Mathematical modeling for optimizing the blood supply chain network

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Abstract

Purpose – This research studies a location-allocation problem considering the m/m/m/k queue model in the blood supply chain network. This supply chain includes three levels of suppliers or donors, main blood centers (laboratories for separation, storage and distribution centers) and demand centers (hospitals and private clinics). Moreover, the proposed model is a multi-objective model including minimizing the total cost of the blood supply chain (the cost of unmet demand and inventory spoilage, the cost of transport between collection centers and the main centers of blood), minimizing the waiting time of donors in blood donating mobile centers, and minimizing the establishment of mobile centers in potential places.

Design/methodology/approach – Since the problem is multi-objective and NP-Hard, the heuristic algorithm NSGA-II is proposed for Pareto solutions and then the estimation of the parameters of the algorithm is described using the design of experiments. According to the review of the previous research, there are a few pieces of research in the blood supply chain in the field of design queue models and there were few works that tried to use these concepts for designing the blood supply chain networks. Also, in former research, the uncertainty in the number of donors, and also the importance of blood donors has not been considered.

Findings – A novel mathematical model guided by the theory of linear programming has been proposed that can help health-care administrators in optimizing the blood supply chain networks.

Originality/value – By building upon solid literature and theory, the current study proposes a novel model for improving the supply chain of blood.

Keywords Blood supply chain, Location-allocation problem, Blood products, NSGA-II, Queuing theory

Paper type Research paper

1. Introduction

The management of blood product consumption considers as one of the most complex issues in health-care systems due to some issues such as limitation of blood resources, perishability, special preservation conditions of blood products, and high wastage and shortage costs of blood products (Ramezanian and Behboodi, 2017). Blood supply chain management is one of the major challenges of health systems. Human blood is a scarce resource that is produced only by humans themselves, and there is currently no other chemical product or process that can be used as a substitute and there is currently no other chemical product or process that can be used as a substitute Zahiri *et al.* (2014). Many patients need blood transfusions every day for various reasons (Ramezanian and Behboodi, 2017). Some people, such as dialysis patients and long-term patients, need blood products to survive permanently, and some other patients need blood products due to surgical resection. In cases such as open surgery or neonatal surgery, according to some medical requirements, only fresh blood products should be used (Ghasemi, 2019).

The amount of blood products in hospitals is a function of the number of daily accidents and this amount follows an uncertain trend (Hosseini-Motlagh *et al.*, 2020). For this reason, hospitals prefer to order more blood products to make sure the blood required is not low. However, excessive ordering of blood products by hospitals is not possible due to some factors and limitations in the blood supply chain (Zahiri *et al.*, 2015). The first and most important factor is the limited amount of blood in the regional blood center. The regional blood center is responsible for the distribution of blood between different hospitals and devotes the limited amount of blood available (Hosseini-Motlagh *et al.*, 2020; Ghasemi *et al.*, 2019; Zahiri *et al.*, 2014, 2015; Alfonso *et al.*, 2012). Another reason is that blood is a scarce and perishable product, and storing large quantities of it can lead to spoilage. One of the most important limitations for discussing the issue of location-allocation in the blood supply chain is the issue of time and price (Ghasemi *et al.*, 2019; Zahiri *et al.*, 2014). Many previous studies have been devoted to the blood supply chain.

In former research, the uncertainty in the number of donors, and also the importance of blood donors has not been considered. For example, Ramezanian and Behboodi (2017) designed a blood supply chain network under uncertainties in supply and demand considering social aspects. But the number of donors under uncertainty does not consider. Alfonso *et al.* (2012) studied the processes of collecting blood concerning establishing the cost of temporary and permanent blood facilities in France, but at this research, the number of donors and also the importance of blood donors has not been considered under uncertainty. Zahiri *et al.* (2014) presented a robust possibilistic programming approach to multi-period location-allocation of organ transplant centers under uncertainty. Ghasemi (2019) presented a model for Location Allocation Problem After Disaster Blood Supply Chain. But in this research, the uncertainty in the number of donors has not been considered.

In the current study, a new model for minimizing time and cost with the queue theory considering the blood donor's roles has been applied. It aims to minimize the total cost of the blood supply chain and the waiting time for donors in mobile centers using a three-level nonlinear mathematical model. In the present study and at all levels, blood products have a specific life cycle and bypassing their time, they will be considered as waste products. While recognizing the fact that the importance of the donor position in the blood supply chain is missed in previous works, the current study fills the gap.

The rest of the study is organized as follows. In section 2, we briefly summarized the previous studies in the field of placement-assignment and blood supply chain and we pointed to the lack of these studies. In section 3 with considering queuing model theory, we minimized the waiting time of donors in the mobile blood centers and the time of donating. Also in section 3 by proposing a nonlinear and multi-objective model, we reduced the cost of wastes, transportation, and lack of products, and then with a realistic example, we solved this mode

using the NSGA-II heuristic algorithm. In section 4, we analyzed the solutions obtained in section 3 and we also described the methods to estimate the parameters of the algorithm. Finally considering the research problem, research process and obtained results, we proposed a solution for future works.

