Development of a blood supply chain network design model by considering lateral transshipment and blood substitution

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Abstract. blood supply chain network design is an approach to design an efficient blood supply chain network. This study developed a model for determining the best Blood Supply Chain Network Design solution that considering costs and social sustainability. The developed model was divided into four echelons: blood donation centers, blood banks, regional hospitals, and demand points. The objective of this research was to minimize total supply chain costs while maximize job opportunities. This study considered the concept of lateral transshipment and blood substitution at the third echelon, namely the regional hospital, to ensure that demand was met. The concept of lateral transshipment enabled regional hospitals that having excess of blood unit to satisfy blood supplies to other regional hospitals. Furthermore, blood substitution was a response to emergency conditions, specifically a shortage of appropriate blood product units. Blood substitution scheme is allowed in this research, that is, each type of blood product with a certain group can not only meet its own demand, but can also be used as a replacement for the same product with other compatible groups. a multi-objective possibilistic mixed integer linear programming model was developed. According to the obtained results, the optimal number of facilities to satisfy the uncertain demand, blood flow between supply chain echelons, network cost, and the number of jobs created can be discovered by the model.

1 INTRODUCTION

Human blood units are a different commodity than other commodities because they are a vital thing that can only be produced by humans and cannot be replaced by other products, and the demand for blood units is very random. [1]. Furthermore, blood units have unique characteristics, such as being easily damaged and having a limited donor population [2]. According to data from America's Blood Center, 38% of the population in the United States is able and eligible to become blood donors. However, each year, only about 3% of the US population is willing to donate blood. The percentage of blood donors in a country's population will be lower in developing countries. According to research [3,] developing countries have a lower average blood donation rate than developed countries.

There is also a time limit in the blood donation process between when a person donates blood and when that person is allowed to donate the next blood. This was conveyed by Indonesian Red Cross Society (PMI) in terms of donating blood, namely physically and mentally healthy, the minimum age is 17 years and the maximum age for donors is 60 years, with a maximum age of 65 years for blood donors who have routinely donated blood up to finally stopping at the doctor's consideration, a minimum body weight of 45 kg, normal blood pressure (Systole 100 - 180 and Diastole 70 - 100), for the safety and security of donors, according to PERMENKES 91 of 2015, the time interval since the last blood donation must be at least 2 months. Due to the COVID-19 pandemic, several tests on blood units are added to the process of testing blood before it is sent to the point of request.

The COVID-19 pandemic is an example of a true health crisis, which was officially declared by the World Health Organization (WHO) in early 2020, and has changed many aspects of life. This condition has a significant impact on the global economy, as well as the logistics and health supply chains [4]. Furthermore, COVID-19 has resulted in 450 million people working in the global supply chain experiencing a decrease in income or even losing their jobs [5]. Hospitals face significant challenges as a health facility during and after the COVID-19 pandemic, including providing services to COVID-19-infected patients as well as emergency services for patients with other diseases, both of which must be balanced with the availability of blood supplies for transfusions. [6]. Because of the COVID-19 health crisis, blood banks must add a COVID-19 test to the standard tests they perform on donor blood. These additional tests cause product flow delays and increase overall supply chain costs.

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Natural disasters, in addition to health crises, can have a significant impact on the demand for blood units. To address this, good and efficient supply chain management is required. Because of the unique characteristics of the blood unit, as well as the possibility of health crises and natural disasters, effective supply chain management is required, and decisions on Blood Supply Chain Network Design (BSCND) must be made with cost in mind.

To meet market demands, minimal costs are required to support the supply chain's objectives. Over time, issues or concerns shift to environmental, social, and legal sustainability, and these issues direct the supply chain toward sustainability [7]. Social responsibility in relation to occupational safety, environmental protection, and job creation is one component of sustainability. As a result, Supply Chain Network Design (SCND) has become important in supply chain performance in a variety of industries, including blood units, and must be considered for sustainability.

The objective of this study was to create a model for Blood Supply Chain Network Design with total cost and job opportunity as the objective function. The concept of lateral transshipment and blood substitution based on ABO/RH(D) is considered in the model developed in this study to ensure demand fulfillment.

