Planning Blood Collections To Meet Demand And Minimize Waste

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Abstract

The Blood Supply Chain (BSC) is a fundamental system since it guarantees the blood supply, an essential good for human life. Nevertheless, such supply chain faces challenges that make its management very complex. In this context, a decision tool to support BSC decision-makers is beneficial. In this thesis, we follow this challenge and a mixed integer linear programming model is developed to support blood planning collections. The model considers blood perishability and blood group type substitutability. Uncertainty of blood potentials and demand is addressed by implementing a two-stage stochastic approach. Within the model objectives, it is aimed at minimizing: distance travelled, wastage, shortage, blood types substitution, transhipment, and the number of temporary fixed CCs to open. The model is tested considering deterministic and stochastic cases. The model is applied to the real case of *Instituto Português do Sangue e da Transplantação* (IPST) the institution responsible for managing the Portuguese BSC. A sensitivity analysis of a Current Case is conducted by varying blood potentials and demand. Additionally, a Tragic Case is tested to understand the model behaviour when faced with a crisis. Finally, the two-stage stochastic approach is tested. A more robust solution is obtained, even with a cost increase of 17% as if uncertainty was known since patient service for different scenarios is ensured.

Keywords: Mobile Collection Centres; Blood Collection; Perishability; Substitutability; Uncertainty; Two-Stage Stochastic Approach

1. INTRODUCTION

Blood is essential to survival as it performs the function of carrying oxygen and nutrients to the human body's cells (Lowalekar & Ravichandran, 2014). Blood can be separated into four main products, each with a different shelf-life: Red Blood Cells (RBC) with 42 days, platelets with 5 days, plasma and cryoprecipitate with 36 months (Hardwick, 2008). Considering blood products importance, patients must receive blood transfusions without delay. However, maintaining a high service level may lead to an unwanted accumulation of blood inventory. Due to the perishable nature of blood, high inventory levels can translate into high levels of wastage. Blood shortage refers to when there are not enough blood units to perform transfusions. Shortage is unwanted since it may delay surgeries, untreated patients, and even deaths (World Health Organization, 2017). Blood wastage occurs in consequence of the obsolescence of blood units. As they are not used before the end of their shelf-life, units are forced to be disposed of if not used on time (Özener et al., 2019). To mitigate the adverse effects of blood wastage or shortage, the quantity of blood supplied should be chosen to meet demand as closely as possible (Hamdan & Diabat, 2019). Besides perishability, the primary reason why wastage and shortage happen is due to the difficulty of predicting the demand since it depends on patients' needs. Donations are necessary to fulfil demand, but as they are voluntary, the blood supply is also unpredictable.

Portugal follows the worldwide trend in having an increasingly ageing population that requires more health care. It is essential to meet the needs of the people by ensuring the right health care service level. Thus, optimizing the processes in the Blood Supply Chain (BSC) is considered of vital importance. A high service level is achieved by meeting demand but simultaneously minimizing blood wastage and shortages along the chain. However, collecting enough blood to meet demand without wastage or shortage represents the most considerable trade-off in BSC design. In this context, blood collection planning deserves to be carefully studied.

This context motivates the present research which aims to develop and use Operations Research techniques to improve the Portuguese BSC regarding blood collection planning to meet the uncertain demand and minimize blood products wastage and shortage as well as the total costs associated with

blood collection activity while maintaining the service level and considering the BSC characteristics. To meet these goals, Portuguese BSC features lead to the development of an optimization model which covers different decisions: mobile Collection Centres (CCs) routes, facilities location-allocation, temporary fixed CCs to open, schedule for blood withdrawals definition and the quantity of blood to collect. Despite being inspired by the Portuguese BSC, the model is applicable to different BSC systems, contributing to the blood collection planning literature.

2. BLOOD SUPPLY CHAIN CHARACTERIZATION

Since blood has a perishable nature, its supply chain presents particular challenges. The short shelf-life complicates the products supply chain since it leads to an easy deterioration. The substitutability of blood group types according to the ABO and RhD groups is also a singularity of the BSC, i.e., the opportunity to use a different blood group type if this is compatible with patient's blood when there is a lack of blood units. As the quantity of blood used in hospitals is not possible to predict since it depends on patients' needs, blood demand has a stochastic nature. In addition, for transfusions to be performed, blood must be available. However, blood supply is irregular as most donations are voluntary and performed by altruist donors (Osorio et al., 2018). Being a voluntary donation, blood wastage becomes unethical, and blood shortage may affect a patient's life. If it is collected too much blood when the demand is not high, then wastage can occur. A shortage occurs if there is a lack of supply, but the demand is high. It is hard to balance this trade-off since both supply and demand are uncertain, so their prediction is inaccurate.

The Portuguese BSC follows the structure proposed by Pirabán et al. (2019). There are five echelons through which the blood flows: Donors, mobile and fixed CCs, Blood Centre (BC), Demand Zones (DZs) and Patients. Donors go to a mobile or fixed CC or go directly to a BC (Collection). A fixed CC can be a hospital or a temporary fixed CC which need to be open. A shipment of the collected blood goes from all CCs to BCs. In BCs, the WB suffers an eligibility test which can be rejected and disposed of or is considered eligible for the next processes (Testing). The collected blood suffers separation into its components (Processing) which remain stored (Inventory) until a request is made from a DZ (Distribution), such as hospitals, where patients are waiting for a blood transfusion (Transfusion). Therefore, BSC is summarized in six stages: Collection, Testing, Processing, Inventory, Distribution, Transfusion.

