OPERATIONS AND SUPPLY CHAIN MANAGEMENT
Vol. 17, No. 3, 2024, pp. 211 - 221
ISSN 1979-3561 | EISSN 2579-9363

Blood Supply Chain Optimization Model with Transshipment and Multiple Blood Products

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ABSTRACT

The blood supply chain is a complex, integrated system, involving multiple echelons that requires optimization to obtain optimal solutions. This study develops a mixed-integer linear programming (MILP) model for blood supply chains with multi-echelons including donors, blood centers, and hospitals. The model also considers multiple blood products, vehicle routing, and transshipment between blood centers, with the aim of minimizing the total costs of the blood supply chain. The results of the computational model indicate that there is a significant relationship between the number of blood centers and the total cost of the blood supply chain. In addition, the volume of blood products distributed between blood centers is inversely proportional to the volume of blood products produced in each blood center.

Keywords: *blood product transshipment, blood supply chain, vehicle routing*

1. INTRODUCTION

According to the World Health Organization (WHO), accessing blood donations is a problem experienced by the healthcare industry around the world, but particularly in developing countries (Asadpour *et al*., 2022). The problem arises because donors cannot donate blood at any given time, instead having to wait for the right time to be able to donate blood (Torrado & Barbosa-Póvoa, 2022). Managing blood distribution so that blood supply shortages are minimized requires the design of a blood supply chain that is integrated from upstream to downstream (Zahiri *et al*., 2018). Blood supply chain is a one type of supply chain management. Delivering goods and services from upstream to downstream supply chain activities is a part of supply chain management. Strategic and operational considerations have a dual role in today's global and competitive supply chain management and decision-making process (Mujkić *et al*., 2018).

The blood supply chain consists of several echelons including donors, blood centers, and hospitals, as well as multiple phases such as collecting, processing, inventory, and distribution. The *collecting* phase occurs in the donor echelon. In this phase, blood collection activities occur at bloodmobiles or donors can go directly to blood centers. Bloodmobile is one of logistics needed in the medical field. The findings show that medical related logistics are poorly organized, including the distribution of medical supplies, the transfer of casualties, and the dispatch of ambulances. Medical logistics must meet urgent demands in order to be successful and efficient. The procedure of distributing medical treatment can be described as vehicle routing issues with timely collection and delivery (Liao *et al*., 2017).

When collecting blood donations through bloodmobiles, optimizing the route of bloodmobile to reach the most donors and locations and maximize the blood collection is critical. To optimize blood collection using a bloodmobile, vehicle routing and transportation costs resulting from the bloodmobile trip must also be considered.

Although previous studies have discussed the processing phase of the blood supply chain (Eskandari-Khanghahi *et al*., 2018; Ghahremani-Nahr *et al*., 123 C.E.; Ghasemi *et al*., 2022; Halawani, 2022; Hamdan & Diabat, 2019; Jin *et al*., 2021; Kazemi Matin *et al*., 2022; Lker Karadag *et al*., 2021; Rajendran & Ravindran, 2017; Soares *et al*., 2020; Soltani *et al*., 2021; Yousefi Nejad Attari *et al*., 2019), they have not considered vehicle routing. In the blood supply chain model, vehicle routing aims to minimize total transportation and production costs at the time of blood collection. In addition, existing studies have also used stochastic and probabilistic approaches to anticipate uncertainty in these studies. Environmental impacts should also be considered and minimized during blood collection and distribution. Considering the carbon emissions caused by bloodmobile transport during blood collection and distribution as well as the levels of blood supply inventory in blood centers and hospitals can also be used to minimize environmental impacts along the blood supply chain (Mansur, Handayani, *et al*., 2023).

The blood center echelon is involved in the processing step. During this phase, the blood center examines the blood acquired from donors to determine if it is suitable for distribution to hospitals. Adequate and appropriate blood supply inventories are not always available to fulfil hospital demand, requiring transshipment from other blood centers. By permitting lateral transshipment inside the echelons, supply chain systems, and therefore inventory systems, may be built with greater flexibility (Gholamian & Nasri, 2019) . Several previous studies addressing the processing phase of the blood supply chain have considered transshipment between blood centers as a solution to blood supply shortages (Dehaghani *et al*., 2021; Liu *et al*., 2021; Wang & Ma, 2015). Previous research has also considered the transshipment of blood between hospitals, with the aim of minimizing the overall cost of the blood supply chain (Kazemi Matin *et al*., 2022; Shih & Rajendran, 2020). However, the inherent features of blood such as its limited shelf life, differentiation into several blood products (including red blood cells RBC, platelets, and plasma), and differentiation by ABO/Rh(D) blood type mean that the allocation of blood units requires special consideration. In emergency cases where there is a shortage of blood, ABO/Rh(D) blood substitution is allowed. This means that blood products of a certain type can be used as a substitute for other compatible blood types.

Several previous studies have addressed inventory management in the blood supply chain model, which includes bloodmobiles, blood centers, and hospitals (Dillon *et al*., 2017; Ejohwomu *et al*., 2021; Ghasemi *et al*., 2022; Shih & Rajendran, 2020). These papers have incorporated inventory costs at blood centers and hospitals, which can include storage costs, blood supply shortage costs, and costs due to expired blood. (Mansur, Vanany, *et al*., 2023) conducted a discrete event simulation model to improve the blood bank performance by considering supply and demand uncertainty. One of the scenarios used in the development of the model is to make inventory an improvement target. Improving blood blank performance would improve patients requirements for blood bag services and the health of Indonesian blood bank staff.

