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RESEARCH PAPER

Designing a Multi-Product Blood Supply Chain with Different Transportation Systems and Processing Technologies

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ABSTRACT
Blood supply chain (BSC) is a key part of a health care system whose design has challenges due to the perishability of the product. In this research, a model for multi-product BSC network is presented considering deterioration. We consider a four-echelon BSC which includes blood donation centers (BDCs), blood processing centers (BPCs), blood products (BPs) storage centers (BPSCs) and finally hospitals as the user of the BPs. The locations of BPCs and BPSCs are determined. Furthermore, considering different levels of technologies for blood processing, the suitable level for each opened center is also determined. In addition, different types of vehicles are considered for blood transfer between different levels of the network. The objective is minimizing the total logistical costs including the costs of opening and running the BPCs and BPSCs and BPs transfer costs between different levels of the supply chain (SC). Finally, we employ the given model to a real case in Iranian BSC; then, sensitivity analysis is carried out on some key model parameters. In the end, managerial aids are given to practitioners in this area.

KEYWORDS: *Blood supply chain design; Location-allocation; Technology levels; Transportation systems.*

1. Introduction

Supply chain network design (SCND) is known as an important function in supply chain management (SCM), with critical role in its efficiency in the long run. SCND is on determining the numbers, locations, and capacities of physical facilities and material flows in an SC in long run as [20] declare. Human blood is a valuable material which could only be made by human beings with no alternative [5]. Thus, its management is a challenging problem for decision makers. The need for blood and its by-products have always absorbed the attention of academics such as [4] [7] [19].

BSC begins with the donation of blood by donors at collection centers. The collected blood is sent to BPCs. At the BPC, the blood is breakdown into various parts; then, it is processed and tested for any possible diseases such as Hepatitis A, B, C, HIV, or West Nile Virus [1]. Processed blood is collected at blood banks in order to be given to healthcare centers [5]. Blood components include plasma, red blood cells (RBC) and platelets; the major problem concerned with these components is their short shelf life. While RBCs and plasma are of longer lives of 42 days and one year respectively, platelets are of short life of 5 days [1]. Moreover, there are some reasons which raise the importance of BSC management compared with other goods. For example, BPs do not have alternatives for their applications; moreover, the blood supply is a volunteer-based process [8].

This study investigates facility location and allocation aspects in BSC design. The considered network is composed of four echelons BDCs as the first echelon who collect and send the bloods to the final demand points such as clinics and hospitals in the fourth echelon. The second and third echelons are BPCs and BPSCs, respectively. The paper provides a BSC design mathematical model to find the locations of BPCs and BPSCs, assign donors and hospitals to the addressed centers, address the amount of flow of BPs between each pair of echelons, select the suitable vehicle and technology level in processing centers by

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minimizing the total supply chain costs. The issues of selecting among different levels of technologies for blood processing centers and blood transportation vehicles are of the key points in the given model. The adequacy of the model is investigated utilizing data of a case study in Iranian BSC. The rest of the paper is presented as follows: Section 2 supplied a review of the BSC design studies. Problem definition and mathematical formulation of the model are given in Section 3. Section 4 is on numerical results and sensitivity analysis utilizing case study data. Conclusions and more research ideas are supplied by Section 5.

2. Literature Review

On BSC design, [4], [16] [17] published a comprehensive review and analysis. The vital topics in this area could be collecting, screening and producing, inventory control and distribution of blood and BPs. In the rest of this section, a review of the related studies on BSC network design is presented.

[18] [16] worked on tactical and strategic topics of BSC handling including blood-banking operations, demand and supply coordination, blood collection, inventory control, and so on. A large amount of studies concentrated on inventory challenges and problems within BSC while a small part worked on location-allocation aspects such as [27]. [22] proposed a two-objective model for the addressed problem in the Turkish Red Cross Society. The first one was on minimizing total costs of transportations while the second one was on minimizing the maximum response time as a service level measure. [5] gave a set covering model for designing BSCs. They minimized total fixed costs of the chain's design together with transportation costs of the chain. [14] investigated location–allocation, inventory control and vehicle routing aspects of the problem as an integrated decision. [15] developed a mathematical model for a BSC including collection centers, laboratories, storage and distribution sites and consumption zones. [24] proposed a location-allocation model for blood bank installations in a multi-period horizon. [13] extended a single-product model for a BSC network in crisis situation. [26] developed a model for blood collection and distribution minimizing total costs of BSC. [9] presented a stochastic two-objective model for designing BSC in disasters. Minimization of total cost and total spent time were considered in the model. [3] presented a multi-objective mathematical model for designing a BSC network and located blood banks, and allocated different members in the SC. The SC parts existed in the addressed study were donation centers, testing and processing laboratories, blood banks, and consumption areas. It was concluded that consumption areas such as clinics were dependent on the BPs and any shortages in replenishment could lead to a death toll; for this reason, a transshipment sub-network was added to the studied BSC network. [6] addressed a mixed-integer programming model (MIPM) for designing a BSC network considering both strategic and tactical decisions in a multi-period horizon. Robust programming approach was applied to tackle the inherent randomness of the model parameters. [10] studied the a two-objective BSC network design problem with uncertainty while minimizing the total system costs and shortage simultaneously. They put under consideration the blood group compatibility and perishability in order to raise their model's applicability. [21] developed an MIPM for BSC network design considering various social aspects which had effect on the decision of donators like distance, advertising costs, and experience. [8] developed a mathematical model for a multi-objective sustainable BSC with uncertain condition during and after a disaster. Donor groups, blood collection installations, distribution points, and hospitals were the members of the BSC. [23] presented a multi-objective mathematical model for BSC design and determined the locations of distribution points. The SC of BPs under the motivational initiatives was focused by [12]. They concentrated on the uncertainty of BPs' disruption. Arani et al. [2] proposed a stochastic multi-objective MIPM for the BSC design and studied the impact of lateral resupply and cross-matching in the mentioned SC. [11] presented a nonlinear multi-objective random model for Tehran's BSC in case of crisis. Expected costs along with the delivery time of BPs were minimized. [25] studied BSC network design in the pandemic condition such as COVID-19 pandemic considering uncertainty on both supply and demand of BPs. Socio-economic factors were assumed in this research.

