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A Reliable and Sustainable Design of Supply Chain in Healthcare under Uncertainty Regarding Environmental Impacts

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Abstract

Nowadays, designing a reliable network for blood supply chains by which most blood demands can be supplied is an important problem in the health care systems. In this paper, a multi-objective model is provided to create a sustainable blood supply chain, which contains multiple donors, collection centers, distribution centers, and hospitals at different echelons. Regarding the potential of a blood shortage occurring, the suggested model considers the supply chain's capacity to meet hospitals' blood demands as dependable and a means of achieving the societal purpose. In addition, limiting the overall cost and environmental effect of designing a supply network and blood transportation are considered economical and environmental objectives. To solve the proposed multi-objective model, an improved ε-constraint approach is first employed to construct a single-objective model. Additionally, an Imperialist Competitive Algorithm (ICA) is developed to solve the single-objective model. Several test cases are analysed to determine the technique's effectiveness. CPLEX is then used to compare the results.

Keywords: Supply chain, Sustainability, Reliability, Blood supply chain, Environment, Imperialist competitive algorithm.

1 | Introduction

SCN Design (SCND) has a substantial effect on network components, including the quantity and placement of facilities, their capabilities, and the allocation of information and material flows. Changes to the network infrastructure are not possible in the near future because of the costs and time required. The SCND factor significantly impacts on supply chain management choices, both strategic and operational [1]-[4]. Environmental, social, and regulatory concerns drive firms to investigate the environmental and the social consequences of designing a sustainable supply chain [5], [6]. In this regard, Corporate Social Responsibility (CSR) refers to the impact of a company's activities on a wide range of persons. Since human blood supply is a finite and valuable resource, no other product or chemical technique can be utilized in its place at this time, and human blood is the only source available [7]. Only a small fraction of donated blood units is helpful, and there is a necessary interval between the donor's contribution and the next round of blood collection.

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Consequently, the body can restore depleted blood if given sufficient time. Platelets are the most quickly degraded of several blood components, lasting just five days until they are no longer viable. Therefore, platelets play a critical role in healing. Even though they are only utilized in rare circumstances, the number of units that must be transfused at once might be staggering when they are employed. Consequently, platelet needs vary greatly [8]. Many components of supply networks are not well defined, and this has a substantial impact on the chain of supply. It is thus essential to include uncertainty in supply chain architecture and optimization [9]. A catastrophe happens in a supply chain when several links in the supply chain are broken, causing considerable delays in the movement of products and services [10]. Below is a breakdown of the rest of the essay: Section 2 reviews the literature on supply chain networks and blood supply chains in a concise manner. Section 3 of this paper details the issue and its mathematical formulation. Section 4 explains how the suggested approach would work. For the proposed model's implementation and evaluation, see Section 5. Finally, in Section 6, the model's outcomes and possible research prospects.

2 | Literature Review

This section focuses on blood supply networks. Researchers have looked at the problem of blood supply chains from several perspectives. The model established by Haijema et al. [11] functioned successfully at a regional blood centre since it took into account seasonal characteristics, such as the holiday season, when it is almost challenging to collect donations. Nagurney et al. [12] employed bi-objective linear programming to identify a blood centre. Duan and Liao [13] created a quantitative inventory model for the Red Blood Cell (RBC) supply chain that considers various blood types and the possibility of replenishment. In this inquiry, simulation-optimization used to get a nearly optimal solution.

Jokar and Hossein-Motlagh [14] used a Mixed-Integer Linear Programming (MILP) model to reduce the emergency costs of the whole blood supply chain. The platelet collection appointment and collection schedule system proposed by Mobasher et al. [15] takes into account real-time limitations on platelet production. To enhance platelet formation, the MILP model was used. Blood unit age was taken into consideration in the creation of Gunpinar and Centeno's [16] platelet inventory model for hospitals. Yousefi Nejad Attari et al. [17] analysed a two-tier blood supply chain using a constrained bi-objective mathematical model to reduce the hospital's blood supply shortage and waste. They also lowered the disparity between the hospital's demand for blood transfusion services and the available blood supply. For disasters, Fahimnia et al. [18] developed an emergency supply network for blood supplies. With the use of Lagrangian relaxation, they came up with an innovative solution to the epsilon constraint problem. From a blood bank standpoint, RBC inventory management was introduced by Puranam et al. [19]. Many independent merchants were taken into consideration in this strategy. Rajendran and Ravindran [20] employed a stochastic programming technique to deal with the platelet's inventory management challenge. A set of four heuristic rules was devised to deal with the problem of platelets that had a varying shelf life in a medical supply system. Using a priority matching rule, an improved platelet supply chain has been suggested by Hosseinifard and Abbasi [21]. Lowalekar and Ravichandran [22] worked on a blood bank's integrated age-stock ordering model. For improved inventory management, this model considers the remaining shelf life of blood products as well as the current stock levels.

