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Research Article

Minimizing Packed Red Cell Shortages in the Blood Supply Chain: A Discrete Simulation and Taguchi-based Approach

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Abstract

The blood supply chain is critical in providing better quality services in the health care system. Packed red cells (PRC) are the most demanded product in hospitals. However, the shortage is still a challenge due to its uncertain demand. This research aims to address that challenge. In this research, a blood bank is considered to be at the middle level in the echelons of the blood supply chain. The discrete event simulation approach develops a simulation model representing a complex blood supply chain system. The Taguchi Method technique is employed to identify the control variables and levels for analysis. The novelty of this research is to develop a simulation model dedicated to observing the uncertainty of supply and demand in the blood supply chain. The model provides an opportunity to customize blood age, which the customers (hospitals) requested. The control variables used in this research are supply arrangement, maximum target of inventory, and production percentage. This research result is a policy that could effectively reduce the shortage. Compared to the existing conditions, the proposed decision could increase the order fulfillment rate by up to 99% and decrease outdated products by 16.28%.

Keywords: Blood supply chain; Shortages; Discrete event simulation; Taguchi method; Indonesia

1. Introduction

The function of Packed Red Cells (PRC) in the human metabolism system is overly critical since there are no substitute alternatives. PRC is one of the components in blood that transports oxygen from the heart to the whole body and disposes of carbon dioxide. PRC transfusion is used to help anemic patients or those with hemoglobin disorders caused by cancer or else. If someone has a deficiency of red blood cells, it will cause chronic illness and death. Ironically, humans always need donors from others for specific reasons to ameliorate their health level. The institution with the right to organize the blood donor activity and separate the blood components is called a blood bank. In Indonesia, the organization that was given a mandate from the government to act as a blood bank is the Indonesian Red Cross (IRC). The particular challenges to be solved by IRC were overcoming the shortage and outdated products (Gunpinar & Centeno, 2015; Dillon et al., 2017; Mansur et al., 2023a). Another challenge to pay attention to is optimizing the financial side of the IRC institution, as it is a non-government institution. In the blood supply chain, IRC is responsible for collecting the blood from the donors, producing blood products, and distributing the PRC to the hospitals. Figure 1 shows Indonesia's total blood bag donations, voluntary, paid, and family donations over the last ten years.

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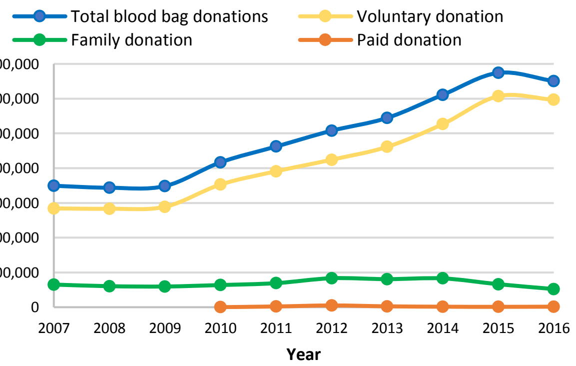


Fig. 1. The total blood donations in Indonesia (Nurhasim, 2024)

According to Figure 1, the Indonesian Ministry of Health data in 2016 (Nurhasim, 2024) revealed a significant gap in the nation's blood supply. While the total demand for blood bags across Indonesia was approximately 5.1 million, the available supply was only 4.2 million, meeting 81% of the required amount. This shortfall of around 19%, or 1 million blood bags, underscores a critical challenge in the country's healthcare system. The inability to meet this demand could lead to severe consequences, particularly in emergency medical situations where timely access to blood is crucial. Addressing this shortage is essential to improving patient care and ensuring that the healthcare system can respond effectively to the population's needs.

This research aims to manage the policies of a blood bank to maintain the sustainability of PRC supply by minimizing shortages in complex environments. The shortage amount is calculated based on the number of PRC requests that cannot be fulfilled for one year. The novelty of this work is a model answering these issues: (1) the fluctuation rate of supply as a response to the activity pattern of donors in the Mobile Unit Model (MUM) and the Fixed Location Model (FLM); (2) the fluctuation of demand; (3) blood age customization.

The structure of this paper is organized as follows: Subsections 1.1-1.2 involve a systematic literature review using PRISMA methodology and a review of recent literature, respectively. Subsection 1.3 describes the research gap and contributions of this research. Section 2 provides the research methodology. The results and findings are provided in Section 3. In Section 4, we present the discussions and managerial insight. Finally, in Section 5, we summarize the results obtained and propose directions for future research.