In the distribution phase, the echelons involved are blood centers and hospitals. The process of blood distribution requires transportation from the donors to the hospitals, making it necessary to plan transportation routes to minimize the total cost and time of blood distribution (Şahinyazan *et al*., 2015). Previous studies have discussed the process of blood distribution using vehicles, from blood centers to hospitals, or between blood centers or between hospitals (Liu *et al*., 2021; Mousazadeh & Darestani, 2019; Zahiri *et al*., 2018). Based on the existing literature on blood distribution, the following research questions arise:

a) How is blood allocation best determined in a supply chain when considering multiple blood products and transshipment?
b) How does the amount of blood product transshipment between blood centers affect the overall cost of the blood supply chain?
c) How many units of whole blood, RBC, and platelets can each blood center make and distribute to each hospital?

To answer these questions, we propose a deterministic model using mixed-integer linear programming (MILP) to optimize the blood supply chain involving multiple echelons, multiple blood products, vehicle routing, and transshipment. The aim of this study is to develop a blood supply chain model that minimizes the total cost of the collection, processing, inventory, and distribution processes. This research is distinct from previous studies as it takes into account bloodmobile routes for blood collection, inventory management, and the potential for blood supply shortages when developing the blood supply chain models for each blood center. In addition, this study considers the transshipment of blood products between blood centers.

The remainder of this paper is organized as follows: Section 2 presents the literature review and an analysis of the research gap. The problem is described in Section 3. Section 4 includes the development of the mathematical model. A computational example and sensitivity analysis are given in Section 5, managerial implications are presented in Section 6, and conclusions are discussed in Section 7.

2. LITERATURE REVIEW

(Şahinyazan *et al*., 2015) considered bloodmobile and shuttle routes to develop a supply chain model in the blood collection phase. The study aimed to develop routes in which the movement of a bloodmobile and shuttle transporting collected blood from the bloodmobile to the blood center was most efficient so that the total cost of the blood supply chain was minimized. The authors utilized a MILP model with a heuristic approach to achieve optimal solutions. (Zhang *et al*., 2019) determined the ideal number and locations of bloodmobiles with the aim of minimizing costs and maximizing the amount of blood collected. Heuristic approaches are also used to obtain the optimal solution. Determination of bloodmobile routes was also carried out by (Rabbani *et al*., 2017) who used a fuzzy approach to resolve uncertainty parameters in supply chain model development in order to minimize costs and maximize the amount of blood collected from donors.

(Mousavi *et al*., 2021a) conducted research related to the blood supply chain involving donors, bloodmobiles, blood centers, and hospitals while considering the three pillars of sustainability—economic, environmental, and social factors. A MILP model was developed in the study with two objective functions: minimizing the environmental impacts of the supply chain and maximizing the amount of blood collected from donors. The stochastic approach was used with a metaheuristic method in an effort to find the optimal solutions. (Liu *et al*., 2021) similarly suggested an MINLP model to determine the optimal route for a bloodmobile in the process of blood collection. Echelons involved in this research included donors, bloodmobiles, blood centers, and hospitals. The research considered transshipment and blood stock inventories in blood centers to anticipate blood supply shortage conditions.

(Heidari-Fathian *et al*., 2017) discussed the development of multi-echelon blood supply chain models, including donors, bloodmobiles, blood centers, and hospitals. Demountable centers, or temporary facilities used to collect blood from donors in areas where it is difficult to build a permanent location, were also considered in the study. To identify the best solution to meet multi-objective functions, such as reducing transportation expenses, inventory costs, and blood shortage costs, a stochastic approach was utilized. (Zahiri *et al*., 2018) developed a MILP model that considers transshipment between blood centers, blood supply inventory levels, and shortages of blood stocks in hospitals. The optimal solution was determined using metaheuristic methods based on differential evolution and variable neighbourhood search.

The goal programming method has also been used to attain optimal blood supply chain conditions. (Zahiri & Pishvaee, 2017) conducted studies that also take into account blood groups. The objective of their research was to minimize costs while maximizing the freshness of blood. To develop their blood supply chain model, they employed a probability approach. Other studies on blood products were conducted by (Zahiri & Pishvaee, 2017), who developed multi-echelon blood supply chain models, utilizing metaheuristic approaches to obtain optimal solutions. (Asadpour *et al*., 2021) also considered blood groups in developing their blood supply chain models, again with two objectives: minimizing both costs and environmental impacts.

Several previous studies have considered transshipment in the blood supply chain model. (Dehghani & Abbasi, 2018) conducted research on the blood supply chain in hospitals, using a heuristic approach to determine optimal solutions with the objective of minimizing blood supply chain costs. The blood supply inventory in hospitals was considered in the development of the model. In addition, transshipment between hospitals was included to anticipate blood stock shortages. (Arani *et al*., 2021) also consider transshipment between hospitals in the blood supply chain model, taking into account the amount of expired blood stock and the economic, social, and environmental aspects of sustainability. The model aimed to minimize the cost of the entire blood supply chain using the goal programming method to find optimal solutions. (Zhou *et al*., 2021) developed a multi-echelon blood supply chain model with the aim of minimizing transshipment costs between blood centers. The amount of expired blood supply was also considered in the study. A stochastic approach with the DESS method was used to identify optimal solutions.