An attempt was made by Baş et al. [23] to balance blood supply chain production by looking at the appointment scheduling issue in more detail. Both pre-booked donors and unreserved donors would be taken into account in the proposed reservation system. Bashiri and Ghasemi [24] presented a two-stage stochastic programming approach to a blood supply inventory-routing challenge that can only be solved selectively. ÖZener and Ekici [25] addressed vehicle routing issues in the blood supply. To optimise the amount of blood that could be utilised for platelet formation, the model was designed. The model also included the possibility of platelet donation at random. Using a new transshipment policy that centred the hospital's inventory, Hosseinifard and Abbasi [21] attempted to improve the blood supply chain performance. Some hospitals believe they can meet their blood supply needs by relying on nearby blood banks. The model improves the system's average age and the pace at which it is obsolete. When it comes to RBC inventory routing, Jafarkhan and Yaghoubi [26] developed a comprehensive model to consider unforeseen events. The model incorporates transshipment and replacement flexibility to appropriately remedy the gap. Hamdan and Diabat [27] analysed the RBC supply chain using a stochastic programming framework considering production, inventory, and location. This strategy simultaneously reduces the quantity of wasted blood, system expenditures, and delivery time. The organisation has developed three-tier blood supply networks [28]. Quality factories were identified according to product storage conditions, taking into account blood storage equipment. According to Larimi et al. [29] the itemized-platelet supply chain may be modelled stochastically. Under uncertainty, Rajendran and Ravindran [30] proposed a supply chain inventory management approach for platelets. Stochastic genetic algorithms were updated to tackle the issue. The blood supply system was explored within the context of motivational efforts [31]. Uncertainty about product disruption in collecting facilities was handled in this approach. It was solved with the help of CPLEX, a computer algorithm. Khalilpourazari et al. [32] created a model for a disaster blood supply chain that incorporated helicopters and ambulances, as well as other modes of delivery. Hosseini-Motlagh et al. [31] emphasised for the first time the significance of motivational programmes in the blood supply chain networks. Haeri et al. [33] studied the durability of a blood supply network. They employed a data envelopment analysis approach to choose data collection facilities. Hosseini-Motlagh et al. [34] created a plasma supply chain architecture. The plasma supply chain has several distinctive aspects, including a freezing time interval and a need in both the medical and pharmaceutical industries. The longer the plasma had been frozen, the better the quality. Finally, a study of the blood supply system takes into consideration operational and failure risks [35]. This model was created to assist in the planning of the blood supply chain in an emergency. Lagrangin relaxation was used by Hamdan and Diabat [36] to overcome an issue with a disaster zone's blood supply system. They took into account the system's course and the distribution of facilities. TQM concepts, such as quality control systems, preventive maintenance and inspections, were utilised by Moslemi and Pasandideh [37] to highlight the quality flaws in blood supply chain. They found that the network's performance may be significantly affected by having the correct transit conditions. Asadpour et al. [38] employed multi-objective modelling to investigate the impact of wastes on the long-term sustainability of the blood supply chain. Blood transshipment between hospitals is the subject of a mathematical model created by Arani et al. [39]. In this model, there are a lot of variables and several goals. Models for economic, social, and environmental sustainability were devised. They came up with a workaround based on a modified version of the multi-choice goal programming approach. Soltani et al. [40] utilised the hub location idea to investigate a blood supply chain network under crisis scenarios. Particle swarm and DE optimization were used to tackle the problem at hand. Dehghani et al. [41] studied the blood supply chain inventory concerns. The goal was to optimise hospital ordering and transshipment choices via the use of a two-stage stochastic programming approach. In this work, we employ a mathematical model based on reliability concept that integrates the idea of shortages to better understand why the demand is not being satisfied. In this study, a multi-objective mathematical model for network design of a multi-level blood supply chain was developed. Many layers of the supply chain were evaluated, such as blood donors as suppliers, blood facilities as collection sites, blood centres as distribution hubs, and hospitals as demand places for blood products. The supply chain was analysed. The entire cost of the network was considered an objective function alongside environmental and social goals in the design of the network for sustainability. To ensure social responsibility, the supply chain's ability to meet hospital blood demand was examined considering anticipated shortages.

3 | Problem Definition

This study examines the challenge of network design for a multi-echelon blood supply network including multiple donors, blood facilities, blood centres, and hospitals. The donors play the supplier role and visit blood facilities which work as collection centers in this supply chain to donate blood. First, following registration, all blood donors are examined for blood-transfusion-related disorders. Additionally, the blood samples are analyzed for a variety of blood disorders. Moreover, the compatibility test is performed before a blood transfusion to avoid any negative outcomes due to incompatibility. On the other side, the blood centers (as distribution points in the supply chain) with specific capacity, receive the demand from the hospitals (demand points). Accordingly, these centers get the donated blood types from the collection centers and supply the blood demands. This supply chain assumes that the platelet apheresis method is used to get blood platelets. It is possible to extract platelets and their components from a donor's blood using a specialized apparatus known as platelet apheresis, an advanced platelet collection and preparation technique. Once the remaining blood components have been restored to the patient's body, the patient will be discharged. In this manner, a greater number of platelets may be produced from a single donor than would otherwise be possible. The configuration of the model is shown in *Fig. 1*, in which the red colored notations indicate decision variables for each echelon.

Locating the collection and distribution centers in this network are decision variables which are determined for potential locations. Also, the blood centers' capacity must be defined. Moreover, allocation of the facilities between different echelons and the blood flow through the network are other decision variables. According to the capability of open blood centers in supplying the blood demand and the possibility of shortage occurrence in satisfying the demand, the reliability concept is determined in the network. These characteristics should be identified in a manner that will lead to the creation of a network for a sustainable blood supply chain. As a matter of social duty, the objective of the network design challenge is to maximise the network's dependability in meeting blood demand. Moreover, minimization of the total cost and environmental impacts are considered as economical and environmental goals, respectively.