1.1. SLR with PRISMA methodology

This subsection provides a concise overview of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach and a summary of the bibliometric analysis and systematic literature review (SLR) stages. The PRISMA methodology is typically divided into four stages: identification, screening, eligibility, and inclusion (Marques et al., 2020; Wangsa et al., 2022; Alghamdi et al., 2023; Agac et al., 2023). Figure 2 illustrates the PRISMA utilized in this study.

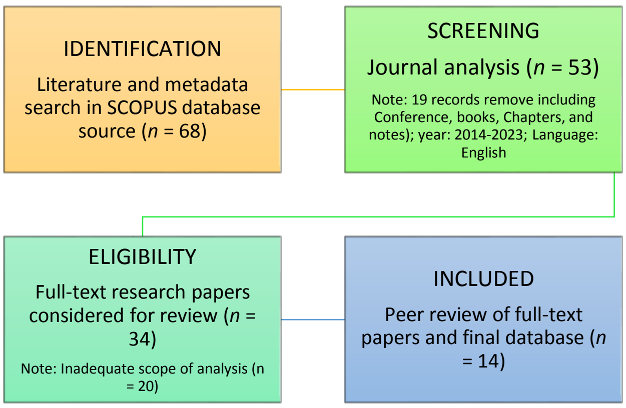


Fig. 2. The PRISMA methodology on the blood supply chain

In the initial stage, literature and metadata were extracted from the Scopus database in December 2023. We selected Scopus due to its comprehensive collection of peer-reviewed research across various fields, including science, technology, medicine, social sciences, and the arts and humanities. Fahimnia et al. (2015) noted that Scopus hosts 20,000 peer-reviewed journals from publishers such as Elsevier, Emerald, Informs, Taylor & Francis, Springer, and Inderscience. The subsequent stages involved screening with specific criteria—focusing on journal articles from 2014 to 2023 published in English—and assessing the relevance based on subject areas. This process initially yielded 53 articles, with 19 remaining after applying the screening filters. After a thorough review, 20 irrelevant reports were removed in the final stage, resulting in a final count of 14 relevant articles.

The study's keywords are categorized into three themes: "*inventory and supply chain*", "*blood products*" and "*simulation methods*". The search used a combination of keywords from each theme in the search fields "*Article title, Abstract, Keywords*" on the Scopus database. The keywords were selected based on a combination of terms from previous research. The search was limited to English-language articles published in academic journals between 2014 and 2023.

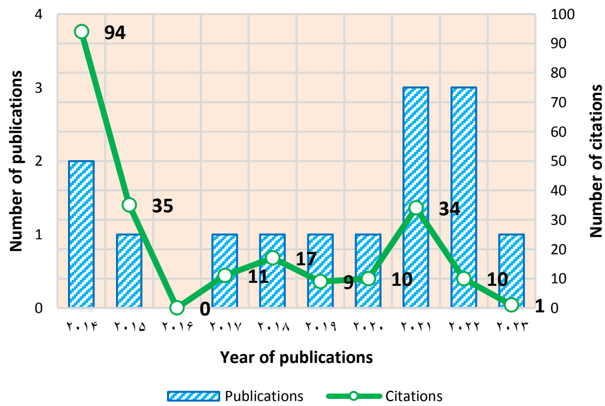


Fig. 3. Total publications and citations of the blood supply chain literature using the simulation method from 2014 to 2023

Figure 3 depicts the trend in article publications from 2014 through February 2023, with 14 articles. The data shows that the number of publications in 2016 was fewer than zero articles. The figure increased in 2021 and 2022, with three articles published. From 2014 to 2023, an average of 22.1 papers were cited per year. The peak year was 2014, which saw the highest number of publications, with a total citation of 94 articles.