Table 1 presents the research on blood supply chain management published between 2015 and 2022 and compares the approaches with that of the present study. This study proposes an MILP model for rare, real-world scenarios that considers multiple echelons, blood products, vehicle routing, and transshipment to minimize cost. The main features and contributions of the existing literature are as follows:

Table 1 Comparison between the proposed model and previously published models

Author(s)	Multi Echelon	Blood Product	Vehicle Routing	Transshipment	Multi Period	Model
Sahinyazan *et al*	-	-	√	-	√	MINLP
Zhang *et al*	-	-	√	-	-	MILP
Rabbani *et al*	-	-	√	-	√	Fuzzy
Mausavi *et al*	√	√	√	-	√	Metaheuristic
Liu *et al*	√	-	√	√	√	MINLP
Dehghani *et al*	-	√	-	√	-	Heuristic
Arani *et al*	√	-	-	√	√	MILP
Heidari *et al*	√	-	-	-	√	MILP
Zahiri *et al*	√	√	-	√	-	MSDV
Zhou *et al*	√	-	-	√	√	DESS
Asadpour *et al*	√	√	-	-	√	MILP
Zahiri *et al*	√	√	-	-	√	Age Based
Mansur *et al*	√	√	-	-	√	MILP
Abdolazimi *et al*	√	-	-	-	√	Stochastic
Present study	√	√	√	√	√	**MILP**

The main contributions of our research, in comparison to previous studies, are as follows:

1) While previous studies have explored vehicle routing (Rabbani *et al*., 2017; Razavi *et al*., 2021; Zhang *et al*., 2019), the vehicle routing structure proposed in this study differs from past research. (Zhang *et al*., 2019) only specified the location of the bloodmobiles that donors can visit, while (Rabbani *et al*., 2017) and (Mousavi *et al*., 2021b) only determined the route of the bloodmobile during blood collection without considering the use of shuttles. In contrast, the present study takes into account both bloodmobile and shuttle routes during the collection of blood from donors, before distributing it to blood centers.
2) To the best of our knowledge, no prior research has been conducted on an integrated blood supply chain model that involves multiple blood products, vehicle routing, and transshipment to minimize the overall cost of the blood supply chain.

In the present research, we develop a MILP model for blood supply chain optimization that allows for the inclusion of multiple blood products, vehicle routing, and transshipment.

3. PROBLEM DESCRIPTION

The blood supply chain consists of collecting, processing, inventory, and distribution phases which take place in the echelons of donor location, blood centers, and hospitals. There are two types of vehicles used during the blood collection phase: bloodmobiles and shuttles. Bloodmobiles are vehicles that contain the equipment needed for blood donation and collection procedures. The purpose of a bloodmobile is to process blood donations from donors at the donor location, rather than having donors travel to a blood center. Bloodmobiles cannot visit more than one donor location on the same day, and the collected blood must be transported to the blood center for examination and storage no later than 24 hours following collection as a result of its perishable nature. For this reason, bloodmobiles must return to a designated blood center at the end of each day to deliver the collected blood to avoid spoiling.

At the beginning of a collection event, bloodmobiles start their tours from the blood center and they may remain in the field as long as there are unvisited donor locations with the potential for blood collection. A bloodmobile can remain in a donor location for multiple days if its estimated blood collection potential is very high. The use of shuttle service can eliminate the need for bloodmobiles to make daily trips between the donor location and the blood center. Instead, the collected blood is transported to the blood center by the shuttle, which visits all bloodmobiles in the field at the end of each day. An illustration of an integrated bloodmobile and shuttle system is shown in **Figure 1**.

Blood stocks collected by bloodmobiles are delivered to blood centers and combined with blood stocks collected independently at each blood center. Collected blood is then processed into three types of blood products: whole blood, RBC, and platelets. This article considers the inventory balance in the blood center so that demand for blood stocks from hospitals can be anticipated. Information related to blood supply shortages at the blood center is also considered in this article.

This research also allows for the transshipment of blood products between blood centers in the case of a shortage of blood product stocks in a specific blood center. Blood products from the blood center are delivered to hospitals based on individual hospital demand.

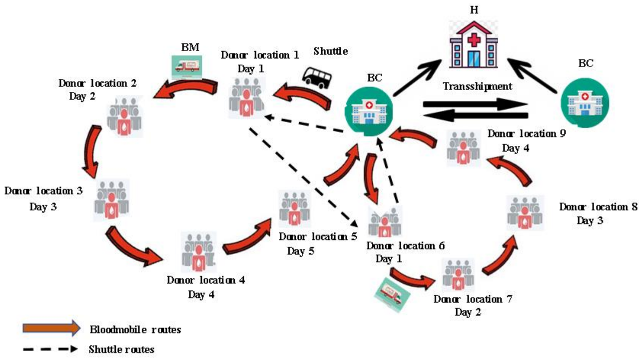

Figure 1 An integrated bloodmobile and shuttle blood collection system

The indices, parameters, and decision variables used to develop the proposed model will be described in the next section. The following assumptions are made to formulate the model:

- The bloodmobiles, blood centers, and hospitals have a maximum capacity.
- Bloodmobiles and shuttles must always depart from the same blood center.
- Transshipment between blood centers is allowed to meet fluctuating demands through redistribution of inventories across the whole system.
- The model does not consider the blood lifetime.

4. MATHEMATICAL MODEL

To formulate the problem mathematically, we introduce the following indices, parameters, and decision variables described in Sections 4.1, 4.2, and 4.3.