A stock transfer mechanism between locations in the same echelon of an inventory system in a supply chain is known as lateral transhipment [11]. According to Firouz, Keskin, and Melouk (2017), lateral transhipment or delivery between echelon levels can improve supply chain flexibility and resilience [12].

According to the National Health Service (2012), each blood product has eight blood types: O-, O+, A-, A+, B-, B+, AB-, and AB+. Furthermore, in the event of a blood shortage during an emergency, ABO/RH(D) blood substitution is permitted. The blood substitution in question is that each type of blood product with a specific blood type can be used not only to meet their own needs, but also as a substitute for the same blood product with another compatible blood group. ABO/RH(D) compatible blood substitutes are an option that can be used to meet demand when supplies of certain blood products are limited or in emergencies. The blood product modelled in this study was Red Blood Cell (RBC) with eight blood groups, namely O-, O+, A-, A+, B-, B+, AB-, and AB+, and blood substitution was taken into account [13]. Red Blood Cell (RBC) substitution as shown in Table 1.

2 METHOD

2.1 Problem Definition

The developed model was divided into four echelons: blood donation centres, blood banks, regional hospitals, and markets. The function of the model developed in this study was to minimize total costs while increasing job opportunities. Lateral transshipment at regional hospitals echelon was taken into account when developing the model. Blood substitution was also being considered at the regional hospital echelon. Figure 1 describes the system.

Table 1. Possible ABO/Rh(D)-compatible substitutions for red blood cell (RBC)

Penerima	Pendonor							
	O-	O+	A-	A+	B-	B+	AB-	AB+
O-	√							
O+	√	√						
A-	√		√					
A+	√	√		√				
B-	√		√		√			
B+	√	√			√	√		
AB-	√		√		√		√	
AB+	√	√	√	√	√	√	√	√

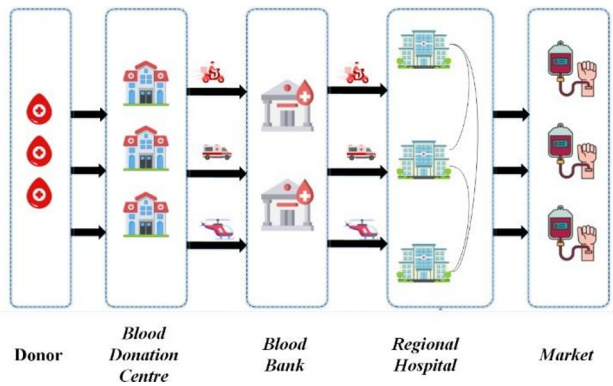

Fig. 1 Description of the proposed SC

2.2 Formulasi Model

Model assumption:

- One period is one day.
- To reduce shortages, lateral transshipment is allowed,and blood substitution is permitted.

Indices:

d = Blood Donation Centre (BDC), $d \in D$

b = Blood Bank (BB), $b \in B$

h = Regional Hospital (RH), $h \in H$

t = Blood group, $t \in T$

i = Market, $i \in I$

o = Transportation mode, $o \in O$

p = Period, $p \in P$

r = Blood product, $r \in R$

u = blood groups that can be substituted by blood group l, $u \in U$

v = blood groups that can substitute blood group l, that is $v \in V$

Decision variable:

$$yd = \begin{cases} \text{If Donation Center d is employed} \\ 0, \text{otherwise} \end{cases}$$

$$yb = \begin{cases} If\ Blood\ Bank\ b\ is\ employed \\ 0, \text{otherwise} \end{cases}$$

$$yhip = \begin{cases} 1, \text{If Market i dis supplied from Regional} \\ \text{Hospital h at period p } 0, \text{otherwise} \end{cases}$$

$Xdbortp$ = Allocation of blood product r blood group t from BDC d to BB b using mode of transportation o in period p($unit$)

$Xbhortp$ = Allocation of blood product r blood group t from BB b to RH h using mode of transportation o in period p($unit$)

$Xhirtp$ = Allocation of blood product r blood group t from BB b to RH h using mode of transportation o in period p($unit$)

δ_{hrtp} = Shortage blood product r blood group t in RHh in period p ($unit$)

V_{brtp} = Total blood product r blood group t processedat BB b in period p($unit$)

