A LOCATION-ALLOCATION MODEL FOR QUALITY-BASED BLOOD SUPPLY CHAIN UNDER IER UNCERTAINTY

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Abstract. Providing blood with high quality at the lowest cost and the shortest time is main challenge of blood supply chain management. This paper presents a new model for designing a dynamic and three level blood supply chain incorporating the quality issues. The proposed model intends to locate facilities, and to determine the best strategy for blood allocation by minimizing both cost and time and maximizing the customer satisfaction based on quality of blood delivery. In order to deal with consideration of real world, intricacies such as blood freshness, both separation and apheresis extraction methods, Cross match to Transfusion ratio (C/T) and equipment failure have been involved. Also, Interval Evidential Reasoning (IER) approach is applied to handle the uncertainty of blood product demand. Since the proposed model is NP-hard, MOPSO and NSGAII algorithms are utilized to solve it. Finally, to demonstrate the applicability of the problem some numerical examples are designed in different sizes and the most favorable algorithm is determined using TOPSIS method.

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1. Introduction

Blood is a highly perishable product in nature that is related to human life and its supply chain is a critical problem. Among specific characteristics of blood supply chain, the quality concern is the most significant one. Nowadays, organizations are passing from the traditional supply chain management to supply chain quality management. Supply chain quality management which leads to improve performance, focuses on value creation and meeting satisfaction of customers [17,37]. Best practices of supply chain quality management are detected in principles of Total Quality Management (TQM). Key principles of TQM are as follows [29]:

– Define quality based on requirements of costumers.
– Follow quality at the source.
– Emphasize objective analysis instead of subjective analysis.
– Stress prevention of defects rather than identifying them.
– Concentrate on process rather than output.
– Try to achieve zero defects.
– Focus on continuous improvement.

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– Inculcate that quality is responsibility of all staff.

Despite key role of quality management in supply chain; exploring quality of blood supply chains has not been widely discussed. High quality of blood supply chain is dependent on adequate financial resources, skilled and experienced staff, high quality of blood delivery, availability of holding and laboratory equipment, appropriate holding and transportation conditions, correct patient identification and effective quality management systems. Therefore, the main objective of this study is presenting a new location-allocation model to design a multi-product and multi-period blood supply chain network in which principles of TQM inclusive preventive maintenance, quality control system, inspection, staff training and performance evaluation are contributed for the first time to satisfy customer expectations. To deal with real world considerations, uncertainty of blood demand is considered and Interval Evidential Reasoning (IER) approach is used to cope with it. The objective functions of the proposed model consist of minimizing the total cost and time spent on the blood supply chain and maximizing quality of blood delivery.

In order to solve the model in large dimensions, MOPSO and NSGAII metaheuristics algorithms are executed. The following decisions are made by solving the model:

– Number and location of blood collection centers and blood transfusion centers.
– Allocation of blood collection centers to blood transfusion centers.
– Allocation of blood transfusion centers to hospitals.
– Inventory level of facilities including blood collection centers, blood transfusion centers and hospitals at each time period.
– Quantity of blood products to be produced at blood transfusion centers.
– Quantity of blood products to be transferred from each level to the next level through vehicles in the network.
– Quantity of blood shortage at hospitals.

The rest of this paper is organized as follows:

Section 2 deals with the relevant literature, research gaps, and contributions of the paper. Section 3 explains the structure of blood supply chain in detail and proposed mathematical model. the Interval Evidential Reasoning (IER) approach is described in Section 4. In Section 5, some numerical examples are designed and the suggested algorithms are implemented. Finally, the results and concluding remarks as well as directions for further studies are summarized in Section 6.

2. LITERATURE REVIEW

2.1. Location-allocation models for blood supply chain

Pierskalla [34] presented an overview of optimization models to allocate donors to blood transfusion centers that determine the optimal number and location of centers in each region and matches supply and demand. Nagurney *et al.* [32] proposed a two-objective and single period optimization model for localization of blood bank systems, including collection centers, processing facilities, storage facilities, distribution centers, and hospitals with probabilistic demand and determined optimal allocations, risk supply and waste costs through the model. The their model aims to minimize total operating costs, waste disposals costs in each route, penalty costs for warehouses and costs of lack of demand, as well as minimizing the total supply risks on different routes. Nagurney *et al.* [31] developed the previous model to determine the optimal flow in each route and to add costs of increasing capacity. Muriel *et al.* [30] suggested bi-objective integer linear programming model for donor's allocation in the blood supply chain. The objective functions consider total cost minimization and amount of donors required. Hemmelmayr *et al.* [20] decided on the selection of hospitals that should be covered daily by blood transfusion vehicles using integer programming models. The authors also considered the uncertainty in demand and determined the amount of required blood in each hospital per day. Kaveh and Ghobadi [22] proposed an algorithm that allocates blood transfusion centers based on p-median methodology and metaheuristic optimization algorithms. Da *et al.* [10] nominated a strategic model for determining and locating donation areas

and blood bank. They stated that the blood supply chain should be viewed as a general system, not a sub system. Daskin and Shen [11] and Shen *et al.* [43] developed nonlinear integer single period location-inventory models for blood supply of hospital to determine the number and location of blood transfusion centers and the inventory level in each center. Also, they proposed heuristic methods to solve the complex models. Cetin and Sarul [6] proposed a multi-objective model for locating blood banks among hospitals and clinics u, with the aim of minimizing location cost and distance between blood banks and hospitals. Shahin *et al.* [39] introduced a single period p-median location-allocation model for regionalization of the Turkish Red Crescent blood service, considering hierarchical services that consist of regional blood transfusion centers, blood stations and mobile units, assuming the concentration of city demand on one place. The aim of the model is to minimize the weighted distance and the number of blood stations and maximizing the covered population. Alfonso *et al.* [2] provided a model for locating fixed and mobile blood collection facilities in France and also examined donor management. Arvan *et al.* [4] designed a supply chain network composed of donated points, laboratories, central blood banks and hospitals, with the goal of minimizing total transportation and operational costs, as well as minimizing the perishability of blood. The model focuses on locating blood donation centers and blood banks and contained most of the intricacies in blood supply chain such as transshipments between demand points, blood waste and blood decomposition in laboratory facilities.

Salehipour and Sepehri [41] dealt with blood distribution management to minimize total waiting time of hospitals and medical centers and tackled a real problem containing 24 hospitals. Şahinyazan *et al.* [40] examined how blood from mobile centers is collected and sent to blood banks. They considered a vehicle for each district to move from a blood bank, collect donated blood from temporary centers, and then return to the same blood bank.

For designing a blood supply chain network, Zahiri and Pishvaee [47] proposed a bi-objective MILP model that minimizes the total cost and maximum unsatisfied demand, and considers blood group compatibility and uncertainty of parameters.

2.2. Quality in supply chain management

There are many studies on supply chain management and total quality management; but, few researches have been addressed integration of them.

Forker *et al.* [16] studied relation between TQM and supply chain management by combining linear (regression) and nonlinear (DEA) analyses. The results demonstrated that promoting TQM lead to better performance of the different level of supply chain. Kannan and Tan [21] examined the linkage of Total Quality Management (TQM), supply chain management and Just in time and their impact on business performance. According to results, there is a linkage between all three items at both operational and strategic levels, and focus on quality along with understanding supply chain dynamics is the main diver of performance. In 2005, Flynn and Flynn [15] examined the supply chain improved through quality management approach. In this regard, four hypotheses were developed and tested, and eventually, they approved that there was a positive relation between two approaches. Casadesu's and de Castro [5] analyzed the effect of standardized quality management system on supply chain performance improvement. They found that it is beneficial for successful SCM. Romano and Vinelli [38] addressed how to manage quality through the supply chain perspective. Outcome revealed that supply chain can meet the consumer expectations in terms of quality by the co-management of quality practices. Chen *et al.* [7] proposed an analytical framework for dual-channel supply chain focusing on services and quality effort. Results showed that customer loyalty to the channel has impact on the retailer's and manufacturer's services and quality strategies. Fynesa *et al.* [18] extended a conceptual framework to survey effect of dimensions of supply chain relationships on quality performance. To manage quality effectively in supply chain, Lin *et al.* [26] recognized the factors influencing the supply chain quality management (SCQM) using data collected from Hong Kong and Taiwan. The results indicated that Quality Management (QM) practices are correlated with the supplier selection and participation strategy. Lo and Yeung [27] identified critical SCQM items and clustered them in three groups: supplier selection, supplier development and supplier integration. Their study has not covered the relationship among supplier quality, buyer quality and supply quality management. Kaynak and Hartley [23]

in their work on extension of quality management into the supply chain, found that the coverage of supplier quality management and customer focus in the QM model confirm the importance of internal and external integration for quality performance. In 2008, a study has been conducted by Foster [17] to understand the effect of practice of quality management in supply chain management. They defined SCQM and identified Key quality management variables including supplier relations, quality practices, customer focus, leadership, safety, HR practices and business results.

2.3. Preventive maintenance in supply chain management

Abdul Malik *et al.* [28] surveyed the effect of disruption factors including equipment failure, shortage of supply and lack of buying power on supply chain of Small and Medium Enterprises (SMEs). They found that equipment failure has the strongest effect on their supply chain performance. Khosrojerdi *et al.* [25] described a method for robust designing of power grid supply chain structure and scheduling preventive maintenance considering power supply failures scenarios. The results demonstrate that targeted failures impact on the performance of the power grid with a higher degree than random failure. Aldaihani *et al.* [1] determined the optimal production lot size and preventive maintenance schedules for supply chain with one producer and multiple newsvendors assuming that production process may fail at any time of production run.

2.4. Quality (freshness) of the perishable product

Kendall and Lee [24] applied a goal programming model to improve perishable product inventory. The model intends to reduce shortages, wastage and excessive costs, and maintain quality (freshness) of the product. Amorim *et al.* [3] proposed production and distribution planning as a multi-objective model for perishable products with fixed and loose shelf-life to meet customer satisfaction in terms of both economic and freshness aspects. Ogier *et al.* [33] presented a mixed integer programming formulation to design a short and local fresh food supply chain network. They developed effective techniques to solve the model. Pires *et al.* [35] addressed production planning of perishable food covering main complexities such as value of freshness, expiry dates, age dependent demand, customers' behavior and discarding costs. Gunpinar and Centeno [19] formulated integer programming models for reducing the total cost, shortage and wastage levels of blood products involving red blood cells and platelets at hospitals. They incorporated two types of patients, blood age, uncertain demand rates and crossmatch-to-transfusion ratio in the models. Farahani *et al.* [14] integrated production and distribution planning for perishable food products in the form of mixed integer programming modelling approach to investigate how the quality of delivered food products can be improved through decreasing the time interval between delivery and production.

As the existing literature reveals, many studies have focused on the Location-allocation of blood supply chain. Also, some papers have taken quality management and preventive maintenance in supply chain but none of them incorporate these items in blood supply chain. Moreover, only small numbers of researches have considered the complete (three level) structure of blood supply chain.

Motivated by the research gap found in the literature, we propose a mathematical model considering various dimensions of quality and different complexities of blood supply chain. The dimensions which distinguish this study from relevant works are as follows:

- Three level structure of blood supply chain including blood collection centers, blood transfusion centers and hospitals.
- Different types of blood products (whole blood, red blood cells and platelets) with different lifetime.
- Two types of collection methods including whole blood and apheresis collection.
- Quality concepts including quality of blood delivery, preventive maintenance, blood bag inspection, quality control of blood products, staff training, performance evaluation, infection disease and cross match tests, returning the products (due to expiration dates, inappropriate transportation condition, etc.), penalty of late/early delivery of blood products at hospitals and staff safety.

– Integrated location-allocation model along with simultaneous minimization of time and cost and maximization of quality of blood delivery.
– Most important costs associated with quality (evaluation, prevention and failure), production, holding, transportation, waste, shortage, product returning, equipment, inspections, etc.
– Most important time spent on the blood supply chain: transportation, processing, cross match release period, preventive maintenance, stop times of equipment, inspection, etc.
– Quantifying quality of blood delivery as a function of the blood freshness, rate of coverage of blood demand and utility of lead time.
– Taking into account uncertainty of the demand and using IER approach to handle the uncertainty.
– Intricacies such as age-dependent blood demand, Cross-match to Transfusion ratio (C/T), blood freshness, equipment failure and vehicles with limited number and capacity.

3. Problem definition and mathematical model

3.1. Blood supply chain

Blood supply chain is comprised of blood collection centers, blood transfusion centers and hospitals. It begins with blood collection and ends with blood transfusion to patients. In detail, supply chain process is as follows:

Blood collection centers and blood transfusion centers are constructed at potential points. First, whole blood donors go to one of the blood collection centers voluntarily, and after various examinations, they donate blood. Then, the donated blood is sent to warehouse of blood collection center. At the warehouse, the received blood will waste if holding equipment (refrigerators, etc.) fails or holding condition is not appropriate (temperature, light, etc.). At each time period, this process is repeated for a short time at blood collection centers. Thereafter, all the remaining healthy whole blood at warehouse of blood collection centers is transferred to blood transfusion centers with limited reception capacity by allocated and capacitated vehicles in less than a few hours.