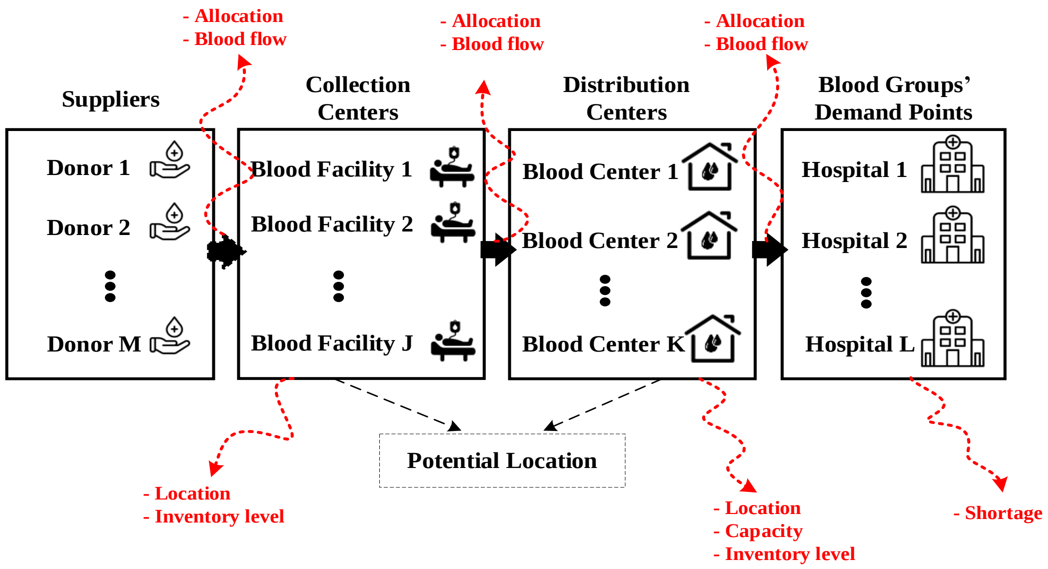

Fig. 1. Problem configuration.

3.1 | Assumptions

There are some assumptions for our model, which have been gathered as follows:

I. Platelets have a five-day life expectancy, plus two days required for testing.
II. When a hospital places an order for blood products, there is no delay in delivery.
III. A wide range of vehicles are available, each with a distinct carrying capacity.
IV. A single vehicle is limited to one visit per period to any given hospital or open blood facility.
V. Each route can only have one vehicle allocated to it.
VI. Each day is equal to one period.
VII. A blood facility, blood center, or hospital can only provide a limited amount of blood.
VIII. There must be an open blood center at the beginning and conclusion of every journey.
IX. Platelet ages are known for each unit of blood. If a platelet is less than three days old, it is referred to as "young".
X. The sites of hospitals and donor groups are predetermined; thus, there is no room for error.

XI. Wastes generated by blood-related illnesses, blood expired in blood center or healthcare center, and unused blood during tests.
XII. In the absence of sufficient supplies, the price of not being able to meet demand is allowed to rise.
XIII. Supplying demand, procuring, collecting, producing, testing, and distributing blood all contribute to the total cost of manufacturing.

The study of Pishvaee et al. [42] outlines certain sustainability concepts. The suggested model seeks to estimate the locations and sizes of the blood facilities and blood centres, the volume of shipping, and the most reliable vehicle routes such that the following sustainable objectives may be realised simultaneously:

I. Economic goal: minimizing the total cost including transportation costs, holding costs, dispatching costs, centers and facilities' establishing costs, operating and production costs and blood disposal costs.
II. Environmental goal: minimizing the environmental impacts due to establishing and shipping blood through the supply chain network.
III. Social goal: maximizing the reliability of blood supply in the supply chain network.

3.2 | Notations

The notations used in the mathematical model are as follows:

3.2.1 | Sets

M: Areas designated for blood donors, $m\epsilon M$.

J: List of potential locations for blood collection facilities, $j, j_1\epsilon J$.

K: Set of prospective locations for blood clinics, $k, k_1\epsilon K$.

L: Set of hospitals as demand centers, $l, l_1\epsilon L$.

D: Set of blood centers' capacity, $d\epsilon D$.

S: Set of blood age, $s\epsilon S$.

U: Set of distinct planning horizons, $u\epsilon U$.

G: Consolidated groups of hospitals and potential blood supply locations, i.e., $L\ V\ K$ and $g, g_1\epsilon G$.

B: Set of the age range for blood, $b\epsilon B$.

3.2.2 | Parameters

Db_{jk}: Fixed transportation costs from the blood facility j to blood center k.

Db_{gg_1}: Fixed transportation costs between location g to location g_1.

UF_{jm}: Donors' transportation costs from their location j to m.

PD_{ku}: The cost of operating a blood facility for one unit of blood center k in time span u.

DD_{ju}: Operational costs associated with collecting blood units at a particular location j in time span u.

PDH_{lu}: Cost of operating a single unit of blood at hospital l in time span u.

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TD_d: Each blood center's maximum storage capacity is determined by its size d.

DG: The capacity of fixed blood facility.

DU: The capacity of temporary blood facility.

DH: The upper level of capacity for every hospital.

ND_{jj_1u}: Transferring the costs associated with each temporary blood facility from its current location j_1 to location j in the planning period t.

GC_{kd}: Expenses associated with the establishment of a blood facility at a prospective site k with size d.

Gq_j: Expenses related to the establishment of a permanent blood facility at a prospective site j.

HC_{ku}: The cost of storing a blood unit at a blood facility k at time span u.

HH_{lu}: The expense of storing each unit of blood at a hospital l at time span u.

V_m: The upper level for blood supply for the permitted donor group m.

π_s^0: Costs associated with utilizing old blood for patients requiring young blood during the planning phase s.

π_s^1: Costs associated with the use of young blood for patients with any blood need during the planned period s.

EG_j: Environmental consequences of building a permanent blood collection facility at a particular site j.

EC_{kd}: Consequences of blood donation on the environment center k with size d.

ES_{jk}: The environmental burden of transporting each collection of blood from site j to location k.

ES'_{gg_1}: The environmental burden of transporting each collection of blood from site g to the location g1.

E'_{blu}: Demand for blood group b at the hospital l in planning period u.

ED: Cost of waste blood disposal and transportation on a unit basis.

ρ: Cost of penalties associated with the environmental impact of waste blood.

γ: Blood loss rate during the manufacturing process.

η_1: Rate of blood lost during examination after blood center receipt.

η_2: Blood loss rate during hospital inspections after blood receipt.

ω: Estimated proportion of blood in inventory which is five years old.

C: Number of hospitals in total.

M: A big number.

