Development of models to optimize IPST blood collections

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Abstract

The blood supply chain includes the activities of collecting, processing, inventorying, and distributing blood and its derived components from donors to patients. The ultimate goal of managing the blood supply chain lies with the challenge of balancing storage and wastage of blood units to ensure that blood is available when needed and at the same time guarantee that the number of wasted blood units is minimal. Blood donors play an indispensable role in the blood supply chain as they are the only current source of human blood. But blood donation is a voluntary and unpaid activity, so the supply of donor's blood is irregular. On the other hand, the demand for blood products is highly stochastic. Thus, it is necessary to motivate donors to donate blood to ensure there are no shortages. The present work aims to characterize the Portuguese blood supply chain and propose an optimization model to deal with decisions concerned with blood collection planning, contributing to its improvement. To do so, an integer linear programming approach is developed, establishing the optimal locations for mobile blood collection facilities and the donors' allocation to the collection points with the goal of minimizing the total costs of the blood supply chain. The Instituto Português do Sangue e da Transplantação provided data on historical blood collection records that allowed us to recognize the needs and restrictions involved in the collection of blood, which enabled obtaining a more correct mathematical formulation. The developed model was validated with the provided data, allowing the consequent obtainment of the optimal locations for blood collection facilities.

Keywords: Blood Supply Chain, Blood Donation, Optimization, Integer Programming

1. Introduction

Human blood is a scarce resource. It can only be produced by human beings and currently there are no other products or chemical processes that can be used to generate blood [1]. The blood supply chain (BSC) ensures that blood is available when needed, such as in emergency procedures, surgical operations, or routine medical treatments. As a result, an effective healthcare system should incorporate a well-thought-out plan for managing the BSC. Blood supplies are, in fact, a critical component of the healthcare infrastructure that helps save people's lives in everyday medical situations [2]. A principal characteristic of blood supplies is their perishable nature. By definition, a perishable product has a limited lifetime during which it can be used and after which it should be discarded [3]. Perishability of blood and blood components (red blood cells (RBC), platelets, white blood cells, and plasma) contributes to making even harder the management of the BSC. Given the BSC's complexity and associated costs, its ultimate goal is to provide safe and adequate blood supplies. The BSC includes the activities of collecting, processing and testing, inventorying and distributing blood and its components from donors to patients [4].

Managing the BSC comprises the challenge of balancing storage and wastage of blood units. Due to the perishable nature of blood products, storing an excessive number of blood units could result in outdates, which raises ethical issues as people voluntarily donate blood to help those in need, being its waste viewed with disapproval by society. On the other hand, having shortages may be tragic since lives can be lost if there is no available stock when it is needed, which consequently leads to an increase in the mortality rate. Moreover, the nature of blood is unpredictable, as the supply of donor's blood is irregular and the demand for blood products is highly stochastic [5], making it a challenge to match supply and demand to avoid the wastage and shortage of blood products. Since human lives are at risk, it is evident the importance of a good management of the blood supply chain.

Due to the irregularity of the blood donor's supply, blood is a product that is becoming increasingly limited. In fact, the number of blood donations has dropped, in general, to a new low. So, blood donation must be encouraged in the population to reverse this drop in donation numbers. The management of blood donations is made at the collection stage, the first echelon of the BSC. At this stage, decisions about the optimal locations of blood collection facilities are made to ensure that the blood demands are fulfilled. Thus, considering the importance of the product in question, particularly the fact that it can only be produced by human beings, as well as the challenges in the BSC, blood collection management is a subject that deserves to be studied.

This work is a collaboration with Instituto Português do Sangue e da Transplantação (IPST) with the goal of characterizing the Portuguese blood supply chain and proposing an optimization model for the planning of blood collections, contributing to its improvement.

The contributions offered by this work are twofold. First, there is not much literature focusing on the Portuguese BSC, in fact, there is only one article published in 2020 on this subject [6], and to the best of our knowledge, the collection echelon of the BSC was never studied in Portugal. Thus, this work aims to close this gap. Second, the main goal of this work is to contribute to the efficient management of the BSC. So, a generic mathematical programming model is presented to optimize the planning of the blood collections. An optimization model based on integer programming is proposed to locate mobile blood collection facilities while the total BSC costs are minimized. For the development of the proposed model, data related to blood collection records were first analyzed so that the proposed model correctly describes the collection echelon of the BSC. Afterward, the developed model was validated with historical data from IPST, demonstrating a real-world application of the proposed model.