2. Literature review

In this research, we focus on two different topics including the blood supply chain and the problem of placement-assignment. This section explains related works that have been done for both focuses.

2.1 Blood supply chain

Fazli-Khalaf et al. (2019) discussed the problem of controlling available blood and optimized the available amount by proposing a model. Şahinyazan et al. (2015) used a spreadsheet for calculating data envelopment analysis (DEA); their conclusion was among the scale of the studied blood centers, expanding the level of operation more than one point causes the reduction in efficiency concerning the scale. Alfonso et al. (2014) established the benchmarking goals in hospitals for blood red cells. Their logical regression results indicated various pair groups. Between these groups, benchmarking could be done. They also used bubble sheets for indicating the pairs. Williams et al. (2020) used a simulation model using FORTRAN to simulate the daily deliveries of the simple blood bank. They used this simulation as proof for their theory model.

Surveys illustrate that the researchers do not tend to design the blood supply chain using queue models, and few works tried to use these concepts for designing the blood supply chain networks. Hosseini-Motlagh et al. (2016) combined numerical analysis with Markov chains. They developed a model in which it was able to convert blood demand to access possibility and blood usage to efficiency as a function of the blood distribution policy of the local blood center and blood storage policy of the hospital blood bank.

2.2 Placement-assignment

Osorio et al. (2015) used integer linear programming to model the blood product shipments to Australian hospitals using the effective cost method. They studied changes from customer-based to seller-based to see which model is better. They also compared their method with an alternative solution based on neighborhood search. As the result, they realized they could reduce travel costs considerably by having a more complex delivery policy by 30 percent. Heidari-Fathian and Pasandideh (2018) considered a solution for the two objectives model for the distribution of perishable materials in the blood supply chain in their studies. These goals were minimizing the total cost of the system and balancing the distances passed by vehicles. Their model was solved by epsilon limitation and NSGA-II methods and then by some indexes, and the results were evaluated. Finally, Govindan et al. (2016) proposed a simulation of the supply chain of very perishable products. They presented a delivery chain composed of a distribution center and few platelet using centers. Their objective function minimized the maximum possible amount of shortage. They also proposed a new strategy of ordering products based on remained product's lifetime. Later, comparison was made with strategies proposed by Fortsch and Khapalova (2016) called "EWA" and "Order-Up-To" under centralized and decentralized conditions. The result showed that the rate of wastes in the centralized condition was reduced significantly from 19.6 percent to 4.04 percent.

As the related works suggests, the scholars considered different sections of the blood supply chain, but it is obvious that the insignificant amount of studies optimized the complete blood supply chain (Rahmani, 2019; Dutta et al., 2018; Ramezanian and Behboodi, 2017; Chaiwuttisak et al., 2016; Khalili-Damghani et al., 2015; Zahiri et al., 2015). Queuing theory is

the mathematical study of the congestion and delays of waiting in line. Queuing theory (or queue theory) examines every component of waiting in line to be served, including the arrival process, service process, number of servers, number of system places and the number of customers – which might be people, data packets, cars, etc. Also, queue theory is was not the attention of researchers, and the researches on queue theory were not related to the blood supply chain and were more related to the stock of blood banks. The importance of ordering and delivering very perishable blood products while considering the minimization of the total cost of the supply chain is an important topic that was not considered a lot by researchers while it is very critical. Blood donation is critical to all transfusion therapy, as it provides the starting product. In the United States and many other economically developed nations, all of the blood is given by volunteer and nonremunerated donors. Donated whole blood is then made into transfusable components, which include, but are not limited to, packed red blood cells (RBCs), platelets and frozen plasma or cryoprecipitate (Zeger *et al.*, 2007). Therefore, in this paper, we focused on the queue theory to minimize the total cost of the chain and we achieve two other goals that are minimizing the waiting time for customers and minimizing the establishment time for mobile blood centers.

3. Modeling
In this section, we first describe the problem, its assumptions, limitations, and we propose three objective mathematical models. Then, we describe the three objectives solution method for the NSGA-II algorithm.

3.1 Problem statement
Respecting the goals of this research which are minimizing the total cost of the blood supply chain and minimizing the waiting time for donors in mobile centers, a three-level nonlinear mathematical model is presented. In this research and at all levels, blood products have a specific life cycle, and bypassing their time, they will be considered as waste products. It is worth noting that blood demand in this model follows the uniform distribution function, and entering donors to the mobile blood centers follows the exponential distribution function. Also, we took advantage of queue theory for potential places for collecting blood such as reducing the waiting time of donors in blood centers and optimize the time for the establishment of mobile blood centers. In other words, the proposed model is a combination of placement-assignment problem and queue theory problems that aims to achieve three goals include first, minimizing the transportation cost, waste and lack of demand; second, minimizing the establishment of mobile blood centers and third, reducing the waiting time of donors in blood centers. Also considering the input and output strategy of blood products, we decided to use FIFO for queuing model.