1.2. Literature review

Several studies have been conducted on inventory management in blood banks. Alfonso et al. (2013) and Mansur et al. (2023b; 2023c) proposed discrete event simulation to reduce outdated products in the blood supply regulation. Kopach et al. (2008) and Dillon et al. (2017) optimized inventory control by determining the target inventory level. However, the limitation of their studies was that they needed to provide demand customization space regarding blood age. Moreover, Rytilä & Spens (2006), Blake & Hardy (2013), and Mansur et al. (2020) used a simulation approach to optimize bloodstock. However, the limitation of their studies was less adaptive in responding to changes in supply and demand. Dalalah et al. (2019) proposed a hybrid simulation and optimization approach, namely simulated annealing, to minimize the shortage and outdated blood bags. Ghasemi et al. (2022) developed a mathematical model with the goal of multi-objective ways to minimize the total cost and maximize the level of satisfaction in order to meet blood demand. The model was solved by using scenario-based robust optimization. Lucas et al. (2022) simulated two near-optimal heuristics using the Beta distribution. Their research provides a theoretical contribution to guide hospital staff's decision-making in heuristic conditions to determine the optimization of blood product inventory. Dalalah & Alkhaledi (2023) proposed an artificial intelligent method to seek the optimal order-up-to-level quantities of blood, which minimizes its shortage and outdated units. A case study in their study was conducted on the transfusion of red blood cells for emergency medical conditions such as surgery, anemia, and cancer.

1.3. Research gap and contributions

This study fills a critical gap in blood supply chain management research that needs more exploration. Although there have been several studies on different sections of blood supply chains, such as inventory or distribution, studies have yet to combine these results into an analytic decision-making framework that systematically addresses red blood cell shortages at the national level. This research has yet to exploit the full capacity inherent within discrete event simulation and Taguchi methods, thereby creating a significant void regarding how they can be used wholly to improve the efficiency of the blood supply chain.

This research offers a novel perspective on optimizing the blood supply chain by adopting discrete event simulation and Taguchi methods. Discrete-event simulation allows for detailed dynamic behavior and variability analysis within any supply chain. On the other hand, the Taguchi method provides a systematic approach to process optimization and shortage reduction. In summary, this work is meant to shed light on what makes it challenging to manage the movement of RBCs from artificial sources to patients who need transfusions and what measures should be taken to solve this problem. Also, the case study's focus on Indonesia gives it more context and practicality. These methods were applied in Indonesia and were used to reduce red cell demand better than before by utilizing discrete event simulation and Taguchi approach.

2. Research Methodology

This research used the Taguchi method and discrete event simulation. The primary aim of the Taguchi technique is to minimize the impact of extraneous variables and identify the optimal values for the main controllable components through the use of Taguchi's resilient design principles. Taguchi utilized orthogonal array (OA) designs to allocate the selected components for the experiment (Zahraee et al., 2015). The orthogonal array determines the primary and interaction effects by doing the minimum number of tests. Discrete event simulation is well-suited for intricate systems that involve dynamic and time-dependent processes. It is an excellent tool for improving and assessing the blood supply chain. The blood supply chain encompasses multiple stages, from donation to distribution. Discrete event simulation can aid in modeling and enhancing these processes' efficiency, dependability, and cost-effectiveness. The method used in this research is due to its advantages in describing the complex and uncertain environment (Zahraee et al., 2015).

2.1 Model development

The primary entity observed in this research was the Packed Red Cells component (PRC). The parameters examined to make this model in detail were:

1. There is uncertainty about the supply rate from the donor in MUM and FLM.
2. Blood components' age in the inventory
3. The restriction of blood life span in PRC components
4. Percentage of blood that passed the quality control
5. There needs to be more certainty about the demand rate from hospitals and blood banks.
6. The uncertainty of demand rate from hospitals without blood banks.
7. Age customization of the PRC is according to the demand from hospitals and blood banks.
8. Age customization of PRC according to the demand from hospitals with and without blood banks.
9. The inventory maximum target in PRC components

The simulation model design requires a detailed understanding of the organization's business process in blood banks. The simulation process that had been accomplished, including:

1. Donor analysis: At this stage, the activity that could be carried out was to observe the behavior of donors (MUM and FLM) so that the statistics distribution from the time between donors' arrivals and the entities per arrival of donors could be identified.
2. Demand analysis: The activity in this stage was to observe the hospitals' blood demand behavior, such as the statistical distributions of the demand time between arrivals, the entity of each demand arrival, and age customization.
3. The scenarios/experiments design involved supply regulations in MLM and FLM, PRC percentages

regulation from the total production, and the inventory target of the maximum number of PRC.