LT = Lateral transshipment unit blood product r blood group t from RH h to RH q in period p ($unit$)

INV_{hrtp} = Inventory of blood products r blood group t inRH h in period p($unit$)

INV_{brtp} = Inventory of blood products r blood group t inBlood Bank h in period p($unit$)

Y_{vtrhp} = Blood product unit r blood group v used to substitute blood group t in RH h in period p($unit$)

Parameter:

$CFIX$ = Fixed cost of Blood Donation Centre (BDC) d ($)

$CFIX$ = Fixed cost of Blood Bank (BB) b ($)

$CFIX$ = Fixed cost of Regional Hospital (RH) h ($)

$CRAW$ = Cost of blood supply from BDC d to BB b with of transportation o ($\frac{\$}{unit}$)

CD= Disposal cost ($)unit

$CLAB$= Cost of laboratory test at BB b ($)

unit

$CTrans$ = Cost of transportation for transferring blood from BDC d to BB b with transportation mode o($)unit

$CTrans$ = Cost of transportation for transferring blood from BB b to RH h with transportation mode o($)unit

$CSUB$ = Subsidy cost of market I dari RH h ($) unit

CSH = Shortage cost at RH h ($)unit

$JFIX$ = Fixed job opportunity of Blood Donation Centre (BDC) d

$JFIX$ = Fixed job opportunity of Blood Bank (BB) b

$JFIX$ = Fixed job opportunity of Regional Hospital

Jv = Variable Job opportunity of BDC

Jv = variable Job opportunity of Blood Bank (BB) b

$CAPb$ = Capacity of Blood Bank (BB) b (unit)

$CAPh$ = Capacity of Regional Hospital (RH) h (unit)

$Chold$ = Inventory cost at BB and RH

CLT = Lateral transshipment cost

$CCross$ = Penalty cost of blood substitution

$Lmax$ = Maximum substitution rate at RH

$\tilde{c}apd$ = capacity of BDC ($unit$)

$\tilde{a}rt$ = Disposal rate blood product r blood group t

$\tilde{\varphi}$= Minimum amount of demand allocated to deploy a facility($unit$)

$\tilde{D}irtp$ = Demand of market i for blood product r blood type t in period p($unit$)

Minimal total cost:

$$Min\ Z_1 = \sum_{d}^{D} C_d^{FIX} y_d + \sum_{b}^{B} C_b^{FIX} y_b + \sum_{h}^{H} C_h^{FIX} y_h + \tag{1}$$

$$\sum_{\substack{d \\ B}}^{D} \sum_{\substack{b \\ R}}^{B} \sum_{\substack{o \\ T}}^{O} \sum_{\substack{r \\ P}}^{R} \sum_{t}^{T} \sum_{p}^{P} C_{dbo}^{RAW} X_{dbortp} +$$

$$\sum_{\substack{b \\ D}}^{B} \sum_{\substack{r \\ B}}^{R} \sum_{\substack{t \\ O}}^{T} \sum_{\substack{p \\ R}}^{P} C_{LAB} V_{brtp} +$$

$$\sum_{\substack{d \\ B}}^{D} \sum_{\substack{b \\ H}}^{B} \sum_{\substack{o \\ O}}^{O} \sum_{\substack{r \\ R}}^{R} \sum_{t}^{T} \sum_{p}^{P} C_{dbo}^{Trans} X_{dbortp} +$$

$$\sum_{\substack{b \\ I}}^{B} \sum_{\substack{h \\ H}}^{H} \sum_{\substack{o \\ R}}^{O} \sum_{\substack{r \\ T}}^{R} \sum_{t}^{T} \sum_{p}^{P} C_{bho}^{Trans} X_{bhortp} +$$

$$\sum_{\substack{i \\ H}}^{I} \sum_{\substack{h \\ R}}^{H} \sum_{\substack{r \\ T}}^{R} \sum_{t}^{T} \sum_{p}^{P} C_{SUB} \tilde{D}_{irtp} y_{hip} +$$

$$\sum_{\substack{h \\ H}}^{H} \sum_{\substack{r \\ R}}^{R} \sum_{\substack{t \\ T}}^{T} \sum_{\substack{p \\ P}}^{P} C_{SH} \delta_{hrtp} +$$

