

Towards an Optimized and Socio-Economic Blood Supply Chain Network



Ana Torrado and Ana Paula Barbosa-Póvoa

Abstract In this work, a two-stage allocation model involving healthcare facilities with blood services is developed to design the Blood Supply Chain (BSC), where economic and social aspects were considered. In the first stage, the design of a BSC network is considered to support blood supply and demand, and the geographical distribution for donors/patients according to the location of the healthcare facilities. Based on the first stage results, the product flow among blood centers (BC) and hospitals, as well as the minimization of costs are studied in the second stage. Economic aspects were considered through cost minimization while the social aspect was explored by allocating donors/patients to the closest facilities. Exploratory experiments are conducted using Portuguese National Health Services data to test the model's applicability. From this, it was concluded that there is a need for additional blood services for the collection phase, and a large number of healthcare facilities with non-licensed blood services should be licensed in the considered SC network. Regarding donors, the allocation costs represent 90% of the total costs, meaning that more types of collection facilities are needed in the context of our study. For patients, adding healthcare facilities with licensed blood services represents the higher costs (78%). Concerning the product flow optimization, the production costs correspond to 82%. Additionally, the model allows the improvement of the distribution of the hospitals according to the existing BCs at reduced costs.

Keywords Blood supply chain · Socio-Economic · MILP · Optimization

A. Torrado (✉) · A. P. Barbosa-Póvoa
Center for Management Studies, Instituto Superior Técnico, University of Lisbon, Lisbon,
Portugal
e-mail: ana.torrado@tecnico.ulisboa.pt

A. P. Barbosa-Póvoa
e-mail: apovoa@tecnico.ulisboa.pt

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193

1 Introduction

Blood is scarce and has a prominent role in human life. As the availability of blood products through healthcare services is often a matter of life or death to the patient, blood shortages or outdated blood products should not occur when managing the Blood Supply Chain (BSC). As a result, managing the Supply Chain (SC) decisions to deal with minimum unmet demand levels is crucial [1]. The BSC network plays an important role in the healthcare systems all over the world [2], presenting different activities and services, such as blood collection, testing, processing, inventory, distribution, and transfusion in hospitals [3, 4]. As a service-oriented SC, BSC includes critical features—perishability, the freshness of transfused blood, multiplicity and respective lifetimes of blood products, fluctuations in blood supply and demand, and blood compatibility among donors and patients—involving several cooperating stakeholders [5]. These features increase the complexity of such systems and consequently, it is important to design and plan accordingly to them [6, 7]. During the last years, Blood Supply Chain Network Design (BSCND) and planning assumed a significant role in promoting the increased performance of these SCs while capturing the researcher’s attention [6, 8, 9]. BSCND focuses on designing the SC’s network concerning the system’s entities (e.g., number of collection facilities, storage facilities, transportation vehicles) and the respective improvement of the processes involved. Additionally, reaching an efficient BSCND is a strategy to follow, that should contribute to refining the SC performance through the coordination of the different processes to guarantee the optimal match between blood supply and demand [10, 11]. Any improvement in the management of these SCs will positively impact the supply of blood as a life-saving product [2]. The location-allocation decisions involved (e.g., related to the number of infrastructures and respective allocation of donors to the collection infrastructures) are one example of possible improvement which can contribute to the achievement of an optimal BSCND. An optimal BSCND solution must guarantee collection strategies, production factors, social and geographical considerations [6, 12] that support high quality at the lowest cost and in the shortest time. This is challenging and implies accurate management and a sustainable mindset (while considering economic, environmental, and social dimensions) [13]. First, the economic dimension involves the trade-off of minimizing total costs and maximizing social benefits [14]. Second, the concept of going green corresponds to a necessity nowadays [15]. Third, concerning the social dimension, according to the World Health Organization (WHO), improving the health of populations, responsiveness, and fairness/equity are defined as three main purposes for health systems [7]. Based on the combination of BSCND and sustainability, this work aims to contribute to improvements in the BSC. However, this is a first step of our research that explores the social and economic dimensions of sustainability and aims to easily support the decision-makers when designing and planning the BSC. Thus, this work does not consider perishability and uncertainty, important aspects of the problem in study, but considers assumptions related to the minimum demand and supply that should be taken into account allowing a buffer to deal with uncertainty in these critical

variables. It takes into consideration: (1) the estimated percentage of the population that will provide or receive blood, (2) the lowest distances that contribute to better geographical accessibility and equity, and (3) the respective related transportation and production costs, as well as (4) the analysis of the product flow optimization that contributes to understanding the best distribution of hospitals about the available blood centers (BC). To reach that aim, a simple two-stage network model for the design and plan of the BSC is developed and proposed. It considers the strategic design of the BSC, simultaneously with the tactical planning. This model incorporates the collection, production in the BCs, and transfusion in the hospitals. It defines (i) the design of a BSC network that regulates the fluctuations in supplies and demands while considering the geographical distribution for donors/patients, and (ii) the optimal product flow among the BCs and hospitals. The developed work is validated in an exploratory case study to show the respective applicability.

The remainder of this work is structured as follows. Section 2 presents an overview of the existing literature related to this work. In Sect. 3, a comprehensive description of the problem is given, as well as, in Sect. 4, the characterization of the model formulation is explained. Section 5 presents some input data used in the case study. Section 6 demonstrates the applicability of the model. Finally, conclusions and future research directions are drawn in Sect. 7.

2 Literature Review

Generally, the BSC location-allocation decisions follow a strategic/tactical planning nature, involving not only the SC entities but also the donors that donate blood at the collection infrastructures and the patients that will receive that donated blood at the demand nodes. In this section, the location-allocation studies related to the BSC, and connected with social and economic sustainability dimensions, are analyzed.