Instituto Português do Sangue e da Transplantação (IPST) is the institution responsible for managing the Portuguese BSC. IPST is split among three regional BCs located in Oporto (CSTP), Coimbra (CSTC), and Lisbon (CSTL), each one covering up different geographic areas, Northern, Centre and Southern region, respectively. Regarding blood collection, hospitals and BCs are responsible for planning their collection schedules. However, campaigns performed by mobile and temporary fixed CCs are planned annually by the corresponding regional BC.

By gathering data from IPST's 2019 annual report, it is concluded that better planning for collections is required since there is a need for a better attempt to meet the stochastic supply and demand throughout the country and hence, minimize blood shortage and wastage.

The dissertation aims to optimize blood collection planning in Portugal. For proper planning, BSC decision-makers must decide regarding each mobile CC's routes, facilities location-allocation, temporary fixed CCs to open, scheduling definition, and the blood quantities to collect. These collection planning decisions must be made considering supply and demand uncertainty, the perishability of the products, the substitutability of blood group types, and the resources constraints of collection facilities. Also, collection decisions must be made considering that multiple facilities and echelons need to be aligned for the same main purpose: the patient service level's high quality. Therefore, integrability should be assured to avoid the bullwhip effect and minimize the impact of uncertainty on blood collection planning decisions.

3. LITERATURE REVIEW

Literature is reviewed to understand how these BSC properties have been addressed as well as the decisions regarding blood collection planning.

Dealing with uncertain environments

The environment's representation is essential because if neglected, a supply chain's plausible performance in future conditions will be in doubt.

Stochastic programming approach is used by Bozorgi-Amiri et al. (2013), Jabbarzadeh et al. (2014) and Salehi, Mahootchi, & Husseini (2017) to develop a robust stochastic programming approach to design an emergency BSC facing supply and demand uncertainties. Zahiri et al. (2014) and Ghasemi (2019)

model supply and demand uncertainty with a scenario-based method, but for a location-allocation problem. Cheraghi et al. (2017) treat specifically blood platelet production planning.

Fuzzy programming approach is applied to deal uncertainty when making decisions over a multi-period regarding location-allocation of facilities by Zahiri et al. (2013). Samani & Hosseini-Motlagh (2018) and Zahiri & Pishvaee (2017) use the same approach to ensure a consistent BSC network reliability and robustness at a minimum cost. Rabbani et al. (2017) find the best mobile CCs location routing regarding the system for platelet production, considering the number of donors as a fuzzy parameter.

Planning for Perishable Products

A perishable product is characterized by at the end of its shelf-life, the product no longer has any value for the consumer, being spoiled. The perishability issue came up by Nahmias (1982) with inventory modelling in a blood bank. Nagurney, Masoumi, & Yu (2012) suggest using arc multipliers to capture the blood perishability. Dillon, Oliveira, & Abbasi (2017) propose the following of blood age by the time periods in which blood pack units are collected comparing to the time period in hand.

Planning Blood Collection

Since blood collection is the first activity in the supply chain, and only from it is the product available for use, its performance must be excellent. Planning collections encompasses several decisions (Osorio et al., 2015): donor arrival policies; staff allocation; routing decisions; facilities location-allocation; scheduling definition; and blood quantities to collect.

Donor arrival and staff allocation

A collection facility may have a staff team to ensure donors support (Güre et al. 2018).

The distribution during the day of walk-in donors may be described with a simulation-based approach as proposed by Alfonso et al. (2013) and Alfonso, Xie, & Augusto (2015). Alfonso, Augusto, & Xie (2013;2015) predicts expected number of donations and the human resource requirements based on demographics, donor generosity, and donor availability. Baş et al. (2017) propose pre-allocate time slots to blood group types.

Routing decisions

Mobile CCs have to visit specific locations to collect blood from donors. Therefore, routes must be defined. Şahinyazan et al. (2015) and Gunpinar & Centeno (2016) solve the Vehicle Routing Problem (VRP) considering variable visits duration. Rabbani et al. (2017) cover the blood collection planning problem for platelet production.

Location-allocation decisions

Although possible facilities locations are already defined, adjustments should be made to address blood supply and demand uncertainty.

Zahiri et al. (2013), Ramezanian & Behboodi (2017) and Zahiri & Pishvaee (2017) consider a multi-period location-allocation problem. Jabbarzadeh et al. (2014), Salehi et al. (2017), Samani & Hosseini-Motlagh (2018) and Ghasemi (2019) deal with disaster situations.

Other planning decisions

Osorio, Brailsford, & Smith (2018), Osorio et al. (2018) and Özener et al. (2019) consider different collection methods to obtain blood products. Lowalekar & Ravichandran (2010), Zahiri & Pishvaee (2017), Osorio, Brailsford, & Smith (2018), Osorio et al. (2018), Ghasemi (2019) and Hamdan & Diabat (2019) consider the ABO compatibility and substitution permissibility. The proposed model addresses the decision of opening temporary fixed CCs.

Literature Review Conclusion

It can be concluded that many approaches focus only on a particular BSC echelon or challenge or limit the blood collection planning to one to three decisions, which keeps literature far from a complete model.

4. MODEL FORMULATION

Problem Statement

The proposed model aims to assist BSC decision-makers on tactical and operational decisions regarding blood collections planning. The goal is to ensure the patient service level by overcoming BSC challenges.

The blood collections planning comprises the first three echelons (Donors, Mobile and Fixed CCs, and BCs) and the early three BSC stages (Collection, Testing and Processing).