In blood transfusion centers, once the whole blood is received, initial control on blood bags in terms of hemolysis, clots, and discoloration is carried out and some of the bags are returned. The remaining healthy blood bags are sent to the warehouse 1 with limited capacity and their samples are sent to the laboratory for infection disease (HIV, hepatitis, etc.) tests. The blood bags remain in warehouse 1 until the test results are determined (end of the period). There is also a possibility of waste due to equipment failure and holding conditions in this warehouse.

After determining the test results, the percentage of healthy whole blood is sent to separation unit to be converted to the blood products (random products), a fixed percentage of them is sent to Quality Control (QC) unit and the remaining bags are sent to the inspection unit. Per blood bag sent to the separation unit, two bags of blood products including platelets and red blood cells are obtained. A percentage of the products is sent to the QC control to ensure the quality of them and remaining percentage is sent to inspection unit.

On the other hand, apheresis donors also come to blood transfusion centers and their blood samples are tested, and if they are healthy, apheresis will be done. As well as random products, percentage of blood products obtained through apheresis (apheresis products) is sent to the QC unit for quality control and remaining of them is sent to inspection unit.

In inspection unit, bags of blood products including whole blood are controlled and approved products are sent to warehouse 2. Considering the key role of blood in human health, samples sent to the QC unit will be approved if none of them are defective. In the case of sample acceptance, the products in warehouse 2 are transferred to blood distribution unit and in the case of non-acceptance, inventory of warehouse 2 is considered to be defective. the healthy products along with sent whole blood are transferred to the blood distribution section.

According to demands of hospitals based on the age of the blood products in a clear time window, the blood transfusion centers transfer the blood bags containing whole blood and random and apheresis products to the hospitals by allocated vehicles . The sent blood bags are controlled at the time of receipt, and some of them are returned. Healthy blood bags are sent to unallocated warehouse and cross-match test is carried out on samples

of them. Considering blood waste at unallocated warehouse, blood products with positive test results are sent to allocated warehouse and remained for a certain time period called the liberalization period of cross-match and eventually transfused into the patients. Figure 1 depicts structure of the blood supply chain network.

3.2. Description of model

In this paper, we proposed a new model for three level blood supply chain emphasizing on TQM principles to attain high quality of blood delivery at low time and cost. Best practices in blood supply chain quality management based on TQM principles considered in the model can be clustered in four critical elements of the supply chain:

Costumers. Timely delivery of appropriate blood, as close as possible to the demand, to the end customer (patients) has remarkable effects on the supply chain. Freshness is one of the main characteristics of high quality blood products in view point of costumers specially those who are vulnerable to bacterial contamination. In the model, quality of blood delivery is defined based on blood freshness, rate of coverage of blood demand and utility of lead time.

Processes. TQM principles emphasize on source inspection, process control to identify, track and improve root cause analysis. Therefore, providing infectious diseases and cross match tests and inspection of final blood products are not enough for improving quality of blood supply chain. In this paper, continuous performance evaluation and quality control of blood products are considered in addition to the mentioned items.

Equipment. Due to key role of equipment of blood supply chain (refrigerators, freezers, agitators, etc.) in processing, holding and transportation of blood, failure of this equipment at any stage of the supply chain is very costly and leads to blood wastage. However, it is inevitable to have some failures. To minimize the occurrences of such failures, ways such as preventive maintenance (PM) which is scheduled activity should be performed.

Staff. Quality is not just the responsibility of quality inspectors. Each staff should be aware of the quality problem and trained to collaborate in improving quality.

3.2.1. Assumptions

– The problem is multi-period, multi-product and multi-vehicle.
– Planning horizon is short time.
– Each period is equivalent to one day and the times are in hours.
– Blood products include whole blood, platelets and red blood cells.
– Platelets and red blood cells can also be produced through apheresis.
– Unit of the blood products is blood bag.
– Age of blood products is known and changes overtime.
– Blood demand at hospitals in uncertain and IER approach is used to handle the uncertainty.
– Capacity of warehouse of blood collection centers, capacity of warehouses 1, blood distribution unit and QC unit at blood transfusion centers and capacity of unallocated warehouse of hospitals are limited.
– The number of vehicles allocated to blood collection centers and blood transfusion centers is known and capacity of them is limited.
– The number of equipment at each facility is known.
– Blood collection centers and blood transfusion centers are located by solving the model, but the location of the hospitals is fixed.
– Preventive maintenance is implemented at each level. However, failure of the equipment is inevitable.
– Failure rate of equipment has exponential distribution.
– In equipment failure conditions, if the equipment can be repaired within a short time, they will be repaired and if they fail again, new equipment will be purchased.
– In equipment failure conditions, if the equipment is not repairable, they will be purchased immediately.
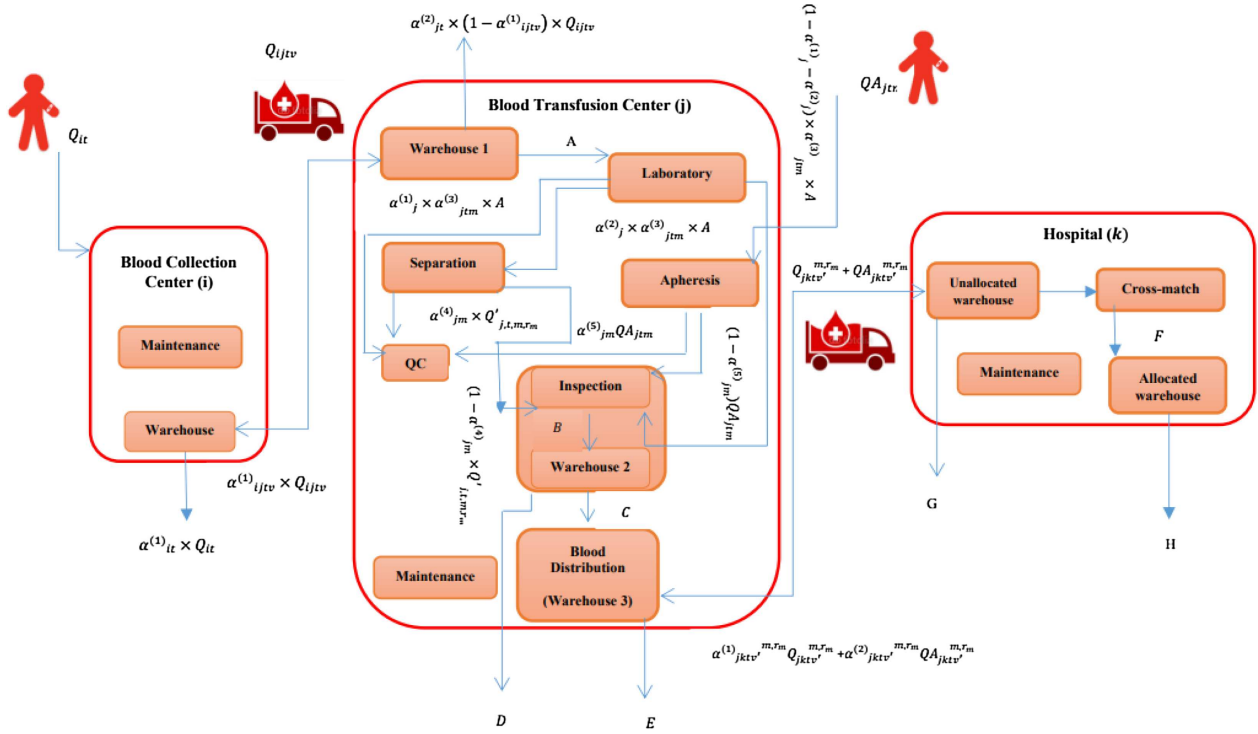
FIGURE 1. Blood supply chain model. $A = \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}$;

$B = P_{jtm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q'_{j,t,m,r_m} + PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)}\right) \times QA_{jtm} + P_{jt1} \times \left(1 - \alpha_{j}^{(1)} - \alpha_{j}^{(2)}\right) \times \alpha_{jt}^{(3)} \times A$;

$C = \left[\left(1 - \alpha_{j,t,m,r_m}^{(2)}\right) \times PQ_{jtm} \times P_{jtm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q'_{j,t,m,r_m}\right] + \left[PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)}\right) QA_{jtm} \times (1 - \alpha jtm) \times PQA_{jtm}\right] + \left[\left(1 - \alpha_{j,t,1,r_1}^{(2)}\right) \times PQ_{jt1} \times P_{jt1} \times \left(1 - \alpha_{j}^{(1)} - \alpha_{j}^{(2)}\right) \times \alpha_{jt}^{(3)} \times A\right]$;

$D = \left[\alpha_{j,t,m,r_m}^{(2)} \times PQ_{jtm} + \left(1 - PQ_{jtm}\right) \dfrac{\left(1 - EP_j^{(1)}\right) \times \sum_m \sum_{r_m} \left[P_{jtm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q'_{j,t,m,r_m}\right]}{\sum_m \sum_{r_m} Q'_{j,t,m,r_m}}\right] \times P_{jtm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times$

$Q'_{j,t,m,r_m} + PA_{jtm} \times \alpha_{jm}^{(5)} \times QA_{jtm} \times \left(1 - \alpha jtm\right) \times PQA_{jtm} + \alpha_{j,t,1,r_1}^{(2)} \times PQ_{jt1} \times P_{jt1} \times \left(1 - \alpha_{j}^{(1)} - \alpha_{j}^{(2)}\right) \times \alpha_{ft}^{(3)} \times A + \left[\alpha_{j,t,1,r_1}^{(2)} PQ_{jt1} + \left(1 - PQ_{jt1}\right) \times \sum_j \sum_t \dfrac{\left(1 - EP_j^{(2)}\right) \times \sum_i \sum_v P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}}{\sum_i \sum_v \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}}\right] \times$

$P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} + PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)}\right) QA_{jtm} \times \left[\alpha_{jtm} \times PQA_{jtm} + \left(1 - PQA_{jtm}\right) \sum_j \sum_t \dfrac{\left(1 - EP_j^{(3)}\right) \times \sum_m PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)}\right) QA_{jtm}}{\sum_m QA_{jtm}}\right]$;

$E = \left[PQ_{jm} \times \left(1 - \alpha_{j,t,m,r_m}^{(2)}\right) \times P_{jm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q'_{j,t,m,r_m} + IS'_{j(t-1)}{}^{m,r_m}\right] \alpha_{j,t,m,r_m}^{(3)} + \left[\sum_i \sum_v \sum_{r_1} PQ_{j1} \times \left(1 - \alpha_{j,t,1,r_1}^{(2)}\right) \times P_{j1} \times \left(1 - \alpha_j^{(1)} - \alpha_{(2)j}\right) \times \alpha_{jt}^{(3)} \times A + IS'_{j(t-1)}{}^{1,r_1}\right] \alpha_{j,t,1,r_1}^{(3)} + \left[PQ_{jm} \times \left(1 - \alpha_{jtm}\right) \times PA_{jm} \times \left(1 - \alpha_{jm}^{(5)}\right) \times QA_{jtm} + IA_{j(t-1)}{}^{m,r_m}\right] \alpha_{j,t,m,r_m}^{(4)}$;

$F = \left[\left(1 - \alpha_{jktv}^{m,r_m}\right) Q_{jktv}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) PC_{k,t,m,r_m} + \left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m}\right) Q_{jktv}^{m,r_m} + In_{k(t-1)}^{m,r_m} \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) - \left(\left[\dfrac{\left(\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m}\right) Q_{jktv'}{}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) \times PC_{k,t,m,r_m}}{a}\right] \times a\right) + \left[\left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m}\right) QA_{jktv}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right) PCA_{k,t,m,r_m}$;

$G = \left[\left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \times \alpha_{k,t,m,r_m}^{(5)} + \left[\left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m}\right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \times \alpha_{k,t,m,r_m}^{(6)}$;

$H = \left(\left(1 - \alpha_{jktv'}^{(1)}{}^{1,r_1}\right) Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1}\right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)}\right) \times PC_{k,t,1,r_1} - QT_{k,t,r_1}$.
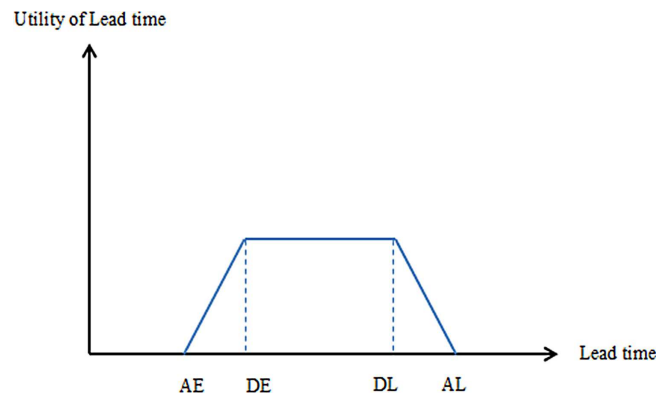
FIGURE 2. Utility of lead time in hospitals.