2.1 *Social Dimension*

Concerning the social pillar, Ramezani and Behboodi [8] concentrated on the increase of blood donors' utility to reduce shortages, but also on strategies to motivate donors to donate blood (such as distance of blood donors from blood facilities, the experience of donors, and advertising budget). Focusing on the SC strategies, in particular on the minimization of the distances, Karadağ [5] analyses the re-organization of a BSC to generate improvements, presenting a novel multi-objective mixed-integer location-allocation model for a BSC design problem, consisting of mobile and permanent units. There are other aspects to take into consideration that influence the performance of the BSC, such as uncertainty of demand, geographical accessibility, prioritizing patients based on urgency levels, and hierarchical structure of networks. Zarrinpoor [16] proposed a novel reliable hierarchical location-allocation model,

addressing a real-world health service network design problem, which considers the previous key issues. Additionally, also Gilani Larimi and Yaghoubi [17] reported main issues that affect the quantity of blood for donation, in particular different types of donors (first-time, regular), the number of booked/non-booked donors within and after working hours, the submission of social announcements, and the allocation of blood extraction technologies to the demand nodes. However, the technology allocation in hospitals is expensive, but technologies can support the hospitals' efficiency.

2.2 *Economic Dimension*

Concentrating on the economic pillar, Nagurney and Masoumi [18] developed a network design model for a BSC to determine the optimal network capacities under demand uncertainty of perishable products, considering costs (discarding, shortages/surpluses at the demand points), and quantifying the supply-side risk associated with procurement. Nagurney [19] developed a generalized network optimization model for regional blood banking systems handling demand uncertainty, including collection sites, testing, processing facilities, storage facilities, distribution centers, and demand points. Zahiri [2] presented a mixed-integer linear programming (MILP) model to make strategic-tactical decisions in a blood collection system over a multi-period planning horizon. Zahiri and Pishvaei [20] addressed the design of the BSC network, adding the blood group compatibility. A bi-objective mathematical programming model is developed to minimize costs and unsatisfied demand. Attari and Jami [21] concentrated in expand a regionalized BC system with just one blood product, aiming to minimize the total costs (of establishing and relocating facilities, operational and delivering blood) and to minimize the average delivery time among facilities. Osorio [12, 22, 29] presented different models which support the decision-makers to redesign the SC network, by considering the blood products at different levels of centralization intending the determination of the ideal collection and production strategies to minimize the total costs. Hamdan and Diabat [23] presented a two-stage stochastic programming problem, considering eight distinct blood types, to achieve the optimal BSC network able to minimize the outdated blood units applying First In First Out (FIFO) network costs, and blood delivery time. They determine the number of mobile blood collection facilities, as well as inventory and production decisions. Samani [24] proposed a multilateral perspective for BSC network design, using a novel multi-objective mathematical model by incorporating both quantitative and qualitative factors—aiming to minimize the loss of product freshness and total cost of the SC. Reza [25] proposed a bi-objective model for an integrated blood SC network design to minimize the total network cost and maximize the quality factor. On the other hand, Bruno [26] formulated the facility location problem and aimed, at reorganizing regional blood management systems, to reduce total management costs without compromising the self-sufficiency goal. Arani [9] studied a BSC network design consisting of donors, blood collection facilities, BCs, and hospitals while considering the ABO-Rh factors and shelf lives of blood products. An integrated

inventory system for sharing hospitals' inventory levels (lateral resupply) was used to investigate cross-matching and outdated units—to satisfy the demand by the other hospitals' inventories in the absence of the required product at the BC and the excess in any hospital. There are also studies joining location-allocation and inventory problems [27, 28]. Hsieh [27] studied a two-echelon SC in which each regional BC sends blood to different BCs and then delivers it to different allocated hospital blood banks. First, the model is proposed to obtain the location-allocation decisions, by determining how many BCs should be in an area, where BCs should be located, and which services should be assigned to Community Blood Centers (CBCs). Second, a model is implemented to acquire the inventory control decisions to achieve optimal blood replenishment quantity for each CBC. Both models aimed to minimize the total SC costs and the maximization of the responsiveness level. Hosseini-Motlagh [28] developed a bi-objective two-stage stochastic programming model to determine the optimum location-allocation and inventory management decisions; aiming to minimize the total cost of the SC—fixed, operating, inventory holding costs, wastage, and transportation costs—along with minimizing the substitution levels to provide a safe transfusion.

From the above analysis it can be said that several works have been published considering strategic decisions, however, few have a social vision—while considering the demand and the supply of blood at the same time in a multi-product decision approach. Additionally, it is important to notice that the environmental aspects are relevant to completing the sustainability approach in BSC [30]. In this work, the environmental dimension will be indirectly explored, by reducing the traveled distances and consequently the associated emissions. The main aim of this study is to propose a two-stage socio-economic BSC model that provides a strategic-tactical plan for designing a sustainable BSC, addressing the problems related to the mismatch between supply and demand of blood concerning an expected population of donors and patients in a location, but also the respective minimization of costs for donors and patients. SC's costs, such as production and transportation costs to measure the SC's performance in terms of economic goals are considered. Regarding the social component, the distribution of the population among the different hospitals and BCs in Portugal is included to pursue a more equitable BSC (in terms of geographical equity and geographical access measured by population density and traveled distance).

The next sections are dedicated to the problem definition and mathematical formulation, taking into account the previous goals in mind.

3 Problem Definition

The location-allocation of blood facilities affects the utility for donors and patients. The location of the BSC facilities usually results in weak geographical accessibility. Improving the accessibility of demand zones while considering the equality of demand satisfaction is vital. Blood donations occur via main or temporary facilities. Focusing on fixed facilities, establishing them is more costly. However, main fixed

facilities have higher levels of capacity and technology allowing to decrease possible risks to the BSC. The received whole blood is sent to BCs to be separated into the blood components (platelets; red blood cells, RBCs; and plasma). In this study, the BSC network corresponds to a single-product (whole blood) network before the BCs; and after the BC, the network transforms into a multi-product BSC. All the perishable blood components are sent from BCs to the demand zones. The allocation problem is divided into two stages and solved sequentially (observe Fig. 1). In the first stage, the usage of the existent SC superstructure (healthcare facilities) to deal with the reception and delivery of blood is considered and the necessary capacity optimized, with respect to supply (donors) and demand (patients). The goal is to find how existent licensed facilities should be used and which non-licensed facilities should be licensed to accommodate donors and patients from different districts (locations). The donors provide the whole blood in the healthcare facilities and the patients can receive different blood products. In the second stage, the healthcare facilities (for patients) obtained from the previous stage are considered and the optimal flow/ allocation of the RBCs (A+/-, B+/-, AB+/-, O+/-), among hospitals and BCs, is performed while minimizing production and transportation costs. Concerning this