$$\sum_{\substack{h \\ H}}^{H} \sum_{\substack{r \\ H}}^{R} \sum_{\substack{t \\ R}}^{T} \sum_{\substack{p \\ T}}^{P} C_{hold} INV_{hrtp} +$$

$$\sum_{\substack{h \in H \\ V}}^{H} \sum_{\substack{q \in H \\ T}}^{H} \sum_{\substack{r \\ R}}^{R} \sum_{\substack{t \\ H}}^{T} \sum_{\substack{p \\ P}}^{P} C_{LT} \mathrm{LT} +$$

$$\sum_{\substack{v \\ D}}^{V} \sum_{\substack{t \\ B}}^{T} \sum_{\substack{r \\ O}}^{R} \sum_{\substack{h \\ R}}^{H} \sum_{\substack{p \\ T}}^{P} \sum_{P}^{P} C_{Cross} Y_{vtrhp} +$$

$$\sum_{d}^{D} \sum_{b}^{B} \sum_{o}^{O} \sum_{r}^{R} \sum_{t}^{T} \sum_{p}^{P} \tilde{a}_t C_D X_{dbortp}$$

Maximize job opportunity:

$$Max\ Z_2 = \sum_{d}^{D} J_d^{FIX} y_d + \sum_{b}^{B} J_b^{FIX} y_b + \sum_{h}^{H} J_h^{FIX} y_h + \sum_{b}^{B}\sum_{r}^{R}\sum_{t}^{T}\sum_{p}^{P} J_b^{v}\ V_{brtp}/CAP_b + \sum_{b}^{B}\sum_{h}^{H}\sum_{o}^{O}\sum_{r}^{R}\sum_{t}^{T}\sum_{p}^{P} J_h^{v} X_{bhortp}/CAP_h \quad (2)$$

Constrain

$$\sum_{u}^{U} Y_{turhp} \le \sum_{b}^{B}\sum_{o}^{O} X_{bhortp} \quad (3)$$

$$\sum_{v}^{V} Y_{vtrhp} \le (\sum_{i}^{I} X_{hirtp} + \delta_{hrtp})\, L_{max} \quad (4)$$

$$(1-\tilde{a}_t)\sum_{d}^{D}\sum_{o}^{O} X_{dbortp} = \sum_{h}^{H}\sum_{o}^{O} X_{bhortp} \quad (5)$$

$$X_{hirtp} + \delta_{hrtp} = y_{hip}\,\tilde{D}_{irtp} \quad (6)$$

$$\sum_{p}^{P} y_{hip} = 1 \quad (7)$$

$$\sum_{h}^{H}\sum_{o}^{O} X_{bhortp} = V_{brtp} \quad (8)$$

$$\sum_{b}^{B}\sum_{o}^{O} X_{dbortp} \le \tilde{c}ap_d\, y_d \quad (9)$$

$$\sum_{r}^{R}\sum_{t}^{T} V_{brtp} \le CAP_b\, y_b \quad (10)$$

$$\tilde{\varphi}\sum_{b}^{B} y_b \le \sum_{d}^{D}\sum_{b}^{B}\sum_{o}^{O}\sum_{r}^{T} X_{dbortp} \quad (11)$$

$$\sum_{b}^{B}\sum_{o}^{O}\sum_{r}^{R}\sum_{t}^{T} X_{bhortp} \le CAP_h\, y_h \quad (12)$$

$$\sum_{i}^{I} \tilde{D}_{irtp} \le \sum_{h}^{H} INV_{hrtp-1} - \sum_{h}^{H} \delta_{hrtp-1} + \sum_{b}^{B}\sum_{h}^{H}\sum_{o}^{O} X_{bhortp} + \sum_{v}^{V}\sum_{h}^{H} Y_{vtrhp} - \sum_{u}^{U}\sum_{h}^{H} Y_{turhp} + \sum_{q}^{H}\sum_{h}^{H} LT - \sum_{h}^{H}\sum_{q}^{H} LT \quad (13)$$