Considering: (1) A set of groups of donors; (2) Different facilities to perform blood withdrawals, each with a limited capacity; (3) Candidate locations for mobile and temporary fixed CCs; (4) The initial state of the system; (5) A fixed planning horizon; (6) BCs having their own mobile CCs; (7) Groups of donors' blood potentials; (8) Each BC's demand; (9) Blood being distinguished by blood group types; (10) WB being processed at BCs to obtain blood products, namely RBC and Platelets; (11) A WB wastage percentage due

to diseases-free testing; (12) A fixed minimum inventory level for each blood group type of blood products; (13) Travel distance and duration for blood withdrawals constraints; (14) Performance indicators and distance travel costs. The model determines mobile CCs routes; facilities location-allocation; temporary fixed CCs to open; schedule definition; and quantity of blood to collect. To: minimize the distance travelled costs; the perceived costs of the blood pack units wasted, shorted, substituted, and transhipped; and the perceived costs of opening temporary fixed CCs.

The conceptual model is shown in Figure 1.

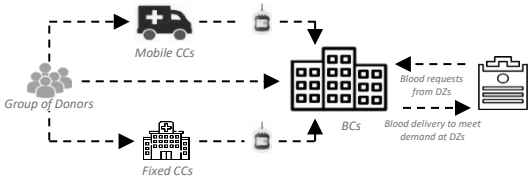

Figure 1 - Problem flows

Mathematical Formulation

The model developed considers a two-stage stochastic programming approach to make realistic decisions regarding supply and demand uncertainty. In the first stage, decisions that do not depend on parameter stochasticity are made, such as mobile CCs routes, location-allocation of facilities, temporary fixed CCs to open, and the schedule definition. Decisions depending on uncertainty, such as the quantity of blood to collect, are delayed for the second stage.

The notation required for the model is presented in Table 1, while model parameters and decision variables are introduced in Table 2.

Table 1 – Model Notation

Sets	
$i, j, b, b', h \in N$	Set of BCs locations and candidate locations for mobile CCs
$f \in F$	Set of fixed CCs locations
$m \in M$	Set of mobile CCs
$d \in D$	Set of groups of donors
$t, t' \in T$	Set of time periods
$p \in P$	Set of WB and derived products
$g, g' \in G$	Set of blood group types
$s \in S$	Set of scenarios
Subsets	
$i, j \in I$	Candidate locations for mobile CCs
$b, b' \in B$	BCs locations
$p \in P^{dp}$	Derived WB products
$f \in F^H$	Hospitals locations
$f \in F^T$	Temporary fixed CCs locations

Table 2 – Parameters and Decision Variables

Parameters	
$dist_{ij}$	Distance from location i to location j
$distfb_{fb}$	Distance from location f to location b
π_{ib}	Correspondence matrix of which locations i belong to BC b
π'_{fb}	Correspondence matrix of which fixed CC at location f transport blood to BC b
t_{mb}	Correspondence matrix of which mobile CC m belong to BC b
ri_{di}	Distance between the centre of a group of donors d and location i
ri_0	Coverage radius of mobile CCs (if $ri_{di} \leq ri_0$, d is covered by i)
rf_{df}	Distance between the centre of a group of donors d and location f
rfH_o	Coverage radius of hospitals (if $rf_{df} \leq rfH_o$, d is covered by $f \in F^H$)
rfT_o	Coverage radius of temporary fixed CCs (if $rf_{df} \leq rfT_o$, d is covered by $f \in F^T$)
rb_{db}	Distance between the centre of a group of donors d and location b
rb_0	Coverage radius of BCs (if $rb_{db} \leq rb_0$, d is covered by b)
$travelt_{ij}$	Travel time from location i to location j
$departur$	Mobile CCs departure time from BCs
$arrival$	Mobile CCs arrival time to BCs
$iniI_{bpg}$	Initial inventory level of blood product p of group type g in each BC b
$Imin_{bpg}$	The minimum stock level of blood product p of group type g in each BC b
β_p	Production factor of blood product p
SL_p	The maximum shelf-life of blood product p
σ^-	Lower bound factor for WB sample wastage
σ^+	Upper bound factor for WB sample wastage
dem_{bpgst}	Demand for blood product p of group type g at BC b in scenario s for time period t
pot_{dgst}	Expected blood potentials of group type g that group of donors d donate in scenario s in time period t
$\Delta_{g'g}$	ABO group compatibility matrix
$\nabla_{g'g}$	ABO group substitution priority matrix
Qm	Mobile CCs capacity
Qv	The capacity of vehicles which transport blood product units from fixed CCs and between BCs
Qb	BCs capacity
$Hmax$	The maximum length of time a mobile CC can be held in a location
$Dmax$	The maximum distance a mobile CC can travel in each period
$OpenHf$	Number of hours a fixed CC is available to perform blood withdrawals
$OpenHb$	Number of hours a BC is available to perform blood withdrawals
$transpC$	Cost of transporting blood pack units per km

$wstC$	Cost per blood product unit wasted
$stgC$	Cost per blood product unit shorted
$trspC_p$	Cost per blood product unit transhipped
$openfC$	Cost per temporary fixed CC open
θ^1	Weight for distance travelled cost
θ^2	Weight for wasted units cost
θ^3	Weight for shorted units cost
θ^4	Weight for ABO substitutions cost
θ^5	Weight for transhipments cost
θ^6	Weight for opening temporary fixed CCs cost
$ps(s)$	Probability of scenario s

