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Amelioration in cross-matching policy with subtypes of A for priority-based demand

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ABSTRACT

Blood transfusion is a medical procedure that requires prolonged intervention. In clinical treatment, red blood cells (RBCs) play a vital role and most demanded product in blood transfusion. The ABO/RhD system was considered in several research projects in the absence of subtypes of blood inventory management (BIM). In the issuing process, without considering the age of the blood, it becomes a risk factor for the recipient after transfusion. To overcome this problem and provide effective treatment, BIM should enhance its stock of specific subtypes and classify the blood's age (shelf-life). In past, no studies on issuing policies have examined A_1A_2BO substitution in inventory management with a new A_1A_2BO compatible and A_2O priority table. For this reason, in this paper blood units of different ages are examined from two perspectives: (1) the current age of each unit and its substitution possibilities, and (2) providing effective medical services. Furthermore, the proposed system can determine the optimal order up to level quantities. Medical procedures and inventory management can both be managed effectively with this model. Hence, the goal of this research proposal is to minimize wastage and shortages along with service level substitution with age-dependent demand. By providing a numerical example, the model can validate the fact that compatibility substitution reduces wastage and blood shortages. Using a cross-matching policy, the enhanced model significantly improves the objective of this model compared to ABO substitution.

1. Introduction

Inventory control is typically a marketing strategy used to increase sales or productivity in businesses or organizations (Kamau and Kagiri, 2015). However, monitoring inventory in pharmacies and blood banks is not only focusing on costs but also preventing the wastage of crucial items like blood and blood components that may provide an effective service level. Despite significant advancements in medical science, whole blood and its components-erythrocytes, leukocytes, platelets, and plasma-are still regarded as valuable resources. The short shelf life of blood makes it a perishable commodity. Hence, Red Blood Cells (RBC) bags are recommended to be transfused within 42 days; otherwise, they will become outdated or ineffective. From the clinical point of view, managing blood inventories is a very complicated task thereby the researcher must focus on the pharmaceutical sector. Karl Landsteiner, an Austrian immunologist, discovered the blood groups A, B and O in 1901 (Lefrère and Berche, 2009). Generally, people are familiar with only eight blood groups. In managing inventories, the researchers are just taking into account the eight different blood groups in the ABO system. However, in the clinical sector of human blood, there are 42 types of blood groups: A, B, O, Rh, Duffy, etc., (Dean, 2005). Recently, An Indian with the first EMM-negative blood type was identified during the preliminary procedure for cardiac surgery (Shah et al., 2021).

Blood types with Rhesus factor (RhD), such as Rh+ve and Rh-ve, are recognized as per the medical condition before the blood transfusion. Each has its own percentage of existence in a population, with the phenotypic frequencies of ABO blood groups being $O > A > B > AB$. Essentially, Rh-ve donors can donate blood to both Rh+ve and Rh-ve recipients. Nonetheless, Rh+ve donors may donate blood to Rh+ve patients (Table 1). According to the observation, the wastage of Rh+ve is more than Rh-ve and the shortage of Rh-ve is more than Rh+ve.

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Depending on ABO/RhD compatibility table, the universal donor is a non-recipient. This may create more shortages of blood type O.

There are several subtypes of A, including $A_1, A_2, \ldots, A_x, \ldots, A_{end}, \ldots. A_{el}$. Among these, A_{el} has the least amount of A antigen. For this reason, a unique test is required. Furthermore, a patient in North India was recently diagnosed with the subtype of A_{el} (Rutam, 2022). The identification of blood subtypes is important for providing clinical treatment that does not negatively impact the patient. The International Society of Blood Transfusion Committee on Terminology for RBC Antigens has determined that A_1 and A_2 are the RBC subtypes of A have the following antigens: A_1, A_2, A_1B and A_2B. According to OPTN/UNOS policies, any subtype not A_1 is termed as non-A_1. Health medical specialists at the University of California San Francisco (UCSF) recommend three requirements for organ transplants: Blood type, HLA (Human Leukocyte Antigens), or tissue testing and cross-matching (UCSFHealth, 2022). Until the subtype is classified, no other donor blood type O was available to make a donation to blood type O. However, after classifying the subtype, A_2 blood type patients who donate their organs to O and B are eligible for transplantation (Tierney and Shaffer, 2015). Hence, by classifying the blood subtype into the blood bank and blood transfusion, donor O and B can receive blood from donor A_2.