– At warehouses of blood collection centers and blood transfusion centers and unallocated warehouse of hospitals, blood products will be wasted if holding equipment (refrigerators, etc.) fails or holding condition is not appropriate (temperature, light, etc.)
– Holding time and cost at warehouse of blood collection centers, warehouse 2 at blood transfusion centers and allocated warehouse of hospitals are negligible.
– In each period, in blood transfusion centers, the initial tests on received whole blood is taken up to the end of the period. Therefore, in the first period, no random products are produced and only the apheresis products are prepared.
– In blood transfusion centers, due to the high cost of apheresis, the initial test is first carried out on apheresis donor blood sample and if it is healthy, the apheresis will be done. Therefore, the minimum age of the apheresis product is zero.
– Apheresis products are transferred to hospitals after approving the product in inspection and QC units and sending it to the blood distribution unit. Since all of these steps can be done in a short time, age of the sent apheresis products is at least one.
– Due to the duration of the initial test on the whole blood and the next steps, separation, inspection and quality control, age of the random products and whole blood sent to hospitals is at least two.
– In each period, whole blood, apheresis and random products are transferred to each allocated hospital simultaneously by only one vehicle.
– Utility of lead time in hospitals in terms of desirable and acceptable late and early lead time is generally illustrated in the Figure 2.
– In hospitals, whole blood transfused to patients (T) is usually less than the prepared blood for transfusion (C).
– Blood shortage in hospital is allowed.
– Patients are adults and each adult requires an average of 8 bags of random products which is equivalent of 1 bag of apheresis product. For this reason, the amount of random products sent to allocated warehouse of hospital is a multiple of 8.
– In each period, each facility will provide services to at least one of its next level facility by only one vehicle.
– In each period, each facility receives at least one service.
– In each period, each vehicle is used once.

3.2.2. Notations

Tables 1–19 represent sets, parameters and variables used in formulation of the proposed model.

TABLE 1. Sets of model.

I	Set of blood collection centers, $i = 1, \ldots, I$	V	Set of different vehicles of blood collection centers, $v = 1, \ldots, V$
J	Set of blood transfusion centers, $j = 1, \ldots, J$	V'	Set of different vehicles of blood transfusion centers, $v' = 1, \ldots, V'$
K	Set of hospitals, $k = 1, \ldots, K$	O	Set of different equipment of blood collection center, $o = 1, \ldots, O$
M_p	Set of blood products, $m = 1, \ldots, M_p$	P	Set of different equipment of blood transfusion center, $p = 1, \ldots, P$
R_m	Set of age of different blood products, $r_m = 0, \ldots, R_m$	Q	Set of different equipment of hospital, $q = 1, \ldots, Q$
T	Set of time periods, $t = 1, \ldots, T$		

TABLE 2. General parameters.

M_p	Types of blood products	T	Planning horizon time
n_v	Number of vehicles of blood collection centers	$n'_{v'}$	Number of vehicles of blood transfusion centers
R_m	Life time of blood product m	ne_{io}	Number of equipment o at blood collection center i
ne'_{jp}	Number of equipment p at blood transfusion center j	ne''_{kq}	Number of equipment q at hospital k
Q_{it}	Quantity of whole blood received from donors at blood collection center i and period t	QT_{k,t,r_1}	Quantity of whole blood with age r_1 transfused to patients at hospital k at period t

TABLE 3. Capacity parameters.

$capv_v$	Capacity of vehicle v	$capv'_{v'}$	Capacity of vehicle v'
cap_j	Capacity of blood transfusion center j for holding whole blood at warehouse 1	$capa_{jm}$	Capacity of blood transfusion center j for producing blood product m through apheresis
$capw_{km}$	Capacity of allocated warehouse at hospital k for holding blood product m	$capnw_{km}$	Capacity of unallocated warehouse at hospital k for holding blood product m
cap_{jm}	Capacity of warehouse 2 at blood transfusion center j for holding blood product m	$capd_{jm}$	Capacity of blood distribution unit at blood transfusion center j for holding blood product m
$capq_{jm}$	Capacity of Quality Control (QC) unit at blood transfusion center j for controlling blood product $m (m \geq 2)$		

TABLE 4. Demand.

d_{k,t,m,r_m}	Demand of hospital k for blood product m (including random product and whole blood) with age r_m at period t	da_{k,t,m,r_m}	Demand of hospital k for apheresis blood product m with age r_m at period t

TABLE 5. Distance parameters.

d_{ij}	Distance between i and j (per kilometer)	d'_{jk}	Distance between j and k

TABLE 6. Cost of constructing facilities and links.

F_i	Fixed cost of opening blood collection center i	F_j	Fixed cost of opening blood transfusion center j
LC_{ij}	Fixed cost of constructing a link (i,j)	LO_{ij}	Operating cost of constructed link on (i,j)
LC'_{jk}	Fixed cost of constructing a link (j,k)	LO'_{jk}	Operating cost of constructed link on (j,k)

TABLE 7. Transportation cost and time.

CT^v_{ij}	Transportation cost of one whole blood unit from blood collection center i to blood transfusion center j by vehicle v (per kilometer)	$CT^{v'}_{jkm}$	Transportation cost of one blood product m from blood transfusion center j to hospital k by vehicle v'
t^v_{ij}	Transportation time period between i and j by vehicle v	$t'_{jk}{}^{v'}$	Transportation time period between j and k by vehicle v'

TABLE 8. Production cost and time.

CM_{jm}	Production cost of one blood product m at blood transfusion center j through separation	CMA_{jm}	Production cost of one blood product m at blood transfusion center j through apheresis
tm_{jm}	Production time period of each random blood product m at blood transfusion center j	tma_{jm}	Production time period of each apheresis blood product m at blood transfusion center j

TABLE 9. Processing cost and time.

CP_i	Processing cost at blood collection center i (medical examination, ...)	CP'_j	Processing cost at blood transfusion center j (initial tests, ...)
CP''_k	Processing cost at hospital k (categorization, apheresis, ...)	tp_i	Processing time period of whole blood at blood collection center i
tp'_j	Processing time period of whole blood at blood transfusion center j	tp''_k	Processing time period of blood products at hospital k

TABLE 10. Holding cost and time.

CH_{jm}	Holding cost of one blood product m at blood transfusion center j	CH'_{km}	Holding cost of one blood product m at unallocated warehouse of hospital k
th	Total holding time of whole blood at warehouse 1 of blood transfusion center	th_j	Holding time of blood products at blood distribution unit of blood transfusion center j
th_{kt}	Holding time of blood products at unallocated warehouse of hospital k at period t		

TABLE 11. Shortage cost.

CS_{km}	Shortage cost of one random blood product m at hospital k	CSA_{km}	Shortage cost of one apheresis blood product m at hospital k

TABLE 12. Prevention cost.

CPr_i	Fixed cost of prevention at blood collection center i (employee training, designing quality procedures, ...)	CPr'_j	Fixed cost of prevention at blood transfusion center j (employee training, designing quality procedures, ...)
CPr''_k	Fixed cost of prevention at hospital k (employee training, designing quality procedures, ...)		

TABLE 13. Cost of process evaluation.

CEV_i	Fixed cost of process evaluation at blood collection center i	CEV'_j	Fixed cost of process evaluation at blood transfusion center j
CEV''_k	Fixed cost of process evaluation at hospital k		

TABLE 14. Inspection parameters.

CI_{io}	Inspection cost of each equipment o at blood collection center i	CI'_{jp}	Inspection cost of equipment p at blood transfusion center j
CI''_{kq}	Inspection cost of equipment q at hospital k	CMI_{jm}	Inspection cost of each blood product m at inspection center of blood transfusion center j
CQC_{jm}	Quality control cost of blood product m at blood transfusion center j	CER_i	Fixed cost of equipment inspection error at blood collection center i
CER'_j	Fixed cost of equipment inspection error at blood transfusion center j	$CERM_{jm}$	Fixed cost of inspection error of blood product m at blood transfusion center j
CA_{jm}	Acceptance cost of defective blood product m including whole blood and random products sent to blood distribution unit at blood transfusion center j	CAA_{jm}	Acceptance cost of defective apheresis blood product m sent to blood distribution unit at blood transfusion center j
tmi_{jm}	Inspection time period of each blood product m at blood transfusion center j	tqc_{jm}	Quality control time of blood product m at QC unit of blood transfusion center j
tc_{km}	Cross match test time for blood product m at hospital k	$\alpha^{(3)}_{jt}$	Percentage of healthy whole blood received from blood collection centers at laboratory of blood transfusion center j at period t
$\alpha^{(4)}_{jm}$	Percentage of random blood product m transferred to QC unit of blood transfusion center j	$\alpha^{(5)}_{jm}$	Percentage of apheresis blood product m transferred to QC unit of blood transfusion center j
$\alpha^{(1)}_j$	Percentage of whole blood transferred to QC unit of blood transfusion center j	$\alpha^{(2)}_j$	Percentage of whole blood devoted to separation at blood transfusion center j

TABLE 14. continued.

P_{jtm}	Percentage of healthy blood product m (including random product and whole blood) at inspection unit of blood transfusion center j at period t	Pa_{jtm}	Percentage of healthy apheresis blood product m at inspection unit of blood transfusion center j at period t
PC_{k,t,m,r_m}	Percentage of the crossmatch test with positive result carried out on blood product m (including random product and whole blood) with age r_m at hospital k at period t	PCA_{k,t,m,r_m}	Percentage of the crossmatch test with positive result carried out on apheresis blood product m with age r_m at hospital k at period t
PQA_{jtm}	Acceptance probability of apheresis blood product m at QC unit of blood transfusion center j at period t	PQ_{jtm}	Acceptance probability of blood product m (including random product and whole blood) at QC unit of blood transfusion center j at period t
$EP_j^{(1)}$	Average error percentage of production through separation at blood transfusion center j	$EP_j^{(2)}$	Average error percentage of initial tests at laboratory of blood transfusion center j
$EP_j^{(3)}$	Average error percentage of production through apheresis at blood transfusion center j		

TABLE 15. Waste parameters.

CW_i	Waste cost of one whole blood unit at blood collection center i (Due to space, holding condition, equipment failure, etc.)	CW_j^{m,r_m}	Waste cost of one blood product m with age r_m produced through separation at blood transfusion center j (Due to separation, space, holding condition, equipment failure, expiration date, cross match, etc.)
CWA_j^{m,r_m}	Waste cost of one blood product m with age r_m produced through apheresis at blood transfusion center j (Due to apheresis, space, holding condition, equipment failure, expiration date, cross match, etc.)	$CW_k'^{m,r_m}$	Waste cost of one blood product m with age r_m at hospital k (Due to canceled surgery, space, holding condition, equipment failure, high C/T, etc.)
$\alpha_{it}^{(1)}$	Waste percentage of whole blood at blood collection center i at period t	$\alpha_{jt}^{(2)}$	Waste percentage of healthy whole blood at blood transfusion center j at period t
$\alpha_{j,t,m,r_m}^{(2)}$	Waste percentage of blood product m (including random product and whole blood) with age r_m at warehouse 2 of blood transfusion center j at period t	$\alpha_{j,t,m,r_m}^{(3)}$	Waste percentage of blood product m (including random product and whole blood) with age r_m at blood distribution unit of blood transfusion center j at period t
$\alpha_{j,t,m,r_m}^{(4)}$	Waste percentage of apheresis blood product m with age r_m at blood distribution unit of blood transfusion center j at period t	$\alpha_{k,t,m,r_m}^{(5)}$	Waste percentage of blood product m (including random product and whole blood) with age r_m at unallocated warehouse of hospital k at period t
$\alpha_{k,t,m,r_m}^{(6)}$	Waste percentage of apheresis blood product m with age r_m at unallocated warehouse of hospital k at period t	α_{jtm}	Waste percentage of apheresis blood product m at warehouse 2 of blood transfusion center j at period t

TABLE 16. Returning product parameters.

$CREP_{jk}^{m,r_m}$	Returning cost of one blood product m with age r_m sent from blood transfusion center j to hospital k (Due to transportation, mismatch with demand, etc.)	$CREP_{ij}$	Returning cost of one whole blood unit sent from blood collection center i to blood transfusion center j (Due to transportation, holding failure, etc.)
$\alpha_{ijtv}^{(1)}$	Returning percentage of whole blood sent from blood collection center i to blood transfusion center j at period t	$\alpha_{jktv'}^{(1)\ m,r_m}$	Returning percentage of blood product m (including random product and whole blood) with age r_m sent from blood transfusion center j to hospital k by vehicle v' at period t
$\alpha_{jktv'}^{(2)\ m,r_m}$	Returning percentage of apheresis blood product m with age r_m sent from blood transfusion center j to hospital k by vehicle v' at period t		

TABLE 17. Lead time parameters.

$YL_{jktv'}$	1 if blood transfusion center j delivery blood products to hospital k late by vehicle v' at period t, 0 otherwise	$YE_{jktv'}$	1 if blood transfusion center j delivery blood products to hospital k early by vehicle v' at period t, 0 otherwise
td_{jk}^{m,r_m}	Lead time of blood product m with age r_m from blood transfusion center j to hospital k	$U(tda_{jkt}^{m,r_m})$	Utility of Lead time of apheresis blood product m with age r_m from blood transfusion center j to hospital k by vehicle v at period t
tw_{ij}	Lead time of whole blood from blood collection center i to blood transfusion center j	$U(td_{jktv}^{m,r_m})$	Utility of Lead time of blood product m (including whole blood and random products) with age r_m from blood transfusion center j to hospital k by vehicle v at period t
tu_k^{m,r_m}	Favorable lead time of blood product m with age r_m from blood transfusion center j to hospital k	tl_k^{m,r_m}	The acceptable earliest lead time of blood product m with age r_m from blood transfusion center j to hospital k
te_k^{m,r_m}	The acceptable latest lead time (time for delivery of) of blood product m with age r_m from blood transfusion center j to hospital k	td_{io}	Lead time of equipment o at blood collection center i
td'_{jp}	Lead time of equipment p at blood transfusion center j	td''_{kq}	Lead time of equipment q at hospital k
te_{kt}	Earliest lead time of blood products at hospital k at period t	CL_k^{m,r_m}	Cost of acceptable late delivery of one blood product m with age r_m at hospital k
CE_k^{m,r_m}	Cost of acceptable early delivery of one blood product m with age r_m at hospital k		

TABLE 18. Preventive maintenance parameters.