3.2.3 | Variables

Y_{jku}: Blood transported from blood facility j to blood center k during the planning period u.

Z_{slwu}: Blood age s heading to the hospital l by car w during the planning time u.

C_{sku}: The blood age s shortage for the blood center k at the end of time span u.

C'_{blu}: The blood group b shortage at hospital l at the end of time span u.

Rel_u: Indicates reliability of supplying blood during time period u.

M_{jku}: A binary variable equal to 1 if the blood facility in location j transferred to blood center in location k during the planning period u; otherwise, 0.

J'_{blu}: The inventory level of blood groups at the hospital l by the end of the planned period u.

J_{sku}: The number of s days remaining on the blood inventory at blood center k at the end of the time span t.

IQ_u: Total volume of waste blood produced during time span u.

F_{jmu}: A binary variable equal to 1 if the blood center at the location j assigned to donor group m during time span u; otherwise, 0.

x_j : A binary variable equals 1 if a permanent facility at site j is opened; 0, otherwise.

P_{kd}: A binary variable equals 1 if a blood center of size d is established at location k; 0, otherwise.

H_{jj_1u}: A binary variable that equals 1 if a temporary facility is positioned at location j_1 during period u-1 and then relocates to location j during planning period u.

W_{klu}: A binary variable equal 1 if the hospital at location l is allocated to the blood center at location k during the planning period u; 0, otherwise.

3.3 | Model Formulation

In this subsection, the objective functions and constraints are described.

3.3.1 | The objective functions

$$\begin{aligned}\text{Min } Z_1 = {} & \textstyle\sum_j^J \sum_k^K \sum_u^U M_{jku} Db_{jk} + \sum_g^G \sum_{g_1}^G \sum_w^W \sum_u^U S_{gg_1wu} Db'_{gg_1} + \\ & \textstyle\sum_j^J \sum_{j_1}^J \sum_u^U M_{d_{jj_1u}} H_{jj_1u} + \sum_j^J \sum_m^M \sum_u^U TF_{jm} F_{jmu} + \sum_s^S \sum_k^K \sum_u^U HC_{kt} J_{sku} + \\ & \textstyle\sum_b^B \sum_l^L \sum_u^U HH_{lu} J'_{blu} + \sum_l^L \sum_u^U \pi_u^0 \delta_{lu}^0 + \sum_l^L \sum_u^U \pi_u^1 \delta_{lu}^1 + \sum_d^D \sum_k^K GC_{kd} P_{kd} + \\ & \textstyle\sum_j^J Gq_j x_j + \sum_j^J \sum_k^K \sum_u^U PD_{ku} Y_{jk} + \sum_s^S \sum_l^L \sum_w^W \sum_u^U PDH_{lu} y_{slwu} + \\ & \textstyle\sum_j^J \sum_k^K \sum_u^U DD_{jt} y_{jkt} (\frac{1}{1-\gamma}) + \sum_u^U EDHq_u + \sum_w^W \sum_u^T WH_{wu} DW_w.\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Min } Z_2 = {} & \textstyle\sum_k^K \sum_d^D EC_{kd} P_{kd} + \sum_j^J EG_j x_j + \sum_j^J \sum_k^K \sum_u^U ES_{jk} M_{jku} + \\ & \textstyle\sum_g^G \sum_{g_1}^G \sum_w^W \sum_u^U ES'_{gg_1} S_{gg_1wu} + \sum_u^U \rho IQ_u.\end{aligned} \tag{2}$$

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The third objective function relates to social responsibility and attempts to maximize the reliability of supplying blood demands in the network. The reliability in each period depends on the total shortages in satisfying different blood groups' demand. Indeed, $Rel_u = 1 - \underset{b\in B, l\in L}{Average}(\frac{C'_{blu}}{E'_{blu}})$.

3.3.2 | Constraints

$$MaxZ_3 = \min_u Rel_u, \quad (3)$$

$$\sum_{s\geq 2}^{S} J_{sku} \leq \sum_{d}^{CD} TD_d P_{kd}, \ u = 2,3,\dots,U \ \text{ for all } k, \quad (4)$$

$$J'_{1lu} + J'_{0lu} \leq DH, \quad u = 2,3,\dots,U \ \text{ for all } l, \quad (5)$$

$$\sum_{k}^{K} y_{jku} \leq x_j DG + \sum_{j_1}^{J} G_{jj_1t} DU, \quad u = 2,3,\dots,T \quad \text{for all } j, \quad (6)$$

$$Y_{jku} \leq M.M_{jku}, \quad u = 2,3,\dots,U \ \text{ for all } j,k, \quad (7)$$

$$x_j + \sum_{j_1}^{J} G_{jj_1u} \leq 1, \quad u = 2,3,\dots,U \ \text{ for all } j, \quad (8)$$

$$\sum_{j_1}^{J} G_{jj_1u} \leq \sum_{j_1}^{J} G_{jj_{1,u-1}}, \quad u = 2,3,\dots,U \ \text{ for all } j, \quad (9)$$

$$\sum_{d}^{D} P_{kd} \leq 1 \quad \text{for all } k, \quad (10)$$

$$\sum_{l}^{l} \sum_{b}^{B} E'_{blu} W_{klt} \leq \sum_{d}^{D} TD_d P_{kd}, \quad u = 3,\dots,T \ \text{ for all } k,l, \quad (11)$$

$$\sum_{k}^{K} W_{klu} \leq 1, \quad u = 3,\dots,T \ \text{ for all } l, \quad (12)$$

$$\sum_{k}^{K} M_{jku} \leq x_j + \sum_{j_1}^{J} G_{jj_1u} \quad \text{for all } j,u, \quad (13)$$

$$M_{jku} \leq \sum_{d}^{D} P_{kd}, \quad u = 2,\dots,T \ \text{ for all } j,k, \quad (14)$$