Table 1: ABO/RhD compatibility preference table (Lang, 2009)

	Recipient							
Donator	$O-ve$	$O+ve$	$A-ve$	$A+ve$	$B-ve$	$B+ve$	$AB-ve$	$AB+ve$
$O-ve$	I	II	II	IV	II	IV	IV	VIII
$O+ve$		I		III		III		VII
$A-ve$			I	II			III	VI
$A+ve$				I				V
$B-ve$					I	II	II	IV
$B+ve$						I		III
$AB-ve$							I	II
$AB+ve$								I

I: most preferable; blank: incompatibility

Based on the above discussion, after including A_1 and A_2, people with $O > A_1 > B > A_1B > A_2 > A_2B$ blood groups are available based on phenotype. So there is less number of donors available for the least population blood type. Hence implementation of cross-matching with substitution can reduce shortages during emergencies.

Ordering and disposal policy decisions are made according to the issuing process. LIFO policy creates more wastage while FIFO policy creates less wastage. Lacroix et al. (2015) analyzed the risk factors related to transfused blood age after treatment. But the FIFO policy's medical intent, however, may not always be appropriate for delivering effective care. Depending on the treatment such as organ transplants and infant treatment, the surgeon may request fresh blood that is 1-7 days (1 week) age of the blood. In cases where the surgeon does not specify the blood's age, the blood bank can provide ordinary blood that is 2-6 weeks old. This paper divides demand into age-dependent and age-independent to stabilize inventory management and efficient medical treatment. This is the first paper that involves A_1, A_2, A_1B, and A_2B blood types in inventory management. Meanwhile, this article provides a new A_1A_2BO substitution and A_2O priority table (Tables 2 and 3).

Table 2: A_1A_2BO/RhD compatibility

	Recipient											
Donator	$O-ve$	$O+ve$	A_1-ve	A_1+ve	A_2-ve	A_2+ve	$B-ve$	$B+ve$	A_1B-ve	A_1B+ve	A_2B-ve	A_2B+ve
$O-ve$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$O+ve$		✓		✓		✓		✓		✓		✓
A_1-ve			✓	✓					✓	✓		
A_1+ve				✓						✓		
A_2-ve	✓	✓			✓	✓	✓	✓			✓	✓
A_2+ve		✓				✓		✓				✓
$B-ve$							✓	✓	✓	✓	✓	✓
$B+ve$								✓		✓		✓
A_1B-ve									✓	✓		
A_1B+ve										✓		
A_2B-ve											✓	✓
A_2B+ve												✓

✓: compatibility; blank: incompatibility

The structure of this article is as follows: An overview of a literature review on RBC inventory management is presented in section 2. For the suggested paradigm, challenges with managing blood inventory were highlighted in Section 3. There are two categories of demand: Age-dependent and age-independent, with consideration of medical aspects. By combining A_1A_2BO substitution formulations with an RBC substitution model, the demand is prioritized to ensure patient safety is explored in Section 4. To validate the objective of this model, the appropriate numerical example (considering the demand for each blood type based on phenotype frequency) with the computational procedure provided in Section 5. The outcome and discussion part have discoursed in Section 6. The conclusion part is available in Section 7.

Table 3: A_2O/RhD compatibility and preference table or priority table for universal donor and A_2

Donator	Recipient			
	$O-ve$	$O+ve$	A_2-ve	A_2+ve
$O-ve$	I	II	II	IV
$O+ve$		I		III
A_2-ve	II	IV	I	II
A_2+ve		III		I

I: most preferable; blank: incompatibility

2. Research history

In recent years, healthcare management gained considerable attention in optimizing medical sources for providing effective service due to the COVID-19 pandemic. As per WHO guidelines, COVID-19 vaccination can minimize the fatality rate. To provide the best measure of patient care, mortality rates of Coronavirus-infected individuals were statistically analyzed in consideration of pandemic protocol aspects (Syed et al., 2022). An important part of the medical sector is the blood bank which plays a crucial role in saving patients' lives. Specifically, blood inventory management has attracted significant enthusiastic researchers and has become a theme of their research articles. In terms of complexity and challenges, BIM is a very challenging system. BIM is responsible for satisfying the demand by reducing wastage and avoiding shortages.

To advance the clinical sector both hospitals and blood banks require blood inventory management. In 1963, Elston and Pickrel (1963) introduced the inventory model for Hospital Blood Banks (HBB) (Elston and Pickrel, 1963). Effective control of shortages and outdated cross-matching with prior allocation provides better service levels to patients and reduces costs (Jagannathan and Sen, 1991). Ultimately, several improvements have been made in the administration of blood inventories in Indian blood banks. In the end, efficient inventory management can improve the quality of both blood management and medical activities (Lowalekar and Ravichandran, 2014).

Using stochastic programming, a model was created for managing HBBs (Meneses et al., 2021). However, there exists another model which includes an ABO substitution that minimizes wastages, shortages, and overall costs associated with BIM (Attari and Abdoli, 2020). Taking account of ABO/Rh(D) compatible substitutions and transshipment possibility with an age-dependent request, the model proposed a multi-objective integer programming" to manage inventory in hospital blood banks (Najafi et al., 2017).