CPA_{io}	Cost of prevention activities for each equipment o at blood collection center i	CPA'_{jp}	Cost of prevention activities for each equipment p at blood transfusion center j
CPA''_{kq}	Cost of prevention activities for each equipment q at hospital k	CR_{io}	Repair cost of equipment o at blood collection center i
CR'_{jp}	Repair cost of equipment p at blood transfusion center j	CR''_{kq}	Repair cost of equipment q at hospital k
CB_o	Purchasing cost of each equipment o	CB'_p	Purchasing cost of each equipment p
CB''_q	Purchasing cost of each equipment q	tpa_{io}	Time period of preventive maintenance actions for equipment o at blood collection center i
tpa'_{jp}	Time period of preventive maintenance actions for equipment p at blood transfusion center j	tpa''_{kq}	Time period of preventive maintenance actions for equipment q at hospital k
tmd_{io}	Stop time period of equipment o at blood collection center i (including first and second inspections and repairs)	tmd'_{jp}	Stop time period of equipment p at blood transfusion center j
tmd''_{kq}	Stop time period of equipment q at hospital k	λ_{io}	Failure rate of equipment o at blood collection center i at time period (0–T)
λ'_{jp}	Failure rate of equipment p at blood transfusion center j at time period (0–T)	λ''_{kq}	Failure rate of equipment q at hospital k at time period (0–T)
N_{io}	Frequency of preventive maintenance actions for equipment o at blood collection center i at time period (0–T)	N'_{jp}	Frequency of preventive maintenance actions for equipment p at blood transfusion center j at time period (0–T)
N''_{kq}	Frequency of preventive maintenance actions for equipment q at hospital k at time period (0–T)	PDR_{io}	Percentage of defective and repairable equipment o at blood collection center i
PDR'_{jp}	Percentage of defective and repairable equipment p at blood transfusion center j	PDR''_{kq}	Percentage of defective and repairable equipment q at hospital k
PR_{io}	Percentage of repaired non-defective equipment o at blood collection center i	PR'_{jp}	Percentage of repaired non-defective equipment p at blood transfusion center j
PR''_{kq}	Percentage of repaired non-defective equipment q at hospital k		

3.2.3. Mathematical model

The model is formulated as below:

$$\text{Min } Z_1 = \text{Total Costs.}$$

First objective is associated with minimizing costs (see Appendix A). The costs include, respectively, the following:

Fixed cost of opening blood collection centers and blood transfusion centers, operating cost of constructing links, transportation cost from blood collection centers to blood transfusion centers, transportation cost from blood transfusion centers hospitals, preparation cost of blood products through separation and apheresis, processing cost at blood collection centers (doing medical examination including checking blood donation eligibility criteria), processing cost at blood transfusion centers including initial tests on donated blood (HIV, hepatitis, etc.), processing cost at hospitals (classification of received blood products, controlling patient's clinical and laboratory signs before and after blood transfusion, controlling patient profile before blood transfusion and matching it with blood bag), holding cost of whole blood at warehouse of blood collection centers and warehouse 1 of blood transfusion centers, holding cost of blood products at warehouse 3 of blood transfusion centers

TABLE 19. Variables of the model.

Q_{ijtv}	Quantity of whole blood sent from blood collection center i to blood transfusion center j at period t	Q'_{j,t,m,r_m}	Quantity of produced blood product m with age r_m through separation at blood transfusion center j at period t
QA_{jtm}	Quantity of produced blood product m through apheresis at blood transfusion center j at period t	$Q\pi_{kt}^{m,r_m}$	Quantity of shortage of blood product m (including random product and whole blood) with age r_m at hospital k and period t
$Q\pi a_{kt}^{m,r_m}$	Quantity of shortage of apheresis blood product m (including random product and whole blood) with age r_m at hospital k and period t	$Q_{jktv'}^{m,r_m}$	Quantity of blood product m (including random product and whole blood) with age r_m sent from blood transfusion center j to hospital k by vehicle v' at period t
$QA_{jktv'}^{m,r_m}$	Quantity of apheresis blood product m with age r_m sent from blood transfusion center j to hospital k by vehicle v' at period t	Qw_{jtr_1}	Quantity of healthy whole blood with age r_1 at laboratory of blood transfusion center j at period t
I_{jt}	Inventory level of whole blood at warehouse 1 of blood transfusion center j and period t	IS_{jt}^{m,r_m}	Inventory level of blood product m (including random product and whole blood) with age r_m at blood distribution unit of blood transfusion center j at period t
IA_{jt}^{m,r_m}	Inventory level of apheresis blood product m with age r_m at blood distribution unit of blood transfusion center j at period t	In_{kt}^{m,r_m}	Inventory level of blood product m with age r_m at unallocated warehouse of hospital k at period t
InA_{kt}^{m,r_m}	Inventory level of apheresis blood product m with age r_m at unallocated warehouse of hospital k at period t	Y_i	1 if blood collection center i is opened, 0 otherwise
Y'_j	1 if blood transfusion center j is opened, 0 otherwise	Y_{ijtv}	1 if link (i,j) is established through vehicle v at period t, 0 otherwise
$Y'_{jktv'}$	1 if link (j,k) is established through vehicle v' at period t, 0 otherwise	th_{kt}	Total holding time of blood products at unallocated warehouse of hospital k at period t

and unallocated warehouse of hospitals, shortage cost of whole blood and blood products produced through separation and apheresis at hospitals, cost of acceptable late and early delivery of blood products at hospitals, fixed costs of prevention (employee training, designing quality procedures, etc.), cost of process evaluation and equipment inspection error in each facility, fixed cost of inspection error of blood products at blood transfusion centers, waste cost of whole blood at warehouse of blood collection centers and warehouse 1 of blood transfusion centers, waste cost of random and apheresis blood products and whole blood at warehouse 2 of blood transfusion centers in both conditions of acceptance and rejection of samples at QC unit (considering error percentage in separation, apheresis and initial tests), waste cost of blood products including random, whole blood and apheresis at warehouse 3 of blood transfusion centers and unallocated warehouse of hospitals, waste cost of whole blood at hospitals because of high ratio of C/T, blood returning costs, inspection cost of blood products (apheresis, random and whole blood) at inspection unit of blood transfusion centers, fixed cost of prevention activities for equipment in each facility, cost of purchasing and repairing equipment in each facility, cost of quality control on blood products at QC unit of blood transfusion centers and cost of accepting defective blood products approved in the inspection due to error percentage in apheresis, separation and initial tests.

$$\text{Min } Z_2 = \sum_i \sum_j \sum_t \sum_v t_{ij}^v \times Y_{ijtv} + \sum_j \sum_k \sum_t \sum_{v'} t'^{v'}_{jk} \times Y'_{jktv'} + \sum_i \sum_t tp_i \times Q_{it} \times Y_i + \sum_i \sum_j \sum_t \sum_v tp'_j$$

$$\times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} \times Y'_j + \sum_j \sum_k \sum_t \sum_{v'} \sum_{m=2} \sum_{r_m} CP''_k$$

$$\times \left[\left[\frac{\left(\left(1 - \alpha_{jktv'}^{(1)\ m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) \times PC_{k,t,m,r_m}}{a}\right] \times a\right.$$

$$\left. + \left(\left(1 - \alpha_{jktv'}^{(2)\ m,r_m}\right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right) PCA_{k,t,m,r_m}\right] + \sum_j \sum_k \sum_t \sum_{v'} \sum_{r_1}$$

$$\times tp''_k \times \left(\left(1 - \alpha_{jktv'}^{(1)\ 1,r_1}\right) Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1}\right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)}\right) \times PC_{k,t,1,r_1} + \sum_j \sum_t \sum_{m=2} \sum_{r_m} tm_{jm}$$

$$\times Q'_{j,t,m,r_m} + \sum_j \sum_t \sum_{m=2} tma_{jm} \times QA_{jtm} + \sum_i \sum_j \sum_t \sum_v th \times \text{sgn}\left[\left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}\right]$$

$$+ \sum_j \sum_t \sum_m \sum_{r_m} th_j \times \left(IS_{jt}^{m,r_m} + IA_{jt}^{m,r_m}\right) + \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} tc_{km} \times \left[\left(1 - \alpha_{jktv'}^{(1)\ m,r_m}\right)\right.$$

$$\left. \times Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) + \sum_j \sum_k \sum_t \sum_{v'} \sum_{m=2} \sum_{r_m} tc_{km} \times \left[\left(1 - \alpha_{jktv'}^{(2)\ m,r_m}\right)\right.$$

$$\left. \times QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \times \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right) + \sum_i \sum_o tpa_{io} \times N_{io} \times ne_{io} + \sum_j \sum_p tpa'_{jp} \times N'_{jp}$$

$$\times ne'_{jp} + \sum_k \sum_q tpa''_{kq} \times N''_{kq} \times ne''_{kq} + \sum_j \sum_t \sum_m tmi_{jm} \times \left(Q'_{jtm} + QA_{jtm}\right) + \sum_i \sum_o \sum_t tmd_{io}$$

$$\times \lambda_{io} \times T \times PDR_{io} + \sum_j \sum_p \sum_t tmd'_{jp} \times \lambda'_{jp} \times T \times PDR'_{jp} + \sum_k \sum_q \sum_t tmd''_{kq} \times \lambda''_{kq} \times T \times PDR''_{kq}$$

$$+ \sum_i \sum_o td_{io} \times \lambda_{io} \times T \times \left[(1 - PDR_{io}) + PDR_{io} \times (1 - PR_{io})\right] + \sum_j \sum_p td'_{jp} \times \lambda'_{jp} \times T$$

$$\times \left[(1 - PDR'_{jp}) + PDR'_{jp} \times (1 - PR'_{jp})\right] + \sum_k \sum_q td''_{kq} \times \lambda''_{kq} \times T \times \left[(1 - PDR'_{kq}) + PDR''_{kq}\right.$$

$$\left. \times (1 - PR''_{kq})\right] + \sum_j \sum_t \sum_{m=2} \sum_{r_m} tqc_{jm} \times \left(\alpha_{jm}^{(4)} \times Q'_{j,t,m,r_m} + \alpha_{jm}^{(5)} \times QA_{jtm}\right)$$

$$+ \sum_i \sum_j \sum_t \sum_v tqc_{j1} \times \alpha_j^{(1)} \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}.$$

Second objective minimizes total time in the blood supply chain. The time includes the following items:

Transportation time between facilities by available vehicles, processing time in each facility, production time of blood products through separation and apheresis, holding time of whole blood at warehouse 1 of blood transfusion centers, holding time of blood products at warehouse 3 of blood transfusion centers, holding time of blood products at unallocated warehouse of hospitals, cross-match test time at hospitals, preventive maintenance for equipment in each facility, inspection time at blood transfusion centers, stop time and lead time of equipment in each facility and time of conducting quality control on blood products at QC unit of blood transfusion centers.

$$\text{Max } Z_3 = \sum_k \sum_t \sum_j \sum_{v'} \sum_m \sum_{r_m} \left(\frac{1 + R_m - r_m}{R_m} \right) \times \frac{\left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m} \right) Q_{jktv'}^{m,r_m}}{d_{kt}^{m,r_m}}$$

$$\times\, U\left(td_{jkt}^{m,r_m} \right) + \sum_k \sum_t \sum_j \sum_{v'} \sum_{m=2} \sum_{r_m} \left(\frac{1 + R_m - r_m}{R_m} \right)$$

$$\times\, \frac{\left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m} \right) QA_{jktv'}^{m,r_m}}{da_{kt}^{m,r_m}} \times U\left(tda_{jkt}^{m,r_m} \right).$$

The final objective function intends to maximize the quality of blood product delivered to hospitals.
S.T.