4. Calculating the number of shortages and outdated products.

2.2 Design of experiment (DoE)

According to the interview results with stakeholders, they recommended several factors that might affect the number of shortages. In this research, I used the Taguchi method to arrange the design of the experiment. The Taguchi approach is applicable in blood supply chain management to enhance efficiency and develop a resilient blood supply chain system. The approach entails selecting controllable elements, including the arrival rate of donors, maximum inventory level, minimum inventory level, and blood production policy. In the simulation, those factors were called controlling variables, and this research would use 4 factors with three levels, as listed in Table 1. Figure 4 shows the conceptual model of the proposed model by considering the uncontrollable factors and controllable performance indicators in the Indonesian blood supply chain.

1. The supply rate from the donor in MUM and FLM is uncertain.
2. Blood components' age in the inventory
3. The restriction of blood lifespan in the PRC components.
4. Percentage of blood that passed the quality control.
5. There needs to be more certainty about the demand rate from hospitals and blood banks.

The considerations used for the controlling variables in developing the experiment/scenario were as follows:

1. The proposed limitation on the number of donors in the FLM model was intended to reduce the probability of outdated product levels due to the abundant raw material supply.
2. The proposed frequency of event procurement in the MUM model was intended to respond to the dynamics of the supply environment, which impact the intensity of raw material supply.
3. The value of I-max directly impacted the ability to serve requests from the hospital.

Table 1
Controlling variables used in the simulation

Factors	Level 1	Level 2	Level 3
Factor A: FLM Target Regulations	Existing (No Limitation)	Maximum 60 donors/day	maximum 40 donors/day
Factor B: MUM Target Regulations	Existing (No Limitation)	The target of the inter-arrival time is one day.	The target of the inter-arrival time is two days.
Factor C: Maximum Number of PRC Target Inventory (I-Max) Regulations	Existing (No Target)	Type A 788 bags Type B 988 bags Type AB= 196 bags Type O= 1285 bags.	Type A 891 bags Type B 1129 bags Type AB= 235 bags Type O= 1510 bags.
Factor D: Percentage of PRC products if compared with other products.	Existing (65 %)	70 %	80 %

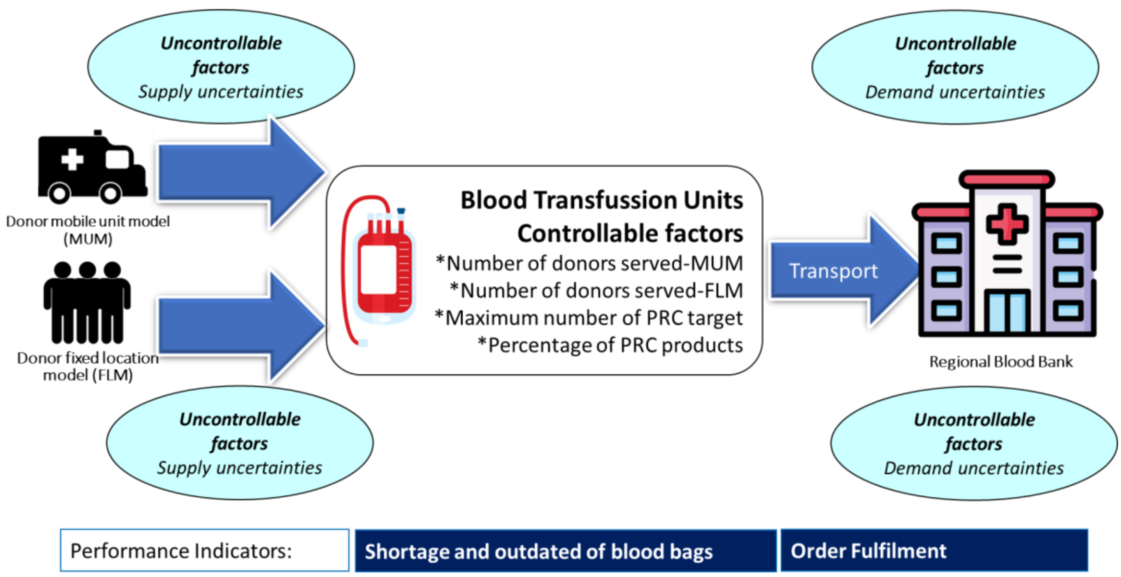


Fig. 4. The conceptual model in the Indonesian blood supply chain

Table 2
Orthogonal Array (OA) L9 (3^4)

