Development of a discrete event simulation model for evaluating a blood supply chain in Brazil

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Abstract. The blood supply chain has similar characteristics to the business supply chain. However, the social impact is even greater since inefficient management can lead to death or delay in medical procedures. In this way, making a blood supply network more efficient is extremely important to improve service to the population. However, there are few research involving blood supply chains in Brazil using Operational Research techniques. Therefore, this work seeks to evaluate the supply network of the state of Santa Catarina, managed by the Santa Catarina Blood Network (HEMOSC). To do this, we use data provided by HEMOSC for the period 2011-2020 and focus on analyzing the red blood cell (RBC) component. Discrete event simulation is used to represent the blood supply chain from blood collection to transfusion. The results show that the Chapecó and Joinville blood centers had the highest losses of bags due to expiration dates, and the Joaçaba blood center had the highest shortage rate among the blood centers. The blood network is also facing challenges in meeting the demand for bags requested by reallocation, particularly in the supply of blood type O-. These results suggest the need to analyze alternative scenario configurations in future research.

Keywords: Blood supply chain, Discrete event simulation, Brazil.

1. Introduction

The blood supply chain is similar to traditional supply chains, but it has some peculiarities: blood is a perishable product with several components, each with a different shelf life; blood has a high variability in supply, place and date of collection; demand and supply are random and have stochastic characteristics and this supply chain has high waste rates [1].

The main objective of blood product management is to supply the quantity requested, in the right place and time, because failure to do so may result in patients not being attended to. However, it is not recommended to store large quantities, as there can be a high level of waste and undesirable storage costs due to the short shelf life of the components.

The management of the blood supply chain is complex, so it is necessary to use tools to assist in decision-making. From this perspective, Operations Research has been used in decision support problems through the implementation of appropriate techniques, especially when random behaviors are observed.

Studies in the blood supply chain focus mainly on developing mathematical models that minimize the levels of shortages and waste in the inventory management stage [2] [3] [4] [5] [6] [7]. However, there are also many studies on the processes of collection [8] [9] [10], production [4] [3] [11], and distribution [12] [13] [14] [15]. Studies that address a regional distribution system based on the regionalization of a blood center are also carried out with the aim of achieving economies of scale [16] [17]. In addition to these studies, many works integrate all the processes of blood chains [18] [1] [19] [20] [21] [22] [23] [24] [25] and consider the need for blood in disaster situations [26] [27] [28].

In Brazil, studies on the blood supply chain using operational research are scarce. However, [6] analyzed inventory management and [29] evaluated the increase in external collections. The lack of studies indicates the need for research on these chains in order to understand specific characteristics and analyze alternative configurations.

Studies that consider only one process of the blood supply chain are frequent, however, a recent trend in research is to consider the complete integration of the chain. [30] point out gaps in current studies, highlighting the need for future research related to the integration of blood supply networks. They suggest the use of simulation, optimization, exact algorithms, and metaheuristics as promising methods for future research. [31] also point out the need for studies that integrate approaches in blood supply chains, contemplating more complex networks, characterized by a greater number of stages and facilities.

To fil these research gaps, our work integrates all stages and facilities of the Santa Catarina state blood supply chain using a discrete event simulation model. The main objective is to evaluate the performance of the blood network, focusing at this first study on red blood cells, to analyze the current scenario and identify potential opportunities for improvement in the network performance measures.

The remainder of this paper is organized as follows. The blood supply system in Brazil is summarized in Section 2. Section 3 describes the HEMOSC network and Section 4 presents the modeling of the HEMOSC network. Section 5 presents the results and discussions of the case study conducted in a blood supply chain in Brazil. Finally, the conclusions of this study and perspectives for future research are discussed in Section 6.