Table 1 gives the major features of the aforementioned researches and compares the current research in this paper with some of them. None of the reviewed researches investigated designing an integrated BSC network while considering different transportation modes and different levels of technologies in BPCs.

Tab. 1. Classification of the given researches of BSC design

Authors	year	SC echelon	location and allocation	BPs	Different vehicles	case study
			Single product	multiple products		
✓		✓			Arvan et al	2015 Integrated
Şahin et al.	2007	Integrated	✓	✓		✓
Cetin and Sarul	2009	Distribution	✓	✓		
Javid and Azad	2011	Distribution	✓	✓		✓
Nagurney et al.	2012	Integrated	✓		✓	
Sha and Huang	2012	Distribution	✓	✓		✓
Jabbarzadeh et al.	2014	Integrated	✓	✓		
Zahiri et al.	2014	Distribution	✓	✓		
Fahimnia et al	2017	Integrated	✓	✓		
Cheraghi et al	2016	Integrated	✓	✓		
Zahiri and Pishvaee	2017	Integrated	✓	✓		✓
Ramezanian and Behboodi	2017	Integrated	✓	✓	✓	✓
Eskandari-Khanghahi et al	2018	Integrated	✓	✓		✓
Hosseini-Motlagh et al.	2019	Integrated	✓	✓		✓
Samani et al.	2019	Integrated	✓	✓		✓
Arani et al	2021	Integrated	✓	✓		✓
Hamidieh and Johari	2022	Integrated	✓		✓	
Tirkolaee et al.	2023	Integrated	✓	✓	✓	✓
This study	__	Integrated	✓	✓	✓	✓

3. Problem Formulation

We address a BSC network design problem including BDCs, BPCs, BPSCs and finally hospitals as the user of the BPs over a one-year planning horizon. The collected blood at BDC is transmitted to BPC for processing and producing BPs after test. Part of the BPs may be failed after the testing stage and discarded. Then, blood and BPs are sent to blood storage centers, and then they are transferred to demand centers which can be hospital or health center (see Fig. 1). The problem is modeled as a multi-product one in order to determine the locations of BPCs and BPSCs and the flows in the SC minimizing the total costs of the entire network.

3.1. Assumptions

We considered the following assumptions:

1. The locations of BDCs and demand centers are known, while there are some candidate locations for BPCs and BPSCs.
2. The capacities of BPCs and BPSCs are limited.
3. BPs are plasma, platelets, and blood cells.
4. There are different levels of technologies for BPCs.
5. There exist different kinds of vehicles with different speeds and costs.
6. Transshipment between BPCs and blood demand centers are not allowed.
7. The final demand is deterministic.
8. All demand must be satisfied (i.e., shortage is not allowed).

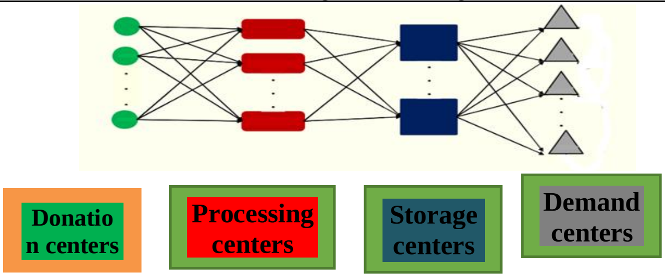


Fig. 1. Schematic of studied BSC network.

3.2. Mathematical model

In this section, the mathematical model of the problem is presented after introducing the sets, parameters and decision variables.

Sets

I Set of BDCs indexed by *i*

K Set of candidate locations for BPCs indexed by *k*

L Set of candidate locations for BPSCs indexed by *l*

J Set of demand centers (i.e., hospitals and medical centers) indexed by *j*

F Set of different BPs indexed by *f*

TE Levels of technologies for BPCs indexed by *te*

M Types of vehicles indexed by *m*

Parameters

$D_j^{\,f}$ Blood demand at demand center *j* for BP *f*

$CAP1_k^{\,te}$ Capacity of BPC *k* with level of technology *te*

$CAP2_l$ Capacity of BPSC *l*

$TC_{ik}^{\,m}$ Unit transportation cost from BDC *i* to BPSC *k* by vehicle *m*

$TC1_{kl}^{\,fm}$ Unit transportation cost from BPC *k* to BPSC *l* by vehicle *m*

$TC2_{lj}^{\,fm}$ Unit transportation cost from BPSC *l* to demand center *j* by vehicle *m*

ds_{ik} Distance between BDC *i* and BPS *k*

$ds1_{kl}$ Distance between BPC *k* and BPSC *l*

$ds2_{lj}$ Distance between BPSC *l* and demand center j

$t_{ik}^{\,m}$ Travel time of BPs from BDC *i* to BPC *k* by vehicle *m*

$t1_{kl}^{\,m}$ Travel time of BPs from BPC *k* to BPSC *l* by vehicle *m*

$t2_{lj}^{\,m}$ Travel time of BPs from BPSC *l* to demand center *j* by vehicle *m*