3.2 Assumptions
The proposed model has been built on the following assumptions:

(1) In each period, blood collecting from each potential place is done only by one mobile blood center.

(2) Mobile blood centers bring collected blood only to their original main blood center.

(3) Transportation cost between main blood centers and mobile blood centers would be considered.

(4) Respecting different blood products, the blood demands of each hospital are only assigned to one main blood center.

(5) Main blood centers cover potential places only if they are in their specific coverage distance range.

(6) A potential place can be blood collected only once during certain periods.

(7) Each red blood cell and platelet would be considered as waste after 25 and 3 days, respectively.

(8) Each demand should be responded to in the same period.

(9) Initially, stock is 0 for all three levels.

(10) Processing one blood unit produces one platelet unit and one red blood cell unit.

(11) The cost of wastes and perishing blood products would be considered.

(12) Responding to the demands is based on FIFO policy.

(13) Main blood centers can transfer blood to each other.

(14) Input and service distribution functions follow Poisson and exponential distribution functions, respectively.

(15) The collected blood should be sent to the lab before 6 h.

(16) Blood collecting centers have a specific capacity.

3.3 Mathematical model of the problem
3.3.1 Indexes.

   I: potential places for collecting blood

   J: blood main centers (test and refinement)

   L: mobile blood centers

   R: blood products

   T: planning periods

   A: products' remained life cycle

   H: demand centers (hospitals)

3.3.2 Parameters.

   μ_i: Service rate to donors by potential center i

   λ_i: Donor see rate in potential center i

   B: maximum establishment time for a mobile blood center at a potential blood center

   H: maximum capacity of a mobile center

   h: minimum capacity of a mobile center

   M: maximum number of servers in mobile centers

   tt_{ij}: transfer time for collected blood from the potential center I to main center j

   e: maximum time for keeping the blood before refinement

   d_{ij}: distance matrix between potential center i and main center j

CO_r: cost of each unit of demanded blood product r

C_r: the cost of each unit of not fulfilled demand in center j

CC: the fixed cost of transferring blood between main blood centers

E: possible distance for assigning potential centers to main blood centers

N: possible distance for transferring blood between main blood centers

SS: possible distance for assigning demand centers to main blood centers

td_{jh}: distance matrix between demand center h and main center j

$dd_{j_1j_2}$: distance matrix between main centers j_1 and j_2

cs_{ij}: the cost of transferring blood between potential center i and main center j

RL_r: maximum allowed time for keeping product r

De_{hr}^t: demanding amount of product r in period t by hospital h

U: a very large number

ε: a very small number

3.3.3 Variables.

π_i: probability of presence of k donors in the potential center i

π_{0i}: probability of presence of no donors in the potential center i

$\bar{\lambda}_i$: entering rate of donors to mobile blood centers of potential center i

L_i: average number of customers in potential center i

T_{ilj}^t: the establishment time for mobile blood center I of the main center j in the potential center i in the period t

m_i: number of beds in potential center i

k_i: capacity of mobile centers in potential center i

In_{jar}^t: stock of product r in main center j with remained life cycle a in the period t

F_{jarh}^t: the amount of shipped product r with remained life cycle a from main center j to hospital h

$G_{j_1j_2}$: if main center j_1 can send its extra blood to main center j_2 then 1 else 0

O_{jr}^t: waste amount of product r in main center j in period t

X_{ilj}^t: if potential center i in period t is assigned to mobile center I from the main center j then 1 else 0

w_{ij}: if main center j covers the potential center i then 1 else 0

$Qg_{raj_2j_1}^t$: shipped amount of blood from blood center j_1 to j_2

$Qs_{raj_1j_2}^t$: shipped amount of blood from main blood center j_1 to j_2

Y_{lj}: if mobile center i is assigned to main center j then 1 else 0

Z_{jh}: if the demand of hospital h is assigned to main center j then 1 else 0

P_{jr}^t: not responded demands (lack of blood products)

s_{ijl}^t: the amount of shipped blood from potential center i by mobile center j which is assigned to the main center I

3.3.4 Proposed model. In the model, the first function, or Function (1), aims to minimize the cost of not fulfilled demand, cost of perishing existing stock, cost of shipment from collecting centers to main centers and transferring blood between main centers.

$$\text{MIN} \sum_t \sum_j \sum_r P_{jr}^t C_r + \sum_t \sum_j \sum_r Co_r O_{jr}^t + \sum_t \sum_j \sum_l \sum_i cs_{ij} X_{ijl}^t \left\lfloor \frac{T_{ilj}^t}{e - tt_{ij}} \right\rfloor$$
$$+ \sum_{j_1} \sum_{j_2} CC \, dd_{j_1 j_2} G_{j_1 j_2}$$