2. Blood supply system in Brazil

The blood transfusion service in Brazil began in the 1930s and has evolved over time. During this period, hemotherapy lacked essential regulations and inspections to guarantee the safety of donors and patients. This negligence contributed to a significant number of contaminations in the process [32]. In 1950, Federal Law 1075/50 was enacted, encouraging voluntary donations as a gesture of solidarity, and granting civil servants a day's pay. It is important to note that during this period, paid donations were not yet prohibited [32]. However, the prohibition of paid blood donation in Brazil was established in 1988, through the inclusion of article 199 in the Brazilian Constitution, which fully prohibits any form of commercialization of blood, as well as its blood components and blood derivatives.

The regulation for the technical and administrative configuration model of the Brazilian blood network establishes that the coordination of the national blood network at the federal level is assigned to Anvisa's General Management of Blood, Other Tissues and Organs, which is linked to the Ministry of Health [33]. This regulation also details the structure of the Brazilian blood network and distinguishes between the public and private blood networks, in which coordinator blood centers and regional blood centers are exclusive to the public blood network, while the other services are present in both. In addition, collection and transfusion units, collection units and laboratory screening centers are optional services that depend on the technical and operational capacity of each state. In this sense, although there is this suggestion to optimize the blood supply network, each state has the autonomy to adopt its own particularities [34].

The public network of the Brazilian blood supply chain can be represented by four main stages: collection, production, storage, and distribution. Fig. 1 describes a schematic view of the this network.

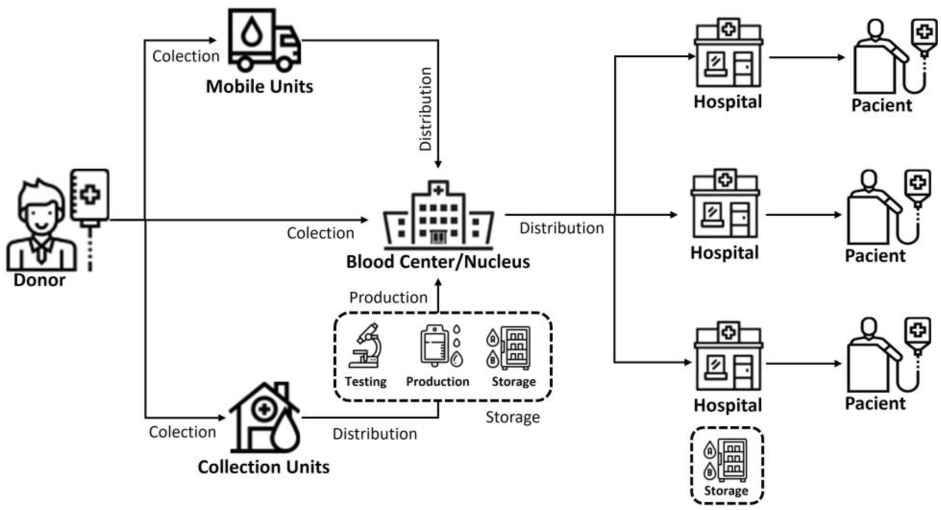

Fig. 1. Overview of the Brazilian public blood supply chain.

Donors can collect from mobile or fixed units. Mobile units use vehicles equipped with the necessary equipment and in compliance with health regulations and are generally used in areas without blood centers or blood banks, or during campaigns to increase the number of blood donations. Donations at fixed units can be made at collection units and in two types of blood centers (the “blood nucleus” and “blood centers”). Collection units, located in densely populated urban areas, seek to increase blood collections, and send the collected blood bags to the nearest blood center. Blood centers perform blood collection, production, storage and distribution for hospitals and transfusion agencies. While blood nucleus serve micro-regions, coordinator and regional blood centers cover macro-regions and carry out additional activities, such as preserving plasma for industry and supporting patients with benign pathologies. Coordinating blood centers, usually located in state capitals, have centralized laboratories for serology and immunohematology testing. Regional blood centers are complementary units and may or may not contain testing laboratories. After production, blood centers wait for blood bags to be in demand before distributing them to hospitals and transfusion agencies. Hospitals keep temporary inventories to guarantee blood supplies for patients. In hospitals without transfusion agencies, pre-transfusion tests and the distribution of blood components are carried out directly by the blood center. It is worth noting, however, that this structure is not the same in all Brazilian states [34].