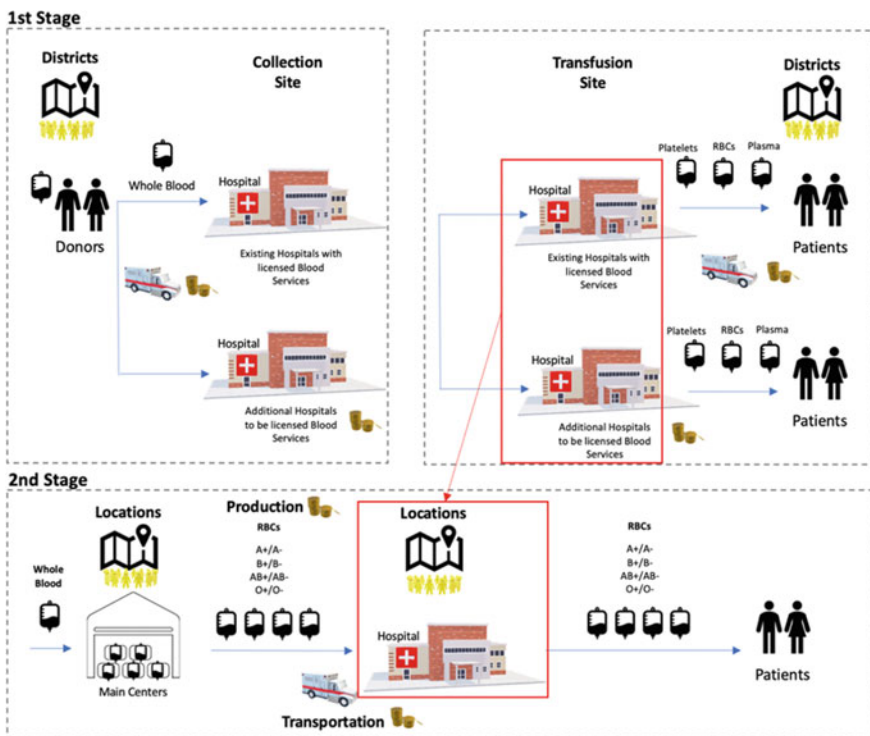


Fig. 1 BSC network and respective relationship between the two stages

stage, the transformation of whole blood in RBCs or transshipment among hospitals or BCs is not considered.

In this problem the following assumptions are considered:

- (1) a single product (whole blood) is shipped through the network before processing (into multiple products);
- (2) the multiple products are transported from the BCs to the Hospitals, after the processing phase;
- (3) at each facility of the network (BCs and hospitals) the existing and the potential capacity is limited;
- (4) the distance between the entities of the SC is considered as a direct distance;
- (5) each district has licensed facilities, but also has the option of adding licensing to the existing facilities to increase the overall capacity to handle the blood need/offer.

As stated, the problem above is solved through a two-stage approach involving in each stage the solution of a MILP model. The first stage model is a simple facility-location model that informs decisions on (1) how to best use the existent capacity, with respect to donors and patients; (2) whether to add new licenses to non-licensed facilities and with what capacity; and (3) how patients/donors from a district should be allocated to the various facilities to ensure that the facilities can provide treatment for the patients and to maximize the demand/supply coverage. No transformation processes within the facilities are considered. Concerning the second stage, the distribution network defined in stage 1 is explored aiming to find the optimal flow of blood products given the transportation and production policies.

4 Mathematical Formulation

The two-stage model is described below. The sets allow the definition of the network structure; and each level of the SC is defined by an entity (hospitals working as collection sites, BCs, hospitals operating as transfusion sites).

Indices and sets

d , index of the different districts, $d \in D$;

h , index of the existing healthcare facilities with licensed blood services, $h \in H$;

a , index of the additional healthcare facilities (without existent licensed blood services) to be added in the network, $a \in A$;

f , index of the total (existing and additional) healthcare facilities, $f \in F = HUA$;

p , index of the blood products, $p \in P$

bc , index of the locations of blood centers, $bc \in BC$

bt , index of the blood type products, $bt \in BT$

Parameters

First stage:

$dem_{d,p}$, Expected population in district d that will need blood product p ;
 $sup_{d,p}$, Expected population in district d who will provide whole blood p ;
 $cap_{f,p}$, Population served by a healthcare facility f that need blood product p ;
 $travDist_{d,f}$, Traveled distance between district d and healthcare facility f ;
 $travCost_{d,f}$, Cost according to traveled distance between district d and healthcare facility f ;
 $adCost_a$, Cost of adding licensed blood services a ;
 $pltyCap$, Penalty of adding extra capacity

Second stage:

$qnt_{bc,f,bt}$, Quantity (per units) of type of blood product bt produced and transported from a blood center bc to a hospital f in a regular (weekly planned) time;
 $transpCost_{bt}$, Transportation cost per unit of a specific bt ;
 $travDist_{bc,f}$, Traveled distance between blood center bc and hospital f ;
 $dem_{f,bt}$, Demand at hospital h of type blood product bt units;
 $capProd_{bc,bt}$, Capacity of the blood center bc to produce blood product bt ;
 $prodCost_{bt}$, Production cost for a specific type of blood product bt when considering a regular (weekly planned) time;
 $reghCap_{bc,bt}$, Regular hour capacity at blood center bc per blood type bt ;
 $perProdDistr_{bt,bc}$, Percentage of production and distribution of type of blood product bt placed in blood center bc

Decision Variables

First stage:

$adF_{a,p}$, equal to 1 if we license facility a (with non-licensed blood services) to provide/receive a product p ; 0, otherwise;
 $adCap_{a,p}$, Extra capacity of new licensed facility a to provide product p ;
 $pop_{d,f,p}$, Population from district d served by a facility f and by product p ;

Second stage:

$prodProd_{bc,bt}$, equal to 1 if a blood center bc produces that type of blood product type bt , else, 0

Two objective functions are presented, the first objective function for stage 1 and the second objective function for stage 2. The first objective function (Eq. 1) corresponds to the minimization of costs for donors and patients. The traveled distances and geographical distribution as social costs are considered in the first stage. The first term corresponds to the traveling cost from the different districts to the healthcare facilities; the second term corresponds to the costs of licensing existing healthcare

facilities for providing blood services; and the third term corresponds to the cost of adding extra capacity to the new licensed facilities.

$$\begin{aligned} MinCosts = & \sum_{d \in D} \sum_{f \in F} pop_{d,f,p} \cdot travDist_{d,f} \cdot travCost_{d,f} + \\ & \sum_{a \in A} adF_{a,p} \cdot adCost_a + pltyCap \cdot \sum_{a \in A} adCap_{a,p} \end{aligned} \quad (1)$$

The second objective function (Eq. 2) aims to find the product flow from the BCs to the hospitals. The first term provides the production cost and the second term gives the transportation cost.

$$\begin{aligned} MinCosts(Prod. + Transp.) = & \sum_{bc \in BC} \sum_{f \in F} \sum_{bt \in BT} qnt_{bc,f,bt} \cdot (prodCost_{bt} \\ & + (transpCost_{bt} \cdot travDist_{bc,f})) \cdot prodProd_{bc,bt} \end{aligned} \quad (2)$$

In both stages, the geographical equity is included through the variation in geographical utilization and geographical access measured by density and traveled distance in terms of the population. The equity of access corresponds to the minimization of the total travel time, and consequently leads to less environmental impacts related to emissions, by ensuring that individuals that provide blood or require blood transfusion receive the blood needed at the closest available service; as well as, by guaranteeing that the access to facilities is being provided to as many individuals as possible. The geographical equity minimizes the level of unmet need for the geographical area(s) with the highest level of unmet need. In this way, it will allow the maximum allocation of blood in the geographical area(s) with the lowest blood provision.

The constraints of this exploratory study involved in the first stage model are dedicated to the relation among the expected population of a district that will need blood concerning the respective estimated demand (1% of the resident population of a district) (3); the expected population of a district that will provide blood according to the respective estimated supply (2% of the resident population of a district)—that should be higher than the demanded blood (4). Additionally, the authors added as constraints the capacity of a blood facility that should satisfy the expected population of a district (5); and that the expected population of a district should be satisfied, if needed with additional blood facilities or extra capacity (6).

$$\sum_{f \in F} pop_{d,f,p} = dem_{d,p}, \forall d \in D, p \in P, \quad (3)$$

$$dem_{d,p} \leq sup_{d,p}, \forall d \in D, p \in P, \quad (4)$$

$$\sum_{d \in D} pop_{d,h,p} \leq cap_{h,p}, \forall h \in H, p \in P, \quad (5)$$

$$\sum_{d \in D} pop_{d,a,p} \leq cap_{a,p} \cdot adF_{a,p} + adCap_{a,p}, \forall a \in A, p \in P, \quad (6)$$

Concerning the second-stage model, this has as input the healthcare facilities defined in stage 1 (f). New constraints are added corresponding to the demand satisfaction at the hospital level (7); the production capacity and product constraint (8); production rate constraint (9) and non-negativity constraints (10).

$$\sum_{f \in F} qnt_{bc,f,bt} = dem_{f,bt}, \forall bc, bt \quad (7)$$

$$\sum_{f \in F} qnt_{bc,f,bt} \leq prodCost_{bc} \cdot capProd_{bc,bt}, \forall bc, bt \quad (8)$$

$$\sum_{f \in F} qnt_{bc,f,bt} \leq reghCap_{bc,bt} \cdot perProdDistr_{bc,bt} \cdot prodProd_{bc,bt}, \forall bc, bt \quad (9)$$

$$\begin{aligned} dem_{d,p}, sup_{d,p}, cap_{f,p}, travDist_{d,f}, travCost_{d,f}, adCost_a, qnt_{bc,f,bt}, \\ transpCost_{bt}, travDist_{bc,f}, dem_{f,bt}, capProd_{bc,bt}, prodCost_{bt}, \\ reghCap_{bc,bt}, perProdDistr_{bt,bc} \geq 0 \end{aligned} \quad (10)$$

5 Case Study

A Portuguese based BSC is studied (Fig. 2).

Data related to the existing licensed blood services and possible blood services (that can be added in the network), for donors and patients, was considered (NHS of Portugal, “Imunohemoterapia”, from 2017). Figure 2 presents the representation of the locations of healthcare facilities for patients that receive blood, donors that provide blood and the location of each BC. According to the previous formulation, the healthcare facilities (f) include hospitals with existing and licensed blood services (h), and existing facilities (a) that may be licensed with blood services. Regarding the donors, 19 existing healthcare facilities (with licensed blood services) were considered and 4 healthcare facilities with non-licensed blood services were proposed; and for the patients, 24 existing healthcare facilities (with licensed blood services) were added in the model and 19 healthcare facilities with non-licensed blood services were proposed.