Function (3) aims to minimize the waiting time for donors in mobile centers.

$$\text{Min} \sum_t \sum_l \sum_j \sum_i \frac{L_i}{\bar{\lambda}_i} X_{ijl}^t$$

Function (3) aims to minimize the establishment time of mobile centers in potential centers.

$$\text{Min} \sum_t \sum_l \sum_j \sum_i T_{ijl}^t X_{ijl}^t$$

Function (4) calculates the input rate of donors in mobile blood centers.

$$\bar{\lambda}_i = \lambda_i (1 - \pi_i) \quad \forall i$$

Function (5) calculates the probability of the presence of k donors in a mobile blood center.

$$\pi_i = \left(\frac{\lambda_i}{\mu_i}\right)^{k_i} \left(\frac{m_i^{(k_i - m_i)}}{k_i!}\right) \Bigg/ \left[\sum_{n=0}^{m_i - 1} \left(\frac{\lambda_i}{\mu_i}\right)^{k_i} \left(\frac{1}{k_i!}\right) + \left(\frac{\lambda_i}{\mu_i}\right)^{m_i} \left(\frac{1}{m_i!}\right) \sum_{n=m_i}^{k_i} \left(\frac{\lambda_i}{m_i \mu_i}\right)^{k_i - m_i} \right] \quad \forall i$$

Function (6) calculates the probability of the presence of no donors in a mobile blood center.

$$\pi_{0i} = 1 \Bigg/ \left[\sum_{n=0}^{m_i - 1} \left(\frac{\lambda_i}{\mu_i}\right)^n \left(\frac{1}{n!}\right) + \left(\frac{\lambda_i}{\mu_i}\right)^{m_i} \left(\frac{1}{m_i!}\right) \sum_{n=m_i}^{k_i} \left(\frac{\lambda_i}{m_i \mu_i}\right)^{n - m_i} \right] \quad \forall i$$

Function (7) calculates the average of customers in a potential center waiting for service.

$$Lq_i = \frac{\pi_{0i}}{m_i} \left(\frac{\lambda_i}{\mu_i}\right)^{m_i} \frac{\frac{\lambda_i}{m_i \mu_i}}{\left(1 - \frac{\lambda_i}{m_i \mu_i}\right)^2} * \left[1 - \left(\frac{\lambda_i}{m_i \mu_i}\right)^{k_i - m_i + 1} \right.$$
$$\left. - \left(1 - \frac{\lambda_i}{m_i \mu_i}\right)(k_i - m_i + 1)\left(\frac{\lambda_i}{m_i \mu_i}\right)^{k_i - m_i} \right] \quad \forall i$$

Function (8) calculates the average of customers in a potential center.

$$L_i = Lq_i + m_i - \pi_{0i} \sum_{n=0}^{m_i - 1} \left(\frac{\lambda_i}{\mu_i}\right)^n \frac{m_i - n}{n!} \quad \forall i$$

Function (9) guarantees that the capacity of the mobile center is more than servers.

$$k_i \geq m_i \quad \forall i$$

Function (10) guaranteed that the efficiency of a system is maximum.

$$\frac{\overline{\lambda}_i}{m_i \mu_i} \leq 1 - \varepsilon \quad \forall i$$

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Function (11) shows the maximum number of servers.

$$m_i \leq M \quad \forall i$$

Function (12) shows the upper bound and lower bound of the capacity of each mobile center.

$$hX_{ilj}^t \leq k_i \leq HX_{ilj}^t \quad \forall i, l, j, t$$

Function (13) shows the maximum time that a mobile center can be established in a potential center.

$$T_{ijl}^t \leq BX_{ilj}^t \quad \forall i, l, j, t$$

Function (14) shows the input blood to main centers.

$$T_{ijl}^t \overline{\lambda}_i X_{ilj}^t = s_{ijl}^t \quad \forall i, l, j, t$$

Function (15) guarantees that each mobile center in each period can be assigned to a maximum of one potential center.

$$\sum_i X_{ilj}^t \leq 1 \quad \forall l, j, t$$

Function (16) guarantees that each area is covered by only one mobile center.

$$\sum_l X_{ilj}^t \leq 1 \quad \forall i, j, t$$

Function (17) guarantees that in each planning period collect blood from each area is done at most once.

$$\sum_t X_{ilj}^t \leq 1 \quad \forall i, j, l$$

Function (18) indicates an area is covered by the main center only if it is in the distance limitation.

$$d_{ij} w_{ij} \leq E \quad \forall i, j$$

Function (19) guarantees collecting blood from each area is done by a mobile center assigned to the main center that covers that area.

$$X_{ilj}^t \leq Y_{lj} \quad \forall i, j, l, t$$

Function (20) indicates blood collection is done by a mobile center only if the mobile center is assigned to the main center that covers that area.

$$X_{ilj}^t \leq w_{ij} \quad \forall i, j, l, t$$

Function (21) guarantees that each mobile center is assigned to exactly one main center.