3. HEMOSC network

The Santa Catarina Blood Network (HEMOSC) is responsible for coordinating all the hemotherapy services that make up the state's public hemotherapy network, which represents 99% of the state’s hemotherapy network [35].

HEMOSC has a coordinating blood center located in the capital, Florianópolis (FLN), as well as six other regional blood centers located in: Lages (LGS), Joaçaba (JBA), Chapecó (CCO), Criciúma (CUA), Joinville (JVE), and Blumenau (BNU). HEMOSC also has two collection units in Jaraguá do Sul (JS) and Tubarão (TU), transfusion agencies and outpatient clinics located within the blood centers (Fig. 2).

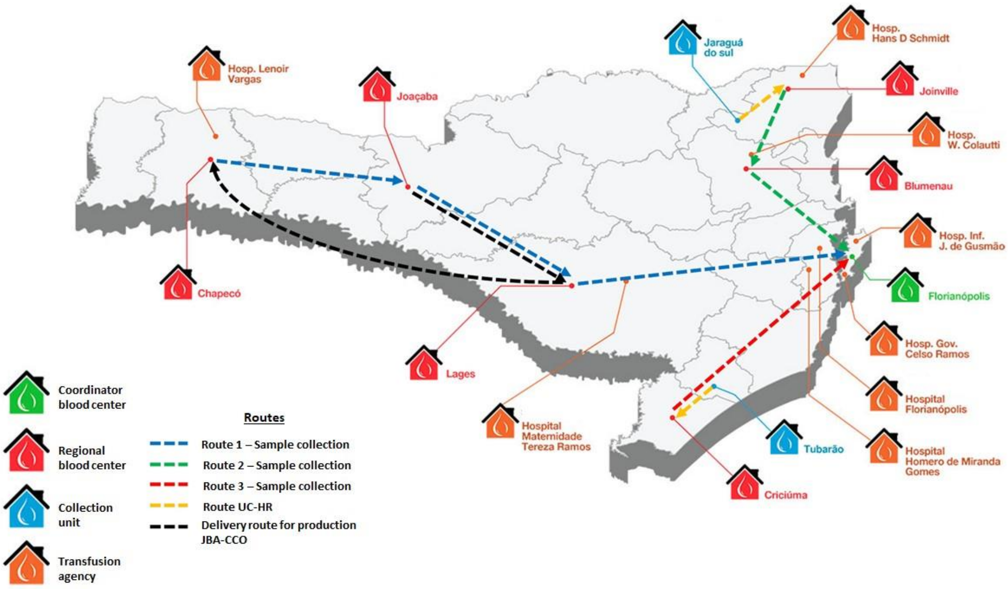

Fig. 2. HEMOSC's supply chain.
Source: Adapted from [35].

Table 1 shows the stages carried out at each unit in the network. The blood center of Joaçaba (JS) is the only one that does not produce its blood bags, while the blood center of Chapecó (CCO) is responsible for the production of its components. Sample testing is carried out exclusively by the FLN blood center, as it is the only blood center that has the necessary equipment to carry out this stage. In this case, the regional blood centers send the blood samples daily to the coordinator blood center using the shipping routes shown in Fig. 2. In addition, the two collection units (JS and TU) send the bags and samples collected to the blood centers to which they are linked, Joinville and Criciúma, respectively, using the routes shown in yellow in Fig. 2.

Table 1. Stages of the HEMOSC according to the network unit.

Stages	**FLN**	**BNU**	**CCO**	**CUA**	**JBA**	**JVE**	**LGS**	**JS**	**TU**
Collection	X	X	X	X	X	X	X	X	X
Testing	X								
Production	X	X	X	X		X	X		
Storage	X	X	X	X	X	X	X		
Distribution	X	X	X	X	X	X	X		

The flow in the blood supply chain begins with the collection of samples and blood bags, which are sent to the testing and production laboratories, respectively. In the testing laboratory, four types of tests are carried out: serological, nucleic acid teste (NAT), immunohematological and hemoglobin S. Once the test results are available, the teams responsible for each test enter the results into the system so that all blood centers have access to these results and can discard the bags that were not approved.