4.1 Indices

i,j : index for donor location, $i.j \in$ I.
d : index for day, $d \in D$.
o : index for bloodmobile, o $\in$ O
m : index for blood center, $m \in M$
h : index for hospital, $h \in H$.
p : index for blood product, $p \in P$

4.2 Parameters

C_{ij} : Unit transportation cost of bloodmobile from location i to location j (\$/allocation).
umc_{md} : Unit operational cost of blood center m on day d (\$/unit/day).
cmh_{mhpd} : Unit transportation cost of delivery of blood product p from blood center m to hospital h on day d (\$/unit/day).
hcm_{mpd} : Unit inventory cost of blood product p at blood center m on day d (\$/unit/day).
sc_{mpd} : Unit shortage cost of blood product p at blood center m on day d (\$/unit/day).
b_j : Potential amount of blood at location j (unit).
e : The numbers of bloodmobile o (unit).
cap_m_{mp} : Total capacity of blood center m for blood product p (unit).
R_{mpd} : Total demand for blood product p at blood center m on day d (unit/day).
$MAXB_d$: The maximum amount of blood that can be collected by the blood center on day d (unit/day).
cp_{mp} : Unit production cost of blood product p at blood center m (\$/unit).
cm_{mm1} : Unit transshipment cost of blood from blood center m to blood center $m1$ (\$/unit).

4.3 Decision Variables

X_{ijd} : Binary variable for bloodmobile movement; 1 if the bloodmobile moves from location i to location j on day d, 0 otherwise.
Y_{ijd} : Binary variable for shuttle movement; 1

		if the shuttle moves from location i to location j on day d, 0 otherwise.
Z_{jd}	:	Binary variable for shuttle requirement; 1 if the location j requires a shuttle on day d, 0 otherwise.
Z	:	Total supply chain cost.
NMM_{md}	:	Amount of blood collected by blood center m on day d.
$NMH_{mhpdd'}$	:	Amount of blood product p delivered from blood center m to hospital h on day d for use on day d'.
IM_{mpd}	:	Inventory level of blood product p at blood center m on day d.
S_{mpd}	:	Shortage quantity of blood product p at blood center m on day d.
W_{mpd}	:	Amount of blood product p at blood center m on day d.
UM_{mm1pd}	:	Amount of blood product p transshipped from blood center m to blood center $m1$ on day d

4.4 Model Formulation

This section outlines the formulation of the mathematical model for the integrated blood supply chain in the considered blood network based on the aforementioned assumptions. The mathematical formulation for the proposed model is given in Equations 1–43. Equations 1–9 show the objective function while Equations 10–43 represent the constraint function.

$$\text{Minimize } Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8 \tag{1}$$

$$Z_1 = \sum_i \sum_j C_{ij} \sum_d X_{ijd} \tag{2}$$

$$Z_2 = \sum_i \sum_j C_{ij} \sum_d Y_{ijd} \tag{3}$$

$$Z_3 = \sum_m \sum_d umc_{md}\, NMM_{md} \tag{4}$$

$$Z_4 = \sum_o \sum_m \sum_p \sum_d cp_{mp}\, W_{mpd} \tag{5}$$

$$Z_5 = \sum_m \sum_p \sum_d hcm_{mpd} IM_{mpd} \tag{6}$$

$$Z_6 = \sum_m \sum_p \sum_d sc_{mpd} S_{mpd} \tag{7}$$

$$Z_7 = \sum_m \sum_{m1} \sum_p \sum_d cm_{mm1}\, UM_{mm1pd} \tag{8}$$

$$Z_8 = \sum_m \sum_h \sum_p \sum_d \sum_{d'} cmh_{mhpd} NMH_{mhpdd'} \tag{9}$$

Constraints

$$\sum_i X_{ijd} = Z_{jd} + X_{ijd+1},\ \forall j \in \{2\ldots,N'\},\ \ \forall d \in \{1\ldots,D\text{-}1\} \tag{10}$$

$$\sum_d X_{j1d+1} + Z_{jd} \leq 1,\ \forall j \in \{2\ldots,N'\},\ \ \forall d \in \{1\ldots,D\text{-}1\} \tag{11}$$

$$\sum_i X_{ijd} = \sum_k X_{jkd+1},\ \forall j \in \{2\ldots,N'\},\ \ \forall d \in \{1\ldots,D\text{-}1\} \tag{12}$$

$$\sum_i X_{1j1} = e \tag{13}$$

$$\sum_j \sum_i X_{ij1} = 0,\ \forall i \in \{2\ldots,N'\} \tag{14}$$

$$\sum_j \sum_d X_{1jd} = e \tag{15}$$

$$\sum_j \sum_d X_{j1d} = e \tag{16}$$

$$\sum_i X_{ijd} \geq X_{j(j+3)(d+1)},\ \forall j \in \{2\ldots,2|N|\},\ \forall d \in \{1\ldots,D\text{-}1 \tag{17}$$

$$X_{(j-3)jd} \geq Z_{jd} + X_{j1(d+1)},\ \forall j \in \{2\ldots,2|N|\},\ \forall d \in \{1\ldots,D\text{-}1\} \tag{18}$$

$$\sum_i Y_{ijd} = Z_{jd},\ \forall j \in N,\ \forall d \in \{1\ldots,D\text{-}1\} \tag{19}$$

$$\sum_i Y_{j1d} = Z_{jd},\ \forall j \in N, \forall d \in \{1\ldots,D\text{-}1\} \tag{20}$$

$$\sum_j Z_{jd} = \sum_j e\ Y_{1jd},\ \forall j \in \{2\ldots,N'\},\ \ \forall d \in \{1\ldots,D\text{-}1\} \tag{21}$$

$$\sum_j Z_{jd} = \sum_j e\ Y_{j1d},\ \forall j \in \{2\ldots,N'\},\ \ \forall d \in \{1\ldots,D\text{-}1\} \tag{22}$$

$$V(i)\text{-}V(j) + e\,Y_{ijd} \leq e - 1,\ \forall j \in \{2\ldots,|N'|\},\ \forall i \in N,\ \forall d \in D \tag{23}$$