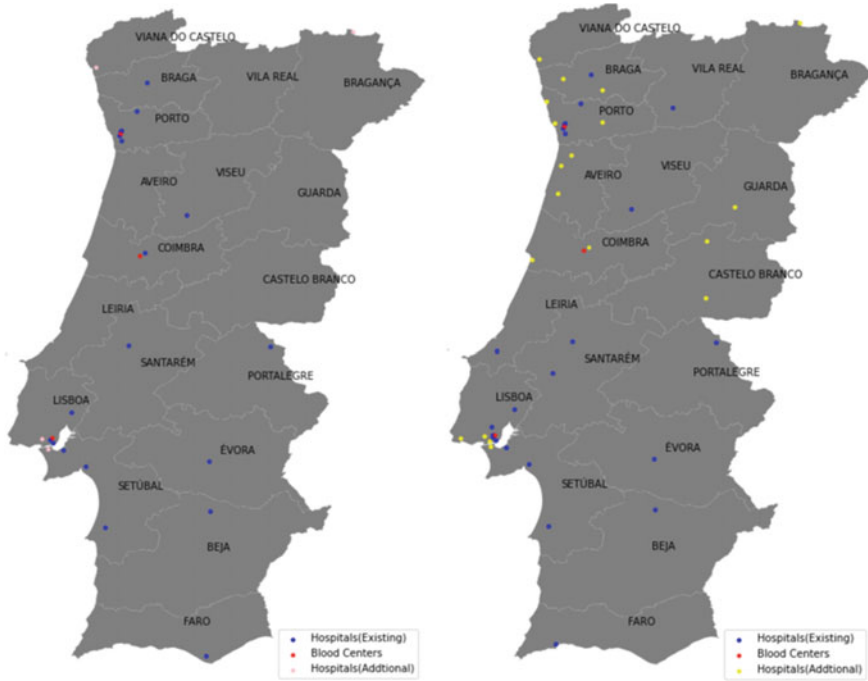


Fig. 2 Healthcare Facilities (including hospitals with existing and licensed blood services, possible non-licensed blood services to be (additionally) licensed in the network and BCs: for donors provide blood (left); for patients receive blood (right))

Table 1 contains the characteristics of each district in Portugal, namely region, the area of each district, coordinates, resident population, population density, as well as, the assumptions for demand (considering 1% of the resident population) and supply (2% of the resident population).

6 Computational Experiments

The above two-stage procedure was modeled in Python and solved through Gurobi on a 2.3 GHz Intel Core i9 and 16 GB of RAM computer. It is important to note that the results below correspond to an exploratory study as the model developed is simple. So these results can only be viewed as a first attempt towards the solution of a more complex BSC. The results were achieved by first solving the first stage and the obtained results were then used as input to solve the second stage of the problem. In the results, three different aspects are analyzed: social aspects; costs; and product flow optimization.

Table 1 The main characteristics of each district in Portugal that are considered in the case study

Region	District	District ID	Area (km ²)	Coordinates	Resident population (hab.)	Population density (hab./km ²)	Estimated demand	Estimated supply
LVT	D1	Lisboa	2761	(38.7071, -9.13549)	2863433 (INE,2019)	821	28634	57268
North	D2	Porto	2395	(41.15, -8.61024)	1778146 (INE,2018)	742	17781	35562
North	D3	Braga	2706	(41.5518, -8.4229)	956185 (INE,2011)	313	9561	19123
LVT	D4	Setúbal	5064	(38.5245, -8.89307)	911794 (INE,2009)	171	9117	18235
North	D5	Aveiro	2798,54	(40.6412, -8.65362)	714200 (INE,2011)	262	7142	14284
Center	D6	Leiria	3505,78	(39.7443, -8.80725)	470895 (INE,2011)	134	4708	9417
LVT	D7	Santarém	6747	(39.2362, -8.68707)	465701 (INE,2009)	70	4657	9314
Algarve	D8	Faro	4960	(37.0154, -7.93511)	434023 (INE,2009)	87,5	4340	8680
Center	D9	Coimbra	3947	(40.2115, -8.4292)	429987 (INE,2011)	109	4299	8599
Center	D10	Viseu	5007	(40.6575, -7.91428)	391215 (INE,2011)	78,13	3912	7824
North	D11	Viana do Castelo	319,02	(41.6946, -8.83016)	88725 (INE,2011)	278,1	887	1774
North	D12	Vila Real	4328	(41.2959, -7.74635)	213775 (INE,2011)		2137	4275
Center	D13	Castelo Branco	6675	(39.8239, -7.49189)	196264 (INE,2011)	34	1962	3925
Center	D14	Guarda	5518	(40.5371, -7.26785)	168898 (INE,2011)	30,61	1688	3377
Alentejo	D15	Évora	7393	(38.571, -7.9096)	168034 (INE,2009)	23	1680	3360
Alentejo	D16	Beja	10229,05	(38.0156, -7.86523)	152758 (INE,2011)	15	1527	3055
North	D17	Bragança	6608	(41.8072, -6.75919)	136252 (INE,2011)	21	1362	2725
Alentejo	D18	Portalegre	6065	(39.2914, -7.43235)	118506 (INE,2011)	19,5	1185	2370

6.1 Social Component Analysis

The results from the first stage are presented in Figs. 3 and 4 and Tables 2 and 3. The social component analysis, associated with the geographical distribution of donors and patients among healthcare facilities, is essentially analyzed in stage 1. Figure 3 represents the number of healthcare facilities needed by the district in view of the whole blood donation. The obtained distribution related to the number of donors,

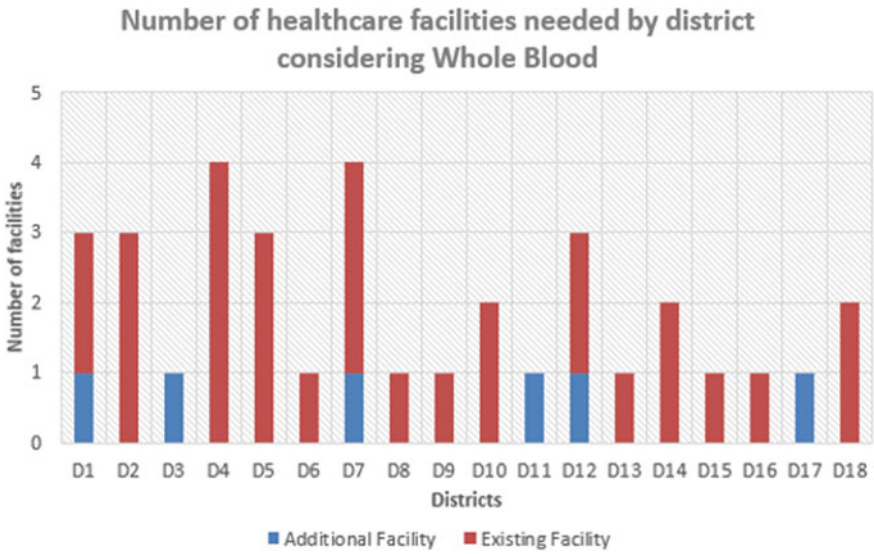


Fig. 3 Number of healthcare facilities needed by district considering the whole blood