$F1_k^{\,te}$ Fixed cost of establishing a BPC *k* with technology level of *te*

$F2_l$ Fixed cost of establishing a BPSC *l*

$tp1_{fk}^{\,te}$ Processing time of BP *f* at BPC *k* with technology level of *te*

$tp2_{fl}$ The average shelf life of BP *f* in BPSC *l*

$pr_k^{\,f}$ Unit processing cost of BP *f* at BPC *k*

$h_l^{\,f}$ Unit holding cost of BP *f* at BPSC *l*

α Percentage of rejected blood due to diseases at each BPC

$Maxt_f$ Maximum lifetime of BP *f*

M A large positive number

Decision variables

$Z_{ik}^{\,m}$ Amount of blood sent from BDC *i* to BPC *k* by vehicle *m*

$Z1_{kl}^{\,fm}$ Amount of BP *f* sent from BPC *k* to BPSC *l* by vehicle *m*

$Z2_{lj}^{\,fm}$ Amount of BP *f* sent from BPSC *l* to demand center *j* by vehicle *m*

$X_{ik}^{\,m}$ 1 if there is blood being transported from BDC *i* to BPC *k* by vehicle *m* , 0 otherwise

$X1_{kl}^{\,fm}$ A binary variable, equal to 1 if there is BP *f* being transported from BPC *k* to BPSC *l* by vehicle *m*; 0 otherwise.

$X2_{lj}^{\,fm}$ A binary variable, equal to 1 if there is BP *f* being transported from BPSC *l* to demand center *j* by vehicle *m*; 0 otherwise.

$X_k^{\,te}$ A binary variable, equal to 1 if BPC *k* with technology level of *te* is opened at location *k*; 0 otherwise.

Y_l A binary variable, equal to 1 if BPSC *l* is opened at location *l*; 0 otherwise.

The model is stated as follows:

$$\text{Min } Z = \left(\sum_k \sum_{te} F1_k^{te} X_k^{te} + \sum_l F2_l\, Y_l\right) + \left(\sum_i \sum_k \sum_m TC_{ik}^{m} . ds_{ik} . Z_{ik}^{m} + \sum_k \sum_l \sum_f \sum_m TC1_{kl}^{fm} . ds1_{kl} . Z1_{kl}^{fm} + \sum_l \sum_j \sum_f \sum_m TC2_{lj}^{fm} . ds2_{lj} . Z2_{lj}^{fm}\right) + \left(\sum_f \sum_k \sum_i \sum_m pr_k^{f} . Z_{ik}^{m}\right) + \left(\sum_f \sum_k \sum_m \sum_l h_l^{f} . Z1_{kl}^{fm}\right) \quad (1)$$

Subject to:

$$\sum_m \sum_i Z_{ik}{}^{m} \leq CAP1_k{}^{te} \quad \forall\, k.te \qquad (2)$$

$$\sum_f \sum_m \sum_k Z1_{kl}{}^{fm} \leq CAP2_l \quad \forall\, l \qquad (3)$$

$$(1-\alpha) \sum_i \sum_m Z_{ik}{}^{m} \geq \sum_f \sum_m \sum_l Z1_{kl}{}^{fm} \quad \forall\, k \qquad (4)$$

$$\sum_k \sum_m Z1_{kl}{}^{fm} \geq \sum_j \sum_m Z2_{lj}{}^{fm} \quad \forall\, l.f \qquad (5)$$

$$\sum_l \sum_m Z2_{lj}{}^{fm} \geq D_j{}^{f} \quad \forall\, j.f \qquad (6)$$

$$\sum_{te} X_k{}^{te} \leq 1 \quad \forall\, k.te \qquad (7)$$

$$\sum_i \sum_k \sum_m t_{ik}{}^{m}.X_{ik}{}^{m} + \sum_k \sum_l \sum_m t1_{kl}{}^{fm}.X1_{kl}{}^{fm} + \sum_l \sum_j \sum_m t2_{lj}{}^{fm}.X2_{lj}{}^{fm} + \sum_k \sum_{te} tp1_{fk}{}^{te}.X_k{}^{te} + \sum_l tp2_{fl}.Y_l \leq Maxt_f \quad \forall\, f \qquad (8)$$

$$Z_{ik}{}^{m} \leq M.X_{ik}{}^{m} \quad \forall\, i.k.m \qquad (9)$$

$$Z1_{kl}{}^{fm} \leq M.X1_{kl}{}^{fm} \quad \forall\, k.l.f.m \qquad (10)$$

$$Z2_{lj}{}^{fm} \leq M.X2_{lj}{}^{fm} \quad \forall\, l.j.f.m \qquad (11)$$

$$X_k{}^{te}, Y_l, X_{ik}{}^{m}, X1_{kl}{}^{fm}, X2_{lj}{}^{fm} \in \{0,1\} \quad \forall\, i.k.l.j.te.f.m \qquad (12)$$

$$Z_{ik}{}^{m}, Z1_{kl}{}^{fm}, Z2_{lj}{}^{fm} \geq 0 \quad \forall\, i.k.l.j.f.m \qquad (13)$$

Objective function (1) minimizes the BSC logistical costs. The first term represents the costs of establishing BPCs and BPSCs, while the second term denotes the transportation costs, and the third term determines the processing and holding costs. Constraints (2) and (3) express the capacity of blood processing and blood storage centers, respectively. Constraint (4) is for decomposition of blood at BPCs. A part of the input blood converts into BPs including platelets, plasmas, and RBCs. Constraint (5) Clarifies the flow balance among BPC, BPSC, and blood demand centers. Constraint (6) ensures that blood demands in demand centers are fulfilled. Constraint (7) shows that there is at most one type of technology in each BPC. Constrain (8) ensures the total time that each BP type is held in the system doesn’t deviate its expiration date. Constraints (9) – (11) declare that blood shipment between nodes occur when there is a link among. Constraints (12) and (13) show the status of variables.