$$\sum_{j}^{J} E_{jmu} \leq 1 \quad \text{for all } j,u, \quad (15)$$

$$E_{jmu} \leq x_j + \sum_{j_1}^{J} G_{jj_1u} \quad \text{for all } j,m,u, \quad (16)$$

$$\sum_{j}^{J} \frac{z_{jku}}{(1-\gamma)} \leq \sum_{m}^{M} V_m E_{jmu} \quad \text{for all } j,u, \quad (17)$$

$$\sum_{s\geq 3}^{S} z_{slwu} \leq WD_w \sum_{g}^{G} S_{glwu}, \ u = 3,\dots,U \ \text{ for all } l,w, \quad (18)$$

$$\sum_{l}^{L} \sum_{w}^{W} z_{4lwu} = 0, \quad u = 1,2,3, \quad (19)$$

$$\sum_{l}^{L}\sum_{w}^{W} z_{5lwu} = 0, \quad u = 1,2,3, \tag{20}$$

$$J'_{0lu} = 1 - \eta_2) \sum_{w}^{W} Z_{3lwu} + \delta_{0lu} - \delta_{1lu} - E'_{10u} + c'_{0lu}, \quad u = 3, \dots, U \text{ for all } l, \tag{21}$$

$$\delta_{olu} = 0, \quad u = 3 \text{ for all } l, \tag{22}$$

$$1 - \eta_2) \sum_{w}^{W} Z_{3lwu} - \delta_{1lu} - E'_{lou} \geq 0, \quad u = 3, \dots, U \text{ for all } l, \tag{23}$$

$$J'_{1lu} = J'_{0l,u-1} + 1 - \eta_2) \sum_{s \geq 4}^{S} Z_{slwu} + \delta_{1lu} - \delta_{0lu} - E'_{l1u} + c'_{1lu}, \ u = 3, \dots, U \text{ for all } l, \tag{24}$$

$$c'_{0lu} J'_{0lu} = 0, \quad u = 3, \dots, U \text{ for all } l, \tag{25}$$

$$c'_{1lu} J'_{1lu} = 0, \quad u = 3, \dots, U \text{ for all } l, \tag{26}$$

$$J'_{0,l,u-1} + 1 - \eta_2) \sum_{w}^{w} \sum_{s \geq 4}^{S} Z_{slwu} - \delta_{olu} - E'_{l1u} \geq 0, \quad u = 3, \dots, U \text{ for all } k, \tag{27}$$

$$IQ_u = \omega \sum_{l}^{L} J'_{1lu} + \sum_{j}^{J} \sum_{k}^{K} (\frac{\gamma}{1-\gamma}) Y_{jku} + \sum_{j}^{J} \sum_{k}^{K} \eta_1 Y_{jku} + \sum_{k}^{K} J_{5ku} \quad \text{for all } k, u, \tag{28}$$

$$J_{sku} = J_{(s-1)k(u-1)} - \sum_{l}^{L} \sum_{w}^{W} W_{klt} Z_{slwu} + c_{sku}, \quad u = 3, \dots, U, \quad s = 3, \dots, S \text{ for all } k, \tag{29}$$

$$J_{2ku} = \sum_{j}^{J} 1 - \eta_1) Y_{jk\ u-1)}, \quad u = 2, \dots, U \text{ for all } k, \tag{30}$$

$$J_{sku} \cdot c_{sku} = 0, \quad u = 2, \dots, U \text{ for all } k, \tag{31}$$

$$y_{jku}, y_{slwu}, c'_{plu}, c'_{1lu} J'_{plu}, J'_{1lu}, J_{sku}, c_{sku} \in Z^{+} \quad \text{for all } j, k, s, h, w, u, \tag{32}$$

$$W_{klu}, WH_{wu}, M_{jku}, X_j, P_{kd}, K_{jj_1u}, S_{gg_1wu} \in \{0,1\} \quad \text{for all } j, j_1, k, l, w, u, g, g_1, d, \tag{33}$$

$$M_{lwu}, IQ_u \geq 0 \text{ for all } l, w, u. \tag{34}$$

The constraints of proposed model are as follows:

To ensure that the blood supply stays within the facility's capacity, *Constraints (4)* and *(5)* must be followed. This restriction limits the amount of blood each blood centre may donate to the system. Blood cannot be transferred to the blood centre from any facility that is not designated to one by *Constraint (7)*, *(8)* restricts the number of facilities that may be opened at a given location to a maximum of one per place. One short-term blood facility may be located at a particular location due to *Constraint (9)* of the design. According to *Constraint (10)*, there can only be one blood centre of a specified size. Using existing blood centres, *Constraint (11)* keeps the capacity constraint in place. *Constraint (12)* mandates that no hospital be allocated to more than one blood centre. For those who live in location I and have access to a blood bank, every single blood facility may be assigned to a single blood centre because of *Constraint (13)*. *Constraint (14)* states that when a blood centre shuts, no new blood facility will be assigned to it. One blood centre may only be assigned to a single donor group, as stipulated by *Constraint (15)*. All blood donors must be sent to existing donation centres as a result of *Constraint (16)*. There is a restriction on the amount of blood that may be taken from each blood centre in order to meet the maximum supply l authorised for the donor group of choice according to *Constraint (17)*. When it comes to blood deliveries to hospitals, there is a limit, as seen in *Constraint (18)*. As a result of these constraints, the time it takes to prepare blood for delivery at particular hospitals is taken into consideration in the calculations. Because of *Constraint (21)* every institution must keep a record of the young people who have given their blood to the institution. This shows that there is no such thing as "ancient" blood in the event of mismatched blood *Constraint (22)*. There is no shortage of "young" blood types, as shown by *Constraint (23)*. It is necessary for each institution to maintain a proper balance of old blood to comply with *Constraint (24)* one variable can only be positive at a time, as shown by *Constraints (25)* and *(26)*. *Constraint*

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(27) shows that patients' usage of Kind 1 blood does not lead to a shortage of "old" blood kinds. *Constraint (28)* affects how much blood is wasted or lost in the supply chain. The end-of-term blood inventory levels at blood centres are tied into *Constraints (29)* and *(30)*. Only one of the variables in *Eq. (31)* may be positive. *Constraint (32)* describe the variables used to make decisions in *Eq. (34)*.