Experiment	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

We proposed an experiment design to determine the best factor and level combination. The Taguchi method was used to design the number of experiments/scenarios. It was based on the capability of the Tathe Gucci model to simplify the number of experiments (Li & Liao, 2012; Zahraee et al., 2,015). Based on the existing condition, it has four factors with three levels; hence, the determination of experiments applied orthogonal array L9 (3^4). Table 2 represents the experiment conducted in this research. The table describes the design of the experiment as follows:

1. In this first experiment, the simulation scenario settings refer to existing conditions.
2. The second experiment was run with the following settings: the number of donors with FLM is not limited, MUM is scheduled with an inter-arrival time of one day, Maximum number of PRC for each blood group targeted (A = 788 bags/day, B = 988 bags/day, AB = 196 bags/day, and O = 1285 bags/day), percentage of PRC product 70% if compared to other products.
3. The third experiment was run with the following settings: the number of donors with FLM is not limited, MUM is scheduled with an inter-arrival time of 2 days, Maximum number of PRC for each blood group targeted (A = 891 bags/day, B = 1129 bags/day, AB = 235 bags/day, and O = 1510 bags/day), percentage of PRC product 80% if compared to other products.
4. The fourth experiment was run with the following settings: the number of donors with FLM is limited with a maximum of 60 donors/day, MUM is an unlimited event, Maximum number of PRC for each blood group targeted (A = 891 bags/day, B = 1129 bags/day, AB = 235 bags/day, and O = 1510 bags/day), percentage of PRC product 70% if compared to other products.
5. The fifth experiment was run with the following settings: the number of donors with FLM is limited to a maximum of 60 donors/day, MUM is scheduled with an inter-arrival time of 1 day, the Maximum number of PRC for each blood group is unlimited, and PRC is 80% compared to other products.
6. The sixth experiment was run with the following settings: the number of donors with FLM is limited to a maximum of 60 donors/day, MUM is scheduled with an inter-arrival time of 2 days, the Maximum number of PRC is unlimited for each blood group, and the percentage of PRC product is 70% compared to other products.
7. The seventh experiment was run with the following settings: the number of donors with FLM is limited with a maximum of 40 donors/day, MUM is an unlimited event, Maximum number of PRC for each blood group targeted (A = 891 bags/day, B = 1129 bags/day, AB = 235 bags/day, and O = 1510 bags/day), percentage of PRC product 70% if compared to other products.
8. The eighth experiment was run with the following settings: the number of donors with FLM is limited to a maximum of 40 donors/day, MUM is scheduled with an inter-arrival time of 2 days, the Maximum number of PRC for each blood group is unlimited, and the percentage of PRC product is 65% compared to other products.
9. The ninth experiment was run with the following settings: the number of donors with FLM is limited to a maximum of 40 donors/day, MUM is scheduled with an inter-arrival time of 2 days, and the Maximum number of PRC for each blood group targeted (type-A = 891 bags/day, type-B = 1129 bags/day, type-AB = 235 bags/day, and type-O = 1510 bags/day). The percentage of PRC products was 65% compared to other products.

2.3 Objective function (blood bank performance)

This research develops a simulation model with three (3) main blood bank performance indicators used to measure the significant impact of the proposed approach, namely:

1) **The blood outdated** is the products or blood bag items that have passed their expiration date.
2) **The blood shortage**: The IRC cannot fulfill all requests for blood bags from hospitals in the IRC operation area. The uncertainty of blood supply and demand impacts the high number of blood shortages. The high number of blood shortages affects hospitals' low performance of the order fulfillment rate.
3) **The order fulfilment**: a percentage of requests that can be met against the overall demand.

The objective function of the proposed model is to minimize the shortage of outdated products (bags) and the shortage of products (bags), as well as maximize the percentage of order fulfillment (%). The formulations are as follows in Eqs. (1-3):

$$\text{Outdated (bags)} = [\text{Inventory } x \text{ expired rate (time)}] \quad \dots (1)$$

$$\text{Shortage (bags)} = (\text{Demand} - \text{Demand fulfilled}) \quad \dots (2)$$

$$\text{Order fulfilment (\%)} = \frac{\text{Demand fulfilled}}{\text{Demand}} \text{x}100\% \quad \dots (3)$$

3. Results and Findings

3.1 A real case study in Indonesia

This research is conducted in a case study of the supply chain of blood products in Indonesia. The data in this study is based on actual case data, most of which was obtained from the Indonesian Red Cross (IRC), especially in Sleman Regency, Yogyakarta at Indonesia (Figure 5). There are four types of blood products: Blood type A, blood type B, blood type AB, and blood type O, with an average shelf lifetime of 25 days.