Decision Variables

y_{ijmt}	1, if mobile CC m travels from location i to location j in time period t; 0, otherwise
x_{dit}	1, if a group of donors d is assigned to location i in period t; 0, otherwise
x'_{dft}	1, if a group of donors d is assigned to a fixed CC f in period t; 0, otherwise
x''_{dbt}	1, if a group of donors d is assigned to a BC b in period t; 0, otherwise
$openf_{ft}$	1, if a temporary fixed location $f \in F^T$ is open in period t; 0, otherwise
u_{imt}	Visit duration of mobile CC m in location i in time period t
u_{ft}	Amount of time a temporary fixed location $f \in F^T$ is open in time period t
svm_{imt}	The time mobile CC m starts servicing location i in time period t
k_{imgst}	Quantity of blood pack units of group type g collected at location i by mobile CC m in scenario s in time period t
k'_{fgst}	Quantity of blood pack units of group type g collected by fixed CC f in scenario s in time period t
k''_{bgst}	Quantity of blood pack units of group type g collected by BC b in scenario s in time period t
z_{bmt}	1, if mobile CC m is selected with a team of BC b to collect blood in time period t; 0, otherwise
l_{imt}	1, if location i is visited by mobile CC m in time period t; 0, otherwise
fl_{ijt}	Number of arcs on the path from BC b to arc (i,j) in the optimal tour per time period
gl_{ijt}	Arc current from BC b to arc (i,j) in the optimal tour per time period
$iftrans_{fs}$	1, if blood product units are transported from fixed CC f to BC b in scenario s in time period t; 0, otherwise
col_{bgst}	Quantity of blood pack units of group type g collected for BC b in scenario s in time period t
$prod_{bpgst}$	Quantity of blood pack units of blood product p of group type g produced in BC b in scenario s in time period t
$v_{bpgt'st}$	Inventory level at BC b of blood product p of group type g collected in time period t' in scenario s at the end of period t
$del_{bpgg't's}$	Quantity of blood pack units of blood product p of group type g collected in period t' delivered by BC b to satisfy the blood demand of group type g' in scenario s at the end of time period t
$trsp_{b'bpgt}$	Quantity of blood product pack units p of group type g collected in time period t' transhipped from BC b' to BC b in scenario s at period t
$iftrsp_{b'bs}$	1, if blood product units are transhipped from BC b' to BC b in scenario s in time period t; 0, otherwise
wst_{bpgst}	Quantity of blood pack units of blood product p of group type g wasted in BC b because of outdatedness in scenario s at the end of time period t
stg_{bpgst}	Quantity of blood pack units of blood product p of group type g lacking in BC b in scenario s at the end of time period t

The mathematical model for blood collection planning is presented next:

$$minimize\ OverallCost = \theta^1.transpC\left(\sum_{i,j,m,t} dist_{ij}.y_{ijmt} + \sum_{i,j,m,s,t} distfb_{fb}.iftrans_{fst}.ps(s)\right) + \theta^2.wstC.\sum_{b\in B,p,g,s,t} wst_{bpgst}.ps(s) + \theta^3.stgC.\sum_{b\in B,p\in P^{dp},g,s,t} stg_{bpgst}.ps(s) + \theta^4.stgC.\sum_{b\in B,p\in P^{dp},g,g',t',s,t} del_{bpgg't'st}.\nabla_{g'g}.ps(s) + \theta^5.\left(\sum_{b,b'\in B,p\in P^{dp},g,t',s,t} trspC_p.trsp_{b'bpgt'st}.ps(s) + transpC.\sum_{b,b'\in B,s,t} iftrsp_{b'bst}.dist_{bb'}.ps(s)\right) + \theta^6.openfC.\sum_{f\in F^T,t} openf_{ft} \quad \textbf{(1)}$$

Subject to:

$$\sum_{j\in N} y_{ijmt} = l_{imt}, \quad \forall i\in I, i\neq j; m; t \quad \textbf{(2)}$$

$$\sum_{m} l_{imt} \leq 1, \quad \forall i\in I; t \quad \textbf{(3)}$$

$$\sum_{j\in I} y_{bjmt} = z_{bmt}, \quad \forall b\in B; m; t \quad \textbf{(4)}$$

$$\sum_{i\in N} y_{ihmt} - \sum_{j\in N} y_{hjmt} = 0, \quad \forall h\in I; m; t \quad \textbf{(5)}$$

$$\sum_{i\in I} y_{ibmt} = z_{bmt}, \quad \forall b\in B; m; t \quad \textbf{(6)}$$

$$y_{bjmt} \leq \pi_{jb}, \quad \forall b\in B; j\in I; m; t \quad \textbf{(7)}$$

$$y_{ibmt} \leq \pi_{ib}, \quad \forall b\in B; i\in I; m; t \quad \textbf{(8)}$$

$$\sum_{m} y_{bbmt} = 0, \quad \forall b\in B; t \quad \textbf{(9)}$$

$$z_{bmt} \leq t_{mb}, \quad \forall b\in B; m; t \quad \textbf{(10)}$$

$$\sum_{(i,j)} y_{ijmt}.dist_{ij} \le Dmax, \quad \forall i \ne j; m; t \quad (11)$$

$$\sum_{b\in B}\sum_{j\in I} fl_{bjt} = \sum_{m}\sum_{j\in I} l_{jmt}, \quad Vt \quad (12)$$