$$\sum_i \sum_v Q_{ijtv} \le cap_j \quad \forall j, t \tag{3.1}$$

$$QA_{jtm} \le capa_{jm} \times Y_j' \quad \forall j, t, m \tag{3.2}$$

$$\sum_{r_m} \alpha_{jm}^{(4)} \times Q'_{j,t,m,r_m} + \alpha_{jm}^{(5)} \times QA_{jtm} \le capq_{jm} \quad \forall j, t, m = 2, \dots, M \tag{3.3}$$

$$\sum_i \sum_v \sum_{r_1} \alpha_j^{(1)} \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv} \le capq_{i1} \quad \forall j, t \tag{3.4}$$

$$\sum_{r_m} P_{jtm} \times \left(1 - \alpha_{jm}^{(4)} \right) \times Q'_{j,t,m,r_m} + PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)} \right) QA_{jtm} QA_{jtm} \le cap_{jm} \quad \forall j, t, m = 2, \dots, M \tag{3.5}$$

$$\sum_i \sum_v P_{jtm} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)} \right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv} \le cap_{jm} \quad \forall j, t, m = 1 \tag{3.6}$$

$$\sum_{r_m} \left[\left(1 - \alpha_{j,t,m,r_m}^{(2)} \right) \times PQ_{jtm} \times P_{jtm} \times \left(1 - \alpha_{jm}^{(4)} \right) \times Q'_{j,t,m,r_m} + IS_{j(t-1)}^{m,r_m} \right]$$

$$+ \left[PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)} \right) QA_{jtm} \times (1 - \alpha_{jtm}) \times PQA_{jtm} + IA_{j(t-1)}^{m,r_m} \right] \le capd_{jm} \quad \forall j, t, m = 2, \dots, M \tag{3.7}$$

$$\sum_i \sum_v \sum_{r_1} \left[\left(1 - \alpha_{j,t,1,r_1}^{(2)} \right) \times PQ_{jt1} \times P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)} \right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv} \right.$$

$$\left. + IS_{j(t-1)}^{1,r_1} \right] \le capd_{jm} \quad \forall j, t, m = 1 \tag{3.8}$$

$$\sum_j \sum_{v'} \sum_{r_m} \left[Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m} \right] + \sum_j \sum_{v'} \sum_{r_m} \left[QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m} \right] \le capnw_{km} \quad \forall k, t, m \tag{3.9}$$

$$\left[\frac{1}{a} \times \sum_j \sum_{v'} \sum_{r_m} \left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m} \right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m} \times \left(1 - \alpha_{k,t,m,r_m}^{(5)} \right) \times PC_{k,t,m,r_m} \right] a + \sum_j \sum_{v'} \sum_{r_m}$$

$$\times \left(\left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m} \right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m} \right) \left(1 - \alpha_{k,t,m,r_m}^{(6)} \right) PCA_{k,t,m,r_m} \le capw_{km} \quad \forall k, t, m \ge 2 \tag{3.10}$$

$$\sum_j \sum_{v'} \sum_{r_1} \left(\left(1 - \alpha_{jktv'}^{(1)}{}^{1,r_1} \right) Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1} \right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)} \right) \times PC_{k,t,1,r_1} \le capw_{km} \quad \forall k, t, m = 1 \tag{3.11}$$

$$Q_{ijtv} \le capv_v \times Y_{ijtv} \quad \forall i, j, t, v \tag{3.12}$$

$$\sum_m \sum_{r_m} \left(Q_{jktv'}^{m,r_m} + QA_{jktv'}^{m,r_m} \right) \le capv'_{v'} \times Y'_{jktv'} \quad \forall j, k, t, v' \tag{3.13}$$

$$\sum_j \sum_v Q_{ijtv} = \left(1 - \alpha_{it}^{(1)}\right) \times Q_{it} \quad \forall i, t \tag{3.14}$$

$$Q'_{j,t+1,m,r_m} = \sum_i \sum_v \alpha_j^{(2)} \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} \quad \forall j, t \geq 1, m \geq 2, r_m = 1 \tag{3.15}$$

$$QT_{k,t,r_1} \leq \sum_j \sum_{v'} \left[\left(\left(1 - \alpha_{jktv'}^{(1)\ 1,r_1}\right) Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1}\right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)}\right) \times PC_{k,t,1,r_1}\right] \quad \forall k, t, m = 1, r_1 \tag{3.16}$$

$$I'_{jt} = \sum_i \sum_v \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} \quad \forall j, t \tag{3.17}$$

$$IS_{jt}'^{\ m,r_m} = \left[PQ_{jm} \times \left(1 - \alpha_{j,t,m,r_m}^{(2)}\right) \times P_{jm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q'_{j,t,m,r_m} + IS'_{j(t-1)}{}^{m,r_m}\right] \left(1 - \alpha_{j,t,m,r_m}^{(3)}\right)$$
$$- \sum_k \sum_{v'} Q_{jktv'}^{m,r_m} \quad \forall j, t \geq 2, m \geq 2, r_m = 1 \tag{3.18}$$

$$IS_{jt}'^{\ 1,r_1} = \left[\sum_i \sum_v \sum_{r_1} PQ_{j1} \times \left(1 - \alpha_{j,t,1,r_1}^{(2)}\right) \times P_{j1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right)\right.$$
$$\left. \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} + IS'_{j(t-1)}{}^{1,r_1}\right] \left(1 - \alpha_{j,t,1,r_1}^{(3)}\right) - \sum_k \sum_{v'} Q_{jktv'}^{1,r_1} \quad \forall j, t, m = 1, r_1 \tag{3.19}$$

$$IA_{jt}^{m,r_m} = \left[PQ_{jm} \times (1 - \alpha_{jtm}) \times PA_{jm} \times \left(1 - \alpha_{jm}^{(5)}\right) \times QA_{jtm} + IA_{j(t-1)}^{m,r_m}\right] \left(1 - \alpha_{j,t,m,r_m}^{(4)}\right)$$
$$- \sum_k \sum_{v'} QA_{jktv'}^{m,r_m} \quad \forall j, t, m \geq 2, r_m \tag{3.20}$$

$$In_{kt}^{1,r_m} = \left[\sum_j \sum_v \left(1 - \alpha_{jktv}^{m,r_m}\right) Q_{jktv}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right)(1 - PC_{k,t,m,r_m}) \quad \forall k, t, m = 1, r_1 \tag{3.21}$$

$$In_{kt}^{m,r_m} = \left[\left(\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(1)\ m,r_m}\right) Q_{jktv}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right)\right]$$
$$- \left[\frac{1}{a} \times \left(\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(1)\ m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) \times PC_{k,t,m,r_m}\right]$$
$$\times a \quad \forall k, t, m \geq 2, r_m \tag{3.22}$$

$$Ina_{kt}^{m,r_m} = \left[\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(2)\ m,r_m}\right) QA_{jktv}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right)(1 - PCA_{k,t,m,r_m})$$
$$\forall k, t, m \geq 2, r_m \tag{3.23}$$

$$Q\pi_{kt}^{m,r_m} = d_{k,t,m,r_m} - \left[\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(1)\ m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) \times PC_{k,t,m,r_m}$$
$$\forall k, t, m = 1, r_1 \tag{3.24}$$

$$Q\pi_{kt}^{m,r_m} = -d_{k,t,m,r_m} - \left[\frac{1}{a} \times \left(\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right) \times PC_{k,t,m,r_m}\right]$$

$$\times a \quad \forall k,t,m \geq 2, r_m \tag{3.25}$$

$$Q\pi a_{kt}^{m,r_m} = da_{k,t,m,r_m} - \left(\left[\sum_j \sum_{v'} \left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m}\right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right) \times PCA_{k,t,m,r_m}\right)$$

$$\forall k,t,m \geq 2, r_m \tag{3.26}$$

$$th_{kt} = \left[24 - \left(te_{kt} + \sum_j \sum_{v'} \sum_m \sum_{r_m} tc_{km} \times \left[\left(1 - \alpha_{jktv'}^{(1)}{}^{m,r_m}\right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m}\right] \times \left(1 - \alpha_{k,t,m,r_m}^{(5)}\right)\right.\right.$$

$$\left.\left. + \sum_j \sum_{v'} \sum_{m=2} \sum_{r_m} tc_{km} \times \left[\left(1 - \alpha_{jktv'}^{(2)}{}^{m,r_m}\right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m}\right] \times \left(1 - \alpha_{k,t,m,r_m}^{(6)}\right)\right)\right] \quad \forall k,t \tag{3.27}$$

$$\sum_i Y_i \geq 1 \quad \forall i \tag{3.28}$$

$$\sum_j Y_j' \geq 1 \quad \forall j \tag{3.29}$$

$$Y_{ijtv} \leq M \times Y_i \times Y_j' \quad \forall i,j,t,v \tag{3.30}$$

$$Y_{jktv'}' \leq M \times Y_j' \quad \forall j,k,t,v \tag{3.31}$$

$$\sum_i \sum_j \sum_v Y_{ijtv} \leq n_v \quad \forall t \tag{3.32}$$

$$\sum_j \sum_k \sum_{v'} Y_{jktv'}' \leq n_{v'}' \quad \forall t \tag{3.33}$$

$$\sum_i \sum_j Y_{ijtv} \leq \quad \forall v,t \tag{3.34}$$

$$\sum_j \sum_k Y_{jktv'}' \leq 1 \quad \forall v',t \tag{3.35}$$

$$\sum_v Y_{ijtv} \leq 1 \quad \forall i,j,t \tag{3.36}$$

$$\sum_{v'} Y_{jktv'}' \leq 1 \quad \forall j,k,t \tag{3.37}$$

$$\sum_j \sum_v Y_{ijtv} \geq 1 \quad \forall i,t \tag{3.38}$$

$$\sum_k \sum_{v'} Y_{jktv'}' \geq 1 \quad \forall j,t \tag{3.39}$$

$$\sum_i \sum_v Y_{ijtv} \geq 1 \quad \forall j, t \tag{3.40}$$

$$\sum_j \sum_v Y'_{jktv'} \geq 1 \quad \forall k, t \tag{3.41}$$

$$YL_{jktv'} \leq Y'_{jktv'} \quad \forall j, k, t, v' \tag{3.42}$$

$$YE_{jktv'} \leq Y'_{jktv'} \quad \forall j, k, t, v' \tag{3.43}$$

$$\sum_i \sum_v \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} = Qw_{jtr_1} \quad \forall j, t \tag{3.44}$$

$$Q_{jktv}, Q'_{j,t,m,r_m}, QA_{jtm}, Q_{jktv'}^{m,r_m}, QA_{jktv'}^{m,r_m}, Q\pi_{kt}^{m,r_m}, Q\pi a_{kt}^{m,r_m} I'_{jt}, IS_{jt}^{m,r_m}, IA_{jt}^{m,r_m}, In_{kt}^{m,r_m}, Ina_{kt}^{m,r_m} \in Z^+ \tag{3.45}$$

$$Y_i, Y'_j, Y_{ijtv}, Y'_{jktv'} \in \{0,1\} \tag{3.46}$$

$$Q'_{j,t,m,r_m} = Q_{jktv'}^{m,r_m} = Qw_{jtr_1} = 0 \quad \forall t = 1 \tag{3.47}$$

$$Q\pi_{kt}^{m,r_m} > 0 \quad \forall t = 1 \tag{3.48}$$

$$Q'_{j,t,m,r_m} = QA_{jtm} - 0 \quad \forall m = 1 \tag{3.49}$$

$$Q'_{j,t,m,r_m} = 0 \quad \forall r_m \geq 2 \tag{3.50}$$

$$Qw_{jtr_1} = 0 \quad \forall r_1 \geq 2 \tag{3.51}$$

$$I'_{jt} = IS_{jt}^{m,r_m} = IA_{jt}^{m,r_m} = In_{kt}^{m,r_m} = Ina_{kt}^{m,r_m} = IS'^{m,r_m}_{jt} = 0 \quad \forall t = 1 \tag{3.52}$$

$$IS_{jt}^{m,r_m} = In_{kt}^{m,r_m} = 0 \quad \forall r_m = 1 \tag{3.53}$$

$$IA_{jt}^{m,r_m} = Ina_{kt}^{m,r_m} = 0 \quad \forall m = 1. \tag{3.54}$$

Constraint (3.1) ensures that quantity of the whole blood sent from blood collection centers to warehouse 1 of each blood transfusion center at each period is less than the capacity to receive blood in the warehouses. Constraint (3.2) shows the capacity of blood transfusion centers to do apheresis at each time period. Constraints (3.3) and (3.4) indicate the capacity of QC unit in blood transfusion centers to receive apheresis and random blood products and whole blood at each time period. Constraints (3.5) and (3.6) respect the capacity of warehouse 2 in blood transfusion centers to receive apheresis and random blood products and whole blood. Constraints (3.7) and (3.8) represent the capacity of warehouse 3 in blood transfusion centers to receive apheresis and random blood products and whole blood at each time period. Constraint (3.9) states that quantity of the blood products sent from blood transfusion centers to unallocated warehouse of each hospital is less than the capacity to receive blood in the warehouses. Constraints (3.10) and (3.11) limit the amount of received apheresis and random blood products and whole blood at each time period to capacity of allocated warehouse of hospitals. Constraint (3.12) ensures that quantity of the whole blood sent from blood collection centers to the blood centers is less than the capacity of the vehicles allocated to blood collection centers. Constraint (3.13) guarantees that quantity of the blood products sent from the blood transfusion centers to the hospitals at each period is less than the capacity of the vehicles allocated to blood transfusion centers. The total amount of whole blood sent from each blood collection center to blood transfusion centers by vehicles at each time period equals the total received blood in the blood collection center (considering blood waste in blood collection center), represented by constraint (3.14). Constraint (3.15) implies that per whole blood bag sent to separation unit, 3 blood bags including platelets, plasma and red blood cells are obtained in blood transfusion centers. Constraint (3.16) shows that whole blood transfused to patients is less than whole blood in allocated warehouse of hospital at each period. Constraint (3.17) calculates whole blood inventory at warehouse 1 of blood transfusion centers in period t. Constraints (3.18) to (3.20) calculate blood products inventory at warehouse 3 of blood transfusion