2. Portuguese blood supply chain

Instituto Português do Sangue e da Transplantação (IPST) is the entity responsible for the regulation and management of the Portuguese BSC. IPST is a central institution with jurisdiction over the entire national territory, with its headquarters in Lisbon, being divided in three areas of operation, each with a main center. They are: (i) Centro de Sangue e Transplantação de Lisboa (CSTL) responsible for the southern region, (ii) Centro de Sangue e Transplantação de Porto (CSTP) that covers the northern region, and (iii) Centro de Sangue e Transplantação de Coimbra (CSTC) that is responsible for the center region.

A simplified version of the Portuguese BSC network is illustrated in figure 1. The Portuguese BSC is similar to the blood supply chain presented by Zahiri et al. [7] and is composed of donors, collection points, main centers, and demand zones. Donors can donate blood at either mobile or fixed collection facilities. The collected blood is then shipped from the collection points to the main centers, where the whole blood is analyzed and separated into different components. The blood components are stored at the main centers until they are needed by demand points.

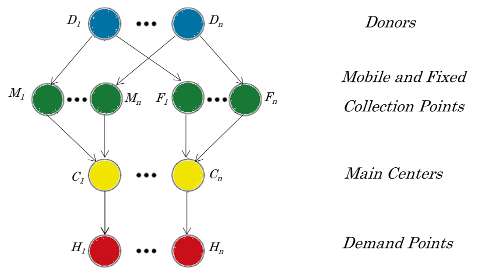


Figure 1: Blood supply chain network in Portugal (adapted from [6]).

Despite being remarkably complex, the Portuguese BSC could be simplified considering only four echelons: Collection, Production, Inventory, and Distribution, as studied by Osorio et al. [4].

The collection stage is the first echelon of the BSC, and its purpose is to obtain the amount of blood and blood products needed to meet demand. This sufficient amount of blood products is achieved by promoting donation in the population. At this stage of the BSC, decisions are made regarding the location and capacity of collection points and which collection methods to use. Follows the production stage, where the whole blood units received at main centers are tested for known diseases and separated into its components (RBC, platelets, and plasma). Next is the inventory stage, where most decisions are related to the definition of inventory policies. Because of blood products' short shelf-life, inventory management of these products is particularly challenging. Inventory management is carried at both the main center and hospital levels, with a minimum inventory level defined based on the capacity to respond to an emergency. Finally, the blood products are distributed from the main centers to the demand points. Typically, hospitals make daily blood requests to the nearest main blood center based on historical data, predictions, and empirical clinical knowledge. The distribution policy of blood units and their components depends on the main centers. However, there is a tendency to follow a FIFO (First In First Out) methodology that assigns first older units to demand points due to the components' perishable nature.

3. Literature review

The study of the BSC started early in the 1960s. In 1982, Nahmias [8] conducted a review on ordering policies and inventory management of perishable products, being this one of the first reviews on the topic. But, it was in 2012 that Beliën and Forcé [5] presented the first complete review of the literature on inventory and supply chain management of blood products. In 2015, Osorio et al. [4] conducted a more recent review of the literature where they evaluate papers according to operational processes and their parameters. Pirabn et al. [9] reviewed and analyzed the most recent literature on blood supply chain published up to 2019. Both authors ([4] and [9]) argued that it is necessary to study the multiple echelons of the supply chain, in order to better manage cooperation and coordination between echelons and minimize the influence of supply and demand uncertainty. Modeling all BSC echelons can help in the identification of bottlenecks as well as the evaluation of policies from a whole-system perspective.

The first-ever study conducted on the Portuguese BSC was published by Araújo et al. [6] in 2020. The authors proposed an integer linear programming (ILP) model for both tactical and operational planning of the BSC while minimizing costs, waste, and dependence on other regions. This work studied the flow of blood from the collection, production, and consumption at demand points. The model provided a solution with lower waste and purchase values, demonstrating there is room for improvement in these areas. Zahiri et al. [7] proposed a mixed integer linear programming (MILP) model to make strategic and tactical decisions for a blood collection system. The proposed model determines the optimal number and locations of main and temporary blood bank facilities over the planning horizon, and it assigns donors to the established facilities with the goal of minimizing total costs. The purpose of the study conducted by Ramezanian and Behboodi [10] was to increase utility and motivate donors to donate blood. This research presents a MILP model that minimizes the BSC costs while determining optimal locations for blood facilities and allocating donors to those facilities based on a blood donors' utility function. The most important result obtained by the proposed model was that blood donors are assigned to near facilities in order to walk or drive shorter distances. Zahiri and Pishvaee [11] presented a location-allocation bi-objective MILP with the aim of minimizing the total blood supply chain costs as well as the shortages. Alfonso and Xie [12] and Alfonso et al. [13] presented mathematical models for blood collection planning. In the former study [12], the objective is to determine weeks of collection at each mobile site to ensure the regional self-sufficiency of the blood supply over a yearly planning horizon. The second paper [13] incorporates detailed weekly planning to determine days of collections at each mobile site for the same self-sufficiency objective. In both papers, two MILP models are proposed, and their efficiency is assessed with field data from the French Blood Service. Hamdan and Diabat [14] presented a two-stage stochastic programming model for a red blood cells supply chain that simultaneously accounts for the production, inventory, and location decisions under demand uncertainty. The proposed model focuses on reducing the number of outdates, the system costs, and blood delivery time.