During an obstetric emergency, a patient with a blood type A_2 was identified (Padmasri et al., 2014). For a group of communities in North India, the statistical approach examined the predominance and gene patterns of the $A_1\,A_2\,BO$ and Rh(D) blood groups (Hussain et al., 2013). From the above study, there are considerable people available in the subtypes A_1 and A_2. Hence, to upgrade the quality of healthcare provision this substitution model involves the A_1, A_2, A_1B and A_2B blood types in inventory management.

In particular, the age of transfused packed red blood cells generates the risk of multiple organ failure after surgery (Zallen et al., 1999). A study recommends that hospital blood banks should issue fresh red blood cells to critically ill patients (Goel and Frank, 2017). The platelets with a FIFO policy yield significant results for platelet inventory management, but this may initiate medical complications in the future (Rajendran and Ravindran, 2017). Issuing policies in inventory management are significantly complicated without knowing the age of the blood. Hence the age of the platelets can be accounted for by the young platelets' for preplanned demands and the ordinary platelets for emergency demands. With this contemplation, a Markov decision process was used to develop the production planning model (Abbaspour et al., 2021).

Moreover, to reduce the waste and scarcity of blood products, both RBCs and platelets, using a stochastic model for age-dependent demand (Gunpinar and Centeno, 2015). Dalalah and Alkhaledi (2021) designed a model for RBC with ABO/Rh(D) compatibility for the eight types of blood groups. He considered the FIFO policy as an emergency preference with ABO compatibility as a priority.

3. Problem identification

The research problem is designed for the following reasons:

- The post-covid-19 pandemic has caused people to be reluctant to donate blood. Due to the lack of donors, the blood bank should make maximum use of the blood available to minimize wastage and shortages.

- Blood transfusions without regard to the shelf life could cause complications after the treatment. Hence, this model classified the demand based on the treatment.
- According to the statistical analysis, 80% of the people in blood group A are in A_1 and 20% in A_2. If there is no classification in A, the patient with blood type A_2 is also served with blood group A. Evidently, it will create a disadvantage for blood type A_2. As a result, this paper entails the subtypes of A, preventing the mismatch between A_1 and A_2.
- There is also the issue of no substitutions in blood banks, which could lead to a higher outdated rate. It is possible to reduce the amount of outdated blood by utilizing a cross-matching policy.
- The universal donor O has no donors available in other blood groups in the ABO system. In this case, as mentioned in the introduction, the A_2 donor can donate their blood to the blood groups O and B. Enhancing the blood group system, ABO into A_1A_2BO provides one higher level of service to the patient and minimizes the shortage with a cross-matching policy.

Hence, this proposed new A_1A_2BO substitution for a cross-matching policy with an age-dependent demand model inspected the above reasons as well as medical considerations to provide effective inventory management.

4. Research model

The section is spitted into two subsections: Mathematical model description and mathematical formulation for comprehension analysis.

4.1. Mathematical model description

A new phase begins with the satisfaction of the comprehended demand based on the fresh blood in the first column of the matrix. The realized demand is for fresh blood, which is satisfied by using the oldest unit first (FIFO), then discarding expired units (older than M weeks but not used by period). Still, the demand is not satisfied by the request for fresh blood. There is no stock available for fresh blood in the specific group j, so the demand is met by the exact blood type of ordinary blood type by the latest unit first (LIFO). In the case of ordinary blood demand, the FIFO policy will satisfy the demand for an exact match.

After filling, fresh and ordinary blood demand with an exact match, still if the demand is not satisfied, then the demand will be satisfied by the cross-matching with A_1A_2BO substitution. In other words, after satisfied fresh and ordinary blood with an exact match, still $BL_j^t > 0$, a substitution or a list of substitutes will be identified from the compatibility and A_2O preference tables (Tables 2 and 3). If two blood groups require the same substitute, then the demand priority for fresh and ordinary levels is used to discriminate between the priorities. This substitution continues until all types in the backlog are filled or the inventory of the compatible types is consumed or it fulfills the remaining backlog of all types.

4.2. Mathematical formulation

On the basis of the proposed model, a mathematical formulation has been developed (Fig. 1). Let the matrix I^t represents the inventory status of the 12 types of blood groups at t,

$$X^t = \begin{array}{c} O- \\ O+ \\ \vdots \\ A_2B+ \end{array} \begin{bmatrix} i_{1,1}^t & i_{1,2}^t & \cdots & i_{1,M}^t \\ i_{2,1}^t & i_{2,2}^t & \cdots & i_{2,M}^t \\ \vdots & \vdots & \ddots & \vdots \\ i_{12,1}^t & i_{12,2}^t & \cdots & i_{12,M}^t \end{bmatrix}. \tag{1}$$