4. Model Implementation and Numerical Results

4.1. Case study

Here, we discuss a real case study for showing different aspects of the proposed BSC model. We consider the case study from Iranian BSC, a country with 31 provinces. Specifically, 9 candidate locations including four locations for BPCs and five candidate locations for BPSCs were considered in the center of five major provinces of Tehran, Alborz, Semnan, Qom and Mazandaran. Fig. 2 shows the candidate locations on the country. Furthermore, eight BDCs and eight demand centers located in Tehran province and its neighboring provinces are depicted in Fig. 3. Since Tehran is a city with high population, we have assumed that it can satisfy its neighbor small cities blood demand as well as its own needs and the model given in this paper exactly covers such idea.

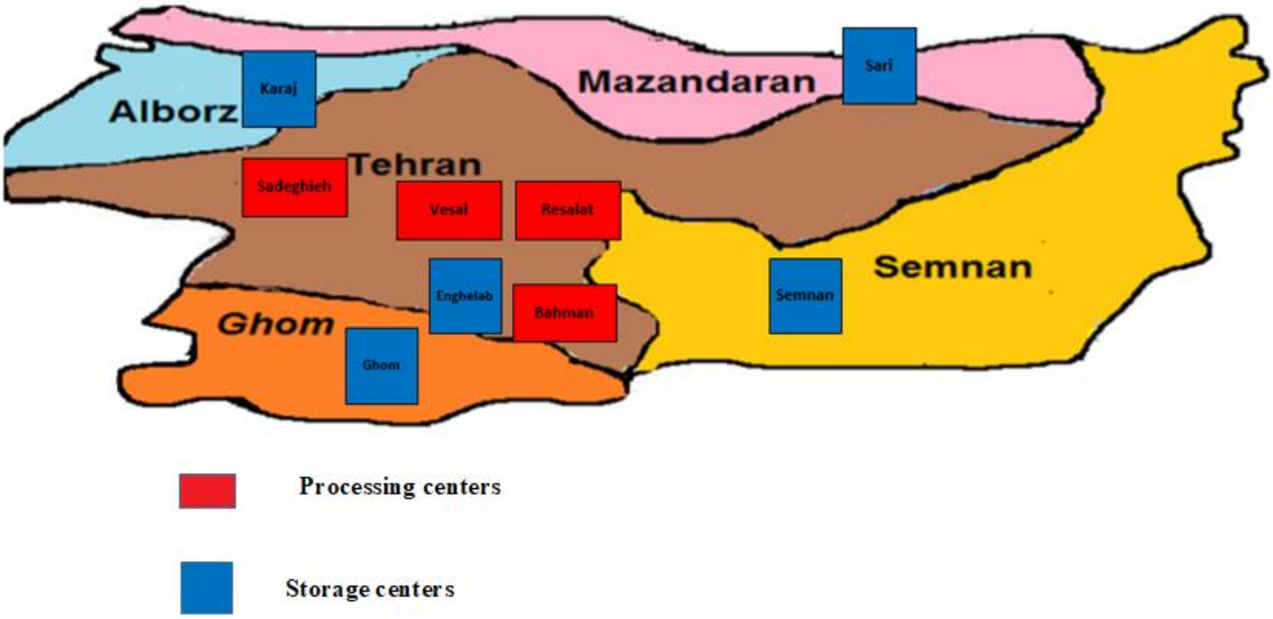


Fig. 2. The nine candidate locations of BPCs and BPSCc.