At the same time as testing, blood components are produced. Production begins after the blood bag is cooled and, in this process, the blood bags are converted into its components: red blood cells, fresh frozen plasma, platelet concentrate, and cryoprecipitate. Centrifuges, extractors, and freezers are the main equipment used in this process.

Before being sent to storage, some bags of red blood cell (RBC) undergo special procedures, with the aim of increasing transfusion safety for the patient. These procedures are leukocyte filtration, which occurs in approximately 20% of cases; irradiation, which occurs in approximately 10% of filtered bags; and aliquoting, which occurs in 7% of filtered and irradiated bags. Irradiation only takes place at the coordinator blood center, due to the availability of the necessary equipment.

Bags of red blood cell (RBC) remain in storage until are requested or discarded. The inventory is checked daily to see if there are bags close to expiration date; if so, these bags are discarded. The blood center waits for requests from transfusion agencies, outpatient clinics and hospitals (type A and B) to send blood bags. HEMOSC provides services in two different ways. The first considers the demand from transfusion agencies, outpatient clinics and Type B hospitals, to which HEMOSC supplies blood bags ready to be transfused to patients. The second type of service is for type A hospitals, which manage their own inventories.

HEMOSC manages its network to meet demands, ensuring that inventories are shared between blood centers when necessary. The total inventory by blood type is checked daily, and donors are called for those blood groups that have less than the safety stock. After evaluating the network, the inventory level by blood type is checked at each blood center. If any are below the safety stock level, the redistribution of inventory among blood centers is evaluated, considering transportation costs and logistical difficulties, to ensure that demand is met, and the network inventory is balanced.

These blood components are transported using the routes shown in Fig. 2 by the same outsourced company that transports the samples to the coordinator blood center. In addition to this company, HEMOSC also sends its blood components using bus lines when necessary.

4. Modeling of the HEMOSC network

The HEMOSC system can be modeled to represent the entire blood network. Thus, a conceptual model representing the stages of the network (Fig. 3) was drawn up, divided into five modules: Inventory initialization, Collection, production and storage, Meeting demand, Inventory relocation and Inventory management.

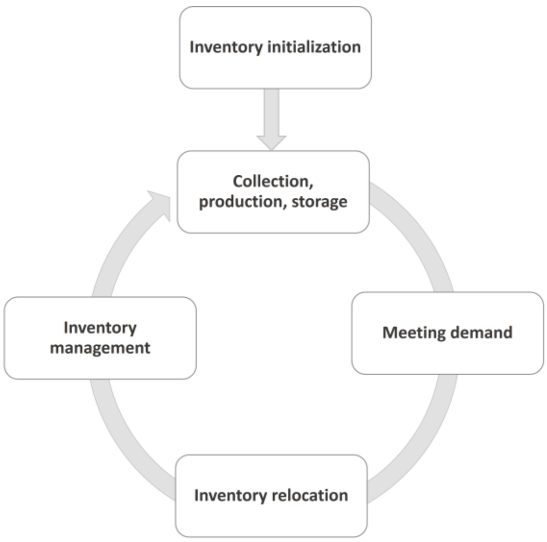

Fig. 3. Stages of the conceptual model.

The Inventory Initialization module initializes the inventory of each blood type in each blood center once when the simulation starts. The Collection, production and storage module then describes the flow, starting with the collection of blood, through to the production of blood components and the testing of samples until the bags of RBC are available in inventory. The Meeting demand module considers the removal of bags from stock in order to meet all or part of type A and B demands. Type A demand is met without considering the possibility of blood substitution when necessary; type B demand takes this possibility into account. In this module, the number of unmet bags (ruptures) and days on which demand was not met is registered.