U_j^ω indicates the "order-up-to-level" vector of the blood group j in week ω, where, $\omega \in [1,2,...,6]$ and an overview of the decision matrix is as follows:

$$U = \begin{array}{c} O- \\ \vdots \\ A_2B+ \end{array} \begin{bmatrix} U_1^1 & \cdots & U_1^6 \\ \vdots & \ddots & \vdots \\ U_{12}^1 & \cdots & U_{12}^6 \end{bmatrix}. \tag{2}$$

The available units of 12 blood groups with all ages are represented in the vector form,

$$\left[\sum_{a=1}^M i_{1,a} \quad \sum_{a=1}^M i_{2,a} \quad \dots \quad \sum_{a=1}^M i_{12,a}\right]. \tag{3}$$

The availability of all ages of a particular blood group j is given by,

$$I_j = \left[i_{j,1}^t, i_{j,2}^t, \dots, i_{j,M}^t\right] \tag{4}$$

where, $1 \le M \le 6$ and $i_{j,1}^t$ denote fresh blood units of a particular blood group j.

The requesting demand based on ages for a blood type j is given by,

$$\omega_j = \begin{cases} 1; & if\ the\ demand\ of\ the\ type\ j\ is\ age\ dependent \\ 0; & if\ the\ demand\ of\ t\ type\ j\ is\ age\ independent \end{cases} \tag{5}$$

Vector form of the demand priority for each blood type given by

$$\omega = [\omega_1 \quad \omega_2 \quad \cdots \quad \omega_j]\ for\ j = 1,2,\dots,12. \tag{6}$$

The availability of particular blood group j at period t, which represents the blood units with the same or older than the age of A in an exact match,

$$\Im_j^t(A) = i_{j,1}^t + \sum_{a=2}^M i_{j,a}^t \tag{7}$$

where, $\sum_{a=2}^M i_{j,a}^t$ is the total available units of blood group j of ordinary blood.