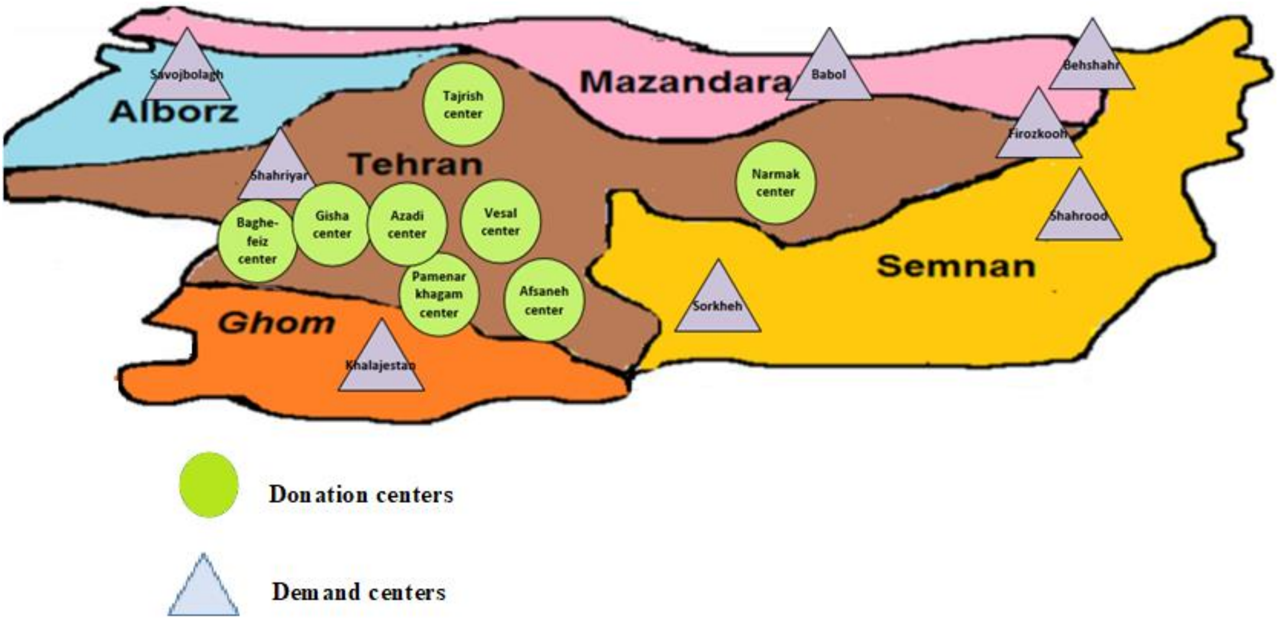


Fig. 3. The locations of BDCs and demand centers

Some of the required data such as the demand for BPs, the capacities of BPCs and BPSCs, percentage of rejected blood due to infections at each BPC, lifetime of BPs, and processing time of BPs at BPCs were collected from documented responses from the Iranian blood transfusion center located in Tehran, Iran. The goal is to find optimal locations for BPCs and BPSCs, assignment of BDCs and blood demand centers to the established facilities minimizing the total costs of the BSC.

Since some cities and centers are located in different provinces far from each other, therefore, transportation costs have key role. Transportation mode is assumed to be of road type and BPs are transported through the border. The distances between different facilities i.e. BDCs, BPCs, BPSCs, and demand centers are calculated by Google Maps. Transportation costs are approximated as a function of the distance between entities and the fuel rates.

Tables 2-4 show the distance between each pair of centers in terms of kilometers. Table 5 represents the total demands by hospitals. Fixed cost of establishing a BPC k with the level of technology te, i.e., $F1_k^{te}$ is considered 80000 to 90000. Fixed cost of establishing a BPSC l, i.e., $F2_l$ is considered between 250 to 300. Capacity of BPC k with level of technology te, i.e., $CAP1_k^{te}$ is considered 170000 to 190000. Capacity of BPSC l, i.e., $CAP2_l$ is considered 70000 for all. Processing cost of BP f at BPC k, i.e., pr_k^f is considered from .004456 to 0.007808. Holding cost of BP f at BPSC l, i.e., h_l^f is considered 0.002228 to 0.003904. Max lifetime of BP f, i.e., $Maxt_f$ is considered 7 to 365. Processing time of BP f at BPC k with technology level of te, i.e., $tp1_{fk}^{te}$ is considered from 1 to 10. The average shelf life of BP f in BPSC l, i.e., $tp2_{fl}$ is considered 4, 20, 30 and 300. Travel time between BDC i and BPC k by vehicle m, i.e., t_{ik}^m is considered from 0 to 1.33. Travel time between BPC k and BPSC l by vehicle m, i.e., $t1_{kl}^m$ is generated between 0.187 to 3.625. Travel time between BPSC l and blood demand center j by vehicle m, i.e., $t2_{lj}^m$ is considered between .25 to 6.44. Travel times between each pairs of centers are calculated by the ratio of average speed of vehicles to the distance traveled by vehicles. The travel times are in terms of kilometer/hour. The capacities of BPCs and BPSCs are in terms of liter and all the monetary data are in terms of ten million Rials. The lifetime of BPs, the average shelf life of BPs at BPSCs are in terms of day, and processing time of BPs at BPCs are in terms of hour. The values of α and M are considered 0.1 and 1000000, respectively. The considered planning horizon is one year.

The problem was solved utilizing optimization package of GAMS 24.7. Table 9 and Figs. 4-6 show the optimal locations of the BPCs and BPSCs together with the final solution. It is clear that from among nine candidate locations of processing and storage centers, six centers were established. This solution permits the model to meet the demand with total cost of 16,609.

Tab. 2. Distance between BDC *i* and BPC *k* (ds_{ik})

k / *i*	1	2	3	4
1	0	20	20	15
2	15	30	40	5
3	25	35	20	25
4	10	25	10	25
5	30	40	5	40
6	15	15	25	25
7	20	15	45	10
8	10	25	5	20

Tab. 3. Distance between BPC *k* and BPSC *l* ($ds1_{kl}$)

l / *k*	1	2	3	4	5
1	270	240	170	60	2
2	280	250	150	70	18
3	290	260	200	50	20
4	250	220	180	70	15

Tab. 4. Distance between BPSC *l* and demand center *j* ($ds2_{lj}$)

j / *l*	١	٢	3	4	5	6	7	8
1	315	135	515	45	55	350	250	200
2	265	85	385	200	260	310	185	25
3	150	290	100	400	470	210	280	265
4	30	200	290	270	350	30	280	305
5	45	145	150	250	300	85	220	245

Tab. 5. Blood demand at demand center j for BP f (D_j^f)

f j				
1	5,000	4,000	8,000	500
2	7,000	8,000	4,000	600
3	8,000	7,000	4,000	400
4	25,000	6,000	6,000	600
5	12,000	5,0000	4,000	500
6	5,000	4,000	5,000	600
7	13,000	6,000	3,000	700
8	15,000	9,500	2,000	600

Tab. 6. Transportation cost from BDC i to BPC k by vehicle m (TC_{ik}^m)

k i	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2
1	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
2	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
3	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
4	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
5	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
6	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
7	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072
8	0	0	0.0006	0.00072	0.0006	0.00072	0.0006	0.00072