$$\sum_{j\in N} fl_{jit} - \sum_{j\in I} fl_{ijt} = \sum_{m} l_{imt}, \quad Vi\in I; i \ne j; t \quad (13)$$

$$fl_{ijt} \le (|I|-1).\sum_{m} y_{ijmt}, \quad Vi,j\in I; i \ne j; t \quad (14)$$

$$fl_{bjt} \le |I|.\sum_{m} y_{bjmt}, \quad Vb\in B; j\in I; t \quad (15)$$

$$gl_{bit} \le b.\sum_{m} y_{bimt}, \quad Vb\in B; i\in I; t \quad (16)$$

$$gl_{ibt} \le b.\sum_{m} y_{ibmt}, \quad Vb\in B; i\in I; t \quad (17)$$

$$\sum_{j\in N} gl_{jit} - \sum_{j\in N} gl_{ijt} = 0, \quad Vi\in I; i \ne j; t \quad (18)$$

$$gl_{ijt} \le |I|.\sum_{m} y_{ijmt}, \quad Vi,j\in I; i \ne j; t \quad (19)$$

$$x_{dit}.ri_{di} \le ri_0.\sum_{m} l_{imt}, \quad \forall d; i\in I; t \quad (20)$$

$$x'_{dft}.rf_{df} \le rfH_0, \quad \forall d; f\in F^H; t \quad (21)$$

$$x''_{dbt}.rb_{db} \le rb_0, \quad \forall d; b\in B; t \quad (22)$$

$$x'_{dft}.rf_{df} \le rfT_0 * openf_{ft}, \quad \forall d; f\in F^T; t \quad (23)$$

$$\sum_{i\in I} x_{dit} + \sum_{f} x'_{dft} + \sum_{b\in B} x''_{dbt} \le 1, \quad \forall d; t \quad (24)$$

$$svm_{bmt} \ge departure.\sum_{j} y_{bjmt}, \quad \forall b\in B; m; t \quad (25)$$

$$svm_{jmt} \ge svm_{bmt} + travelt_{bj} - BigM.(1 - y_{bjmt}), \quad \forall b\in B; j\in I; m; t \quad (26)$$

$$svm_{jmt} \ge svm_{imt} + u_{imt} + travelt_{ij} - BigM.(1 - y_{ijmt}), \quad \forall (i,j)\in I, i \ne j; m; t \quad (27)$$

$$svm_{imt} + u_{imt} + travelt_{ib} - BigM.(1 - y_{ibmt}) \le arrival, \quad \forall i\in I; b\in B; m; t \quad (28)$$

$$u_{imt} \le Hmax.l_{imt}, \quad \forall i\in I; m; t \quad (29)$$

$$u'_{ft} \le OpenHf.openf_{ft}, \quad \forall f\in F; m; t \quad (30)$$

$$\sum_{d} pot_{dgst}.x_{dit}.u_{imt} \ge k_{imgst}, \quad \forall i\in I; g; m; s; t \quad (31)$$

$$\sum_{d} pot_{dgst}.x'_{dft}.u'_{ft} \ge k'_{fgst}, \quad \forall f\in F^T; g; s; t \quad (32)$$

$$\sum_{d} pot_{dgst}.OpenHf.x'_{dft} \ge k'_{fgst}, \quad \forall f\in F^H; g; s; t \quad (33)$$

$$\sum_{d} pot_{dgst}.OpenHb.x''_{dbt} \ge k''_{bgst}, \quad \forall b\in B; g; s; t \quad (34)$$

$$col_{bgst} = \sum_{i\in I}\sum_{m} k_{imgst}.\pi_{ib} + \sum_{f} k'_{fgst}.\pi_{fb} + k''_{bgst}, \quad \forall b\in B; g; s; t \quad (35)$$

$$\sum_{i\in I}\sum_{g} k_{imgst} \le Qm, \quad \forall m; s; t \quad (36)$$

$$\sum_{g} k'_{fgt} \le iftrans_{fst}.Qv, \quad \forall f; s; t \quad (37)$$

$$prod_{bpgst} \le \beta_p.col_{bgst}, \quad \forall b\in B; p\in P^{dp}; g; s; t \quad (38)$$

$$wst_{b"WB"gst} \ge \sigma^-.col_{bgst}, \quad \forall b\in B; g; s; t \quad (39)$$

$$wst_{b"WB"gst} \le \sigma^+.col_{bgst}, \quad \forall b\in B; g; s; t \quad (40)$$

$$\frac{prod_{bpgst}}{\beta_p} + wst_{bWBgst} = \beta_p.col_{bgst}, \quad \forall b\in B; p\in P^{dp}; g; s; t \quad (41)$$

$$v_{bpgtst} = inil_{bpg} + prod_{bpgst} - \sum_{g'} del_{bpgg'tst}.\Delta_{g'g} + \sum_{b'\in B} trsp_{b'bpgtst} - \sum_{b'\in B} trsp_{bb'pgtst}, \quad \forall b\in B; b' \ne b; p\in P^{dp}; g; s; t = 1 \quad (42)$$

$$v_{bpgtst} = prod_{bpgst} - \sum_{g'} del_{bpgg'tst}.\Delta_{g'g} + \sum_{b'\in B} trsp_{b'bpgtst} - \sum_{b'\in B} trsp_{bb'pgtst}, \quad \forall b\in B; b' \ne b; p\in P^{dp}; g; s; t > 1 \quad (43)$$