$$\sum_j Y_{lj} = 1 \quad \forall l$$

Function (22) guarantees that each hospital is under the coverage of exactly one main center.

$$\sum_j Z_{jh} = 1 \quad \forall h$$

Function (23) guarantees that each blood collecting area is under the coverage of exactly one main center.

$$\sum_j w_{ij} \leq 1 \quad \forall i$$

Function (24) calculates the amount of product r with maximum life cycle for each main center.

$$In_{jra}^t = \sum_i \sum_l (1-\alpha)s_{ijl}^{t-1} X_{ilj}^{t-1} - \sum_h F_{jrah}^t + \sum_{j_2} Qg_{raj_2 j_1}^t - \sum_{j_2} Qs_{raj_1 j_2}^t$$

$$\forall t, j, r, a = Rl_r, j_1 \in j$$

Function (25) indicates the blood existing stock with remained life cycle less than maximum life cycle.

$$In_{jra}^t = In_{jra+1}^{t-1} - \sum_h F_{jrah}^t + \sum_{j_2} Qg_{raj_2 j_1}^t - \sum_{j_2} Qs_{raj_1 j_2}^t \quad \forall t, j, r, a < Rl_r, j_1 \in j$$

Function (26) calculates the amount of expired blood in each period which is equal to the amount of blood with life cycle 1 from the previous period.

$$O_{jr}^t = In_{jra}^{t-1} \quad \forall j, r, a = 1, t$$

Function (27) indicates the distance limitation for assigning a hospital to the main center.

$$td_{jh} Z_{jh} \leq SS \quad \forall j, h$$

Function (28) calculates the shortage amount of each product in each main center for each period which is equal to the demanding amount of all hospitals minus the amount of blood shipped to the hospitals.

$$\sum_h De_{hr}^t Z_{jh} - \sum_h \sum_{a=1}^{Rl_r} F_{jrah}^t = P_{jr}^t \quad \forall h, t, r, j$$

Function (29) guarantees the amount of blood shipped to a hospital is not more than the demanding amount of that hospital.

$$\sum_{a=1}^{Rl_r} F_{jrah}^t \leq De_{hr}^t \quad \forall h, t, r, j$$

Function (30) guarantees the amount of receiving blood for each main center from other centers should not be more than the shortage amount of that main center.

$$\sum_{a=1}^{Rl_r} \sum_{j_2} Qg^t_{raj_2j_1} \le P^t_{jr} \quad \forall j,\ t,\ r,\ j_1 \in j$$

Function (31) guarantees the amount of shipped blood from each main center cannot be more than the existing stock of that main center.

$$\sum_{a=1}^{Rl_r} \sum_{j_2} Qs^t_{raj_1j_2} \le \sum_{a=1}^{Rl_r} In^t_{jra} \quad \forall j,\ t,\ r,\ j_1 \in j$$

Function (32) indicates the distance limitation between two main centers for transferring blood.

$$dd_{j_1j_2} G_{j_1j_2} \le N \quad \forall j_1,\ j_2 \in j$$

Function (33) guarantees that the model does not transfer blood from the main center to itself.

$$G_{j_1j_2} = 0 \,|\, j_1 = j_2 \in j$$

Function (34) and Function (35) indicate transferring blood between two main centers is possible only if there is permission for such transfer. These two formulas are written separately for avoiding the model from becoming nonlinear.

$$Qg^t_{raj_2j_1} \le u\, G_{j_1j_2} \quad \forall t,\ a,\ r,\ j_1,\ j_2 \in j$$

$$Qs^t_{raj_1j_2} \le u\, G_{j_1j_2} \quad \forall a,\ t,\ r,\ j_1,\ j_2 \in j$$

Function (36) indicates that blood from the main center to a hospital can be transferred only if that hospital is assigned to that main center.

$$F^t_{jrah} \le u\, Z_{jh} \quad \forall j,\ a,\ t,\ r,\ h$$

Function (37), Function (38) and Function (39) indicate variable types of this model.

$$In^t_{jra},\ O^t_{jr},\ Qg^t_{raj_2j_1},\ Qs^t_{raj_1j_2},\ F^t_{jrah},\ P^t_{jr},\ s^t_{ilj},\ k_i,\ m_i \ge 0,\ int$$

$$X^t_{ilj},\ G_{j_1j_2},\ Z_{jh},\ Y_{lj},\ w_{ij} \in \{0,1\}$$

$$T^t_{ijl} \ge 0$$

3.4 NSGA-II algorithm
NSGA-II is a solid multi-objective algorithm, widely used in many real-world applications. While today it can be considered as an outdated approach, NSGA-II has still a great value, if not as a solid benchmark to test against. NSGA-II generates offspring using a specific type of crossover and mutation and then selects the next generation according to nondominated-sorting and crowding distance comparison. One of the common methods for solving multi-objective problems is NSGA-II that is an improved version that is based on a genetic algorithm (GA) and we used it for our problem-solving.