Based on the studied literature and considering that the problem to be studied concerns the collection echelon of the BSC, the methodology adopted for the development of this work is an optimization model based on integer programming. The different blood components will not be considered in the proposed model, as the focus of the work is the whole blood collected in the collection stage. Thus, red blood cell substitution is a characteristic not addressed. The perishable nature of blood is also not considered due to the added complexity of the model.

4. Model description

In the BSC network, several decisions must be accounted for on all three levels: strategic, tactical, and operational. The problems and decisions here addressed are comprised in the first (strategic) hierarchical level and are associated with the planning level, as the focus of this work is the collection of blood. The underlying problem is therefore determining where the mobile blood collection facilities should be located and when they should be moved to guarantee that the blood demands are fulfilled while BSC total costs are minimized. To do so, an integer programming (IP) approach is adopted.

The supply chain network considered in this study comprises blood donor zones, blood collection facilities - permanent and mobile -, and main blood centers. Donors can donate blood at either permanent or mobile blood facilities within a certain geographical distance, but not at main blood centers. The location of mobile blood facilities can vary over the planning horizon, while the location of permanent blood facilities must be settled at the beginning of the planning horizon and should not change during the planning horizon. The blood collected at blood facilities, both permanent and mobile, is shipped to main blood centers, at the end of each period. The main blood centers process the blood to obtain its derivative products and perform the necessary tests to determine blood type and test for known diseases. The blood components are stored at specific conditions until they are shipped to hospitals and health centers according to their demand needs. The flow of blood between the main centers and the demand zones is not considered in the developed model, as this flow is not the main purpose of this work, and data regarding this flow was not available nor related to the blood consumption at the demand zones. Thus, the three last echelons of the BSC, namely production, inventory, and distribution, were not considered in the model formulated below.

The objective is to minimize the total supply chain costs, including the cost of relocating mobile blood facilities in consecutive periods and transportation costs, while ensuring that the blood demands are fulfilled. At each period of the planning horizon, the proposed model aims to determine the number of needed mobile blood facilities, the optimal location of those facilities, the allocation of donors to the established blood facilities, and the amount of blood required for collection at each facility.

Moreover, the following assumptions are considered in the proposed model: (i) The BSC is single product (whole blood); (ii) The location of main centers and permanent blood collection facilities is given; (iii) The number of donor groups is the number of counties in Portugal and the center point of each county is used for distance calculations; (iv) The storage capacity of collection facilities and main centers is limited; (v) All mobile blood collection facilities have the same storage capacity, which is smaller than the storage capacity of permanent collection facilities, which in turn is smaller than the main blood centers capacity; (vi) All mobile blood collection facilities are initially located at the main centers.

5. Model formulation

5.1. Data

This section describes the data that was made available by the IPST, allowing the formulation of the model presented below.

The data provided corresponds to the period between January 1990 to August 2020 and refers to blood donations registered by the IPST in this period for all main centers. Regarding the information about the donation, the following is registered: the place of the collection identified by district, county, and postal code, the date, the type of collection facility - whether it is a mobile unit or a fixed station -, the facility identification number, the main center that is associated with that collection point, the distance (in kilometers) from the main center to the collection site, the type of collection - whether it is apheresis or not -, the number of expected donors and those who appeared, among others. The locations for establishing mobile blood collection facilities were obtained from the data and include places such as universities, fire stations, churches, or companies, among others. Hospitals are considered permanent blood collection facilities, but they do not exist in all counties of Portugal. Moreover, from the existing hospitals, not all have blood collection services, which is one of the reasons contributing to the establishment of mobile blood collection facilities across the country. From the data provided, the values for the distances between the collection points, both mobile and permanent, and the main centers were obtained.

5.2. Mathematical formulation

In this section, the mathematical formulation of the integer programming model is presented for the problem described above. The sets, parameters, and decision variables used to formulate the proposed model are summarized in table 1. Parameters are constant values and, for notation clarity, lower-case letters are used to represent them and capital letters to represent decision variables.