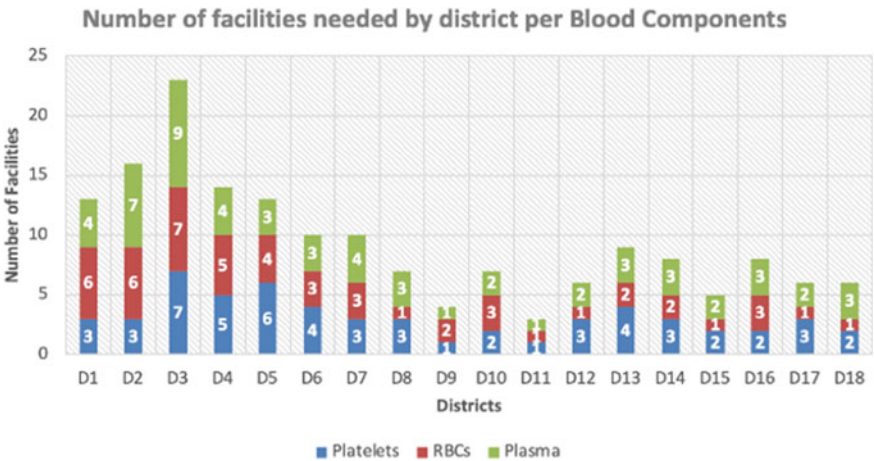


Fig. 4 Number of healthcare facilities (with licensed and non-licensed blood services) needed by district per blood product. Each facility is able to provide more than one blood product

for example for Lisbon (D1), considering healthcare facilities as unique infrastructures (type) to receive donors is not completely operational. The model identified 3 facilities that will receive 8636 (F3 with licensed blood services), 5481 (F14 with licensed blood services), and 37421 (F20 with non-licensed blood services) donors in Lisbon (Table 2). Regarding the SC network, all the healthcare facilities with non-licensed blood services are required (in the SC network) and should be licensed (in

Table 2 Distribution of donors (D1)

Region	Facility	No. Donors (for WB)
LVT	F3	8636
LVT	F14	5481
LVT	F20	37421

Table 3 Distribution of patients (D1)

Region	Facility	No. Patients		
		Platelets	RBCs	Plasma
LVT	F4	1465	7525	1356
LVT	F5	902	5300	1639
LVT	F16	N.A.	1660	N.A.
LVT	F18	762	1667	180
LVT	F28	N.A.	2320	95
LVT	F34	N.A.	3759	N.A.
LVT	F37	N.A.	N.A.	N.A.

terms of blood services) to overcome the estimated supply. Additionally, and concerning the patients, to accommodate the demand, the model identified that at least 18 healthcare facilities with non-licensed blood services should be licensed in the SC network. Figure 4 has represented the number of facilities needed by the district per blood component. According to Fig. 4, district 3 (D3, Braga) has a higher number of healthcare facilities (corresponding to the third district with a higher number of people) and district 11 (D11, Viana do Castelo) has a lower number of healthcare facilities (and people) allocated for the different blood components. Additionally, it should be noticed that one facility can provide different blood products. Focusing on Lisbon (D1) and taking into account the Table 3, this district that has the higher number of people, and presents the distribution of the products aligned to the population needs, 4 healthcare facilities are needed to provide plasma, 6 healthcare facilities for RBCs and 3 healthcare facilities for platelets—however, these facilities are also able to deliver additional blood products to patients. Regarding the optimized patients' distribution of the different blood components for Lisbon (D1): (1) for platelets, the number of patients to be transfused by year is 1465, 902, and 762 for each selected healthcare facility; (2) for plasma, the number of patients by year to be transfused is around 1356, 1639, 180, and 95 (F28 with non-licensed blood services) for each selected healthcare facility; and (3) for the RBCs, the number of patients to be transfused by year is around 7525, 5300, 1660, 1667, 2320 (F28 with non-licensed blood services) and 3759 (F34 with non-licensed blood services) for each selected healthcare facility.

6.2 Costs Component Analysis

Concerning the costs related to patients, the RBCs components are the most transfused product, as a result, RBCs will involve more costs in adding healthcare facilities with licensed blood services (78% for RBCs), as well as, in allocating the patients to the existing licensed healthcare facilities (65% for RBCs). Regarding the costs associated with the donors, allocating them (according to the population distribution) will involve 90% of the costs, while additional licensed blood services (in healthcare facilities) correspond to 10% of the costs. This result shows that there is a need for more infrastructures for collection services to reduce the allocation costs.

6.3 Product Flow Optimization

In the second stage, the focus is on the product flow that was analyzed for just one product (the RBCs), while considering the same healthcare facilities obtained from stage 1 (for patients) and adding the BCs facilities in the SC network. The following distribution of healthcare facilities and demands for each BC was found: BC1 should provide blood to 16 healthcare facilities (where demand corresponds to 51%); BC2 should be responsible for 14 facilities (where demand corresponds to 26%) and BC3 should manage blood to 8 facilities (demand of 23%) (Figs. 5 and 6). According to the results, production costs denote 82% and transportation costs correspond to 18% of the total costs.