$$V(j) \geq 0,\ j \in \{2\ldots,|N'|\} \tag{24}$$

$$\sum_j b_j \sum_i \sum_d X_{ijd} \geq 0 \tag{25}$$

$$\sum_i \sum_d X_{ijd} \leq 1,\ \forall j \in \{2\ldots,|N'|\},\ \forall d \in \{1\ldots,D\text{-}1\} \tag{26}$$

$$X_{(j-3)jd} \leq \sum_k X_{jkd+1},\ \forall j \in \{2\ldots,2|N|\},\ \forall d \in \{1\ldots,D\text{-}1\} \tag{27}$$

$$\sum_j Z_{j1} = 0,\ j \in \{|N| + 1\ldots,3|N|\} \tag{28}$$

$$\sum_d \sum_j X_{ijd} = 0,\ \forall j \in \{2|N| + 1\ldots,3|N|\},\ \forall d \in \{1\ldots,D\text{-}1\} \tag{29}$$

$$\sum_i X_{i1d} = \sum_i \sum_j X_{ijd} - \sum_i \sum_j X_{ijd+1}, \forall d \in \{1\ldots,D\text{-}1\} \tag{30}$$

$$\sum_m \sum_d NMM_{md} \leq MAXB_d, \forall d \in D \tag{31}$$

$$W_{mpd} = \sum_m \sum_p \sum_d a_{pd} \left[\sum_j b_j \sum_d X_{ijd} + NMM_{md}\right], \forall m \in M,\ \forall p \in P,\ \forall d \in \tag{32}$$

$$W_{mpd} + \sum_m um_{mm1pd} \leq cap\_m_{mp}\ , \forall m,\ m1,\ m \neq m1 \in M,\ \forall p \in P,\ \forall d \in \{1\} \tag{33}$$

$$IM_{mpd\text{-}1} + W_{mpd} + \sum_m UM_{mm1pd} \leq cap\_m_{mp},\ \forall m,\ m1 \in M,\ \forall p \in P,\ \forall d \in \{2\ldots D\} \tag{34}$$

$$\sum_d IM_{mpd} = W_{mpd} - \sum_h \sum_d NMH_{mhpdd'} - \sum_m UM_{mm1pd} + \sum_m UM_{m1mpd},\ \forall m,\ m1,\ m \neq m1 \in M,\ \forall p \in P,\ \forall d \in \{1\} \tag{35}$$

$$\sum_d IM_{mpd} = IM_{mpd\text{-}1} + W_{mpd} - \sum_h \sum_d NMH_{mhpdd'} - \sum_m UM_{mm1pd} + \sum_m UM_{m1mpd},\ \forall m,m1,\ m \neq m1 \in M, \forall\, p \in P, \forall d \in \{2\ldots D\} \tag{36}$$

$$\sum_m UM_{mm1pd} \leq \sum_m W_{mpd},\ \forall m,\ m1,\ m \neq m1 \in M,\ \forall p \in P,\ \forall d \in D \tag{37}$$

$$W_{mpd} \leq R_{mpd},\ \forall m \in M,\ \forall p \in P,\ \forall d \in D \tag{38}$$

$$S_{mpd} = R_{mpd} - W_{mpd} - \sum_m UM_{mm1pd},\ \forall m,\ m1,\ m \neq m1 \in M,\ \forall p \in P,\ \forall d \in \{1\} \tag{39}$$

$$S_{mpd} = S_{mpd\text{-}1} + R_{mpd} - W_{mpd} - \sum_m UM_{m1mpd}, \forall m,\ m1,\ m \neq m1 \in M,\ \forall p \in P,\ \forall d \in \{2\ldots D\} \tag{40}$$

$$IM_{mpd}\ S_{mpd} = 0,\ M \in M,\ \forall p \in P,\ \forall d \in D \tag{41}$$

$$NMM_{md},\ NMH_{mhpdd'},\ IM_{mpd},\ S_{mpd},\ UM_{mm1pd},\ W_{mpd} \geq 0, \forall m \in M,\ \forall h \in H,\ \forall p \in P,\ \forall d \in D \tag{42}$$

$$X_{ijd},\ Y_{ijd},\ Z_{id} \in \{0, 1\} \tag{43}$$

The objective function of the model is shown in Equation (1) consisting of eight components ($Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8$) with the goal of minimizing the total cost of the blood supply chain. Equation (2) expresses the transportation cost when the bloodmobile collects blood and Equation (3) expresses the transportation cost for the shuttle to pick up blood from the bloodmobile and deliver it to the blood center. Equation (4) calculates the operational cost of the blood center, while Equation (5) calculates the cost of producing a blood product at the blood center. Equation (6) expresses the cost of blood product inventory at the blood center and Equation (7) expresses the cost of blood product shortage at the blood center. Equation (8) expresses the cost of blood product transshipment between blood centers. Equation (9) calculates the cost of distributing a blood product from the blood center to the hospital.

Equation (10) expresses the condition that if a bloodmobile visits location j on day d, then location j can either be visited by the shuttle or the bloodmobile can return directly to the blood center on $d + 1$. Equation (11) restricts locations from being visited more than once.

Equation (12) states that if a bloodmobile visits location *j* on day *d*, it will leave location *j* on day *d* +1. Equation (13) ensures that all bloodmobiles start running on the first day of the collection drive. Equation (14) restricts bloodmobiles from departing the blood center early. Equation (15) indicates the number of bloodmobiles that leave the blood center and Equation (16) ensures all bloodmobiles return to the blood center.