The objective function (1) minimizes the total cost of moving mobile blood facilities in each period, and the cost of delivering blood from mobile blood collection facilities and permanent collection facilities to main blood centers during the planning horizon.

$$\min \sum_{j_1,j_2,t} c_{j_1,j_2} Y_{j_1,j_2,t} + \sum_{j,k,t} c_{jk} Q_{jkt} + \sum_{l,k,t} c_{lk} Q_{lkt} \tag{1}$$

Constraints (2) to (4) refer to the movement of mobile blood collection facilities in each period. Constraints (2) ensure that at most one mobile blood facility can be moved to each candidate location j_2 in each period. Constraints (3) ensure that a mobile blood facility can be moved to at most one candidate location in each period. Constraints (4) ensure that a mobile blood facility can only be moved to another location (from j_1 to j_2), if in the previous period the facility was relocated to that location (from j to j_1).

$$\sum_{j_1} Y_{j_1,j_2,t} \leq 1, \quad \forall j_2, t \tag{2}$$

$$\sum_{j_2} Y_{j_1,j_2,t} \leq 1, \quad \forall j_1, t \tag{3}$$

$$\sum_{j_2} Y_{j_1,j_2,t} \leq \sum_{j} Y_{j,j_1,t-1}, \quad \forall j_1, t \geq 2 \tag{4}$$

Each main center, located at k, has a limited number of mobile blood facilities that can be moved in each period, which is assured by constraints (5).

$$\sum_{j_2} Y_{j_1,j_2,t} \leq P_k, \quad \forall j_1 = k, t \tag{5}$$

Constraints (6) ensure the minimal interval of d days between two consecutive mobile collections at the same location.

$$\sum_{j_1,t'=t}^{t+d} Y_{j_1,j_2,t'} \leq 1, \quad \forall j_2, t \leq |T| - d \tag{6}$$

Table 1: Sets, parameters and decision variables of the mathematical model.

Sets	
I	set of donor groups ($i = 1, ..., I$)
J	set of possible locations for mobile blood facilities ($j = 1, ..., J$ and $j_1,\ j_2 \in$ J)
K	set of main blood centers ($k = 1, ..., K$)
L	set of permanent blood facilities ($l = 1, ..., L$)
T	set of time periods ($t = 1, ..., T$)
W	set of week periods ($w = 1, ..., W$)
Parameters	
Uncertain parameters	
c_{j_1,j_2}	cost of moving a mobile blood facility from location j_1 to j_2
c_{jk}	transportation cost per unit of blood between the mobile facility located at j and the main blood center located at k
c_{lk}	transportation cost per unit of blood between the permanent facility located at l and the main blood center located at k
r_{ij}	distance between donor group i and the candidate mobile blood facility located at j
w_{il}	distance between donor group i and the permanent blood facility located at l
q_{jk}	distance between the candidate mobile facility located at j and the main blood center located at k
q_{lk}	distance between the permanent blood facility located at l and the main blood center located at k
v_{it}	maximum donation capacity of donor group i in period t
D_t	blood demand (in blood pack units) in period t
Deterministic parameters	
P_k	number of mobile blood facilities in the main center located at k
r_0	maximum coverage radius of mobile blood facilities; if $r_{ij} \leq r_0$, i is covered by j
w_0	maximum coverage radius of permanent blood facilities; if $w_{il} \leq w_0$, i is covered by l
q_0	maximum coverage radius of main blood centers; if $(q_{jk} \vee q_{lk}) \leq q_0$, j or l, respectively, is covered by k
v	maximum transportation capacity (in blood pack units)
v_k	maximum storage capacity (in blood pack units) of the main center located at k
v_l	maximum storage capacity (in blood pack units) of the permanent facility located at l
M	maximum number of collected blood pack units in each period
N	maximum number of allowed mobile blood facilities in weekdays
N'	maximum number of allowed mobile blood facilities in weekend days
A_{kw}	average number of blood pack units for the main center located at k in week w
ω	minimum coverage percentage of total collected blood pack units in each week
Decision Variables	
$Y_{j_1,j_2,t}$	a binary variable equal to 1 if a mobile blood facility is located at j_1 in period $t-1$ and moves to location j_2 in period t, and 0 otherwise
Z_{jt}	a binary variable equal to 1 if a mobile blood facility is located at location j in period t, and 0 otherwise
X_{ijt}	a binary variable equal to 1 if donor group i is assigned to a mobile blood facility located at j in period t, and 0 otherwise
X_{ilt}	a binary variable equal to 1 if donor group i is assigned to a permanent facility located at l in period t, and 0 otherwie
X_{jkt}	a binary variable equal to 1 if a mobile blood facility located at j is assigned to a main blood center located at k in period t, and 0 otherwise
X_{lkt}	a binary variable equal to 1 if a permanent blood facility located at l is assigned to a main blood center located at k in period t, and 0 otherwise
Q_{ijt}	the blood volume (in blood pack units) donated by donor group i in a mobile facility located at j in period t
Q_{ilt}	the blood volume (in blood pack units) donated by donor group i in a permanent facility located at l in period t
Q_{jkt}	the blood volume (in blood pack units) shipped from a mobile blood facility located at j to a main center located at k in period t
Q_{lkt}	the blood volume (in blood pack units) shipped from a permanent facility located at l to a main center located at k in period t