centers in period t. Constraints (3.21) to (3.23) represent blood products inventory at unallocated warehouse of blood transfusion centers at each time period. The amount of blood product shortages in each hospital in period t is determined by constraints (3.24) to (3.26). Total holding time of blood products at each hospital in period t is calculated by constraint (3.27). Constraint (3.28) enforces that at least one blood collection center is opened. Constraint (3.29) ensures that at least one blood transfusion center is opened. The blood collection center can transfer the whole blood to the blood transfusion centers by vehicle v in period t, if both the blood collection center and blood transfusion center are opened, represented by constraint (3.30). Constraint (3.31) indicates that the blood collection center can transfer the whole blood to the blood transfusion centers by vehicle v in period t, if blood transfusion center is opened. Constraint (3.32) ensures that at each time period, the total number of vehicles used for transportation of whole blood from blood collection centers to blood transfusion centers is up to the number of available vehicles. At each time period, the total number of vehicles used for transportation of blood products from blood transfusion centers to hospitals is up to the number of available vehicles, stated by constraint (3.33). Constraints (3.34) and (3.35) enforced that each vehicle is used only for one blood transportation at each time period. Constraint (3.36) and (3.37) guarantee that at each time period, only one vehicle is used for specific blood transportation. Constraint (3.38) indicates that at each time period, each blood collection center transfer whole blood to at least one blood transfusion center through a total of allocated vehicles. Constraint (3.39) lets each blood transfusion center transfer blood products to at least one hospital through a total of allocated vehicles at each time period. Constraint (3.40) limits each blood transfusion center to receive whole blood from at least one blood collection center through available vehicles at each time period. At each time period, each hospital receives blood products from at least one blood transfusion center through available vehicles, is shown by constraint (3.41). Constraints (3.42) and (3.43) express that acceptable late/early delivery will occur if link on (j, k) is constructed. Amount of healthy whole blood at laboratory of blood transfusion center at period t is determined by constraint (3.44). Constraints (3.45) and (3.46) clarify types of the decision variables. At the first period, quantity of random products at blood transfusion centers, quantity of blood products (including random products and whole blood) sent from blood transfusion centers to hospitals and quantity of healthy whole blood at laboratory of blood transfusion centers are zero, represented by constraint (3.47). Constraint (3.48) states that hospitals face blood shortage at the first period. Constraint (3.49) shows that random and apheresis products don't contain whole blood. Age of random products at blood transfusion centers is less than 2, indicated by constraint (3.50). According to constraint (3.51), age of healthy whole blood at laboratory of blood transfusion centers is less than 2. Constraint (3.52) enforces Initial inventory of warehouse of blood transfusion centers and hospitals is zero. Constraint (3.53) shows that age of blood product (including random product and whole blood) at blood distribution unit of blood transfusion center and unallocated warehouse of hospital is more than 1 and finally, whole blood is not included in apheresis products at blood distribution unit of blood transfusion center and unallocated warehouse of hospital, stated by constraint (3.54).

4. Interval Evidential Reasoning (IER) approach

In the presented model, a number of parameters, especially those obtained from human judgment, are inevitably uncertain. Therefore, methods that handle uncertainty should be applied to make the model more realistic and produce reliable solution. For this purpose, we employ one of the most common frameworks named Interval Evidential Reasoning (IER) approach which is extension of Evidential Reasoning (ER) approach.

The ER approach has been developed for multiple attribute decision analysis (MADA) problems based upon Dempster–Shafer (D–S) theory of evidence and decision theory [13, 42, 44–46]. It can model varied types of uncertainties like incompleteness, vagueness and ignorance. In this approach, experts express their opinions in the form of belief structure including well-organized grade and belief degree. Then, the opinions are aggregated using the D–S theory. Detailed explanation of the ER approach can be found in [44].

Since an expert may be unable to provide accurate judgment by giving a single number, using interval numbers can be a sensible option that allows the experts to freely express what they have in mind. Incorporating the

flexibility of the interval theory into the ER algorithm is called IER approach in which the grades are assigned to an individual or interval value. To simplify the understanding of this approach, we describe its procedure through an example [8].

Suppose that there are 5 experts with equal relative weight $(0/2)$ to estimate a parameter in IER belief structure using a set of five grades: $G = \{1, 2, 3, 4, 5\}$. So each grade in the whole range of G can be assigned to the parameter and possible grading matrix is defined as follows:

$$\text{Possible grading matrix} = \begin{bmatrix} 1 & 1-2 & 1-3 & 1-4 & 1-5 \\ & 2 & 2-3 & 2-4 & 2-5 \\ & & 3 & 3-4 & 3-5 \\ & & & 4 & 4-5 \end{bmatrix}.$$

Based on the above assumptions, the experts' opinions on the parameter in IER belief structure are represented as the following possible states:

– Vacillate between single grades with different belief degrees. For example, an expert estimates the parameter by giving grade 3 with belief degree of 70% and grade 4 with the belief degree of 30%: $\{(3, 70\%), (4, 30\%)\}$.
– Vacillate between interval grades with different belief degrees. For example, an expert gives the parameter, grade [3–4] with belief degree of 20% and grade 5 with the belief degree of 50%: $\{(3-4, 20\%), (5, 50\%)\}$.
– Unawareness about the parameter. Because grading scale is [1–5], it will be modeled as: $\{(1-5), 100\%\}$.

The notable point is that when the total belief degrees is below 100% like statement 2, remaining belief degree represents a lack of information and can be assigned to any of the grading scale.

By calculating the expected values. For example, the belief structures of the examples can be modeled by expected values as follows:

$$\{(3, 70\%), (4, 30\%)\} \rightarrow 3 \times 70\% + 4 \times 30\% = 1.6 = [1.41-1.41]$$
$$\{(3-4, 20\%), (5, 50\%)\} \rightarrow [3-4] \times 20\% + 5 \times 50\% + [1-5] \times 30\% = [3.4-4.8]$$
$$\{(1-5, 100\%)\} \rightarrow [1-5] \times 100\% = [1-5].$$

In order to decrease estimation error, the experts' opinions can be integrated. The collective estimation of the parameter $(E(S))$ is obtained from the weighted sum of the expected values of the 5 experts as follows:

$$E(S) = \sum_{l=1}^{5} \lambda_l E\left(S^l\right) \tag{4.1}$$

where λ_l is the weight of expert l and $E\left(S^l\right)$ is expected value of expert l about the parameter.

Finally, to solve the model with these interval parameters, the lower and upper bound of the parameters are assumed to be variables and value of them is computed through the proposed meta-heuristic algorithms.

5. SOLUTION METHOD AND RESULTS

The proposed model is an integer non-linear programming model and NP-hard problem. To solve such models on real scale, heuristic and meta-heuristic methods are applied. In this study, we used NSGAII and MOPSO algorithms which are the most powerful meta-heuristic algorithms for solving multi-objective optimization problems. Sections 5.1 and 5.2 summarize the procedure of these algorithm.

5.1. Non-dominating sorting genetic algorithm-II (NSGA-II)

The non-dominated sorting genetic algorithm II (NSGA-II), presented by Deb *et al.* [12], is a class of multi-objective evolutionary algorithms in which a prompt and powerful sorting procedure is applied to find Pareto front solutions. In this algorithm, off-spring population is obtained from the original one using the typical genetic
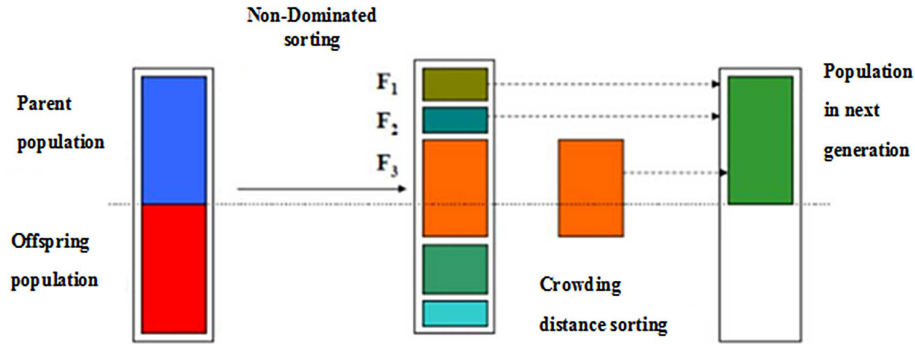
FIGURE 3. Mechanism of NSGA-II algorithm [36].

operators including selection, crossover, and mutation. Thereafter, the individuals are sorted based on their rank which is determined through a process called non domination sorting, and a new population is created. In the case the rank of individuals is the same, the crowding distance criterion is calculated to choose the best solutions. Figure 3 indicates mechanism of NSGA-II.

5.2. Multi-Objective Particle Swarm Optimization (MOPSO)

To employ the PSO algorithm for solving multi-objective optimization problems, Multi-Objective Particle Swarm Optimization (MOPSO) algorithm was proposed by Coello *et al.* [9]. In this algorithm, the principles of the Pareto solutions are taken into account and the population of found non-dominated solutions is kept in the repository. The repository has limited space and if the number of members exceeds its capacity, the extra ones are removed. then, each member selects a leader among the members of the repository to move on. In the next step the position of the particles is updated and the non-dominated solutions are selected to enter the repository. To enter the repository, if there is no particle inside the repository, a new particle is inserted in it, and if there is a particle in the repository while entering, and it dominates the new particle, the new particle does not enter the repository. Procedure of the MOPSO based on a dominance criterion is summarized as follows [48]:

Step 1. Initial population creation.
Step 2. Calculating objective functions.
Step 3. Separating non-dominated solutions and save them in an archive or external repository.
Step 4. Select a leader among achieve solutions for each particle.
Step 5. Update position and speed of each particle.
Step 6. Using the mutation operator.
Step 7. Updating best personal memory of each particle.
Step 8. Adding new non-dominated solutions to the archive and eliminating dominated one.
Step 9. If the number of repository members is more than the specified limit, delete extra members.
Step 10. If the algorithm is converged the operation will stop and the best particle in the swarm will be the solution of the problem. Otherwise, go back to the step 4.

5.3. Numerical example and results

In order to illustrate applicability of the algorithms and compare results, 15 numerical examples in different sizes (small, medium and large) are designed in which demand of hospital**s** in each period are under IER uncertainty. Table 20 represents the dimensions of the designed examples.

In order to set input parameters of the proposed algorithms, Taguchi method is used. According to Table 21, 3-level factors of both algorithms are determined and the experiments are designed and implemented.

TABLE 20. Dimensions of 15 designed problems in different sizes.

Size	Problem	I	J	K	O	P	Q	V	V'	T	M_p	R_1	R_2	R_3
Small	1	10	5	8	2	4	2	12	5	5	3	35	5	42
	2	10	5	8	2	4	2	14	10	5	3	35	5	42
	3	10	5	8	2	4	2	16	5	5	3	35	5	42
	4	14	5	8	4	4	3	14	10	5	3	35	5	42
	5	10	7	8	4	6	3	14	7	5	3	35	5	42
Medium	6	15	7	12	5	8	4	15	10	10	3	35	5	42
	7	17	9	12	5	8	4	15	10	10	3	53	5	42
	8	15	7	12	5	8	5	20	15	10	3	35	5	42
	9	17	7	12	5	10	5	25	20	10	3	35	5	42
	10	15	9	12	5	10	5	15	15	10	3	35	5	42
Large	11	20	10	16	6	12	6	20	10	15	3	35	5	42
	12	25	15	16	8	12	6	25	15	15	3	35	5	42
	13	20	10	16	8	12	7	30	20	15	3	35	5	42
	14	25	10	16	10	14	7	30	10	15	3	35	5	42
	15	25	15	16	10	14	7	30	15	15	3	35	5	42

TABLE 21. Different levels of parameters for proposed algorithms.

Algorithm	Factor	Level 1	Level 2	Level 3
NSGAII	Max iteration	100	150	200
	nPop	50	100	150
	Pc	0.7	0.8	0.9
	Pm	0.2	0.3	0.4
MOPSO	Max iteration	100	150	200
	nPop	50	100	150
	nRep	50	80	100
	w	0.2	0.4	0.6
	mu	0.1	0.15	0.2

In the Taguchi method, Signal/Noise (S/N) ratio is applied for analysis, in which S refers to the response variable and N is standard deviation. Therefore, the higher ratio, the more favorable it is. The response variable is assumed MID, and since it is "less and better", the corresponding S/N ratio is calculated using equation (5.1).

$$\text{S/N} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right). \tag{5.1}$$

Figures 4 and 5 depict this ratio for each algorithm.

According to the results, the parameters are adjusted. The final parameters of both algorithms are presented in Table 22.

In the next step, the problems are solved through both algorithms. Consider Figures 6 and 7, which plots solve sample of the first problem.

In order to compare the results of the algorithms, the following comparative criteria are applied:

– Number of Pareto Solution (NPS).
– Mean Ideal Distance (MID).
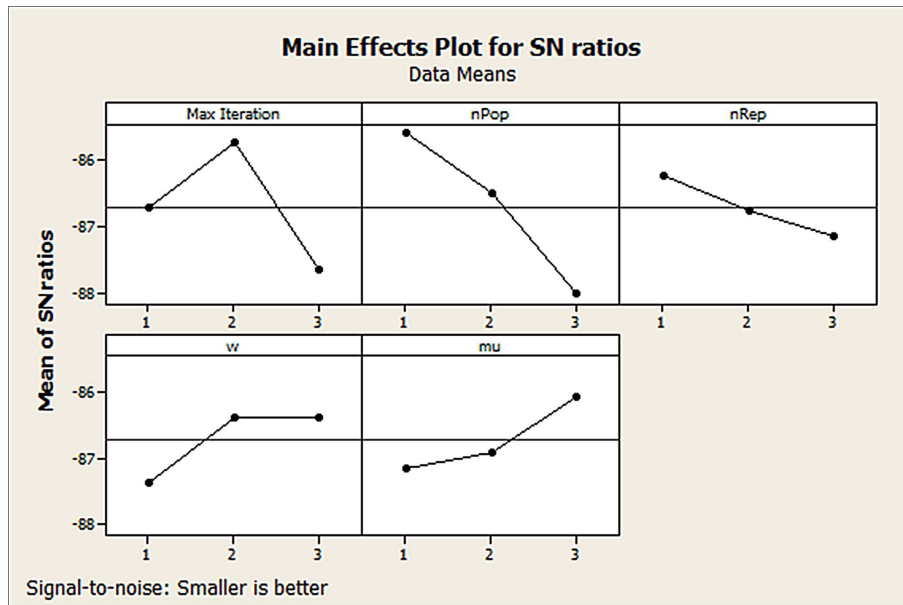– Spacing (S).
– Maximum Diversity (MD).
– Time (T).