$$\sum_{h}^{H} INV_{hrtp} - \sum_{h}^{H} \delta_{hrtp} = \sum_{h}^{H} INV_{hrtp-1} - \sum_{h}^{H} \delta_{hrtp-1} + \sum_{b}^{B}\sum_{h}^{H}\sum_{o}^{O} X_{bhortp} - \sum_{i}^{I} \tilde{D}_{irtp} + \sum_{v}^{V}\sum_{h}^{H} Y_{vtrhp} - \sum_{u}^{U}\sum_{h}^{H} Y_{turhp} + \sum_{q}^{H}\sum_{h}^{H} LT - \sum_{h}^{H}\sum_{q}^{H} LT \quad (14)$$

$$\sum_{h}^{H}\sum_{q} LT + \sum_{v}^{V} Yvtrhp + \sum_{b}^{B}\sum_{h}^{H}\sum_{o}^{O} Xbhortp = \sum_{h}^{H}\sum_{q}^{H} LT + \sum_{u}^{U} Yturhp + \sum_{m}^{M} Xhirtp \quad (15)$$

$$\sum_{m}^{M} Xhirtp + \sum_{h}^{H} \delta hrtp \le \sum_{q}^{H}\sum_{h}^{H} LT + \sum_{v}^{V} Yvtrhp + \sum_{b}^{B}\sum_{o}^{O} Xbhortp \quad (16)$$

Costs in the objective function included fixed costs for BDC, BB, and RH, costed for collecting raw blood at BDC, disposal costs, blood testing costs, shipping costs, subsidy costs, penalty shortage costs, storage costs at RH, and lateral transshipment costs. At BB and RH, the objective function of maximizing job opportunities consisted of total fixed job opportunities as well as job opportunity variables.

The function of constraint (3) ensured that the number of blood product units that can be substituted with blood substitutes do not exceed the number of blood product units allocates at the relevant facility. (4) Made certain that the number of units of blood product used for blood substitution does not exceed the allowable echelon of blood substitution.(5) Ensured a balance between the allocation of blood product units in the blood bank and the allocation of blood product units in regional hospitals. (6) Ensured that demand fulfillment accounts for potential shortages. (7) Ensured that the regional hospital is the only facility serving the

point of request, so that no shipments from other facilities go directly to the point of request. (8) processed to ensure that the number of blood product units processed equals the number of blood product units allocated to the following echelon. (9) The center ensured that the number of units of blood products sent from the blood donation center does not exceed the blood donation center's capacity. (10) The bank ensured that the total number of blood product units processed in the blood bank does not exceed the blood bank's capacity. (11) ensuring that the blood bank's capacity is included in the blood donation center. (12) Ensured that the number of blood product units allocated from the previous echelon does not exceed the regional hospital's capacity. (13) Ensured that demand at the regional hospital does not exceed supply, as well as the allocation of the number of blood units at the regional hospital. (14) Ensured that the number of products stored in a given period equals the number of products stored in the previous period minus the demand for that period, plus the number of products purchased or ordered in the related period. (15) The hospital ensured that the number of blood product units received by the regional hospital from the previous echelon and the lateral transshipment mechanism equals the number of products sent from the regional hospital to the point of request. (16) The hospital ensured that the number of blood product units entering the regional hospital is sufficient to meet demand.

3 RESULT AND DISCUSSION

The LINGO 18 application was used to search for optimal results. This research study was a case study [1]. The solver's output is as follows at Table 2. Based on the optimization results, 5 blood donation centers were opened, 2 blood banks were opened, and 6 regional hospitals were opened, with the results of optimization minimizing costs of $336,872,600 and job opportunities that could be created of 7,693.

Table 2. Hasil pencarian solusi optimal

Fungsi Tujuan	
$\boldsymbol{Z_1}$	$336.872.600
$\boldsymbol{Z_2}$	7693
$\boldsymbol{\mu(Z_1)}$	1
$\boldsymbol{\mu(Z_2)}$	0,99996

4 CONCLUSION

The model developed in this study has two objectives: to minimize total costs and to maximize job opportunities. The concept of lateral transshipment is being considered to reduce the possibility of supply shortages at the point of demand. Furthermore, blood substitution at the regional hospital is permitted in order to reduce the possibility of shortages.

Consider conducting an inventory of all health facilities and conducting real-life case studies for additional research.

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