For example, if the age of the blood is fresh, then

$$\Im_j^t(1) = \sum_{a=1}^1 i_{j,a}^t = i_{j,1}^t. \tag{8}$$

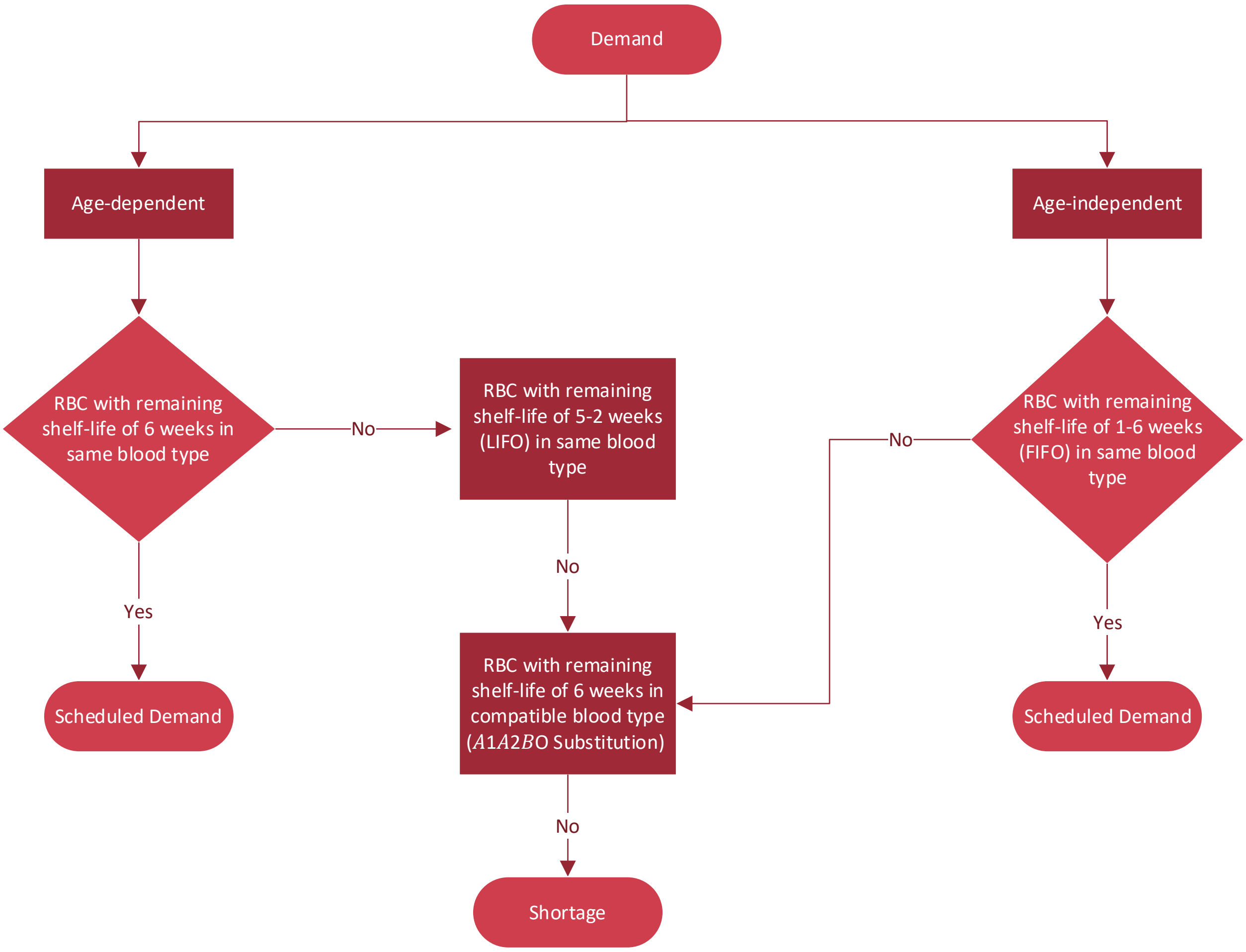

Fig. 1: The proposed system of the RBC inventory model

Let $\Im_j^t(B)$ denotes the blood units of the same blood group j at period t that are equal or older than B, where,

$$\Im_j^t(B) = \sum_{a=2}^{M} i_{j,a}^t. \tag{9}$$

Based on the treatment, the order quantities, and the selected substitution procedures, inventory status changes week by week. Based on the demand priority, the following cases are examined.

Case (i): If the demand is age-dependent $(\omega_j = 1)$ of the blood type j, then the demand is satisfied by its exact match with fresh blood.

Hence, the weekly backlog of group j after being assisted by its perfect match with fresh blood is,

$$BL_j'^t = \left[d_j'^t - \Im_j^t(1)\right]^+, t = 1,2,\ldots,T. \tag{10}$$

Equivalently, Eq. 10 can be expressed as $BL_j'^t = \left[d_j^t - i_{j,a}^t\right]^+$,

where, $[z]^+$ is the $\max(z, 0)$.

Case (ii): If the demand is age dependent $(\omega_j = 0)$ of the blood type j, then the demand can be satisfied by its exact match with ordinary blood (FIFO policy).

Hence the weekly backlog of blood group j after being issued by its perfect match with ordinary blood is,

$$BL_j^t = \left[d_j^t - \Im_j^t(B)\right]^+; t = 1,2,\ldots,T. \tag{11}$$

Case (iii): In the age-dependent demand $(\omega_j = 1)$, if $BL_j'^t > 0$, then a demand can be satisfied with ordinary blood type j with the exact type j (LIFO policy).

Hence the weekly backlog of blood group j after being issued by its exact match with both fresh and ordinary blood is,

$$BL_j'^t = \left[d_j'^t - \Im_j^t(A)\right]^+; t = 1,2,\ldots,T. \tag{12}$$

Case (iv): In the age-dependent demand case, still $BL_j'^t > 0$ for the blood type j, then the demand can be satisfied with a substitution or a set of substitutes is to be consumed by LIFO policy according to the compatibility table and A_2O preference table (Tables 2 and 3).

The overall blood unit used to satisfy the blood group j only by substitution is represented by CM_j^t. As per the above discussion, the noticed scarcity of blood group j at the end of the period t is,

$$S_j^t = \left[BL_j'^t - CM_j^t\right]^+; t = 1,2,\ldots,T. \tag{13}$$

Case (v): In the age-independent demand case, still $BL_j^t > 0$ for the blood type j, then the demand can be satisfied with a substitution or a set of substitutions is to be consumed by FIFO policy Based on compatibility and A_2O preference tables (Tables 2 and 3).

The perceived shortage of the blood group j at the end of the period t is given by,

$$S_j^t = \left[BL_j^t - CM_j^t\right]^+; t = 1,2,\dots,T. \tag{14}$$

According to the above issuing process, the inventory state $i_{j,a}^t$ can be updated.

$$i_{j,a}^t = \begin{cases} \left[i_{j,a}^t - d_j'^t - d_j^t - CS_j^t\right]^+; & a = 1 \\ \left[i_{j,a}^t - \left[d_j^t + d_j'^t - \Im_j^t(a+1) + CS_j^t\right]^+\right]^+; & 2 \le a \le M. \\ \left[i_{j,a}^t - d_j^t\right]^+; & a = M \end{cases} \tag{15}$$

As shown in Eq. 15, each blood group is used up by its own demand with an exact match depending on its age. When the age of the blood is M, either it is consumed within the week otherwise it will be outdated, The inventory of blood units does not include any mature units older than M, $\Im_j^t(M+n) = 0, n > 0$. The age M week blood only provided for the age-independent demand.