Constraints (7) to (9) define, respectively, the maximum storage capacity of each mobile blood facility, each permanent facility, and the maximum capacity of main blood centers.

$$\sum_i Q_{ijt} \leq v, \quad \forall j, t \tag{7}$$

$$\sum_i Q_{ilt} \leq v_l, \quad \forall l, t \tag{8}$$

$$\sum_j Q_{jkt} + \sum_l Q_{lkt} \leq v_k, \quad \forall k, t \tag{9}$$

Constraints (10) restrict the blood volume donated by each donor group in each period.

$$\sum_j Q_{ijt} + \sum_l Q_{ilt} \leq v_{it}, \quad \forall i, t \tag{10}$$

Constraints (11) and (12) ensure that all blood volume collected at each mobile blood facility and at each permanent facility, respectively, is delivered to main centers in each period.

$$\sum_i Q_{ijt} = \sum_k Q_{jkt}, \quad \forall j, t \tag{11}$$

$$\sum_i Q_{ilt} = \sum_k Q_{lkt}, \quad \forall l, t \tag{12}$$

Constraints (13) to (16) guarantee the coverage restrictions between mobile and permanent facilities and main centers, between donors and mobile facilities, and donors and permanent facilities. Constraints (13) assure that a mobile blood facility located at j can be assigned to the main center located at k, if it is covered by the main facility's coverage radius ($q_{jk} \leq q_0$) and there is a mobile blood facility in location j. The same applies to constraints (14) considering permanent facilities and main centers. Constraints (15) ensure that a group of donors i can only be assigned to a mobile blood facility located at j if there is a mobile blood facility in that location and the donor is within the coverage radius ($r_{ij} \leq r_0$). The same applies to constraints (16) between donors and permanent facilities.

$$X_{jkt} q_{jk} \leq q_0 Z_{jt}, \quad \forall j, k, t \tag{13}$$

$$X_{lkt} q_{lk} \leq q_0, \quad \forall l, k, t \tag{14}$$

$$X_{ijt} r_{ij} \leq r_0 Z_{jt}, \quad \forall i, j, t \tag{15}$$

$$X_{ilt} w_{il} \leq w_0, \quad \forall i, l, t \tag{16}$$

Constraints (17) and (18) prevent collecting blood at mobile blood facilities and permanent facilities, respectively, from donors not assigned to those facilities. Constraints (19) ensure that the donated blood cannot be shipped from a mobile blood facility to a main center which is not assigned to it. The same applies to constraints (20) considering permanent facilities and main centers.

$$Q_{ijt} \leq v X_{ijt}, \quad \forall i, j, t \tag{17}$$

$$Q_{ilt} \leq v X_{ilt}, \quad \forall i, l, t \tag{18}$$

$$Q_{jkt} \leq v X_{jkt}, \quad \forall j, k, t \tag{19}$$

$$Q_{lkt} \leq v X_{lkt}, \quad \forall l, k, t \tag{20}$$

Constraints (21) assure that every group of donors, in each period, can only donate blood to either a mobile blood facility or a permanent facility, but not to both. Also, it guarantees that every group of donors only donate blood to a single location, i.e., a group of donors can not donate blood in two permanent facilities nor two mobile blood facilities.

$$\sum_j X_{ijt} + \sum_l X_{ilt} \leq 1, \quad \forall i, t \tag{21}$$

Constraints (22) and (23) guarantee that in each period each blood collection facility, either mobile or permanent, respectively, is not assigned to more than one main center. Moreover, blood can only be delivered from a mobile blood facility from where it is located, which is guaranteed by constraints (24).

$$\sum_k X_{jkt} \leq 1, \quad \forall j, t \tag{22}$$

$$\sum_k X_{lkt} \leq 1, \quad \forall l, t \tag{23}$$

$$X_{jkt} \leq Z_{jt}, \quad \forall j, k, t \tag{24}$$

Constraints (25) assure that in each period the total demand should be satisfied.

$$\sum_{j,k} Q_{jkt} + \sum_{l,k} Q_{lkt} \geq D_t, \quad \forall t \tag{25}$$

Constraints (26) and (27) define the domains of the decision variables.

$$Y_{j_1, j_2, t}, Z_{lt}, X_{ijt}, X_{ilt}, X_{jkt}, X_{lkt} \in \{0, 1\}, \forall i, j, k, t \tag{26}$$

$$Q_{ijt}, Q_{ilt}, Q_{jkt}, Q_{lkt} \geq 0, \quad \forall i, j, k, t \tag{27}$$

The model built by equations (1) to (27) is of type Mixed Integer Programming (MIP) and models a generic blood collection planning problem with a set of donor groups, collection points, and main centers, with the goal of minimizing the total BSC costs, where all collected blood must be shipped to the main centers to ensure all demand is satisfied. This MIP model is referred to as the core model in the following sections.