Equation (17) allows a bloodmobile to stay at a location for more than one day. Equation (18) ensures that if an additional location $(j+|M|)$ is visited on day *d* +1, then location *j* must have already been visited on day *d*. Equations (19) and (20) ensure that the shuttle can pick up blood from the bloodmobile. Equations (21) and (22) ensure that at least one shuttle is used on day *d*. Equations (23) and (24) eliminate the existence of sub-routes on the route.

Equation (25) ensures that the bloodmobiles' blood collection process fulfills the minimum blood supply requirements. Equations (26) and (27) relate to Equations (11) and (18) by eliminating the variable Z_{jd}, ensuring that each location can only be visited once and that if an additional location $(j+|M|)$ is visited on day *d* +1. Equation (28) ensures the shuttle will not visit an artificial node on the first day. Equation (29) ensures the bloodmobile moves in the forward direction and no flow is allowed in the backward direction. Equation (30) ensures no bloodmobile moves to collect blood on the next day.

Equation (31) limits the capacity of the blood collection amount at the blood center. Equation (32) limits the quantity of blood product *p* in blood center *m* on day *d*. Equations (33) and (34) refer to the amount of blood product *p* and ensure the amount of blood product *p* transshipped from blood center *m* to blood center m_1 on day *d* does not exceed the capacity of the blood center. Equations (35) and (36) are used to calculate the total number of blood units at the blood center.

Equation (37) ensures the amount of blood product *p* transshipped from blood center *m* to blood center m_1 on day *d* does not exceed the number of blood products in each blood center. Equation (38) is used to ensure the amount of blood product *p* in blood center *m* on day *d* is lower than or equal to the demand for each product. Equations (39) and (40) calculate the size of the blood product shortage in the blood center. Equation (41) ensures the amount of blood product inventory and shortage in each blood center. Equations (42) and (43) are the expressions of non-negative constraint decision variables and the definition of integrality of the decision variables.

5. COMPUTATIONAL STUDY AND SENSITIVITY ANALYSIS

In this section, we present the data used in our analysis and discuss the numerical results and sensitivity analysis. All computations were done with an Intel (R) Celeron(R) N4020 1.10GHz Processor, 8 GB RAM and LINGO Ver 18.0 Software. The blood supply chain system used in this computational example were taken from real cases related to blood distribution in Surakarta, Indonesia. The blood supply chain in Surakarta uses three bloodmobile units, three blood center units, and five hospital units. Three types of blood products are included in the supply chain and five days was used as the collection period. The parameter values used in this article were sourced from the existing literature and can be seen in **Table 2** (Fallahi *et al.*, 2021; Heidari-Fathian *et al.*, 2017; Zahiri *et al.*, 2018).

Table 2 Parameter values

Parameters	Value	Parameters	Value
C_{ij}	(10,40)	cap_m_{mp}	(4000,6000)
umc_{md}	(1,14)	R_{mpd}	(500,1000)
cmh_{mhd}	(2,7)	$MAXB_d$	8000
hcm_{md}	(2,3)	cp_{mp}	(5,7)
sc_{hd}	(6,9)	cm_{mm1}	(0,1)
b_j	(50,300)		

The blood supply chain model developed in the previous section of this study was used to obtain several decision variables. **Table 3** shows the ideal routes of the bloodmobiles used for blood collection. Bloodmobile 1 collects blood from donors at locations 1, 2, 5 and 8. Bloodmobile 2 collects blood from donors at locations 1, 3, 6 and 9, while Bloodmobile 3 collects blood from donors at locations 1 and 4. The blood collected by each bloodmobile is directly distributed to the blood centers. Every blood mobile begins and finishes at the same donor location. Additionally, every blood mobile visits a different donor location. These results match those found in the study (Şahinyazan *et al.*, 2015). In case, the donor location visited by each bloodmobile is not the same.

Table 3 Bloodmobile and shuttle routes

Blood Mobile	Route	Shuttle	Route
Blood Mobile 1	1-2-5-8-1	Shuttle 1	1-3-2-1
Blood Mobile 2	1-3-6-9-1	Shuttle 2	1-6-5-1
Blood Mobile 3	1-4-1		

The blood collection process can also be conducted at the blood center. **Table 4** shows the amount of blood collected at each blood center on each day of the collection. The volume of blood stocks collected by each blood center on the fifth day was 1,500 units. On days 1, 2, 3, and 4, blood was not collected directly at the blood center. On these days, the demand for blood was covered by the blood collection conducted by the bloodmobiles.

Table 4 Units of blood collected

Blood Center	Day				
	1	2	3	4	5
Blood Center 1	0	0	0	0	1500
Blood Center 2	0	0	0	0	0
Blood Center 3	0	0	0	0	0

The blood collected at each blood center is then separated into three blood products to be distributed to hospitals according to demand. **Table 5** shows the optimal amount of each blood product produced by each blood center on each day. The number of whole blood units produced by blood center 1, 2 and 3 is 2,600, 2,000, and 2,000 units, respectively. The number of RBC and platelets produced by blood center 1, 2 and 3 is 1,950, 1,500, and 1,500 units, respectively.