For a blood age $a, (2 \le a \le M)$ all its blood units older than a will be spent for age-independent demand first and the age-dependent demand (d_j') satisfied by $i_{j,1}$ but if $i_{j,1} = 0$, then the demand satisfied from $i_{j,a}; 2 \le a \le M$ with LIFO policy. Hence the term $[d_j^t + d_j'^t - \Im_j^t(a+1) + CS_j^t]$ refers to the remaining demand after substitution.

Clearly, the out-of-date units at the end of period t are,

$$O_j^t = i_{j,M}^t; t = 1,2,\dots,T. \tag{16}$$

The inventory received for the new units has an age of one week and all blood units get age-old by one week. Next week $t+1$will begin with the current inventory as the starting point.

This is represented as,

$$i_{j,a}^{t+1} = \begin{cases} [U_j^{MOD(t,6)+1} - \Im_j^t(B)] & ; \quad a = 1 \\ i_{j,a-1}^t & ; \quad 1 < a \le M \end{cases}. \tag{17}$$

where, L_j^ω is the maximum stock boundary of the week ω.

The modular division in $MOD(T,6)+1$ is the function that returns an index from 1 to 6 to identify the 6 weeks.

In order to determine replenishment quantities,

$$OQ_j^t = U_j^{MOD(t,6)+1} - \Im_j^t(B), \tag{18}$$

which will be available in the next week.

At the end of each week, the below equality should hold.

$$\Im_j^t(A) = U_j^{MOD(t,6)+1}. \tag{19}$$

Therefore, the complete shortage of the blood group j over the planning period T is,

$$KS_j = \sum_{t=1}^T S_j^t;\ j = 1,2,\dots,12. \tag{20}$$

Similarly, the complete outdates of blood group j over the same planning period T is,

$$KO_j = \sum_{t=1}^T O_j^t\,; j = 1,2,\dots,12. \tag{21}$$

In order to achieve this, two measurements are available for each blood group Eqs. 20 and 21. The sum of Eqs. 20 and 21 are the total shortage and outdated units of the 12 types of blood groups. Thus, the objective of this proposed model can be described as follow:

$$min \sum_{j=1}^{12} KS_j + \sum_{j=1}^{12} KO_j. \tag{22}$$

5. Numerical example

The RBC inventory is considered for 1 week assuming a maximum shelf-life of 6 weeks or 42 days along with compatible substitution. Assume that the demand priority for fresh blood:

$$d = [0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1].$$

Order up to the level of this week,

$$U^1 = [30 \quad 45 \quad 60 \quad 30 \quad 15 \quad 10 \quad 25 \quad 20 \quad 20 \quad 35 \quad 8 \quad 5].$$

Let's begin with 12 blood groups as the initial inventory,

$$I^1 = \begin{array}{r} O- \\ O+ \\ A_1- \\ A_1+ \\ A_2- \\ A_2+ \\ B- \\ B+ \\ A_1B- \\ A_1B+ \\ A_2B- \\ A_2B+ \end{array} \begin{bmatrix} 10 & 2 & 3 & 4 & 1 & 0 \\ 7 & 5 & 3 & 0 & 0 & 0 \\ 15 & 1 & 7 & 9 & 3 & 4 \\ 20 & 4 & 2 & 4 & 0 & 0 \\ 10 & 3 & 2 & 0 & 0 & 0 \\ 5 & 3 & 1 & 1 & 0 & 0 \\ 20 & 3 & 2 & 0 & 0 & 0 \\ 10 & 5 & 3 & 2 & 0 & 0 \\ 5 & 3 & 4 & 2 & 2 & 4 \\ 25 & 6 & 1 & 1 & 1 & 1 \\ 3 & 2 & 2 & 1 & 0 & 0 \\ 3 & 2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Hence, the available quantities of all types,

$$[20 \quad 15 \quad 34 \quad 30 \quad 15 \quad 10 \quad 25 \quad 20 \quad 20 \quad 35 \quad 8 \quad 5].$$

Let the demand

$$D^1 = [25 \quad 20 \quad 10 \quad 35 \quad 3 \quad 2 \quad 15 \quad 10 \quad 22 \quad 5 \quad 0 \quad 3]$$

is satisfied by an exact match with fresh blood by the priority and ordinary blood for non-priority of the age of the blood.

$$I^1 = \left[\begin{array}{r|cccccc} O- & 0 & 0 & 0 & 0 & 0 & 0 \\ O+ & 0 & 0 & 0 & 0 & 0 & 0 \\ A_1- & 5 & 1 & 7 & 9 & 3 & 4 \\ A_1+ & 0 & 0 & 0 & 0 & 0 & 0 \\ A_2- & 7 & 3 & 2 & 0 & 0 & 0 \\ A_2+ & 5 & 3 & 0 & 0 & 0 & 0 \\ B- & 10 & 0 & 0 & 0 & 0 & 0 \\ B+ & 10 & 0 & 0 & 0 & 0 & 0 \\ A_1B- & 0 & 3 & 4 & 2 & 2 & 4 \\ A_1B+ & 20 & 6 & 1 & 1 & 1 & 1 \\ A_2B- & 3 & 2 & 2 & 1 & 0 & 0 \\ A_2B+ & 0 & 2 & 0 & 0 & 0 & 0 \end{array}\right]$$