In the Inventory relocation module, the need to transfer blood bags between the network's blood centers is checked. In this check, the inventory of each blood type at each blood center is compared to the safety stock, considering the possibility of relocating all or part of the requester's needs and the proximity of blood centers (blood centers with the shortest distance are prioritized in relocation). After the Inventory relocation, the Inventory Management module checks the expiration date of each bag at each blood center and counts the losses of the bags that have expired. Subsequently, Collection, production and storage module is carried out again, resulting in a repetition of the described flow.

To develop the conceptual model, some assumptions are adopted: (i) The system starts with the inventory at half of its maximum storage capacity for each blood type in each blood center; (ii) The shelf life of RBC bags is 42 days; (iii) The blood bags collected always arrive at 8:30 a.m. from Monday to Friday and occasionally on Saturdays. We group the arrival of the bags at this time, as information on the time of collection was not available; (iv) Production runs from Monday to Friday and on Saturdays when collections take place, according to the production schedules at each blood center; (v) Demand is met only once a day, at 12:00 am, on each blood center's operating days; (vi) The assessment of the need to relocate inventory is evaluated once a day at 1:00 pm, on each blood center's operating days; (vii) Inventory management is carried out daily at 00:00, on each blood center's operating days. At this moment, the need to dispose of expired blood bags is assessed. It is worth noting that these assumptions are adopted for modeling purposes.

The data analyzed in this study was obtained from multiple sources, including reports from HEMOSC's computerized system, institutional documents, interviews, and questionnaires. This data covers information on blood collection and transfusion between 2011 and 2020, totaling 1,240,759 collection records and 1,054,353 transfusion records. The analyses show that the O+ and A+ blood types presented the highest proportions in both collections and transfusions, reflecting the distribution of the Brazilian population. Statistical tests, including ANOVA, were performed to assess the homogeneity of the collections over years, months, and days of the week, showing significant variation in each temporal aspect at a 95% confidence level. However, when the homogeneity of transfusions over years and months was evaluated, no significant difference was found at a 95% confidence level.

Once the conceptual model was built and the data collected, the computer implementation stage was carried out using the Arena simulation software. After implementing the computer model, each module was checked and then the model was validated. Face-to-face validation was carried out by a HEMOSC professional, ensuring that the logic implemented corresponds to the way the system works. In the operational validation of the model, the paired t-test was used to verify that the results obtained from the simulation were statistically equivalent to the average of the ten-year historical data.

5. Results and discussion

Once the computational model has been verified and validated, the computational experimentation stage is carried out. This phase involves running multiple replications to obtain robust conclusions, considering random inputs and outputs from the system.

In this study, the procedure described by [36] was used. Initially, ten replications were carried out to assess the percentage of losses in the blood network followed by the calculation of the sample's precision. Based on the results and in a confidence level of 5% and a desired accuracy of ± 2.5% of the mean, it was determined that 64 replications would be necessary to guarantee the reliability of the results In addition, a warm-up period of 365 days was established for the system and the values obtained during this period were eliminated.

The simulation carried out used the simulation model developed in Arena software, which took into account all the assumptions described in Section 4, as well as the number of replications defined previously. Thus, the aim is to evaluate the performance of the blood network analyzing its current scenario using the network performance measures.

The weighted average percentage of losses in the blood network obtained by the simulation was 12.75%, in contrast to the average of 5.08% observed in the historical data. This difference may be associated with the assumptions adopted in modeling the problem, since some of the rules for operating the blood network adopted in the modeling may not have been fully applied during the operation of the system.

In the analysis by blood center, the Chapecó and Joinville blood centers had the highest loss rates at 28.72% and 23.43%, respectively. This behavior may be associated with the greater geographical distance between these blood centers and the others. Consequently, when considering the reallocation of inventory in the blood network, these two blood centers are less likely to be selected, contributing to the high loss rates observed in these blood centers.