Table 5 Units of blood products at each blood center

Blood Center	Blood Product	Day				
		1	2	3	4	5
Blood Center 1	Whole Blood	600	600	400	400	600
	RBC	450	450	300	300	450
	Platelets	450	450	300	300	450
Blood Center 2	Whole Blood	600	600	400	400	0
	RBC	450	450	300	300	0
	Platelets	450	450	300	300	0
Blood Center 3	Whole Blood	600	600	400	400	0
	RBC	450	450	300	300	0
	Platelets	450	450	300	300	0

Table 6 shows the inventory levels of each blood product in the blood centers on each day. The inventory amount of whole blood in blood centers 1, 2, and 3 is 1,800, 600, and 600 units, respectively. The inventory amount of RBC and platelets in blood centers 1, 2, and 3 is zero units at each center. **Table 7** presents the shortage of blood products in each blood center on each day. There is a total shortage of 1,200 units of whole blood at each blood center over the course of the experiment period. The total shortages of RBC and platelets at each blood center are 2,250 units, respectively. In other words, the total blood collected by the bloodmobiles and the blood centers cannot meet the blood demand of the hospitals.

Table 6 Inventory level of blood products at each blood center

Blood Center	Blood Product	Day				
		1	2	3	4	5
Blood Center 1	Whole Blood	600	1200	0	0	0
	RBC	0	0	0	0	0
	Platelets	0	0	0	0	0
Blood Center 2	Whole Blood	600	0	0	0	0
	RBC	0	0	0	0	0
	Platelets	0	0	0	0	0
Blood Center 3	Whole Blood	600	0	0	0	0
	RBC	0	0	0	0	0
	Platelets	0	0	0	0	0

Table 7 Blood product shortages at each blood center

Blood Center	Blood Product	Day				
		1	2	3	4	5
Blood Center 1	Whole Blood	0	0	0	0	0
	RBC	150	150	0	0	150
	Platelets	150	150	0	0	150
Blood Center 2	Whole Blood	0	0	0	0	600
	RBC	150	150	0	0	600
	Platelets	150	150	0	0	600
Blood Center 3	Whole Blood	0	0	0	0	600
	RBC	150	150	0	0	600
	Platelets	150	150	0	0	600

There is a trade-off between the amount of inventory and the shortage which shows the balance in the blood center. This can be seen in **Tables 7** and **8**. These results are consistent with the study of (Momenitabar *et al*., 2022).

Table 8 shows the optimal amount of blood products delivered from the blood center to the hospital. Blood center 1 distributed 2,600 units of whole blood to hospital 1 and 3, 1,950 units of RBC to hospital 1 and 1,750 units of platelets to hospital 1, 2 and 3. Blood center 2 distributed 2,000 units of whole blood to hospital 2 and 5, and each 1,500 units of RBC and platelets to hospital 1, 2, 3 dan 5. Blood center 3 also distributed each 450 units of whole blood and RBC to hospital 3 and 2. There are several hospitals that do not receive blood products from blood center, because demand at these hospitals can be met by the existing blood stock supplies in each hospital.

Table 8 Units of blood product delivered to hospital

Blood Center	Hospital	Blood Product	Day				
			1	2	3	4	5
Blood Center 1	Hospital 1	Whole Blood	0	0	1600	0	0
		RBC	0	450	300	300	450
		Platelets	0	450	300	0	450
	Hospital 2	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	100	0
	Hospital 3	Whole Blood	0	0	0	400	600
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 4	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 5	Whole Blood	0	0	0	0	0
		RBC	450	0	0	0	0
		Platelets	450	0	0	0	0
Blood Center 2	Hospital 1	Whole Blood	0	0	0	0	0
		RBC	450	0	0	0	0
		Platelets	450	0	0	0	0
	Hospital 2	Whole Blood	0	0	400	0	0
		RBC	0	0	300	0	0
		Platelets	0	0	300	0	0
	Hospital 3	Whole Blood	0	1200	0	0	0
		RBC	0	450	0	0	0
		Platelets	0	450	0	0	0
	Hospital 4	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 5	Whole Blood	0	0	0	400	0
		RBC	0	0	0	300	0
		Platelets	0	0	0	300	0
Blood Center 3	Hospital 1	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0

Table 8 Units of blood product delivered to hospital (Con't)

	Hospital	Blood Product	Day 1	2	3	4	5
Blood Center	Hospital 2	Whole Blood	0	0	0	0	0
		RBC	450	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 3	Whole Blood	450	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 4	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0
	Hospital 5	Whole Blood	0	0	0	0	0
		RBC	0	0	0	0	0
		Platelets	0	0	0	0	0

Table 9 Volume of blood products transshipped

Blood Center (origin)	Blood Center (destination)	Blood Product	Day 1	2	3	4	5
Blood Center 1	Blood Center 2	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0
	Blood Center 3	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0
Blood Center 2	Blood Center 1	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0
	Blood Center 3	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0
Blood Center 3	Blood Center 1	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0
	Blood Center 2	Whole Blood	0	0	100	100	0
		RBC	0	0	150	150	0
		Platelets	0	0	150	150	0

In this study, transshipment between blood centers is allowed if a blood center has a shortage of blood products. In the transshipment process, a fee is charged for each unit of blood sent from one blood center to another. **Table 9** shows the optimal number of transshipments of blood products between blood centers. The total volume of whole blood transshipped between blood centers amounted to 1,200 units, while 1,800 units of both RBC and platelets were transshipped between blood centers.

Table 10 presents the bloodmobile and shuttle transportation costs, blood center operational costs, blood product production cost, blood product stock inventory costs at blood centers, blood product stock shortage costs at blood centers, blood product transshipment costs between blood centers, and blood delivery costs to hospitals over the course of the computation calculated using the model proposed in the study. The total cost is $173,195 for five days. It can be seen that the costs needed for the process of collecting blood from donors with bloodmobile, blood production at the blood center and distributing blood products to the hospital are high. Therefore, all these processes need to be organized so can get the optimal results. Coordination is needed between all echelons involved from upstream to downstream in this blood supply chain. The distribution cost component dominates all other components at $82,500 and the lowest cost component is the transportation cost of the shuttle at $145.