The resulting backlog

$$BL^1 = [5 \quad 5 \quad 0 \quad 5 \quad 0 \quad 0 \quad 0 \quad 0 \quad 17 \quad 0 \quad 0 \quad 0].$$

If fresh blood is not available, then go for ordinary blood with an exact match, there is no stock available for blood type $O-, O+, A_1+$. But there is stock available in ordinary blood for A_1B- is 15 units
So the resulting backlog is,

$$BL^1 = [5 \quad 5 \quad 0 \quad 5 \quad 0 \quad 0 \quad 0 \quad 0 \quad 2 \quad 0 \quad 0 \quad 0],$$

where, the blood groups $O-, O+, A_1+, A_1B-$ are still have a shortage of 5, 5, 5, and 2 units respectively.

By preference A_2O substitution table, choosing the cross-matching substitutes, the 5 units short of $O-$ can be fully satisfied by the substitutes of fresh blood of A_2-. In this case, either there is no stock available on A_2- or does not involves the A_1A_2BO substitution of the blood group $O-$ becomes a shortage.

Next, by preference A_2O substitution table, choosing the cross-matching substitutes, the 5 units short of $O+$ satisfied by the priority $O-, A_2+, A_2-$. The blood type $O-$ has no units, hence the 5 units short of $O+$ can be fully satisfied by the substitutes of fresh blood of A_2+. Then the 5 units unavailability of A_1+ can be met by the substitutes of fresh blood of A_1-.

Finally, after being satisfied with the exact match of ordinary blood, it still A_1B- has 2 units short. Therefore the 2 units short of A_1B- satisfied by the fresh blood of $B-$.

After satisfying the backlog by substitution, the remaining inventory level is,

$$I^1 = \left[\begin{array}{r|cccccc} O- & 0 & 0 & 0 & 0 & 0 & 0 \\ O+ & 0 & 0 & 0 & 0 & 0 & 0 \\ A_1- & 0 & 1 & 7 & 9 & 3 & 4 \\ A_1+ & 0 & 0 & 0 & 0 & 0 & 0 \\ A_2- & 2 & 3 & 2 & 0 & 0 & 0 \\ A_2+ & 0 & 3 & 0 & 0 & 0 & 0 \\ B- & 8 & 0 & 0 & 0 & 0 & 0 \\ B+ & 10 & 0 & 0 & 0 & 0 & 0 \\ A_1B- & 0 & 0 & 0 & 0 & 0 & 0 \\ A_1B+ & 20 & 6 & 1 & 1 & 1 & 1 \\ A_2B- & 3 & 2 & 2 & 1 & 0 & 0 \\ A_2B+ & 0 & 2 & 0 & 0 & 0 & 0 \end{array}\right]$$

Therefore, the vector of shortage in the first week is,

$$S^1 = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0].$$

That is, there is no shortage on that week.

After satisfied the backlog, the last row of the state matrix will be outdated, where,

$$O^1 = [0 \quad 0 \quad 4 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0].$$

The restocking inventory with all ages taken into consideration to the predetermined level I_j^1. Next, we will examine the new inventory state matrix,

$$I^1 = \left[\begin{array}{r|cccccc} O- & 30 & 0 & 0 & 0 & 0 & 0 \\ O+ & 45 & 0 & 0 & 0 & 0 & 0 \\ A_1- & 40 & 0 & 1 & 7 & 9 & 3 \\ A_1+ & 30 & 0 & 0 & 0 & 0 & 0 \\ A_2- & 8 & 2 & 3 & 2 & 0 & 0 \\ A_2+ & 7 & 0 & 3 & 0 & 0 & 0 \\ B- & 17 & 8 & 0 & 0 & 0 & 0 \\ B+ & 10 & 10 & 0 & 0 & 0 & 0 \\ A_1B- & 20 & 0 & 0 & 0 & 0 & 0 \\ A_1B+ & 6 & 20 & 6 & 1 & 1 & 1 \\ A_2B- & 0 & 3 & 2 & 2 & 1 & 0 \\ A_2B+ & 3 & 0 & 2 & 0 & 0 & 0 \end{array}\right]$$

This the total inventory level is equal to the order up to level,

$$I_j^t(1) = [30 \quad 45 \quad 60 \quad 30 \quad 15 \quad 10 \quad 25 \quad 20 \quad 20 \quad 35 \quad 8 \quad 5] = U_j^1.$$

As a result, at the start of week 2, the inventory at the end of week 1 will be existing, which is updated as $I^{1+1} = I^1$.