Fig. 5. Sleman regency in yogyakarta, Indonesia

Figure 6 shows the Indonesian blood supply chain has three (3) echelons, which are supply-side or upstream (donors), production-side or middle stream (regional blood bank), and hospitals as demand-side (downstream). Donors represent the supply side in this chain, and hospitals represent the demand side. Both have uncertain environments. The blood bank on the middle streams synchronizes the supply and demand sides. The blood bank has two types of supply sources, namely, MUM and FLM. The difference between MUM and FLM is the collection strategy. Using MUM, the blood bank would actively pick up the potential donors, whereas FLM, the blood bank, would wait for the donors to come. Blood bank customers are divided into two types: hospitals with and without blood banks. The difference between these hospitals is the freshness rate or the age of the PRC product's request to a blood bank. Hospitals with blood banks only accepted PRC with a shorter than seven-day lifespan, while hospitals without blood banks were more flexible. It agreed to receive PRC less than 30 days old. If the blood bank addresses these variations, the product's outdated risk will stay the same. The simulation and analysis were obtained using ARENA software on a Lenovo AMD A9-9400.

3.2 Validation test

The validation model test proved that the simulation model was already suitable for the actual system condition. The parameters used to compare were the number of outdated PRC products recorded in the actual system and the number of outdated PRC products according to the simulation result. The statistical test results for all categories of blood types are presented in Table 3.

Table 3

The results T-test Two-Sample Assuming Equal Variances

Blood type	t_{stat}	**P(T<=t) two-tail**	$t_{Critical}$ **two-tail**	**Decision**
A	1.378226	0.205448	2.306004	Accepted
B	0.097056	0.925069	2.306004	Accepted
AB	2.348177	0.046814	2.306004	Accepted
O	1.854086	0.100842	2.306004	Accepted

Based on Table 3, the comparison between the number of outdated PRCs in the real system vs. the simulation had t stat in the range $-t_{critical} \leq t_{stat} \leq t_{critical}$. That phenomenon indicated no solid reason for rejecting H_0 (There was no difference between the simulation model and the actual system). Therefore, it could be concluded that the proposed model is valid. In other words, the model can be used to test the proposed scenarios.

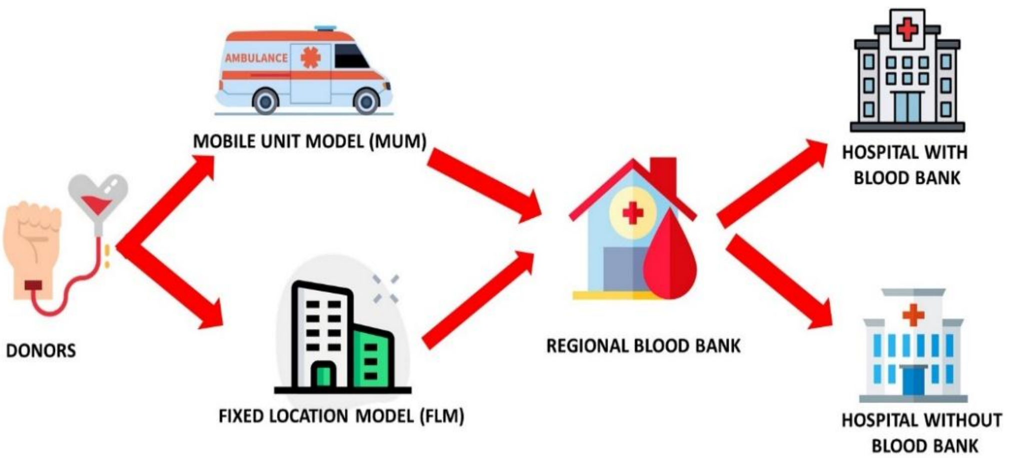
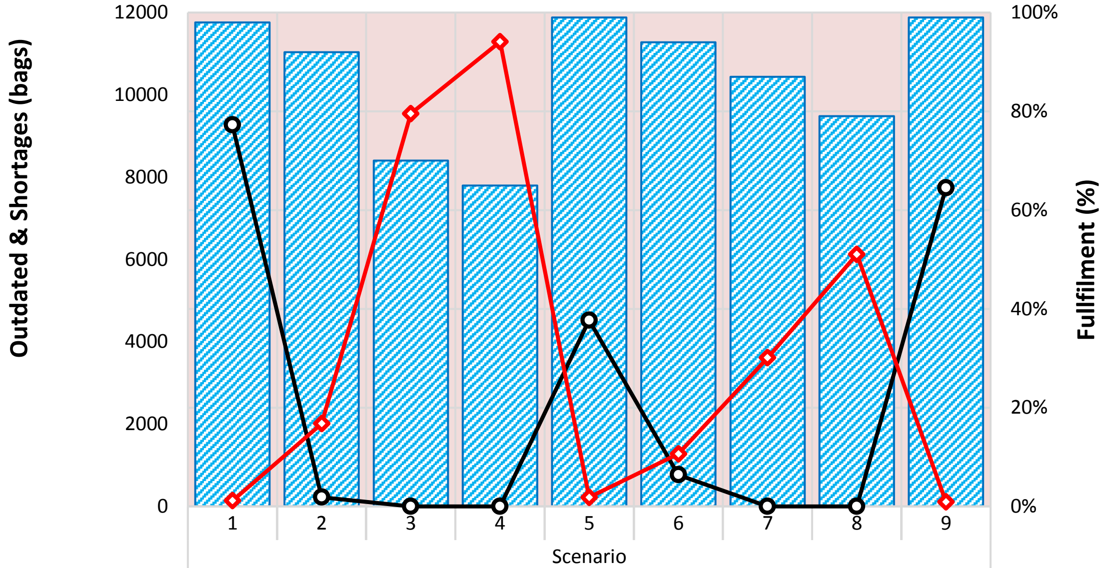