$$v_{bpgt'st} = v_{bpgt's(t-1)} - \sum_{g'} del_{bpgg't'st}.\Delta_{g'g} + \sum_{b'\in B} trsp_{b'bpgt'st} - \sum_{b'\in B} trsp_{bb'pgt'st} - v_{bpg(t-SL)s(t-1)}, \quad \forall b\in B; b' \ne b; p\in P^{dp}; g; t-SL \le t' < t; s; t \quad (44)$$

$$\sum_{t'=t-SL}^{t} v_{bpgt's t} \ge Imin_{bpg}, \quad \forall b\in B; p\in P^{dp}; g; s; t \quad (45)$$

$$\sum_{p\in P^{dp}}\sum_{g}\sum_{t'=t-SL}^{t} v_{bpgt's t} \le Qb, \quad \forall b\in B, s; t \quad (46)$$

$$\sum_{t'=t-SL}^{t}\sum_{g'} del_{bpggt't'st}.\Delta_{g'g} = dem_{bpgst} + stg_{bpgst}, \quad \forall b\in B; p\in P^{dp}; g; s; t \quad (47)$$

$$\sum_{t'=t-SL} v_{bpgt's(t-1)} = wst_{bpgst}, \quad \forall b\in B; p\in P^{dp}; g; s; t \quad (48)$$

$$\sum_{p\in P^{dp},g,t,t'} trsp_{bb'pgt'st} \le iftrsp_{b'bst}.Qtrsp, \quad \forall (b,b')\in B; s; t \quad (49)$$

The objective function (1) minimizes costs weighted by six parameters that control the relative importance of each objective function term denominated by indicators. The objective function minimizes the distance travelled costs; the perceived costs of the blood pack units wasted, shorted, substituted, and transhipped; and the perceived costs of opening temporary fixed CCs.

Constraints (2) guarantee that if there is an arc leaving node i by mobile CC m in period t, then node i must have been visited. Constraints (3) force each location

to be visited no more than once each period. Constraints (4)-(6) are arc flow constraints for each time period t indicating that if a mobile CC has at least one location to visit then, it must leave from a BC b, after visiting a location i it has to leave for another destination, and, finally, it must arrive at the BC b. Constraints (7) and (8) ensure that if a mobile CC m leaves or arrives from or to BC b, mobile CC must travel to or from a location which belongs to BC b coverage area, respectively. Constraints (9) forbids tours between BCs. Since each BC has its own mobile CCs, then constraints (10) ensure that a mobile CC m leaves only from its respective BC. Constraints (11) limit the total travel distance of mobile CC m in each period.

Constraints (12)-(15) eliminate possible subtours by applying the single commodity flow formulation proposed by Gavish & Graves (1978). Constraints (16)-(19) define the arc-current formulation proposed by Bektas, Gouveia, & Santos (2020), which is used to ensure that mobile CCs return to their original BC at the end of their route. Constraints (20)-(23) indicate coverage restrictions for each facility. To guarantee that group of donors donate blood at the nearest location, constraints (24) assure that in each time period, each group of donors only donate to one of the donation locations, namely the closest one.

Constraints (25)-(28) define the schedule constraints for mobile CCs regarding departure and arrival time at BC and candidate locations. Constraints (29) and (30) limit the number of hours a mobile, or temporary fixed CCs can perform blood withdrawals, respectively, in time period t. Constraints (31)-(34) define the amount of blood pack units of each blood group type that can be collected by each facility from the respective allocated groups of donors. Constraints (35) define the total blood pack units of group type g collected from mobile CCs, fixed CCs, and the BC itself which belong to the BC's cover region in scenario s in time period t. Constraints (36) and (37) are capacity constraints for mobile and fixed CCs, respectively, in each time period and per scenario s. The WB available at a BC in scenario s in time period t is decomposed into derived blood products according to a given production ratio, as constraints (38) define. Before processing, blood must be tested to ensure the donor is diseases free. As in this testing stage, the blood sample tested is wasted, constraints (39) and (40) ensure minimum and maximum blood wastage from the WB collected, respectively. Constraints (41) assure the flow conservation of WB in each BC.

Constraints (42)-(44) model are inventory conservation constraints for each BC in every time period per scenario s. Constraints (45) and (46) ensure a minimum and maximum stock level at BCs, respectively. If the blood delivered by BCs does not satisfy all the blood product demand, there is a shortage of the blood packs units, modelled by constraints (47). Constraints (48) define that the blood not used before the end of its shelf-life is wasted. Finally, constraints (49) ensure the vehicle capacity constraints when transhipping blood products units between BCs.

5. RESULTS

This section presents the model's application to deterministic and stochastic cases based on 2019 Portuguese BSC data. The model was implemented in GAMS and solved through the IBM ILOG CPLEX solver version 12.8 in multi-thread mode. The experiments were conducted on a computer with two 6-Core 3.33 GHz Intel® Xeon® X5680 processors with 12 threads and 24.0 GB of RAM.

Deterministic Cases

Current Case

The Current Case considers annual 2019 data for blood potentials and demand, converted into hourly and daily data, respectively. Through an activity level regarding the studied municipalities population, Oporto has the highest blood potentials, followed by Braga, Lisbon, Setubal, Aveiro, and Leiria. The activity level was also used to deduct the BCs blood demand, higher at CSTL followed by CSTP and CSTC. The blood potentials per hour are generated with a Normal distribution, while daily blood demand is generated with a Poisson distribution.