There is also a variation in the proportion of loss by blood type, with the AB- and AB+ blood types accounting for the highest proportions (Fig. 4). Considering the prevalence in the Brazilian population and the total number of transfusions in the blood network, these blood types are present in a smaller portion of the population, resulting in a lower demand for transfusions due to blood compatibility. However, in absolute terms, the greatest losses occur in types A+, B+ and O+. Furthermore, when analyzing losses by blood type and by blood center, type O- shows low losses by expiration in all blood centers because as a universal donor this blood type is used in situations where the patient's blood type is unknown.

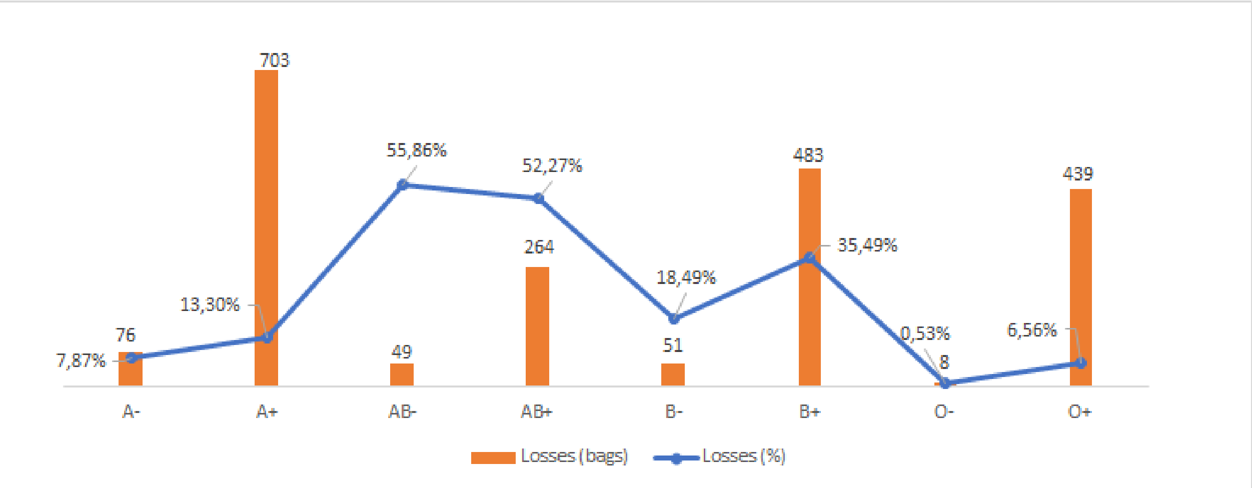

Fig. 4. Losses by blood type.

Another important measure of performance is the percentage of shortages in the blood network. The results of the simulation were 1.18%. As there is no historical data available, this result was compared with the acceptable percentage used by the system, which is 10%. The low percentage of shortages obtained may be related to the use of an exhaustive verification rule in all blood centers during modeling, as there is no systematic rule applicable in all cases of inventory reallocation.

When evaluating the percentage of shortages by blood center, the Joaçaba blood center has the highest rate of not meeting demand (15.48%), which can be explained by the fact that this center is not responsible for processing blood bags. These bags are sent to the Chapecó blood center for processing only twice a week. Regarding the percentage of ruptures by blood group, O+ and A+ had the highest percentage of shortages compared to the other blood groups

(Fig. 5). It is worth noting that these blood groups are the most common in the Brazilian population.

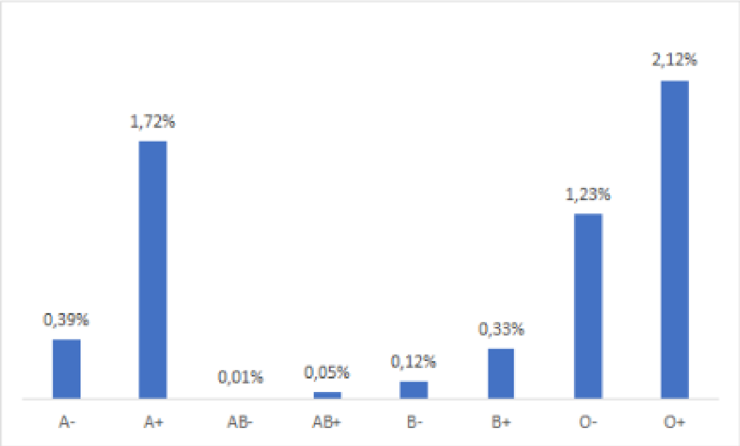

Fig. 5. Shortages by blood type.