Fig. 6. The structure of the Indonesian blood supply chain

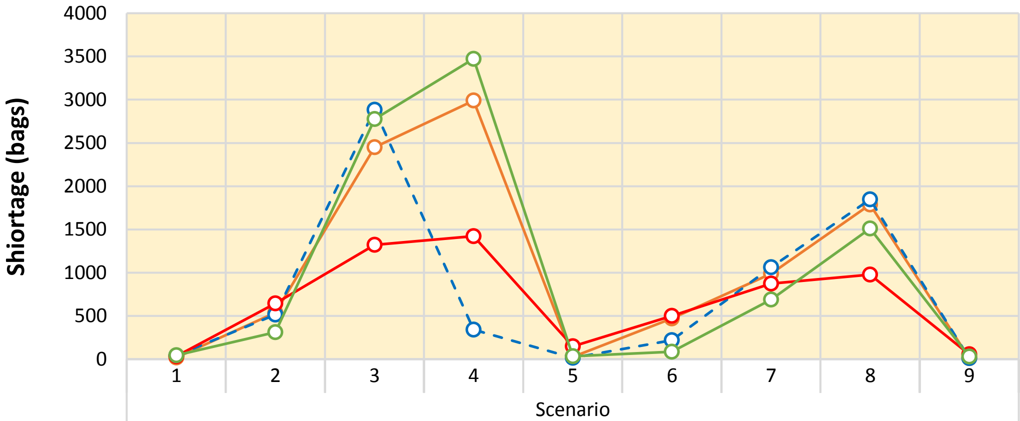
3.3 Scenario results

Based on the simulation result, the number of shortages, outdated, and percentage of order fulfillment rate from each scenario is presented in Figure 7. The figure shows that the current system condition (Scenario 1) had shortages of 136 blood bags in one year with a 98% order fulfillment rate. If the service level targeted by the blood bank was as much as possible to reach 100%, without considering the risks of outdated products that would happen, then Scenario 9 was the best choice where the shortage that produced was 110 blood bags/year. The distribution of blood types that are in shortage is shown in Figure 8. The figure shows that shortages occur for each blood type due to uncertainty in demand. The results of the running simulation show that shortages always occur in every simulation scenario that is run. The figure shows that the IRC faces the risk of shortage. Among the rare blood types, A blood type has the smallest risk of shortages, and AB blood types have the highest shortages.