Based on the data made available by the IPST, it was necessary to include new concepts in the proposed model so that it better represents the Portuguese BSC. These new concepts will be discussed in the following section.

5.3. Additional constraints

For the model built by equations (1) to (27) presented in the previous section to better model the Portuguese scenario, new concepts had to be introduced along with their respective model parameters. They are the maximum daily number of collected blood pack units, M, and a maximum number of allowed mobile blood facilities that can be moved in each period, N and N'. Consequently, new constraints had to be added to the MIP base model presented in the previous section, which will be detailed below. The need for adding these constraints is explained in more detail further ahead.

Constraints (28) ensure that the number of blood pack units collected in each period does not exceed the maximum allowed value.

$$\sum_{i,j} Q_{ijt} + \sum_{i,l} Q_{ilt} \leq M, \quad \forall t \tag{28}$$

Constraints (29) and (30) guarantee that the model does not move more mobile blood collection facilities than the ones that are allowed. Constraints (29) are responsible for defining this limit for the weekdays, from Monday to Friday, and constraints (30) for the weekend days, Saturday and Sunday.

$$\sum_{j_1} \sum_{t'=t-6}^{t-2} Y_{j,j_1,t'} \leq N, \quad \forall k, j = k, t \geq 7 \tag{29}$$

$$\sum_{j_1} \sum_{t'=t-2}^{t} Y_{j,j_1,t'} \leq N', \quad \forall k, j = k, t \geq 7 \tag{30}$$

Constraints (31) ensure the minimal interval of d' days between two consecutive donations of the same donor group.

$$\sum_{t'=t}^{t+d'} \sum_{j} X_{ijt'} \leq 1, \quad \forall i, t \leq |T| - d' \tag{31}$$

Constraints (32) assure that in each week at least ω-percent of the average number of collected blood units should be satisfied. These constraints replace the constraints (25) of the base model.

$$\sum_{t'=t-6}^{t} \left[\sum_{j} Q_{jkt'} + \sum_{l} Q_{lkt'} \right] \geq \omega A_{kw}, \ \forall k, t\%7 = 0, w \tag{32}$$

This new model built by equations (1)-(24) and (26)-(32) is referred to as the model considering all constraints in the following sections and models a generic blood collection planning problem adapted to the reality of the Portuguese BSC.

6. Experimental evaluation

The proposed model is applied to the provided data, obtaining the following results.

To prove the validity of the core model, daily demand data is required. However, information regarding blood consumption in hospitals was not available as hospitals and main centers do not keep detailed records of this information. So, in order to obtain reliable and realistic results, and considering that the focus of this work is the collection echelon of the BSC, constraints (25) of the core model that considered daily consumption values were replaced by constraints (32) that take into account the number of units of blood collected per week. Through the available data, more precisely 2019 data, it was possible to calculate the average number of donated blood units. To guarantee that the model is accurate, the average was calculated separately for each of the main centers. Thus, the model tries to collect at least ω-percent of the blood units collected per week in 2019 instead of trying to fulfill the blood demands, which is expressed by constraints (32).

6.1. Wastage

When analyzing the core model's solution, it was noticed that there were days when too many units of blood were collected and others when no units were collected, with no uniform distribution of blood units collected over the days. There were even weeks in which the average number of blood units equivalent to a week was collected in a single day. Due to the perishable nature of blood and the fact that blood consumption does not always keep up with donation levels, collecting too many units of blood at once can lead to its waste. To try to prevent the wastage of blood units, it was imposed a maximum number of blood pack units that can be collected per day, forcing the model to not collect more units than the maximum allowed. Constraints (28) enforce this limit.

The obtained results demonstrate that with the addition of these constraints there are more days when units of blood are collected, and these are collected in smaller amounts each day. Collecting a smaller number of units each day prevents the wastage of blood since each blood pack unit after being collected has a limited period during which it can be used and after which it should be discarded.

In addition to the maximum daily number of collected blood pack units imposed, another way to try to prevent the wastage of blood units is to limit the number of mobile blood facilities that can be moved to collection points in each period. Adding this limit is a way of preventing having too many collection sessions on the same day, and consequently, avoiding collecting too many units of blood at once, which can end up wasted.