As you see in Figure 1, the algorithm is composed of different steps. And this algorithm is an iterative algorithm that after certain iterations converges to the optimum result. The main important part of this algorithm is the genetic operator that uses genetic selecting, crossover and mutation to find the optimum population.

Figure 1.
The flowchart of
NSGA-II algorithm
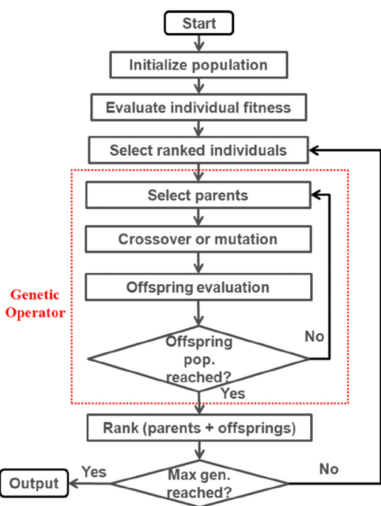
4. Performance evaluation

In this section after solving small problems, evaluate the results and evaluate the performance of the algorithms explained in the previous section. Since the proposed model is multi-objective and some of the parameters are based on probability, we first assume the model as single objective and also definitive parameters and solve the model accurately by GAMS software and then we solve the same problems by the GA that is the core of our proposed algorithm (NSGA-II). Later after proving the performance of GA, we solve the complete model, considering all objectives and probable variables using the NSGA-II algorithm.

4.1 Parameters definition

In this research, we work with two kinds of parameters, the parameters with definitive and constant value and the parameters produced by statistical distributions. Table 1 below shows the definition of the parameter for this research.

4.2 Computational results

The problem with mentioned parameters in part 4.1 is solved by GAMS software for small and medium-dimension problems. The result is shown in Table 2. For solving the model accurately GAMS software version 24.2 and solver CPLEX are used in the integer linear

Parameter	Value and distribution	Parameter	Value and distribution
A	$U \sim (0.01, 0.05)$	E	200
B	480 min	N	300
d_{ij}	$U \sim (10, 400)$	SS	200
tt_{ij}	$60 \times d_{ij}/\text{Velocity} = N \sim (90, 10)$	td_{jh}	$U \sim (50, 500)$
e	180 min	$dd_{j_1 j_2}$	$U \sim (150, 500)$
CO_r	$U \sim (20000, 50000)$	cs_{ij}	$5000 \times d_{ij}$
C_r	$U \sim (20000, 50000)$	RL_r	$RL_1 = 3, RL_2 = 15$
CC	5,000	De_{hr}^t	$U \sim (20, 80)$

Table 1.
Parameters definition

model condition. Since the model is multi-objective and nonlinear and because of probable parameters, it is not possible to code and solve the model even in small dimensions. Therefore, by removing two goals of models and removing part of the limitations related to the queue, we made the solution possible. Note that THR stands for Period, Hospital, Product type, Collecting, Main center, Potential center.

The model was solved in various dimensions by GAMS and MATLAB. The time of accurate solution was bound to 7.441 s. As Table 2 shows, GAMS is not able to solve the model in the dimension of 40 potential centers, 2 main centers, 10 mobile centers, 2 products, 30 hospitals and 25 periods. Therefore, to achieve the results in bigger dimensions and less time, we used the GA algorithm.

4.3 Case study

In this part, we solve the model using the NSGA-II algorithm considering all the objectives of the model and all the limitations of the problem. For this study, input parameters are selected based on Table 3 and other parameters such as model size and index values are selected based on Table 4.

The Parto graph of the algorithm NSGA-II is shown in Figure 2.

The result of solving the model is shown in Table 5. Note that because of the probable nature of the model, accurate solving software could not solve it.

	GA		GAMS		THR
GAP %	Time	Goal	Time	Goal	Dim
0	31.2	5,660,000	0.016	5,660,000	6-5-1-2-1-10
0.082	88.2	8,213,000	0.125	7,540,000	14-10-1-4-1-20
0.093	372	280,914,000	1762.36	254,830,000	15-20-2-5-2-25
	473.4	430,215,000			25-30-2-10-2-40
	1042.8	758,703,000			30-50-2-13-2-8-