The proposed model is a MINLP model because of *Eq. (3)* and *Constraints (25)*, *(26)*, *(29)* and *(31)*. To have a MILP model, the following changes are needed:

Objective *Function (3)* can be simply linearized using replacing *Eq. (3)* with *Eq. (35)*. Furthermore, *Eq. (36)* should be considered as a new constraint in the proposed model.

$$\text{Max } Z_3 = \text{Rel}'. \tag{35}$$

$$\text{Rel}' \geq \text{Rel}_u \quad \text{for all } u. \tag{36}$$

To linearize the *Constraint (29)*, in which integer and binary variables are multiplied, term $W_{klt}Z_{slwu}$ should be replaced by Q_{sklwt} and *Constraints (37)-(40)* should be added to the model.

$$Q_{sklwt} \leq Z_{slwu}, \quad u = 3, \dots, U, \quad s = 3, \dots, S \quad \text{for all } k, l, w. \tag{37}$$

$$Q_{sklwt} \leq MW_{klu-1}, \quad u = 3, \dots, U, \quad s = 3, \dots, S \quad \text{for all } k, l, w. \tag{38}$$

$$Q_{sklwt} \geq M\ W_{klu-1} - 1) + Z_{slwu}, \quad u = 3, \dots, U \quad s = 3, \dots, S \ \text{ for all } k, l, w. \tag{39}$$

$$Q_{sklwt} \in Z^+. \tag{40}$$

Finally, to linearize *Constraints (25)*, *(26)* and *(31)* in which two integer variables (X.Y) are multiplied, *Constraints (41)-(44)* should be considered in the model.

$$Y \leq M.K'. \tag{41}$$

$$X \leq M.K''. \tag{42}$$

$$K' + K'' \leq 1. \tag{43}$$

$$K', K'' \in \{0,1\}. \tag{44}$$

4 | Solution Approach

To solve the proposed multi-objective MILP model, first, it is converted to a single-objective model. Then, an Imperialist Competitive Algorithm (ICA) is used as a metaheuristic approach to solve this single-objective model, approximately. *Fig. 2* indicates the overall parts of developed solution approach.

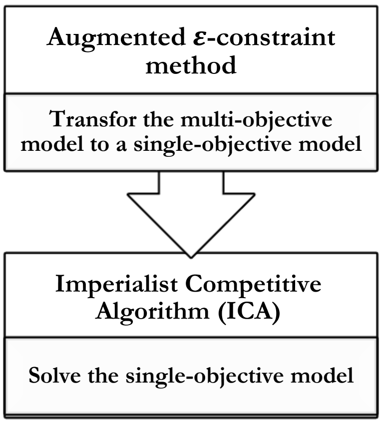

Fig. 2. General part of solution approach.

4.1 | Single-Objective Model

To simplify the multi-objective model, ε-constraints are used. As a result, this technique prioritises the most critical goal function and regards all other goals as constraints. A single-objective framework has been implemented to focus on the most critical objective function [43]. This method generates more nondominant answers, which decision-makers like. *Eq. (1)* shows how the suggested model is reworked using the enhanced e-constraint technique in *Eq. (45)*.

$$\begin{aligned}
&\text{Optimize } (\text{OF1}, \text{OF2}, \text{OF3}) \rightarrow \\
&\quad \text{s.t.} \quad \text{Constraint} \\
&\text{Optimize } \text{FO}_{\text{e-constraint}} = \left(\text{OF1} + \delta\left(\frac{\text{sl}_2}{\text{Range}_2} + \frac{\text{sl}_3}{\text{Range}_3}\right)\right), \\
&\qquad\qquad \text{s.t.} \quad \text{Constraints} \\
&\qquad\qquad\qquad \text{OF2} + \text{sl}_2 = \text{e}_2, \\
&\qquad\qquad\qquad \text{OF3} - \text{sl}_3 = \text{e}_3,
\end{aligned} \tag{45}$$

where e_i is the epsilon value for objective functions considered as new constraints, sl_i is slack or surplus variables, determined based on minimization or maximization objective functions and $Range_i$ indicate range of variations for each objective functions. This single-objective model is solved for different values of e_i.

4.2 | Approximate Solution Approach

The ICA is used as an approximation solution method to solve the single-objective model proposed in this paper. A population-based evolutionary algorithm developed by Atashpaz-Gargari and Lucas [44] is known as a population-based evolutionary algorithm. Based on of the phenomena of imperialism and the fight amongst imperialists to extend their empire and conquer weaker nations, the ICA operates [45]. *Fig. 3* depicts the suggested algorithm's stages. It all begins with establishment of empires, complete with imperialists and the territories they control. Secondly, the colonies migrate toward their imperialist. The third phase is to ensure that the imperialists are not replaced by stronger colonies. After then, empires battle for control of the weaker empires' colonies in order to increase their overall dominance. It's at this point when empires without colonies are eliminated, and the algorithm's execution is stopped.