Controlling the number of mobile blood facilities that can be moved is also a measure of controlling the number of professionals needed in each collection session. For each blood collection session, it is necessary to move a multidisciplinary team to carry out the collection. So, by limiting the number of collection sessions, it is possible to ensure that the limited number of human resources is not exceeded, making the model more reliable. As the number of collection sessions is different for the weekdays and the weekend days, two constraints were added to the model to assure it is trustworthy, constraints (29) and (30), respectively for weekdays and weekend days.

These limits discussed above aim to ensure that the number of wasted blood units is as minimal as possible, as the model tries not to collect units in excess.

6.2. Geographic dispersion

By analyzing the solution obtained for each main center about the locations chosen by the model after adding the constraints mentioned above, it was noticed that the blood collections always took place in the same municipalities, particularly in those located closer to the main center. This happened mainly due to the following factors: (1) the model prefers locations that are at a shorter distance from the main center since the transportation costs are lower once these are obtained through the distance between the main center and the collection points, which is in line with the goal of cost minimization; (2) as donors are considered by groups and not individually, no restriction prevented the same donor group from donating blood whenever collections were organized in a specific county, even if the collections were on consecutive days.

Figure 2a shows the geographic distribution of CSTL collection points after running the core model with the constraints discussed above. It can be seen there is no considerable geographic dispersion, as all blood collection sessions were carried out in neighboring locations. Despite existing a restriction that guarantees that there is a minimum interval of d days between collections, what happens is that, in each county, there are different mobile blood collection units, and each one has an identification number associated, being this restriction applied to each identifier and not the county itself. Thus the model always selects units from the closest counties once they are at a shorter distance from the main center.

To force the geographic dispersion of collection points, constraints (31) have been added to the model. These constraints impose a minimum day interval between donations from the same donor group enforcing the model to choose different locations to reach its goals since the donor groups are allocated

(a) Result for the core model. **(b)** Result for the model after adding constraints (31).

Figure 2: The result of the model for launching collection facilities for the CSTL.

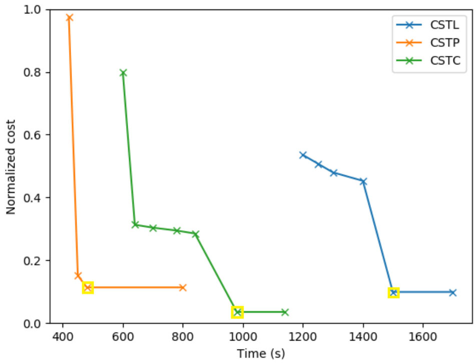
based on the Portuguese counties. Figure 2b shows the geographic dispersion of CSTL collection points after running the model with constraints (31). Now, with the imposed time interval between donations of the same donor group, the model has to choose locations that are at a longer distance from the main center because it is forced to choose more locations to achieve its goals since each donor group donates less often.

The addition of the constraints discussed above aims to ensure the model's reliability while gives the possibility for all donor groups to donate blood easily, as donors do not have to travel large distances to donate blood once the model forces the movement of mobile units to different locations.

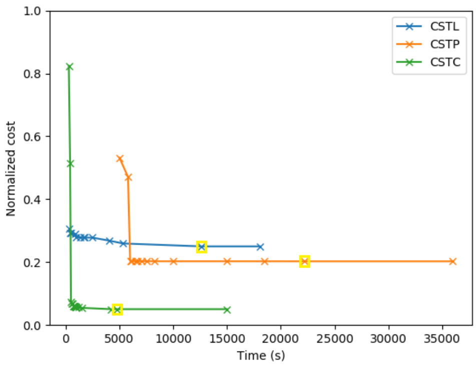
6.3. Allocation

One important aspect to analyze is the allocation of donor groups to the collection points, both mobile and permanent. To establish these allocations, it was considered the travelled distance (in kilometers).

When analyzing the obtained model's solution, it was noticed that the model never allocates some donor groups to any collection facility, meaning the model never moves mobile units to those counties, which can be explained by its goal of cost minimization since the higher the number of mobile units moved, the higher the costs. On the other hand, the donor groups are assigned to the nearest facilities, which is in line with the donors' goal of walking or driving shorter distances, as studied by Ramezanian and Behboodi [10]. When analyzing the locations chosen by the model, it was visible the model's preference to move mobile units to furthest away locations, despite increasing costs, as the donor groups closer to the permanent points donate there. So, the donor groups that are closer to the fixed points are allocated to them. This allocation is coherent with the model's goal of cost minimization since permanent facilities have lower costs than mobile units. The costs are lower because there is no need to move vans or multidisciplinary teams to the collection points, and the distance between the fixed points and the main centers is smaller than for most mobile units. The model tries to keep the number



(a) Results for the core model



(b) Results for the model with all constraints.