Table 2.
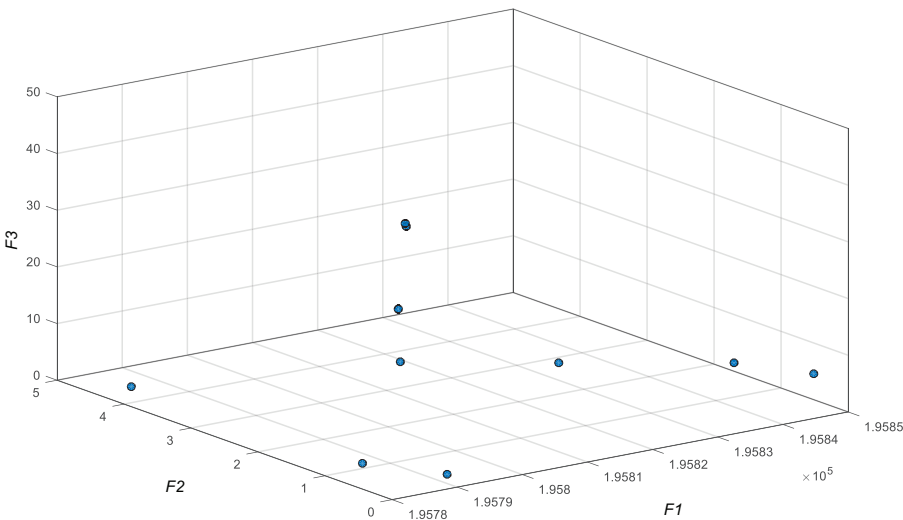Objective function values after solving the problem as a single objective problem

Parameter	Value and distribution
μ_i	Poisson $\sim$ (20)
λ_i	Poisson $\sim$ (40)
H	10
h	4
M	4

Table 3.
The model parameters

Parameter	Value and distribution
I	52
J	2
L	10
R	2
T	30
A	25
H	57

Table 4.
The model dimensions

Figure 2.
The Parto graph of
NSGA-II

Results	NSGA-II Goal 1	Goal 2	Goal 3
Result 1	195,784	0.1795	46.607
Result 2	195,784	0.1846	47.093
Result 3	195,784	4.2777	1.0446
Result 4	195,834	2.7617	0.5846
Result 5	195,846	0.1251	7.1325
Result 6	195,834	0.1435	11.613
Result 7	195,790	0.1435	1.6983
Result 8	195,784	0.8277	2.0946
Result 9	195,784	0.2949	31.535
Result 10	195,784	0.2660	22.272

Table 5.
Objective function
values

4.4 Parameters setting

For parameter setting, we used the Taguchi method. Taguchi method is a strong experimental design that converts variable values of the result to a rate called the signal to noise (S/N). Generally speaking, signal points to optimum value (mean of result variable) and noise points to nonoptimum value (standard deviation). Therefore, the S/N rate points to the distribution value of the result variable. Taguchi also categorizes objective functions into three categories included the smaller the better, the bigger the better and the nominal amount. Based on the description above, the initialization of the parameters is in Table 6. Then different scenario composed of various levels is presented for selecting parameter values.

	Level 1	Level 2	Level 3
Crossover	0.95	0.9	0.8
Mutation	0.01	0.05	0.1
Population	50	20	10
Max iteration	100	50	20

Table 6.
Initial parameter
design

According to Taguchi instead of $3^4 = 81$ possible combinations (Fazli-Khalaf *et al.*, 2019), we have only nine scenarios, and parameters for each scenario was shown in Table 7.

Later in this section for these nine scenarios, we will have six examples and five iterations for each combination, and the table of the objective function, S/N and RPD is presented. After solving each example of each scenario five times, the following average is achieved for the objective function of each scenario.

In every iteration, according to the Taguchi method, the achieved objective function should be converted to signal-to-noise ratio that is the result variable, and the analysis is done based on its changes. In the Taguchi method, the ratio S/N is a ratio variable and in each iteration, the objective function is converted to this ratio based on the formula below.

$$\left(\frac{S}{N}\right)_s = -10\log_{10}\left(\frac{\sum y_i^2}{n}\right)$$

The average result of running the algorithm is shown in Table 8 for each scenario. This table is RPD and demonstrates the performance of the algorithm. RPD that is abbreviated for Relative Percentage Deviation is computed according to the formula below.

$$\text{RPD} = \frac{M_i - M_{\min}}{M_{\min}}$$

Now based on numbers calculated in this section, we draw the common diagrams in the Taguchi method. Finally, we decide about the scenario and required parameter selection (see Figures 3–5).

For selecting the best scenario, we choose the highest value for each level from S/N. If these values are very close to each other, we refer to RPD and choose the lowest value for each level.

Scenario	Crossover	Mutation	Population	Max iteration
Scenario 1	1	1	1	1
Scenario 2	1	2	3	2
Scenario 3	1	3	2	3
Scenario 4	2	3	3	3
Scenario 5	2	2	2	1
Scenario 6	2	3	1	2
Scenario 7	3	1	2	2
Scenario 8	3	2	1	3
Scenario 9	3	3	3	1

Table 7. Problem scenario design

Scenario	Average
Scenario 1	31,580,716
Scenario 2	1,346,075
Scenario 3	382636.6
Scenario 4	1,558,249
Scenario 5	7,563,922
Scenario 6	1,211,019
Scenario 7	6,976,012
Scenario 8	3,372,684
Scenario 9	595501.7