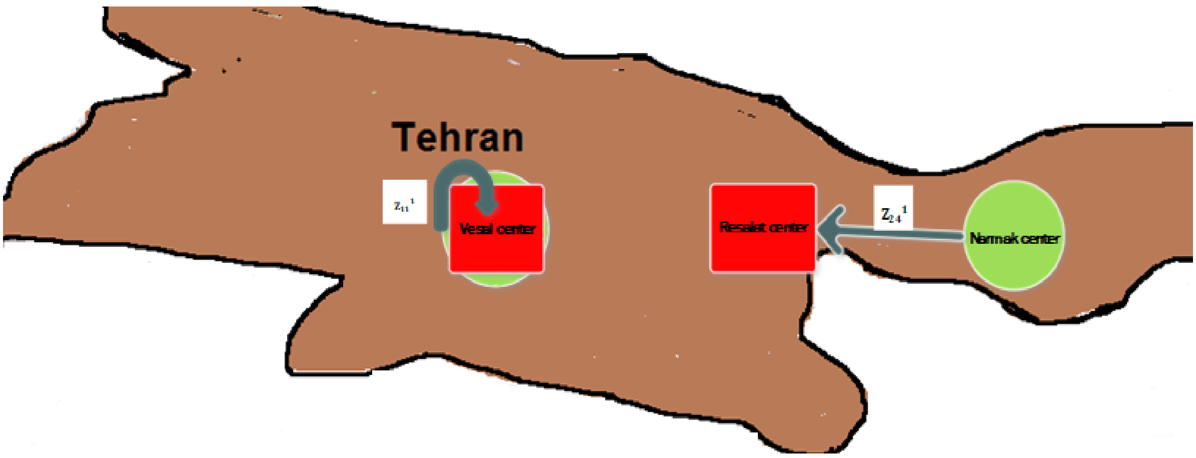


Fig. 4. Blood flows between BDCs and BPCs

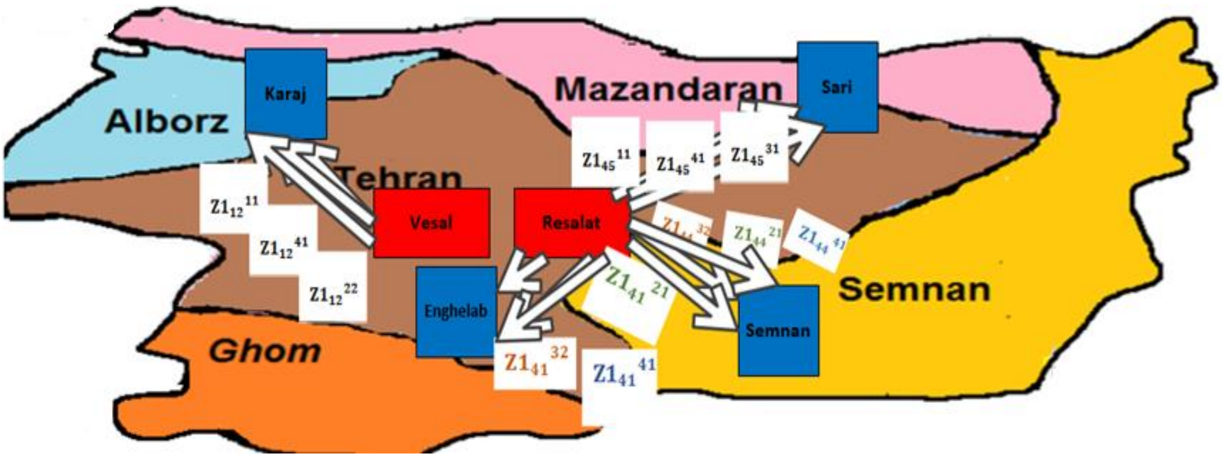


Fig. 5. Blood flows between BPCs and BPSCs

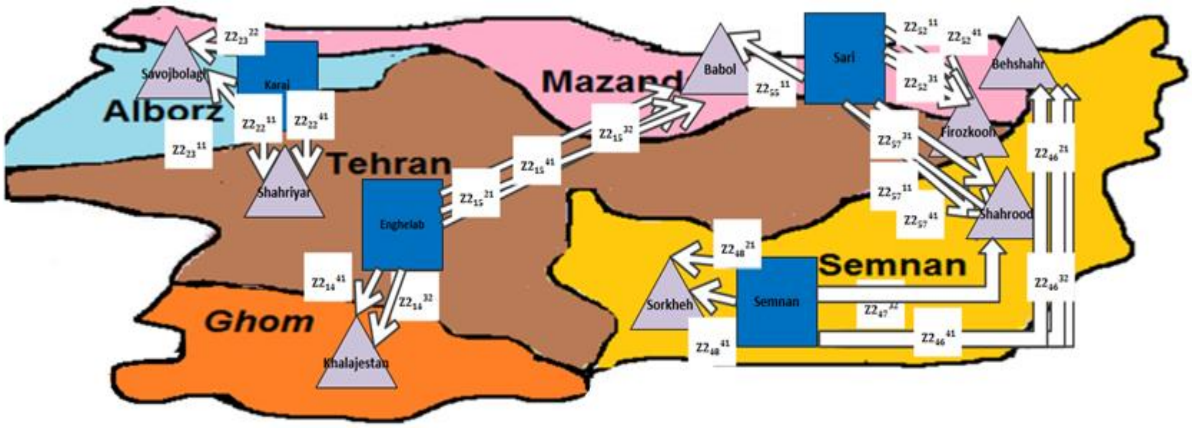


Fig. 6. Blood flows between BPSCs and demand centers

Tab. 7. Transportation cost of BP *f* from BPC *k* to BPSC *l* by vehicle *m* ($TC1_{kl}{}^{fm}$)

l / k	1.1.1	1.1.2	1.2.1	1.2.2	1.3.1	1.3.2	1.4.1	1.4.2	...	5.1.1	5.1.2	5.2.1	5.2.2	5.3.1	5.3.2	5.4.1	5.4.2
1	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003
2	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003
3	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003
4	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003