Figure 3: Running time and cost of the model.

of mobile units that are moved to a minimum.

6.4. Time and cost analysis

Figures 3a and 3b show the relationship between the time model took to find a solution for each main center and its cost, respectively, for the core model and the model with all constraints.

By analyzing figure 3a, it can be seen that the model finds multiple solutions for each main center, taking more time to find an optimal solution for the CSTL than for the CSTC or CSTP. This difference can be explained by the fact that, for the CSTL, there are more mobile blood facilities than for the CSTC or CSTP. There is, therefore, more choice about where to establish the collections points, which increases the size of the problem, and consequently, increases the time the model takes to find the best places for the collection points. Comparing the costs of the optimal solution of the three main centers, CSTC has lower costs than CSTL and CSTP because it is the main center that moves fewer mobile blood facilities. This result can be explained as the CSTC is the main center with the lowest average number of collected blood units in 2019. Regarding the costs of the optimal solutions for the CSTL and CSTP, it can be seen they are similar, meaning that the model's behavior for these two main centers is identical, which makes sense as both Lisboa and Porto are two large urban centers.

The model considering all constraints imposes more boundaries and, consequently, becomes more complex to solve. Thus, when comparing figures 3a and 3b, it can be seen that the model with all constraints, presented in figure 3b, takes more time to run for all main centers than the core model, showed in figure 3a, as would be expected.

Regarding the costs of the optimal solution of the three main centers, it can be seen that for the CSTL and CSTP, the cost is higher for the model that considers all constraints, shown in figure 3b, than for the core model presented in figure 3a. This higher cost can be justified as to solve the model considering all constraints there is a need to move more mobile blood collection facilities than to solve the core model.

6.5. Cost function analysis

For each main center, a comparison is made between the obtained results and the available data for the year 2019 about the type of collection facilities where most blood donations occurred. Based on the provided data and the obtained results, some statistics were obtained regarding where had been made more donations in the time horizon considered. This analysis is made with the goal of demonstrating the impact of the objective function on the results obtained, whose goal is to minimize the total costs of the BSC.

Here, only the results for the CSTL are presented but the model behavior was identical for the remaining main centers. Figure 4 compares the available data with the obtained results for the CSTL regarding the type of collection facilities used. In the first six months of 2019, 31 060 blood donations were registered by the IPST, of which 18 402 occurred in mobile units, representing 59.34% of the total registered donations and 40.66% in permanent facilities. By analyzing the developed model's solution in figure 4, it can be seen that the number of donations is smaller than the number of registered donations by IPST. This difference is justified because, for computational reasons, the considered total number of collected blood units had to be smaller than the total number of donations registered by IPST. Considering the total number of donations with the model, 34.77% occurred in mobile facilities and 65.23% in permanent points. When comparing the obtained results with the ones acquired from the data, it can be seen that the results are not similar once, with the model, there are more donations in the fixed points than in mobile units, and with the data, it is the opposite. This behavior is related to the model's goal of cost minimization. To keep the model's costs to a minimum, the model tries to move as few mobile blood collection units as possible, preferring to

Figure 4: Comparison between the data for 2019 and the obtained results for the CSTL.

allocate the donors to permanent facilities rather than mobile units where the costs are higher.

The demonstrated difference in the results between the IPST data and the developed model can be explained by the model's goal of cost minimization. Although the obtained model results are not very close to the IPST data, the truth is that these results can be a relevant indicator for future planning of the blood collection sessions, as they demonstrate that the total BSC costs can be lower when prioritizing blood collections at the existing fixed blood collection points.

7. Conclusions

The analyzes carried out demonstrated that the model can be promising in the future planning of blood collections by pointing out some relevant indicators. An important aspect to take from this study is the room for improvement in the organization of the collection sessions, as the model's results show that costs can be lower when prioritizing blood collections at existing fixed collection points. Another relevant aspect demonstrated by the model's results is that the donors are allocated to the nearest blood collection facilities to walk or drive shorter distances. In fact, these two aspects can be related to each other, and the encouragement of blood donations at fixed collection points through awareness campaigns carried out in local hospitals can be an asset for the IPST. Another recommendation to the IPST would be to consider the possibility of having more fixed collection points spread across the country. Consequently, more donor groups would be able to donate blood easily once there are always more distant places where the model does not move mobile units due to their higher costs. Also, the Portuguese BSC total costs could be lower as it would be necessary to move fewer mobile blood collection units. In conclusion, the developed approach shows promise in proposing a better blood collection planning, however, it would require further validation by comparing the results with more accurate data.

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