By testing the Current Case, no shortage occurred during the 7-day planning horizon. However, 12 per cent of the blood delivered by BCs to meet DZs demand, was transhipped between BCs. The resulted planning decisions show that transhipment was necessary for CSTL at each day of the planning horizon. Transhipment was made mostly by CSTC but also by CSTP. As there is an unbalance between blood pack units collected and transfused at CSTL, it means that the region is not self-sufficient. In addition, 0.8 per cent of the blood delivered substituted the demand of a compatible blood group type at CSTL. Regarding blood wastage, 2 per cent of WB collected is wasted after diseases-free testing, and 17 per cent of the platelets produced are wasted due to outdatedness.

That is, considering a platelets shelf-life of six days, in the seventh day of the planning horizon, platelets pack units not delivered to DZs are wasted.

Regarding planning decisions, in the Northern and Southern regions, all candidate locations are visited by mobile CCs. In contrast, in the Centre region, all candidate locations are visited only in the first four days of the planning horizon. In the last three days, only two locations are visited at Leiria or Aveiro. In addition, temporary fixed CCs are open only in the first three days. When a mobile or temporary fixed CCs is not visited or open, respectively, it means that or groups of donors are not willing to donate blood, i.e., blood potentials are almost zero, or there is no need to collect blood in those locations.

Regarding objective function perceived costs, the highest indicator cost is the blood units transhipment indicator, representing 78.73 per cent of the total cost followed by the blood wastage and blood substitution with 17.62 per cent and 3.07 per cent.

Tragic Case

When a tragedy occurs, blood must be available in enough quantities to meet the unusual demand. The Tragic Case is based on the 2019 annual demand, which is considered to increase one hundred per cent. To assess the model behaviour, two weeks of the crisis are considered. In both weeks, the demand is assumed to increase one hundred per cent. Regarding blood potentials, in the first week, 2019 blood potentials are considered. However, in the second week, donations increase (due to awareness increase of the ongoing crisis) as if all registered donors had donated 1.55 times during the year.

Despite efforts, a shortage is expected to occur, being CSTL the BC with the highest shortage level as available blood potentials in the region is not proportional to the demand. In general, the shortage units represent 22 per cent of demand.

Comparing Current and the first week of a Tragic Case, the cost of the distance travelled is slightly higher for the Tragic Case. Regarding temporary fixed CCs to open, with higher demand, the need has increased to collect blood from donors not covered by other facilities. Regarding wastage indicator, as the platelets' production factor compared to the RBC production factor is high, for the same blood potentials, more platelets pack units are used to meet the increased demand reducing the blood products wastage. Regarding substitution cost, in crises, all collected blood is vital. Thus, higher demand levels trigger a need to use compatible blood group types to meet the demand for another blood group type instead of shortage. Finally, looking at the transhipment cost, while in the Current Case both CSTC and CSTP have the opportunity to tranship blood for CSTL, in the first week of the Tragic Case, CSTP must meet the regional demand. Thus, CSTC is the only BC transhipping blood. By analysing the planning decisions for the second week of the Tragic Case, groups of donors visit all the possible locations where blood withdrawals can be performed during all two weeks, except one location in Lisbon on day 6 of the first week. This exception is related to the unwillingness to donate of groups of donors, covered by the mobile CC that could have visited the candidate location. Even if the group of donors' blood potentials are low (but higher than zero), the model decided that it was not worth the visit of a mobile CC.

The comparison between the total costs for two weeks during the simulated crisis is depicted in Figure 2.

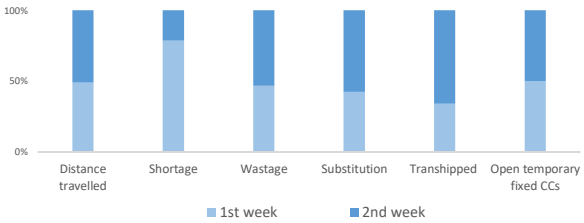

Figure 2 - Total Cost comparison for the two weeks of the Tragic Case.

In the second week, donors' awareness increases as well as the willingness to donate to help the population. This increase in blood donations has a significant impact on the shortage level. In consequence of the donations increasing throughout the country, there is a higher opportunity to tranship blood between BCs. In addition, the higher availability of blood products of all blood group types allows the use of compatible blood group types to satisfy the demand of others which is better than death. Moreover, mobile CCs capacity becomes short in specific time periods which forces the use of more mobile CCs to visit the locations that in a typical day were visited only by one mobile CC. Thus, the distance travelled in the second week is higher than in the first week.

The Tragic Case analysis allows to state that the model proposed in this work is an efficient tool to simulate a crisis. With the simulation, conclusions can be made on which planning decisions to make, and capacity constraints that should be changed.

Two-stage Stochastic Approach

The two-stage stochastic approach is based on scenarios to address parameter uncertainty. The scenarios must be defined previously, differing in blood demand and blood potentials levels, as well as their probability of occurring. The approach was tested with nine different scenarios in which usual donors donate per year only one time or 1.55 times, and registered donors donate 1.55 while the demand varies ±10 per cent. Figure 3 identifies the scenarios used.

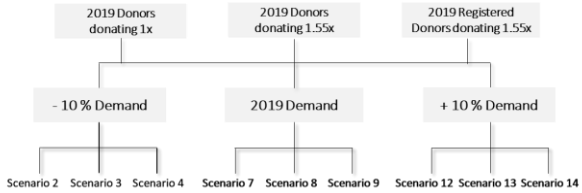

Figure 3 - Scenarios used for the two-stage stochastic approach.