Table 10 Objective function value results

Objective Function	Value ($)
Production cost of blood product at blood centers	49,500
Inventory cost of blood product at blood centers	6,000
Shortage cost of blood product at blood centers	28,500
Transshipment cost between blood center	4,800
Distribution cost of blood product to hospitals	82,500
Total cost	173,195

A sensitivity analysis was conducted to analyze the robustness of the model to changes in decision variables and objective functions by changing the number of blood centers (either two, three, or four centers) involved in the blood supply chain system. The analysis investigated the impact of this change on the total cost, volume of blood product at blood centers, and volume of blood product transshipped. The total cost of the blood supply chain with varying numbers of blood centers can be seen in **Figure 2**. Because one of the cost components of the blood supply chain is the operational cost of the blood centers, the more blood centers that are involved in the system, the greater the total costs. This is linear with the results of the study of (Eskandari-Khanghahi *et al*., 2018). Blood supply chain costs increased by approximately 28% when the number of blood centers used in the proposed blood supply chain model increased by one.

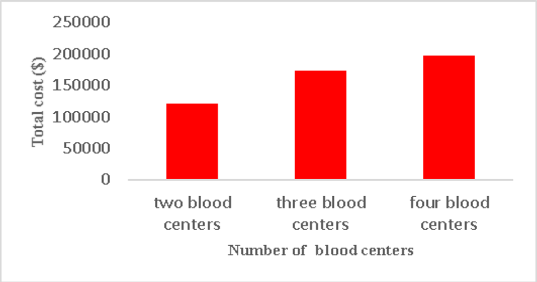

Figure 2 Total blood supply chain costs with varying numbers of blood centers

The impact of changing the number of blood centers on the total volume of blood products at blood centers is shown in **Figure 3**. The volume of whole blood produced in each blood center is greater when compared to RBC and platelets, at 38%, 31% and 31%, respectively.

Figure 4 presents the changes in the transshipment of blood products when the number of blood centers was altered. In all scenarios, the volume of RBC and platelet transshipment is greater than that of whole blood. This is likely because the demand for RBC and platelets exceeds the demand for whole blood and the supply of RBC and platelets entering the blood centers has not been able to meet existing demand. The proportion of transshipment of RBC, platelets, and whole blood is 24%, 38%, and 38%, respectively. This is inversely proportional to the volume of blood products produced in the blood centers. This lack of RBC and platelet supply may be a concern for the blood centers and is important information related to the distribution of blood products between blood centers. The allocation of the number of blood centers can affect the total operational costs of blood centers. The more blood centers are used, the greater the operational costs.

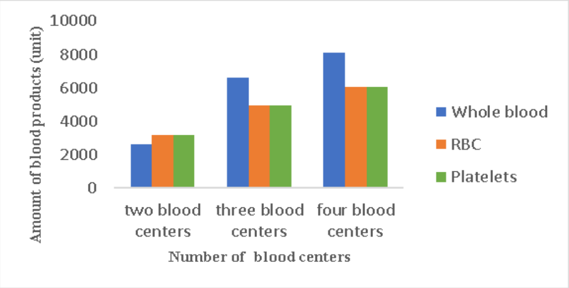

Figure 3 Amount of blood products at blood centers

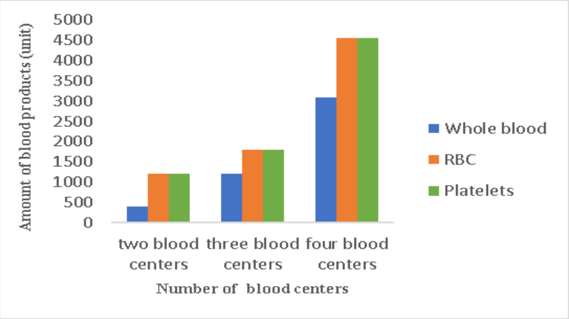

Figure 4 Amount of blood products transshipment

6. MANAGERIAL INSIGHTS

This paper presents some insights on managing the blood supply chain from donors to hospital. The model is more realistic and applicable since it considers the bloodmobile routes, multiple blood product and transshipment in the blood supply chain, which are commonly found in the real situation. Based on the results of this study, the decision maker needs to carefully control and make an appropriate adjustment on all aspects related to the blood distribution process from donors to hospital. The inventory of blood components at the blood center must be optimized by balancing blood supply and demand. The amount of transshipments between blood centers tends to increase, linear with the increase in the number of blood centers. As a result, coordination with other neighbouring blood centers is necessary to limit the emergence of a blood shortage in one of the blood centers. The determination of bloodmobile routes when collecting blood from donors needs to be optimized so it can maximize the amount of blood collected

7. CONCLUSIONS AND FUTURE STUDIES

This paper proposes a MILP model that considers multiple echelons, including donors, blood centers, and hospitals. The novelty of this study compared to previous research is its consideration of multiple blood products, vehicle routing, and transshipment in an integrated optimization model that can be used as a tool for blood centers when making decisions related to blood distribution.

Based on the results of sensitivity analysis, the number of blood centers affects the overall cost of the blood supply chain, the number of blood products produced by each blood center, and the transshipment volume between blood centers. Future research should consider the uncertainty parameters so the model can handle the uncertain situations. The carbon emissions of the blood supply chain to achieve environmental sustainability may also be considered. Additionally, future research can consider the use of metaheuristic methods to construct more complex blood supply chain models so that optimal results are obtained more quickly.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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