In this exploratory study, it is assumed in the beginning more than 40 healthcare facilities (in stage 1) satisfy the demand (of patients); however, in stage 2, focusing

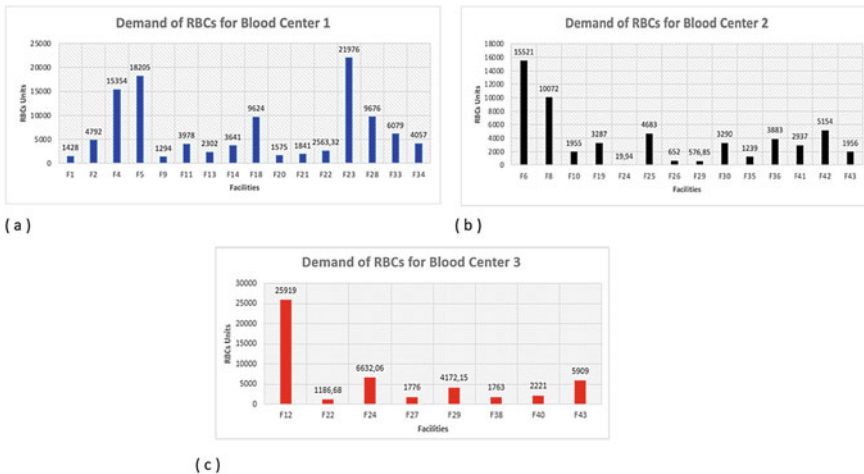


Fig. 5 Product Flow Optimization: Demand of RBCs for (a) BC 1, (b) BSC 2 and (c) BC 3

Fig. 6 Representation of healthcare facilities and demand among the existent BCs distributed in Portugal



just on the RBCs product flow optimization just 38 healthcare were needed. As stated before the model developed is just a first attempt to approach the problem. Future developments are required to represent additional complexities related to the design of the BSC.

7 Conclusions

This work is an exploratory study that appears as a first attempt to the definition of a BSC network able to provide treatment for the patients while maximizing the demand/supply coverage. A simple location-allocation model is formulated and a two stages procedure is developed. In the first stage, the model allocates donors and patients to healthcare facilities (by districts), while considering whole blood for donors and the different blood products for patients. It takes into account the expected population in a district that will need a specific blood product, as well as, the expected population in a district that will provide the whole blood. It considers the minimization of costs for both aspects, supply, and demand in the first stage (using a multi-product approach). It explores the geographic distribution of the population to the healthcare facilities (based on facilities with licensed blood services and without licensed blood services), respective capacities, as well as, the population of each district. The geographical equity of access is translated by the minimization of the total travel time by ensuring that individuals that provide blood or require blood

transfusion receive the blood needed at the closest available service. In this way, it will allow the maximum allocation of blood in the geographical areas with the lowest blood provision. On the other hand, in the second stage, the model is able to optimize the blood units allocation (assuming the healthcare facilities obtained in the first stage) to the BCs based on the RBCs consumption.

Concerning sustainability, (i) BSC costs, such as production and transportation costs are considered to measure the SC's performance in terms of economic goals; and, (2) the social component is explored based on the distribution of the population among the different healthcare facilities to pursue a more equitable BSC. In this work, the authors do not just look at the donors or patients, but we aim to find the product flow from the BCs and the hospitals—in a specific case study—looking for clusters of hospitals allocated to each specific BC. By achieving the blood product flow optimization, we were able to determine how to cluster the hospitals to the BCs—based on population (distribution) needs, adding production aspects in the model, as well as, the transportation part among the BCs and hospitals.

This initial model approach can be the basis to support the decision-makers, since we join the geographical utilization and the geographical access measured by density and traveled distance in terms of the population, and at the same time connecting it with the collection, production, distribution, and transfusion stages.

In future improvement, the model developed should be integrated and enhanced by (i) adding the processing, inventory, and transshipment operations; (ii) having the contribution to the environmental dimension approach; (iii) introducing the dynamics of the problem (e.g. time), and (iv) as a result of the multiple uncertainties that affect the BSC, applying stochastic or robust optimization approaches could be used to solve the problem.

References

1. Ghorashi, S.B., Hamed, M., Sadeghian, R.: Modeling and optimization of a reliable blood supply chain network in crisis considering blood compatibility using MOGWO. *Neural Comput. Appl.* **32**, 12173–12200 (2020). <https://doi.org/10.1007/s00521-019-04343-1>
2. Zahiri, B., Torabi, S.A., Mousazadeh, M., Mansouri, S.A.: Blood collection management: Methodology and application. *Appl. Math. Model.* **39**, 7680–7696 (2013). <https://doi.org/10.1016/j.apm.2015.04.028>
3. Beliën, J., Forcé, H.: Supply chain management of blood products: a literature review. *Eur. J. Oper. Res.* **217**, 1–16 (2012). <https://doi.org/10.1016/j.ejor.2011.05.026>
4. Osorio, A.F., Brailsford, S.C., Smith, H.K.: A structured review of quantitative models in the blood supply chain: a taxonomic framework for decision-making. *Int. J. Product. Res.* **53**, 7191–7212 (2015). <https://doi.org/10.1080/00207543.2015.1005766>
5. Karadağ, İ., Keskin, M.E., Yiğit, V.: Re-design of a blood supply chain organization with mobile units. *Soft Comput.* **25**, 6311–6327 (2021). <https://doi.org/10.1007/s00500-021-05618-3>
6. Samani, M.R.G., Hosseini-Motlagh, S.M.: An enhanced procedure for managing blood supply chain under disruptions and uncertainties. *Ann. Oper. Res.* **283**, 1413–1462 (2019). <https://doi.org/10.1007/s10479-018-2873-4>