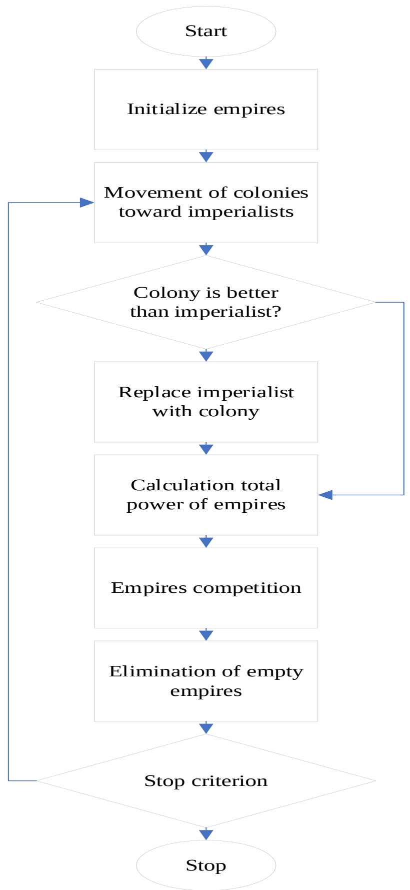

Fig. 3. ICA flowchart.

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4.2.1 | Solution representation

The solution representation of the proposed model consists of three parts, as shown in *Fig. 4*. In order to determine the activate facilities including blood facilities and blood centers, a $1 \times n$ vector is generated randomly based on uniform distribution U 0,1), in which n is determined based on potential existing locations. The second part determine the capacity level in each blood center. In this part, a $1 \times m$ vector is generated randomly based on uniform distribution U 0,1) in which m is defined with regard to the number of blood centers. Random numbers are multiplied by the number of capacity levels, and the results are rounded to calculate the capacity of the blood centre. As a reminder, the capacity level should only be established for the blood centres that were opened in the earlier section of this article. The third portion results in the movement of facilities, shortages, and inventory levels between one another. In this regard, a $x \times y$ matrix is generated, randomly based on uniform distribution $U(0,1)$, in which x and y are defined based on opened facilities, determined in previous parts. Then, for each column (as destination point), the generated numbers are normalized by which share of each sender in supplying demand is specified. The other variables are determined randomly or according to specified variables.

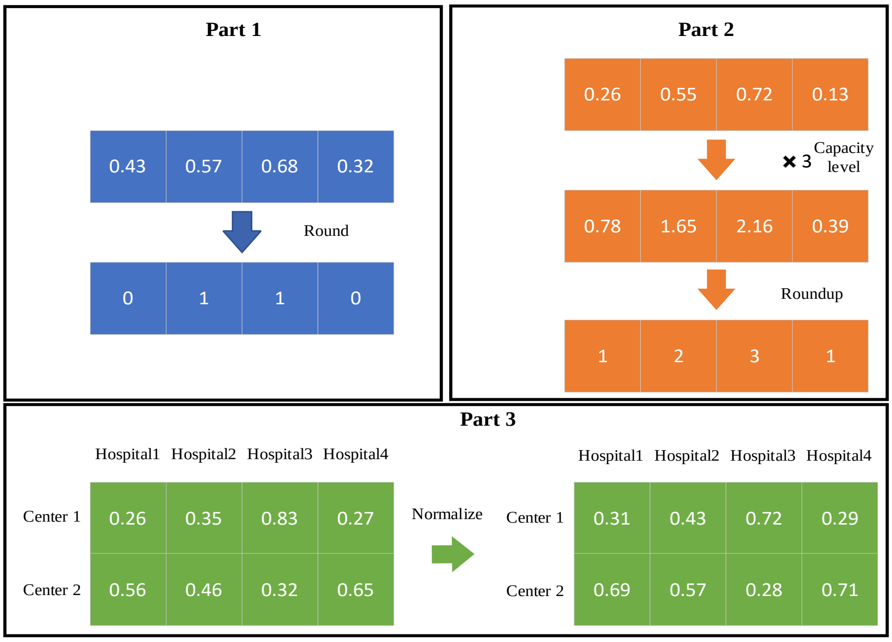

Fig. 4. Solution representation.

4.2.2 | Parameters adjustment

Adjusting the parameter of ICA using the Taguchi approach is done in order to minimise the noise impact in relation to establishing the best level for signal factors [46]. *Table 1* shows different levels of ICA factors, with the corrected values, estimated based on L27 design, being underlined.

Table 1. ICA parameter ranges.

ICA Parameter	Parameter Level		
	Low	Middle	High
Number of population	20	30	40
Number of imperialists	5	10	15
A random variable in movement toward imperialist	1	2	3
Deviation from original direction	0.5	0.6	0.7
Influence coefficient of colonies	0.05	0.1	0.2
Maximum generation	50	100	150

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5 | The Numerical Study

To evaluate the efficiency of presented solution approach in solving the proposed model, several numerical examples are studied. *Table 2* indicates the size of numerical examples. Furthermore, the parameters of numerical examples are generated randomly based on *Table 3*.

Table 2. Size of numerical examples.

Problem No.	Blood Donors	Blood Facilities	Blood Centers	Hospitals	Period
1	2	2	2	2	2
2	3	3	2	2	2
3	4	3	3	3	3
4	5	3	3	3	3
5	7	5	4	4	4
6	8	6	5	4	5
7	10	8	6	5	6
8	12	10	8	6	9
9	12	10	8	7	9
10	15	12	10	8	12

It is necessary to structure all test problems as single-objective models in accordance with the enhanced electronic constraint approach (Section 4.1) and to answer them using an ICA that was built (Section 4.2). It is important to highlight that MATLAB R2013 is utilised to solve the ICA test cases. Additionally, the CPLEX 10.0 solver in GAMS on a 2 GHz machine with 8 GB RAM is utilised to solve the test problems in order to assess the effectiveness of the proposed approach. *Fig. 5* indicates the convergence of ICA in solving test problem 4.

Table 3. The values of parameters in the test problems.