Tab. 8. Transportation cost of BP *f* from BPSC *l* to demand center *j* by vehicle *m* ($TC2_{lj}{}^{fm}$)

j / l	1.1.1	1.1.2	1.2.1	1.2.2	1.3.1	1.3.2	1.4.1	1.4.2	…	8,1,1	8,1,2	8,2,1	8,2,2	8,3,1	8,3,2	8,4,1	8,4,2
1	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036		0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036
2	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036		0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036
3	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036		0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036
4	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036		0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036
5	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036		0.0003	0.00036	0.0003	0.00036	0.0003	0.00036	0.0003	0.00036

Tab. 9. Summary of computational results

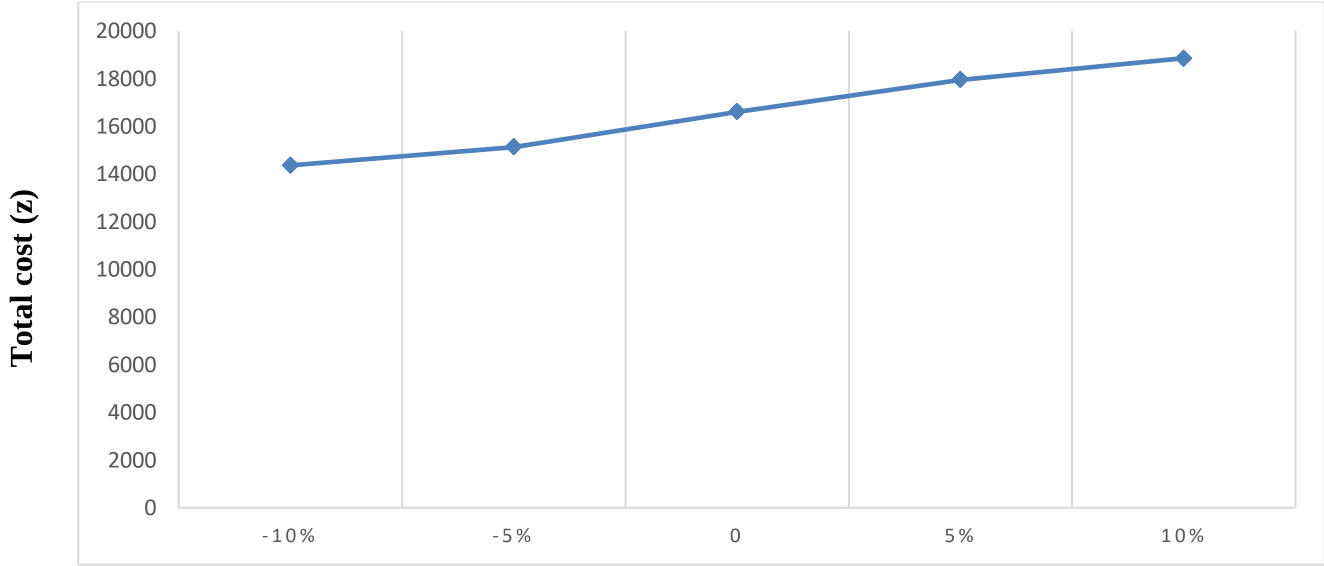
Z	$Z_{ik}{}^{m}$	$Z1_{kl}{}^{fm}$	$Z2_{lj}{}^{fm}$
16,609	250,000	225,000	190,000

4.2. Sensitivity analysis

Some of the network parameters such as opening cost of an installation, the BP demand, transportation costs between installations can have key role in design decisions. Therefore, the impacts from varying the values of such parameters are examined in the rest. The first parameter analyzed is the transportation cost between the nodes. As given in Table 10 and Fig. 7, the total cost generally surges when the transportation costs raise, and vice versa. One of the major decisions in the proposed BSC model is related to opening of BPC and BPSC. Similar to the transportation cost, increasing this parameter brings higher costs to the network. Table 11 and Fig. 8 presents this conclusion in a better way. The BP demand is another key factor could be addressed in the sensitivity analysis. From Table 12, it is concluded that there is a positive correlation between the BP demand and the system's total cost. Fig. 9 shows the addressed fact schematically.

Tab. 10. Sensitivity of the model to transportation cost parameter

Transportation cost	Objective function
-10%	14,361
-5%	15.130
0%	16,609
+5%	17,947
+10%	18,857

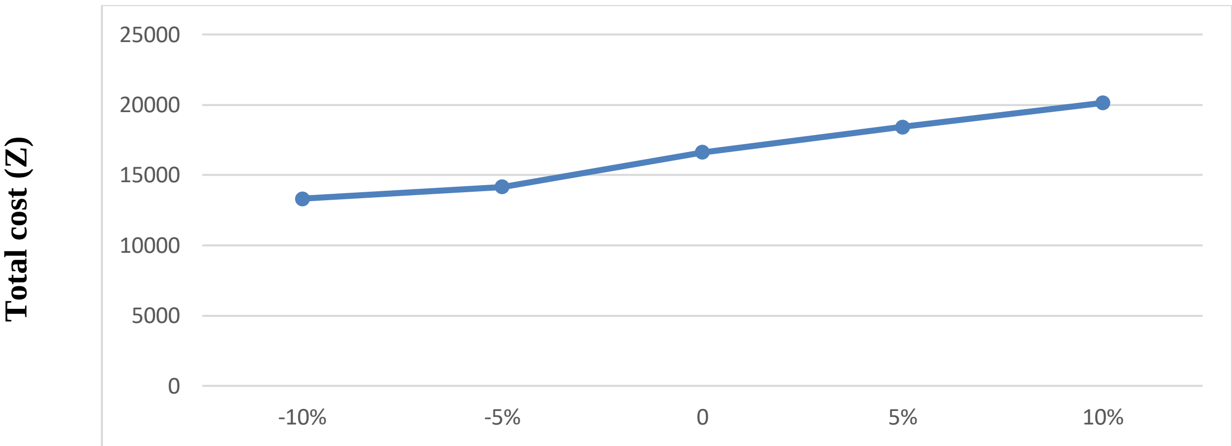


Transportation costs ($TC_{ik}^{m}.TC1_{kl}^{fm}.TC2_{li}^{fm}$)