FIGURE 4. Main effects plot for SN ratios in MOPSO algorithm.
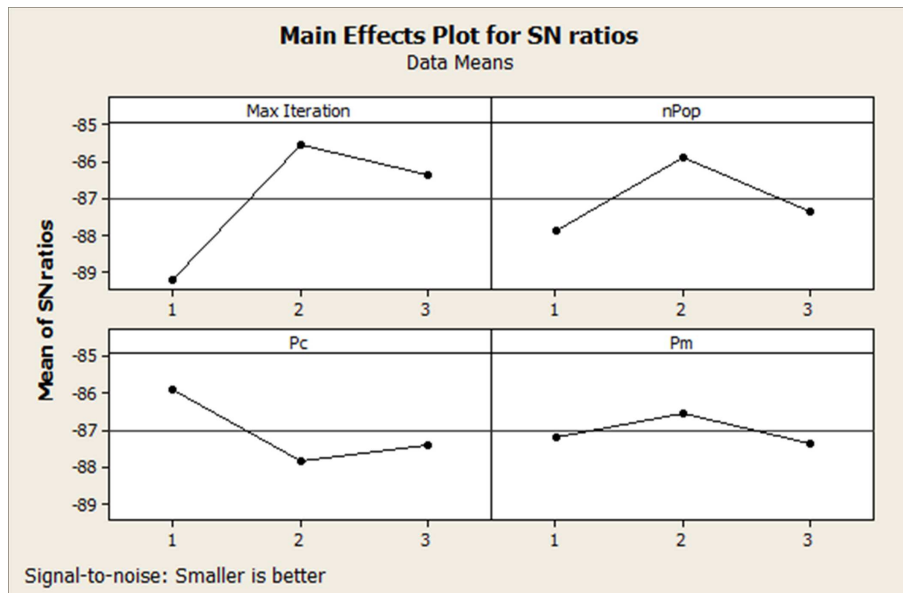

FIGURE 5. Main effects plot for SN ratios in NSGAII algorithm.

The computational results of the criteria for all designed problems can be found in Table 23. Figure 8 depicts average values of the criteria for both of the algorithms in different sizes. The figure indicates that:

TABLE 22. Final parameters of the NSGAII and MOPSO algorithms.

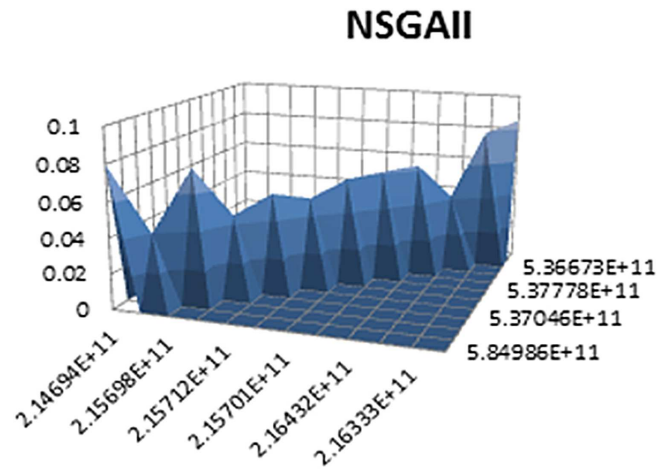| Algorithm	Factor	Optimal level
NSGAII	Max iteration	150
	nPop	50
	Pc	0.7
	Pm	0.3
MOPSO	Max iteration	150
	nPop	50
	nRep	50
	w	0.4
	mu	0.2

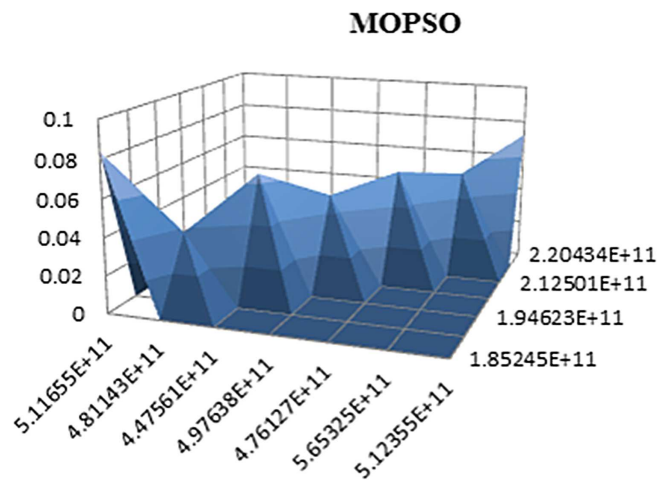FIGURE 6. Pareto solutions of problem1 using NSGAII.

FIGURE 7. Pareto solutions of problem1 using MOPSO.

TABLE 23. Value of comparative criteria in both NSGAII and MOPSO algorithms for all problems.

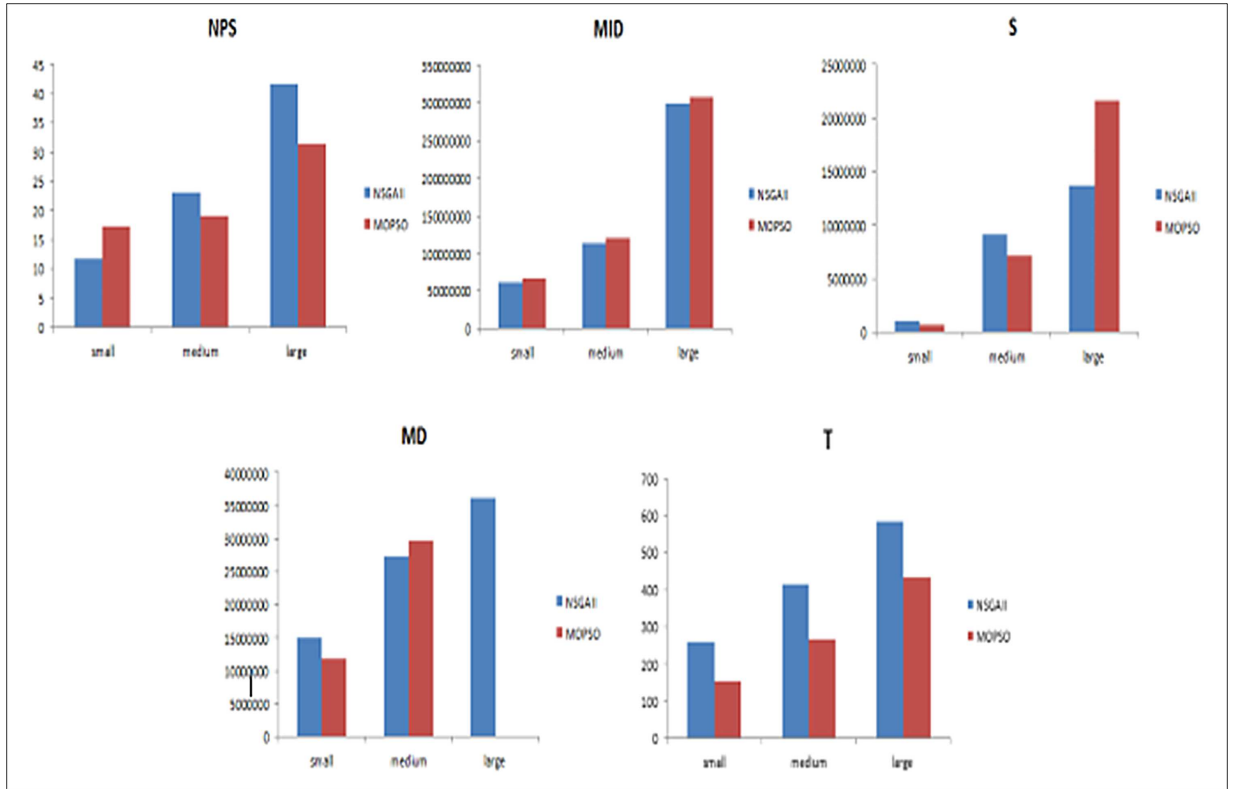| Size	Problem	NPS		MD		S		MID		T	
		NSGAII	MOPSO	NSGAII	MOPSO	NSGAII	MOPSO	NSGAII	MOPSO	NSGAII	MOPSO
Small	1	12	7	9117592/69	7748589/37	763554/81	411225/72	54233279/99	47499617/4	316/37	222/85
	2	13	28	14344674/3	5375737/52	945291/25	727305/66	69988160/55	67456149/75	369/53	260/27
	3	18	25	6435724/42	5109496/12	371631/04	295536/92	63708438/42	48453812/8	330/4	235/12
	4	4	8	27114132/47	24429550/51	2134940/37	984592/6	76268698/72	75415370/69	398/01	279/07
	5	12	18	18330696/28	16175712/64	826713/52	912498/28	70240272/4	65835325/39	382/65	264/46
Medium	6	16	22	10752102/5	14273177/9	5583377/2	3108264/25	75101842/01	76978452/2	459/13	299/85
	7	22	12	19653599/35	25791281/21	5685405/3	5188851/5	87798877/23	92296964/81	487/77	330/54
	8	28	26	26105563/14	27177817/78	10963117/65	7128688/5	131433510/53	142207662/11	521/96	381/08
	9	31	24	42890930/07	45629894/56	11485864/23	12818270/14	162762841/9	180284709/44	565/55	427/46
	10	19	12	36737414/4	35653107/25	11579064/11	7568311/42	112030960/58	115279603/62	532/09	397/4
Large	11	50	41	16254926/3	20054970/06	10165010/44	6138545/23	191419636/7	193440815/15	620/17	475/88
	12	41	27	33102550/85	18100810/82	14215482/04	24185624/94	270839725/41	274063133/75	654/26	515/09
	13	24	25	17157902/13	40993443/19	11785693/9	13312976/6	240960255/16	261716489/04	570/59	427/74
	14	52	34	49132499/66	51530620/8	11756202/1	29333939/83	316074921/14	321207145/65	619/84	453/28
	15	41	30	65236100/78	65500324/2	20768835/37	35382583/2	480675438/04	491819616/57	657/53	482/3

FIGURE 8. Average values of the 6 comparative criteria in different sizes.

– In NSGAII algorithm, the value of the NPS criterion is higher in medium and large sizes, which causes more alternative solutions to the supply chain managers and decision makers.
– The MID criterion in NSGAII algorithm is less than MOPSO algorithm in all sizes (with a small difference). Therefore, the NSGAII algorithm is more favorable in terms of MID.

TABLE 24. Ranking of the algorithms in different sizes based on results of TOPSIS method.

Size	Algorithm	d^+	d^-	CL	Ranking
Small	NSGAII	0/52	0/18	0/26	2
	MOPSO	0/18	0/52	0/74	1
Medium	NSGAII	0/34	0/14	0/3	2
	MOPSO	0/14	0/34	0/7	1
Large	NSGAII	0/21	0/36	0/63	1
	MOPSO	0/36	0/21	0/37	2

– For small and medium problems, MOPSO algorithm has less value than solutions of NSGAII algorithm and for large problem, it is the *vice versa*.
– The fourth criterion is MD and the results show that for medium and large sizes, the MOPSO algorithm is more efficient.
– Since the MOPOS algorithm has a lower T value in all three sizes, it is superior to the NSGAII algorithm.

To compare the proposed algorithms and choose the best one in any size, TOPSIS method is utilized assuming that the weight of all comparative criteria is the same. Table 24 represents the obtained results.

As can be seen in Table 22, the NGAII algorithm has higher efficiency for small size problems and the MOPSO algorithm is more suitable for medium and large sizes.

6. Conclusion

This paper presents a new multi-objective model for designing a dynamic and three level blood supply chain network that aims to attain high quality of blood delivery at low time and cost. The main contribution of the proposed model is incorporating TQM principles clustered in four critical elements of the blood supply chain (costumer, process, equipment and staff) emphasizing on preventive maintenance, inspection and blood delivery quality and complexity of the supply chain inclusive various types of blood products with different lifetime derived from both whole blood and apheresis. Moreover, blood demand is modeled by belief structure of IER approach to handle the uncertainty. For computing solution and illustrating applicability of the model, the NSGAII and MOPSO algorithms are implemented on 15 numerical examples in different sizes. the obtained solutions are compared through TOPSIS method based on criteria inclusive NPS, MID, S, MD and T. Based on the results, it can be concluded that the NSGAII algorithm is more efficient for large size problem and for small and medium sizes; the MOPSO algorithm has a higher utility. For future studies, intricacies like compatibility of blood groups and horizontal collaboration can be addressed. In addition, the proposed model has potential for applications other metaheuristic algorithms and can be successfully implement in real case.