Table 8. Average for achieved objective functions from NSGA-II algorithm

Scenario	Average
Scenario 1	0.52734
Scenario 2	0.484011
Scenario 3	0.504859
Scenario 4	0.514896
Scenario 5	0.431364
Scenario 6	0.454843
Scenario 7	0.506213
Scenario 8	0.499034
Scenario 9	0.495434

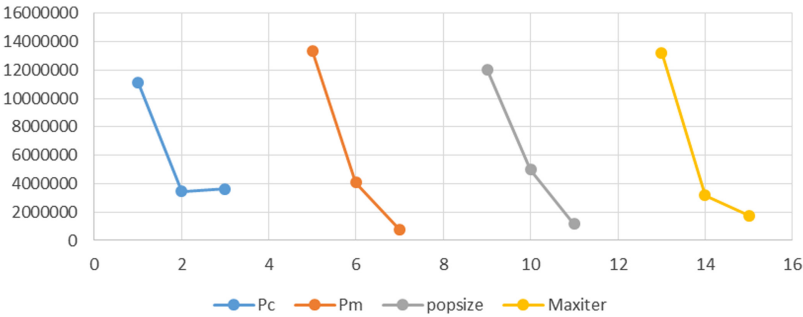**Table 9.**
RPD values

Figure 3.
The objective function

Figure 4.
The S/N diagram
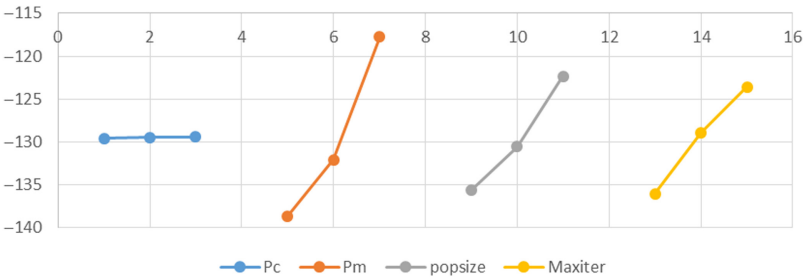
Figure 5.
The RPD diagram
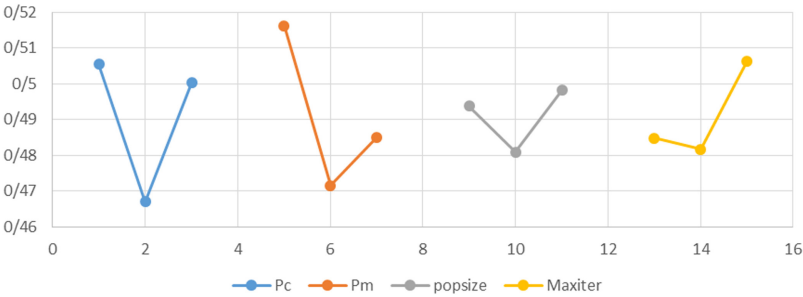
For our example, we choose level 1 from RPD. Other parameters are set based on S/N. Finally, the crossover from level 1, a mutation from level 3, the population from level 3 and iteration from level 3.

5. Conclusion and recommendations

Perishable product supply chain problems include various types in the health sector such as blood product issues. Nowadays due to the lack of viable alternatives to blood and blood products, the only blood that is donated by benevolent that can save other lives. The lack of viable alternatives, the limited shelf life and the constant need for blood and blood products from one side and random demand and irregular supply of this product from the donor, and the complexity of matching demand with supply effectively from the other side doubled the importance of this issue.

In this research, we present a new model for minimizing time and cost with the queue theory considering blood donor's roles. We aim to minimize the total cost of the blood supply chain and minimize the waiting time for donors in mobile centers; a three-level nonlinear mathematical model is presented. In this research and at all levels, blood products have a specific life cycle, and bypassing their time, they will be considered as waste products. Indeed, we presented a three-objective model and solved it with the NSGA-II algorithm. This model was based on queue theory and aimed at the placement-assignment of blood products supply chain networks. For modeling the problem, we considered real conditions such as time limitations, waiting times in blood collecting stations, the life cycle of blood, etc. combination of queue theory, and placement-assignment problem was one of the innovations of this work. Finally, we solve this model by NSGA-II and we saw that this algorithm has a good performance and in proper time can answer the problem.

Considering the importance of uncertainty and resilience in supply chain management (Mahmoudi *et al.*, 2021), in the future, the issue of uncertainty in the number of donors, as well as the importance of blood donors can also be considered to develop robust and resilient frameworks. The focus of this study is on blood donation and the benefits for health-care sectors. The study help reduces stress in communities and improves physical health, and helps to distance oneself from negative emotions. Also, the model presented in this study can alleviate cases and restrictions related to waiting for people in need of blood, as well as improve planning in the healthcare, technology and health information sectors. Before generalizing the findings of the study across the board, future studies can apply the proposed model in different environments, so its significant strengths and limitations are known.

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