The number of bags requested for redistribution that were not filled reflects the inability of the blood network to meet demand, as none of the blood centers in the network were able to provide the requested bags. Our results showed that across the entire blood network only 5.32% of the bags requested for reallocation were not fulfilled. In addition, blood type O- is the most difficult to attend to at all the blood center, as shown in Fig. 6. Blood type O- does not have any other compatible blood type for transfusion, so when evaluating the network, this fact interferes with the availability to meet demands.

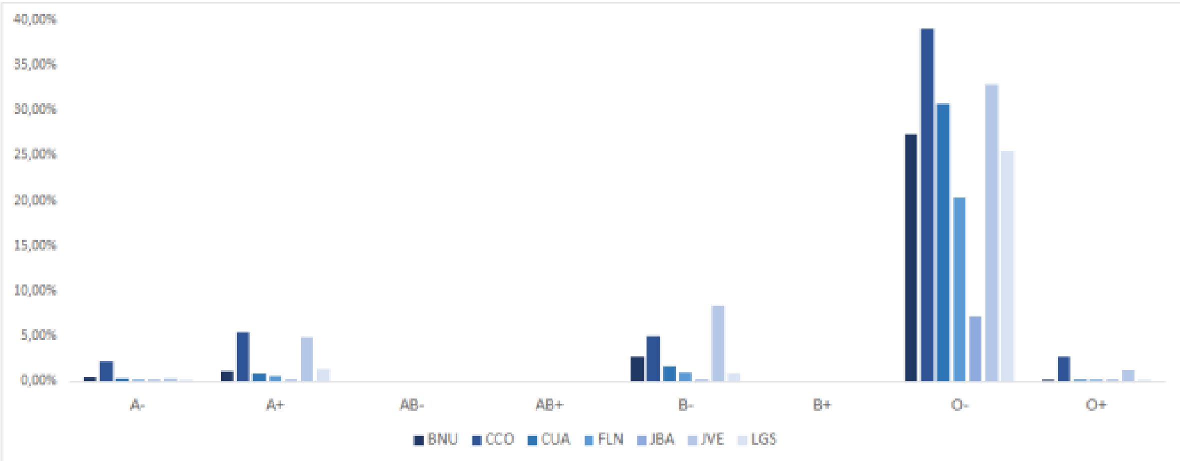

Fig. 6. Percentage of unfilled bags by relocation by blood type and blood center.

Of the bags that were transfused, on average, the bags were used with three days left until the end of their useful life. Fig. 7 shows the remaining shelf life by blood type and blood center. The blood types in which the bags have the shortest time in storage are O+ and A+. These two blood types are the most common in the Brazilian population and consequently have the highest inflow and outflow rates and the shortest time in stock.