Appendix A.

In this section, the first objective function that aims to minimize the total cost is presented as follows:

$$
\begin{aligned}
\text{Min } Z_1 = & \sum_j \sum_p N'_{jp} \times CPA'_{jp} \times ne'_{jp} \times Y'_j + \sum_i F_i \times Y_i + \sum_j F_j \times Y'_j + \sum_i \sum_j \sum_t \sum_v (LO_{ij} + LC_{ij}) Y_{ijtv} \\
& + \sum_j \sum_k \sum_t \sum_{v'} (LO'_{jk} + LC'_{jk}) Y'_{jktv'} + \sum_i \sum_j \sum_t \sum_V CT^v_{ij} \times d_{ij} \times Q_{ijt} + \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} \\
& \times CT^{v'}_{jkm} \times d'_{jk} \times \left(Q^{m,r_m}_{jktv'} + QA^{m,r_m}_{jktv'} \right) + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CM_{jm} \times Q'_{j,t,m,r_m} + \sum_j \sum_t \sum_{m=2} CMA_{jm} \\
& \times QA_{jtm} \times \sum_i \sum_t CP_i \times Q_{it} \times Y_i + \sum_i \sum_j \sum_t \sum_v CP'_j \times \left(1 - \alpha^{(2)}_{jt} \right) \times \left(1 - \alpha^{(1)}_{ijtv} \right) \times Q_{ijtv} \times Y'_j
\end{aligned}
$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_{m=2} \sum_{r_m} CP_k''$$

$$\times \left[\left[\frac{\left(\sum_j \sum_{v'} \sum_m \sum_{r_m} \left(1 - \alpha_{jktv'}^{(1)\ m,r_m} \right) Q_{jktv'}^{m,r_m} + In_{k(t-1)}^{m,r_m} \right) \times \left(1 - \alpha_{k,t,m,r_m}^{(5)} \right) \times PC_{k,t,m,r_m}}{a} \right] \right.$$

$$\left. \times a + \left(\left(1 - \alpha_{jktv'}^{(2)\ m,r_m} \right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m} \right) \times \left(1 - \alpha_{k,t,m,r_m}^{(6)} \right) PCA_{k,t,m,r_m} \right]$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_{r_1} CP_k'' \times \left(1 - \alpha_{jktv'}^{(1)\ 1,r_1} Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1} \right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)} \right) \times PC_{k,t,1,r_1} + \sum_j \sum_t CH_{j1}$$

$$\times I_{jt} + \sum_j \sum_t \sum_m \sum_{r_m} CH_{jm} \left(IS_{jt}^{m,r_m} \right) + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CH_{jm} \times IA_{jt}^{m,r_m} + \sum_k \sum_t \sum_m \sum_{r_m} CH_{km}'$$

$$\times \left(In_{kt}^{m,r_m} + Ina_{kt}^{m,r_m} \right) + \sum_k \sum_t \sum_m \sum_{r_m} CS_{km} \times Q\pi_{kt}^{m,r_m} + \sum_k \sum_t \sum_m \sum_{r_m} CSA_{km} \times Q\pi a_{kt}^{m,r_m}$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CL_k^{m,r_m} \times YL_{jktv'} \times \left(Q_{jktv'}^{m,r_m} + QA_{jktv'}^{m,r_m} \right) + \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CE_k^{m,r_m}$$

$$\times YE_{jktv'} \times \left(Q_{jktv'}^{m,r_m} + QA_{jktv'}^{m,r_m} \right) + \sum_i \left(CPr_i + CEV_i + CER_i \right) \times T \times Y_i + \sum_j \left(CPr_j' + CEV_j' \right.$$

$$+ CER_j' + CERP_j) \times T \times Y_j' + \sum_k \left(CPr_k'' + CEV_k'' + CER_k'' \right) \times T + \sum_i \sum_t CW_i \times \alpha_{it}^{(1)} \times Q_{it}$$

$$+ \sum_i \sum_j \sum_t \sum_v CW_j' \times \alpha_{jt}^{(2)} \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv} + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CW_j^{m,r_m} \times \left[\alpha_{j,t,m,r_m}^{(2)} \times PQ_{jtm} \right.$$

$$+ (1 - PQ_{jtm}) \frac{\left(1 - EP_j^{(1)} \right) \times \sum_m \sum_{r_m} \left[P_{jtm} \times \left(1 - \alpha_{jm}^{(4)} \right) \times Q_{j,t,m,r_m}' \right]}{\sum_m \sum_{r_m} Q_{j,t,m,r_m}'} \left. \right] \times P_{jtm} \times \left(1 - \alpha_{jm}^{(4)} \right)$$

$$\times Q_{j,t,m,r_m}' + \sum_i \sum_j \sum_t \sum_v \sum_{r_1} CW_j^{1,r_1} \times \alpha_{j,t,1,r_1}^{(2)} \times PQ_{jt1} + (1 - PQ_{jt1}) \times \sum_j \sum_t$$

$$\times \left[\frac{\left(1 - EP_j^{(2)} \right) \times \sum_i \sum_v P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)} \right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv}}{\sum_i \sum_v \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv}} \right]$$

$$\times P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)} \right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{ijtv}^{(1)} \right) \times Q_{ijtv} + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CWA_j^{m,r_m}$$

$$\times PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)} \right) QA_{jtm} \times \left[\alpha_{jtm} \times PQA_{jtm} + (1 - PQA_{jtm}) \sum_j \sum_t \right.$$

$$\times \frac{\left(1 - EP_j^{(3)} \right) \times \sum_m PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)} \right) QA_{jtm}}{\sum_m QA_{jtm}} \left. \right] + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CW_j^{m,r_m} \times \left[\left(1 - \alpha_{j,t,m,r_m}^{(2)} \right) \right.$$

$$\times PQ_{jtm} \times P_{jtm} \times \left(1 - \alpha_{jm}^{(4)} \right) \times Q_{j,t,m,r_m}' + IS_{j(t-1)}^{m,r_m} \left. \right] \times \alpha_{j,t,m,r_m}^{(3)} + \sum_i \sum_j \sum_t \sum_v \sum_{r_1} CW_j^{1,r_1}$$

$$\times \left[\left(1 - \alpha_{j,t,1,r_1}^{(2)} \right) \times PQ_{jt1} \times P_{jt1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)} \right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)} \right) \times \left(1 - \alpha_{jt}^{(1)} \right) \times Q_{ijtv} + IS_{j(t-1)}^{1,r_1} \right]$$

$$\times \alpha_{j,t,1,r_1}^{(3)} + \sum_j + \sum_j + \sum_{m=2} \sum_{r_m} CWA_j^{m,r_m}$$

$$\times \left[PA_{jtm} \times \left(1 - \alpha_{jm}^{(5)} \right) QA_{jtm} \times (1 - \alpha_{jtm}) \times PQA_{jtm} + IA_{j(t-1)}^{m,r_m} \right] \times \alpha_{j,t,m,r_m}^{(4)}$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CW_k'^{m,r_m} \times \left[\left(1 - \alpha_{jktv'}^{(1)\,m,r_m}\right) \left(Q_{jktv'}^{m,r_m}\right) + In_{k(t-1)}^{m,r_m} \right] \times \alpha_{k,t,m,r_m}^{(5)}$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CW_k'^{m,r_m} \times \left[\left(1 - \alpha_{jktv'}^{(1)\,m,r_m}\right) \left(Q_{jktv'}^{m,r_m}\right) + In_{k(t-1)}^{m,r_m} \right] \times \alpha_{k,t,m,r_m}^{(5)}$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CW_k'^{m,r_m} \times \left[\left(1 - \alpha_{jktv'}^{(2)\,m,r_m}\right) QA_{jktv'}^{m,r_m} + Ina_{k(t-1)}^{m,r_m} \right] \times \alpha_{k,t,m,r_3}^{(6)}$$

$$+ \sum_j \sum_k \sum_t \sum_{v'} \sum_{r_1} CW_k'^{1,r_1} \left(\left(1 - \alpha_{jktv'}^{(1)\,1,r_1}\right) Q_{jktv'}^{1,r_1} + In_{k(t-1)}^{1,r_1} \right) \times \left(1 - \alpha_{k,t,1,r_1}^{(5)}\right) \times PC_{k,t,1,r_1}$$

$$- QT_{k,t,r_1} + \sum_j \sum_k \sum_t \sum_{v'} \sum_m \sum_{r_m} CREP_{jk}^{m,r_m} \times \left[\alpha_{jktv'}^{(1)\,m,r_m} \left(Q_{jktv'1}^{m,r_m}\right) + \alpha_{jktv'}^{(2)\,m,r_m} \left(QA_{jktv'}^{m,r_m}\right) \right]$$

$$+ \sum_i \sum_j \sum_t \sum_v CREP_{ij} \times \alpha_{ijtv}^{(1)} \times Q_{ijtv} \times \sum_j \sum_t \sum_{m=2} \sum_{r_m} CMI_{jm} \times \left[\left(1 - \alpha_{jm}^{(4)}\right) \times Q_{j,t,m,r_m}' + \left(1 - \alpha_{jm}^{(5)}\right) \right.$$

$$\left. \times QA_{jtm}\right] + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CMI_{jm} \times \left[\left(1 - \alpha_{jm}^{(4)}\right) \times Q_{j,t,m,r_m}' + \left(1 - \alpha_{jm}^{(5)}\right) QA_{jtm} \right] + \sum_i \sum_j \sum_t \sum_v CMI_{j1}$$

$$\times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} + \sum_i \sum_o N_{io} \times CPA_{io} \times ne_{io}$$

$$\times Y_i \sum_k \sum_q N_{kq}'' \times CPA_{kq}'' \times ne_{kq}'' + \sum_i \sum_o CB_o \times [(1 - PDR_{io}) + PDR_{io} \times (1 - PR_{io})] \times \lambda_{io} \times T$$

$$\times Y_i + \sum_j \sum_p CB_P' \times \left[\left(1 - PDR_{jp}'\right) + PDR_{jp}' \times \left(1 - PR_{jp}'\right) \right] \times \lambda_{jp}' \times T \times Y_j' + \sum_k \sum_q CB_q''$$

$$\times \left[\left(1 - PDR_{kq}''\right) + PDR_{kq}'' \times \left(1 - PR_{kq}''\right) \right] \times \lambda_{ky}'' \times T + \sum_i \sum_o \sum_t CR_{io} \times \lambda_{io} \times T \times PDR_{io} \times Y_i$$

$$+ \sum_j \sum_p \sum_t CR_{jp}' \times \lambda_{jp}' \times T \times PDR_{jp}' \times Y_j' + \sum_k \sum_q CR_{kq}'' \times \lambda_{kq}'' \times T \times PDR_{kq}'' + \sum_j \sum_t \sum_{m=2} \sum_{r_m}$$

$$\times CQC_{jm} \times \left(\alpha_{jm}^{(4)} \times Q_{j,t,m,r_m}' + \alpha_{jm}^{(5)} \times QA_{jtm} \right) + \sum_i \sum_j \sum_t \sum_v CQC_{j1} \times \alpha_j^{(1)} \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right)$$

$$\times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} + \sum_j \sum_t \sum_{m=2} \sum_{r_m} CA_{jm} \left[PQ_{jm} \times \left(1 - \alpha^{(2)}{}_{j,t,m,r_m}\right) \times P_{jm} \times \left(1 - \alpha_{jm}^{(4)}\right) \right.$$

$$\left. \times Q_{j,t,m,r_m}' \right] \times \frac{Ep_j^{(1)} \times \sum_m \sum_{r_m} \left[PQ_{jm} \times \left(1 - \alpha_{j,t,m,r_m}^{(2)}\right) \times P_{jm} \times \left(1 - \alpha_{jm}^{(4)}\right) \times Q_{j,t,m,r_m}' \right]}{\sum_m \sum_{r_m} Q_{j,t,m,r_m}'}$$

$$+ \sum_i \sum_j \sum_t \sum_v \sum_{r_1} CA_{j1} \times \left[PQ_{j1} \times \left(1 - \alpha_{j,t,1,r_1}^{(2)}\right) \times P_{j1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \right.$$

$$\left. \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv} \right]$$

$$++ \times \frac{Ep_j^{(2)} \times \sum_i \sum_v PQ_{j1} \times \left(1 - \alpha_{j,t,1,r_1}^{(2)}\right) \times P_{j1} \times \left(1 - \alpha_j^{(1)} - \alpha_j^{(2)}\right) \times \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}}{\sum_i \sum_v \alpha_{jt}^{(3)} \times \left(1 - \alpha_{jt}^{(2)}\right) \times \left(1 - \alpha_{ijtv}^{(1)}\right) \times Q_{ijtv}}$$

$$+ \sum_j \sum_t \sum_{m=2} CAA_{jt} \times \left[PQ_{jm} \times \left(1 - \alpha_{jtm}\right) \times PA_{jm} \times \left(1 - \alpha_{jm}^{(5)}\right) \times QA_{jtm} \right]$$

$$\times \frac{EP_j^{(3)} \times \sum_m \left[PQ_{jm} \times \left(1 - \alpha_{jtm}\right) \times PA_{jm} \times \left(1 - \alpha_{jm}^{(5)}\right) \times QA_{jtm} \right]}{\sum_m QA_{jtm}}.$$

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