Parameter	Distribution	Parameter	Distribution
η_1	U[0.002, 0.005]	FT'_{gg_1}	U [1, 50]
ρ	U [500, 1000]	KP_{kd}	U [1, 10]
v_m	U [200, 2000]	KP'_j	U [2, 20]
E'_{olt}	U [5, 200]	γ	U [0.01, 0.05]
E'_{1lt}	U [5, 200]	WD_w	U [5000, 50000]
ED	U [1000, 2000]	PD_{kt}	U [50, 50]
η_2	U [0.002, 0.005]	MD_{jj_1t}	U [1000,4000]
s_{jm}	U [1, 100]	DG	U [50000, 100000]
Parameter	**Distribution**	**Parameter**	**Distribution**
Db'_{gg_1}	U [30, 200]	GC_{kd}	U [100,50000]
PDH_{lt}	U [10, 150]	Gq_j	U [0,200]
EG_j	U [20, 200]	TD_d	U [20000,100000]
EC_{kd}	U [1, 5]	π_{kt}	U [10000,500000]
ES_{jk}	U [1, 5]	π'_{lt}	U [10000,500000]
Db_{jk}	U [5, 20]	HC_{kt}	U [1000, 5000]
DW_w	U [100, 20000]	π_t^1	U [10, 100]
DD_{jt}	U [2,20]	DG	U [50000,100000]

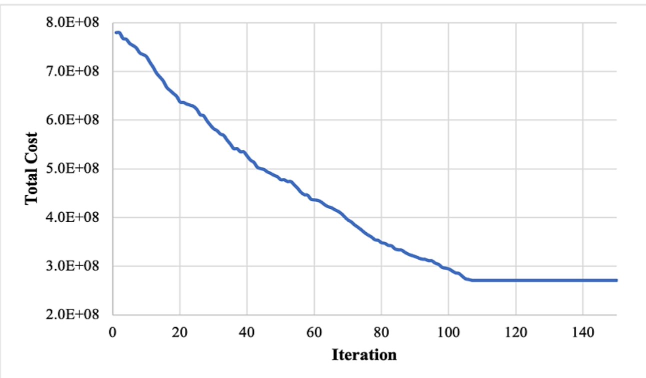

Fig. 5. Convergence of ICA in test problem.

Moreover, the results of solving test problems using CPLEX and developed ICA are indicated in *Table 4*.

Table 4. The values of parameters in the test problems.

Problem No.	OF_1		OF_2		OF_3	
	CPLEX	ICA	CPLEX	ICA	CPLEX	ICA
1	9.33×10^6	9.91×10^6	900	950	0.83	0.82
2	3.98×10^7	4.08×10^7	950	1025	0.87	0.81
3	9.37×10^7	9.86×10^7	1050	1125	0.77	0.74
4	2.51×10^8	2.71×10^8	1275	1350	0.72	0.68
5	9.54×10^{10}	1.09×10^{11}	1725	1800	0.73	0.71
6	2.19×10^{11}	2.34×10^{11}	1850	1950	0.76	0.72
7	4.83×10^{12}	5.23×10^{12}	2200	2275	0.77	0.72
8	9.84×10^{12}	1.24×10^{13}	2475	2550	0.7	0.65
9	NA	3.12×10^{13}	NA	3100	NA	0.64
10	NA	2.26×10^{14}	NA	3300	NA	0.58

As shown in *Table 4*, the CPLEX solver in gams during 15000 seconds lead to no result for test problems 9 and 10. In contrast, ICA resulted in solutions for these large-scale problems. Moreover, a comparison of the results achieved by each solution approach indicates no significant difference between the results and ICA is capable of achieving near optimum solutions. The last column of *Table 4*, indicates CPU time, spent to achieve the final solution using ICA.

Finally, *Table 5* indicates the gap between results that came from each developed metaheuristic algorithm and CPLEX.

According to *Table 5*, it can be concluded that the ICA algorithm can reach near optimum solution in a more reasonable time. Moreover, it is more useful to solve large-scale problems, in contrast with CPLEX which is not enable to reach near optimum solution for this type of problems.

Table 5. The gap between results of solving test problems via CPLEX and ICA.

Problem No.	OF_1	OF_2	OF_3
1	0.06	0.06	0.01
2	0.03	0.08	0.07
3	0.05	0.07	0.04
4	0.08	0.06	0.06
5	0.06	0.04	0.03
6	0.07	0.05	0.05
7	0.08	0.03	0.06
8	0.04	0.03	0.07
9	NA	NA	NA
10	NA	NA	NA

5 | Conclusion

Mathematical models for the design of a multi-echelon blood supply system are described in this paper. The examined supply chain network included many tiers, such as donors as suppliers, blood facilities as collecting locations, blood centres as distribution points, and hospitals as demand points. For the sake of sustainability in designing the network, minimizing the total cost as an economic concern was considered as an objective function besides environmental and social goals. To consider the social responsibility in the proposed model, the reliability of sustainable blood supply chain in supplying hospitals' blood demand was regarded for shortages in meeting the demands. Moreover, the environmental raised from establishing facilities and their operations was considered as an environmental objective function. To solve the described mixed-integer linear model, the augmented ε-constraint approach is first utilised to reduce the multi-objective model to a single-objective one. An ICA, a population-based metaheuristic devised to solve the single-objective model, was also created. Additionally, numerical examples are utilised to assess the suggested solution approach's efficiency, and the results are compared to the results produced by CPLEX. A blood supply chain's capability to fulfil demand is critical, and this research attempted to build a blood supply chain where network dependability is regarded as a social objective alongside well-known economic and environmental goals in meeting blood needs.

However, considering the uncertainty of numerous model components, such as demand, might broaden the scope of this research. In this way, the reliability concept in the proposed model can be developed about the probability of shortage occurrence in supplying the demand. Furthermore, for the sake of simplicity, single-objective optimization is considered, while using multi-objective optimization results in more reliable options for decision-makers. Hence, using multi-objective algorithms by which multiple objective functions are optimized simultaneously is recommended as another future research direction.

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Conflicts of Interest

All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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