Regardless of the scenario, planning decisions for a 7-day planning horizon such as mobile CCs routes, the location-allocation facilities, and which temporary fixed CCs to open are decisions that are taken earlier, for instance, at the beginning of the week.

By analysing the planning decisions, the model decides the visit of all candidate locations by mobile CCs during the planning horizon. However, only in scenarios S4, S9, S12, and S14 mobile CCs collect blood in all visited locations during the 7-day planning horizon. Despite there are inefficiencies regarding the visit of locations and blood collection in those locations, it is essential to note that the stochastic approach returns a more robust solution than deterministic approaches since the solution regards nine different scenarios.

Regarding temporary fixed CCs, the model decides the opening during the planning horizon except on the last day. Figure 4 depicts the number of times temporary fixed CCs are open during the 7-day planning horizon and number of times those perform blood withdrawals per scenario.

Considering the instance used, only in scenario S12, the temporary fixed CC opening rate at Aveiro is equal to its utilization rate. This unbalance creates inefficiencies in the blood collections planning. However, the most valuable performance indicator is patient service. Therefore, to ensure the facilities availability in case donors are willing to donate is preferable than a shortage in BCs and consequently, cause surgeries delay or even deaths.

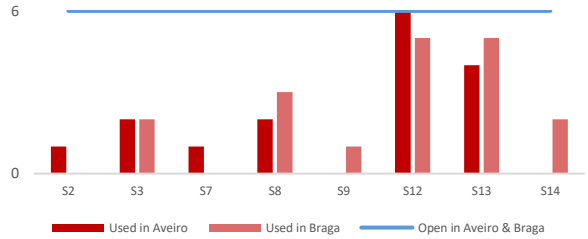

Figure 4 - Open temporary fixed CCs per location vs temporary fixed CCs used per location per scenario.

It is interesting to assess planning decisions recommended by the model as well as their impacts on costs in the realization of each scenario. Figures 5 represents the costs per distance travelled and temporary fixed CCs to open indicators per scenario per deterministic or stochastic approach.

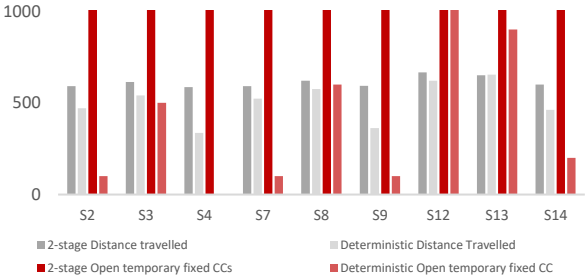

Figure 5 – Distance travelled and opened temporary fixed CCs indicators costs per scenario per approach.

Regarding the two-stage approach, there is a variation of the distance travelled related to the distance travelled by vehicles since the transportation of blood units depends on the scenarios. Although temporary fixed CCs are open during the first six days of the planning horizon, there are time periods in different scenarios that blood withdrawals are not performed in these facilities. That is why the distance travelled indicator's variation is not always the same since there is no blood to transport from temporary fixed CCs to BCs every time temporary fixed CCs are open.

Despite blood collection planning being different between the deterministic and two-stage stochastic approach, the second stage costs are equivalent per scenario. That is due to the opportunity of facilities to choose how much blood to collect to meet demand.

When comparing the stochastic approach solution with each scenario's deterministic solution, there are inefficiencies as if perfect information of uncertain parameters' events was available. As perfect information regarding uncertain parameters is not realistic, the two-stage solution is a more robust solution having redundancy. It ensures high quality of patient service for the occurrence of the nine different scenarios considered.

6. CONCLUSIONS

The BSC is a highly complex system which is designed to ultimately save lives. In this dissertation, the BSC system is studied. Supported on a literature review a two-stage stochastic programming model is proposed. This is applied to the Portuguese BSC using 2019 data with the main goal of improving the Portuguese BSC assisting IPST on blood collection planning while maintaining the service level and considering the BSC characteristics. To do so, mobile CC routes, facilities location-allocation, which temporary fixed CCs to open, the schedule for blood withdrawals and the blood quantity to collect have to be decided. The objectives considered in the model are to minimize costs associated with: distance travelled; shortage, wastage; transhipment of blood pack units; substitutability of blood group types; and temporary fixed CCs to open.

To understand the model behaviour, several cases are studied. The Current Case application proves that Portuguese BCs are not self-sufficient being necessary to transhipment blood mostly between CSTL and other regions. The Tragic Case analysis allows to state that the model proposed in this work is an efficient tool to simulate a crisis. With the simulation, conclusions can be made on which planning decisions to make and capacity constraints that should be changed. By applying the two-stage stochastic approach, the solution is more reliable and robust. It is effective for different scenarios, only with a cost increase of 17 per cent between deterministic and two-stage stochastic approaches as if perfect information regarding uncertainty was known in advance.

This research's main contributions are a model of a BSC system with multiple facilities for groups of donors donate blood and the integration of the main concerns and particularities for proper BSC management.

Besides overcoming limitations regarding data collection, suggestions for future work include: (a) the deferral time consideration; (b) a decrease in donations should be considered when a mobile CC visits the same location in consecutive days; (c) shuttles consideration to pick up the donated blood at mobile CCs; (d) staff allocation; (e) different collection methods; (f) inefficiency cost for the resources spent in locations where donors are not willing to donate; (g) lost opportunity cost of cancelling a location visit. Finally, as the model performance is relatively low due to its high complexity, which creates dimensioning issues, different solution approaches could be considered.

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