Fig. 7. Variations of the total cost versus transportation cost

Tab. 11. Sensitivity of the model to the establishment cost

Establishment cost	Objective function
-10%	13,320
-5%	14,160
0%	16,609
+5%	18,410
+10%	20,130



Establishment costs ($F1_k^{te}.F2_l$)

Fig. 8. Variations of the total cost versus establishment cost

Tab. 12. Sensitivity of the model to the BP demand

BP demand	Objective function
-10%	14,871
-5%	15,250
0%	16,609
+5%	17,342
+10%	18,464

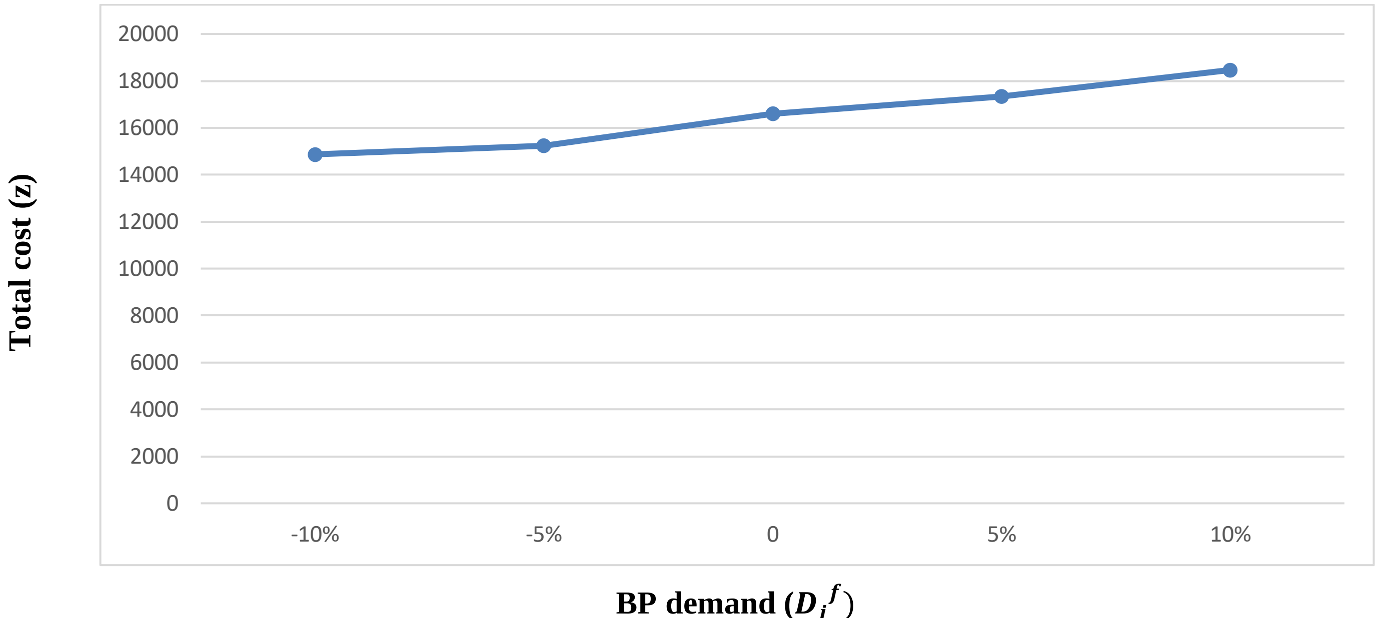


Fig. 9. Variations of the total cost versus demand

5. Conclusions and Future Research Suggestions

This paper presented a mathematical model for BSC network design. The SC included four echelons: BDCs, BPCs, BPSCs and blood demand centers. We considered different levels of technologies for BPCs, the perishability of BPs, and different types of vehicles for blood transfer between different levels of the network. The objective of the model was to minimize the BSC costs; furthermore, the optimal locations of the BPCs and BPSCs were determined as the major outcome of the model. The model was employed to a real case study in Iran, Tehran province and its neighbor provinces. Since Tehran is a city with high population, we have assumed that it can satisfy its neighbor small cities blood demand as well as its own needs and the model given in this paper exactly covers such idea. Among four candidate locations for BPCs and five candidate locations for BPSCs, two locations were selected as BPCs and four locations as BPSCs. Finally, sensitivity analysis was performed on some key parameters of the model in order to extract valuable insights. The variations of the total BSC costs were studied by changing the transportations costs of different vehicles, establishment costs of facilities and demand of the centers. The major outcome of this research for the managers is that they should mind optimization models in designing the BSC networks. The major decisions include determination of locations for BPCs and BPSCs, determination of their technology levels, determination of vehicles for transferring BPs and in the end, the assignment of demand and BDCs to BPCs and BPSCs, respectively.

Considering the uncertainty of demand, researchers can develop the model utilizing different uncertainty approaches such as stochastic programming, and robust optimization. Another direction for future research is that a number of prioritization methods can be utilized for selecting candidate location of installations before optimization models. The locations of BDCs can also be determined by an integrated mathematical model. Lastly, the information-sharing between members of the BSC can be considered in order to save SC costs.

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