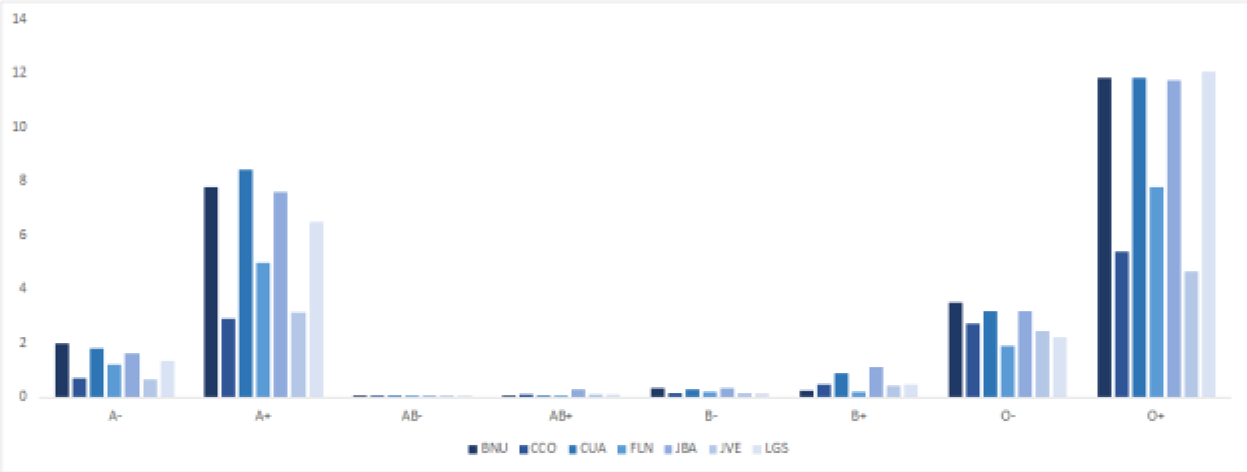

Fig. 7. Remaining shelf life of bags by blood type and blood center (days).

The results obtained show the current behavior of the Santa Catarina blood network, clarifying the strengths and opportunities for improvement in each of the performance measures assessed. In this way, it is possible to identify potential scenarios that can be evaluated in the future using simulation, to find alternatives that can improve the current performance of the blood network.

6. Conclusions and Future Perspectives

Blood is a perishable product of great importance to society that is used in cases of surgery, trauma, cancer, childbirth, and various other procedures that require the replacement of large amounts of blood loss. In this sense, resilient supply chains capable of adapting to changes in both supply and demand are necessary for blood components to be available.

More specifically in the Brazilian context, research analyzing blood supply chains is scarce in the literature, which justifies conducting a case study in a Brazilian setting. Therefore, this study analyzes a blood supply chain, specifically the Santa Catarina state blood network (HEMOSC). This network is responsible for 99% of the state's hemotherapy network, meaning that the conclusions reached for this network can be extrapolated to the entire state of Santa Catarina.

The study used historical data from 2011 to 2020, which was properly processed and analyzed so that it could then be used in the simulation model to represent the behavior of the blood supply network. It was also necessary to obtain information on the management and operation of the network through interviews and questionnaires.

Discrete event simulation was used to represent the HEMOSC's supply network and modeling the arrival of collections, the processing and testing of blood bags and meeting the demand for red blood cell (RBC) at each of the blood centers. The model was validated through comparisons with historical data, debugger, and face-to-face techniques.

The simulation results show that the Chapecó and Joinville blood centers had the highest losses of bags due to expiration dates. In addition, AB- and AB+ blood types have the highest wastage rates, while the lowest rate is observed in O-, probably due to the compatibility between the blood groups.

The shortage rate was less than the acceptable percentage used by the system. However, when analyzing the shortage rates by blood center, the Joaçaba blood center has the highest rate because it center does not produce blood components. Besides, shortage rates by blood type show that O+ and A+ have the highest rates compared to other types.

In addition, the blood network faces challenges in meeting the demand for bags requested by reallocation, as none of the blood centers can meet all the requests. The greatest difficulty is with the blood type O-, which is compatible with all groups, so hospitals prefer to stock this group. Finally, the bags are transfused, in average, three days before their expiration date. Blood types O+ and A+ are the ones that remain in stock for the shortest period, due to their high prevalence in the Brazilian population.

As future work, we intend to analyze scenarios of increase in demand and centralization of production to identify more efficient configurations of the supply network. Deepening studies on blood supply chains in Brazil by incorporating Brazilian specificities into the modeling is also an interesting future direction of work. We also intend to consider the network design problem at the strategic planning level of the blood supply chain management, addressing the location-allocation and size-capacity of blood facilities.

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