6. Results and discussion

In the numerical example, demand and order-up-to-level assumptions are made based on the phenotype frequency of blood groups in India. As a result of implementing the cross-matching with A_1A_2BO substitution, it is evident that this proposed model does not generate a shortage (that means fully backlogged). If A_1A_2BO substitution not happened, there was a shortage of 17 units for all types which must be a great loss. It is evident that after implementing the cross-matching with A_1A_2BO substitution that prevents the 17 unit wastages. Hence this proposed model generates no shortage. Issuing policies LIFO and FIFO, which are age-dependent and age-independent demands, are considered to accomplish the goal of the research model. For example, if this model follows only the FIFO policy, it fails to address patient care, focusing only on inventory management with no waste. Hence, this model will act as a bridge between BIM and the patient's medical procedures.

From the phenotype frequency in the ABO system, $O > A > B > AB$, there are more people available in A next to the blood group O. It is necessary to classify blood types in BIM according to their subtypes. Because the number of people available in the non-A_1 blood group is nearly equal to the number of people available in blood group AB. Hence, the classification is necessary to implement in the blood bank. Implementing A_1 and A_2 groupings are vital to avoid any reactions from these minor incompatibilities, leading to overall implementation in blood transfusion.

This A_1A_2BO substitution provides greater advantages to the universal donor. From this, the universal donor and blood group B can receive blood from the blood group A_2 in an unavoidable situation. The fact revealed in the discussion is that this model achieved the objective of BIM.

7. Conclusion

The most needed blood product is RBC. Consequently, this paper focuses on managing RBC inventory. This model can reduce the shortage of universal donors, which will be a lifesaver in a few decades. As a result of substitution and age-dependent demand, this model minimized wastage and shortages of blood units. According to this model, the blood service center (BSC) decides how to order and use available blood units in such a way as to maintain a desirable level of total inventories.

This proposed model for RBC inventory management provides fresh blood for the substitution that improves the medical treatment service level. The conceptual model was described with the combination of FIFO and LIFO in cross-matching with A_1A_2BO substitution. From our research history (section 2), numerous researchers have designed their inventory management models for RBC with the ABO system. In this system, both A_1 and A_2 blood types are considered as A; there is no difference considered in the ABO system. In this model, after including the A_1 and A_2 blood types, the service level of the blood bank was significantly improved. Compared to ABO substitution, this A_1A_2BO substitution takes the objective of BIM to the next level in health care. The model considers the substitution relations among various blood types in the blood transfusion process to minimize blood shortage and wastage. This article proposes avenues of research for health care. Amelioration in cross-matching policy with subtypes of A for priority-based demand is the synergy in blood inventory management.

List of symbols

a	the age of blood; $a = 1,2,\dots,M$, where, M is the maximum shelf-life of 6 weeks
BL_j^t	backlog of blood type j for the age-independent demand, which is not met by the exact match in the time period t
$BL_j'^t$	backlog of blood group j for the age-dependent demand, which is not met by the exact match in the time period t
CM_j^t	the overall blood unit used to satisfy the blood group j only by substitution
CS_j^t	the total amount of blood group j that has been consumed by compatible substitution
d	$demand\ (d) = \begin{cases} fresh\ blood & if\ a = 1 \\ ordinary\ blood & if\ 2 \le a \le 6 \end{cases}$
d_j^t	the age-independent demand of blood group j in period t
$d_j'^t$	the age-dependent demand of blood group j in period t
D^t	the demand vector of all ages (fresh/ordinary) of all blood groups in t, where, $D^t = [D_1^t, D_2^t, \dots, D_{12}^t]$
$i_{j,1}$	the available units of fresh blood of a particular blood group j at period t
$i_{j,a}^t$	the available units of ordinary blood of a particular blood group j at period t, where, $2 \le a \le M$
I_j	the available units of all ages of a particular blood group j
j	$\{1,2,3,\dots,12\}$ =The list of blood groups (types) $= \begin{Bmatrix} \mathrm{O-, O+, A_1-, A_1+, A_2-, A_2+, B-, B+, A_1B-, A_1B+} \\ \mathrm{, A_2B-, A_2B+} \end{Bmatrix}$
KO_j	complete shortage of the blood group j at the planning period t
KS_j	complete outdates of the blood group j at the planning period t
t	a specific week in T long planning period, $t = 1,2,\dots,T$
M	maximum shelf-life of 42 days (or) 6 weeks
O_j^t	resulting in outdates of the blood group j for the end of the time period t
OQ_j^t	order quantity of blood groups j at the beginning of the time period t
S_j^t	the resulting shortage of the blood group j for the end of the time period t
U_j^ω	order-up-to-level vector of the blood group j in ω, where, $\omega \in [1,2,\dots,6]$
ω_j	the demand priority for fresh/ordinary of the blood group j

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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