7. Haeri, A., Hosseini-Motlagh, S.M., Ghatreh Samani, M.R., Rezaei, M.: A mixed resilient-efficient approach toward blood supply chain network design. *Int. Trans. Oper. Res.* **27**, 1962–2001 (2020). <https://doi.org/10.1111/itor.12714>
8. Ramezani, R., Behboodi, Z.: Blood supply chain network design under uncertainties in supply and demand considering social aspects. *Transp. Res. Part E: Logist. Transp. Rev.* **104**, 69–82 (2017). <https://doi.org/10.1016/j.tre.2017.06.004>
9. Arani, M., Chan, Y., Liu, X., Momenitabar, M.: A lateral resupply blood supply chain network design under uncertainties. *Appl. Math. Modell.* **93**, 165–187 (2021). <https://doi.org/10.1016/j.apm.2020.12.010>
10. Fanoodi, B., Malmir, B., Jahantigh, F.F.: Reducing demand uncertainty in the platelet supply chain through artificial neural networks and ARIMA models. *Comput. Biol. Med.* **113** (2019). <https://doi.org/10.1016/j.combiomed.2019.103415>
11. Hosseini-Motlagh, S.M., Samani, M.R.G., Cheraghi, S.: Robust and stable flexible blood supply chain network design under motivational initiatives. *Socio-Economic Plan. Sci.* **70** (2020). <https://doi.org/10.1016/j.seps.2019.07.001>
12. Osorio, A.F., Brailsford, S.C., Smith, H.K., Blake, J.: Designing the blood supply chain: how much, how and where? *Vox Sanguinis* **113**, 760–769 (2018). <https://doi.org/10.1111/vox.12706>
13. Moslemi, S., Pasandideh, S.H.R.: A location-allocation model for quality-based blood supply chain under IER uncertainty. *RAIRO—Oper. Res.* **55**, S967–S998 (2021). <https://doi.org/10.1051/ro/2020035>
14. Banini, J., Lim, M.K., Lim, M., Anosike, A.: LITERATURE ANALYSIS IN SUSTAINABLE SUPPLY CHAIN MANAGEMENT: LEADERSHIP STYLE AND CULTURE Integration of Lean Six Sigma and Green View project New Journal: Clean Technologies and Recycling View project (2021)
15. Jemai, J., Chung, B., Sarkar, B.: Environmental effect for a complex green supply-chain management to control waste: a sustainable approach. *J. Clean. Prod.* **277**, 122919 (2020)
16. Zarrinpoor, N., Fallahnezhad, M.S., Pishvae, M.S.: The design of a reliable and robust hierarchical health service network using an accelerated Benders decomposition algorithm. *Eur. J. Oper. Res.* **265**, 1013–1032 (2018). <https://doi.org/10.1016/j.ejor.2017.08.023>
17. Gilani Larimi, N., Yaghoubi, S.: A robust mathematical model for platelet supply chain considering social announcements and blood extraction technologies. *Comput. Ind. Eng.* **137** (2019). <https://doi.org/10.1016/j.cie.2019.106014>
18. Nagurney, A., Masoumi, A.H.: Supply chain network design of a sustainable blood banking system. In: *International Series in Operations Research and Management Science*, pp. 49–72. Springer, New York LLC (2012)
19. Nagurney, A., Masoumi, A.H., Yu, M.: Supply chain network operations management of a blood banking system with cost and risk minimization. *Comput. Manag. Sci.* **9**, 205–231 (2012). <https://doi.org/10.1007/s10287-011-0133-z>
20. Zahiri, B., Pishvae, M.S.: Blood supply chain network design considering blood group compatibility under uncertainty. *Int. J. Prod. Res.* **55**, 2013–2033 (2017). <https://doi.org/10.1080/00207543.2016.1262563>
21. Attari, M.Y.N., Jami, E.N.: Robust stochastic multi-choice goal programming for blood collection and distribution problem with real application. *J. Intell. Fuzzy Syst.* **35**, 2015–2033 (2018). <https://doi.org/10.3233/JIFS-17179>
22. Osorio, A. F., Brailsford, S.C., Smith, H.K., Forero-Matiz, S.P.: Simulation-Optimization model for production planning in the blood supply chain. *Health Care Manag. Sci.* **20**(4), 548–64 (2017). <https://doi.org/10.1111/vox.12706>
23. Hamdan, B., Diaban, A.: A two-stage multi-echelon stochastic blood supply chain problem. *Comput. Oper. Res.* **101**, 130–143 (2019). <https://doi.org/10.1016/j.cor.2018.09.001>
24. Samani, M.R.G., Hosseini-Motlagh, S.M., Ghannadpour, S.F.: A multilateral perspective towards blood network design in an uncertain environment: methodology and implementation. *Comput. Ind. Eng.* **130**, 450–471 (2019). <https://doi.org/10.1016/j.cie.2019.02.049>
25. Reza, M., Samani, G., Hosseini-Motlagh, S.-M., Sheshkol, M.I., Shetab-Boushehri, S.-N.: A bi-objective integrated model for the uncertain blood network design with raising products quality (2019)

26. Bruno, G., Diglio, A., Piccolo, C., Cannavacciuolo, L.: Territorial reorganization of regional blood management systems: evidences from an Italian case study. *Omega (UK)* **89**, 54–70 (2019). <https://doi.org/10.1016/j.omega.2018.09.006>
27. Hsieh, C.L.: An evolutionary-based optimization for a multi-objective blood banking supply chain model. In: *Modern Advances in Applied Intelligence. Lecture Notes in Computer Science*, vol. 8481. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-07455-9_53
28. Hosseini-Motlagh, S.M., Samani, M.R.G., Homaei, S.: Blood supply chain management: robust optimization, disruption risk, and blood group compatibility (a real-life case). *J. Ambient Intell. Hum. Comput.* **11**, 1085–1104 (2020). <https://doi.org/10.1007/s12652-019-01315-0>
29. Osorio, A.F., Brailsford, S.C., Smith, H.K.: Whole blood or apheresis donations? A multi-objective stochastic optimization approach. *Eur. J. Oper. Res.* **266**(1), Elsevier B.V., pp. 193–204 (2018). <https://doi.org/10.1016/j.ejor.2017.09.005>
30. Torrado, A., Barbosa-Póvoa, A.: Towards an optimized and sustainable blood supply chain network under uncertainty: a literature review. *Clean. Logist. Supply Chain.* **3** (2022). <https://doi.org/10.1016/j.clscn.2022.100028>