	1	2	3	4	5	6	7	8	9
Order fulfilment	98%	92%	70%	65%	99%	94%	87%	79%	99%
Outdated	9267	225	0	0	4522	768	0	0	7739
Shortage	136	2010	9543	11290	219	1276	3610	6125	110

Fig. 7. Simulation results on each scenario



	1	2	3	4	5	6	7	8	9
A	18	537	2449	2989	25	471	987	1789	12
B	41	515	2885	340	14	219	1061	1847	12
AB	33	646	1323	1422	147	500	874	978	55
O	44	312	2776	3473	33	86	688	1511	31

Fig. 8. The number of shortages of blood bags based on blood types

4. Discussion and Managerial Insight

4.1. Discussion

According to the simulation result, there were several suggestions to enhance the performance of the blood bank. Scenario 9 was recommended because it had the lowest shortages. The regulations proposed for Scenario 9 include the number of donors in the FLM model that is limited to 50 donors per day, the MUM activity that was held within two days of inter-arrival time, the changing of the inventory target of maximum PRC for each blood type (type-A = 778 bags, type-B = 988 bags, type-AB = 196 bags, and type-O = 1285 bags), and the percentage of PRC production was 82% compared with the number of other products. However, Scenario 9 still had many outdated products, which was 7,739 PRC bags in a year.

From the author's view, the blood bank should consider the number of outdated products in its operational decision-making. That was caused by not less than two reasons: first, increase the donors' loyalty and trust (Grant, 2010). Second, the financial value is caused by the outdated product (Abbasi et al., 2017). Therefore, if the blood bank had a service level target of 99% and reducing outdated products became one of the considerations in decision-making, two alternatives became the best for nominations: Scenario 5 and Scenario 9. Compared to the current system, the percentage of reduction of outdated products is 16.48% and 51.20%, respectively. The regulations would be changed if Scenario 5 were chosen, which were limiting the number of FLM donors to a maximum of 50 donors/day, reviewing the intensity of inter-arrival time of donor activity with MLM based on level session (2 days for high session and one day for medium session), changing the inventory target to become percentile 75 from the maximum number of inventories in the current system.

4.2. Managerial insight

This research highlights that integrating discrete event simulation and the Taguchi method can yield optimal solutions by minimizing product shortages and outdated blood supplies and maximizing order fulfillment. These results provide valuable insights for stakeholders, such as the Indonesian Red Cross, as they underscore the potential of these methodologies to enhance the efficiency and reliability of blood supply management, ultimately improving the overall healthcare system. By adopting this approach, organizations can better align their operations with demand, ensuring that critical resources are used effectively and reducing the risk of waste or shortage. Additionally, this method offers a systematic approach to tackling the complexities of blood supply chain management. Stakeholders can identify critical factors influencing supply chain performance by simulating various scenarios and applying robust statistical techniques. This approach allows them to test different strategies and optimize processes without disrupting operations. The resulting insights can help develop more resilient systems that can adapt to fluctuations in demand and supply, thereby ensuring a steady and reliable flow of blood products.

5. Conclusion

This research succeeded in building a model that could be used to design policies in a blood bank to maintain the sustainability of packed red cell availability. The proposed scenarios could be implemented in a blood bank to reduce the number of shortages, which are Scenario 5, with a 99.36% of order fulfillment rate and Scenario 9 with 99.68% of order fulfillment rate, both scenarios had better performance than the current system that had 99.27% of order fulfillment rate. If the management decision in a blood bank only focused on the shortage reduction, then Scenario 9 would be the priority. Nevertheless, if the blood bank considers the number of outdated products reduced and targets the service level as 99%, then Scenario 5 will be the first option because it significantly reduces the number of outdated products.

Although this model could overcome shortages, several limitations could be the following research opportunities. For example, developing models considering multi variant products, inputting outdated and shortage cost elements, and developing collaboration models among blood banks. Finally, the system could be optimized by using the mathematical model, for example, by using the mixed-integer linear programming model (Mansur et al., 2023a), considering sustainability and environmental, such as waste of blood bags (Purnomo et al., 2022; Vanany, et al. 2024), proposing the logistics process of blood bags, for example by using drone technology (Wangsa et al., 2023; Rezaei Kallaj et al., 2023; Ozkan, 2023), and blood transshipment-allocation and routing problems with others hospital or blood bank (Qamsari et al., 2022; Zhou et al., 2023).

Acknowledgments

The authors confirm that the data supporting the findings of this study are available within the article. For more information, potential readers are requested to contact the corresponding author.

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