products remains unchanged.

8. Conclusion

Blood products management is one of the important problems with the complex structure in the field of health logistics. Blood products are vital for surgery, accidents, and chronic diseases. Therefore, the desired products must be available at the demand point. The problem is approached in two steps. We give a p-median type model that the locations of the distribution centers, the allocation of the hospitals to the distribution centers are determined in step I. According to the first model's outputs, in stage II a classical vehicle routing problem model is formulated with adding new constraints including vehicle compartment capacities. These location-allocation-routing models are formulated not only to find a solution to the current structure of the RBC, but also to use these models at different systems.

Case study shows that, by opening new DCs, total routing and emergency service time are significantly decreased with compensating initial investment of the proposed system.

There may be limitations in this study. The proposed model can be used different systems (private, government, clinics, etc.).

8.1. Recommendations and future direction

There are some future suggestions that may be considered as follows. Larger case study such as whole country's blood management can be conducted for investigating the effects of the proposed methods. Heuristic methods can be applied for large case problems.

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