Blood Supply Chain Planning: the case of the Southern region of Portugal

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Abstract

The blood supply chain comprises the activities of collecting, testing, processing and distributing blood and blood products, from donor to patient. Blood products are transfused to patients as part of routine medical treatments or surgical operations and in emergency situations. The availability of the right blood products at the right time in the right quantity is critical for the health provision since shortages can be fatal to patients. The management of these products is particularly challenging. Matching supply and demand in an efficient manner is not straightforward: the supply of donor blood is irregular while the demand for blood products is highly stochastic, and there is a wide range of blood types and products. Moreover, blood products are perishable which hinders the stock accumulation and pressures the stock management. An efficient blood supply chain planning should meet demand while at the same time reduce wastage and minimize costs. In this work an optimization model is proposed to handle tactical and operational decisions, which is then be applied to the case study of the Southern region of Portugal. To do so, a two-stage approach is explored, resorting to an aggregated fist stage to tackle planning decisions and a disaggregated second stage to look into the operational side of the problem. The objective is cost minimization, incorporating also the goals of reducing waste and diminishing the dependency of the southern region of the other two defined national regions. This is the first study ever conducted regarding the Portuguese blood supply chain and presents a case study application in cooperation with Centro de Sangue e Transplantao de Lisboa, a regional blood centre belonging to Instituto Portugus do Sangue e da Transplantao.
Keywords: Blood Supply Chain, Perishability, Supply Chain Management, Mixed Integer Programming

1. Introduction

Companies across the globe strive to reach a competitive edge, which can in fact be achieved by incorporating in their day-to-day activities the all-important management of their supply chains (Barbosa-Póvoa, 2014). Supply chain management can, in this way, be defined as management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole (Christopher, 2011). The overall goal of attaining an effective and organized supply chain by adopting an integrated view of it, can and should be applied to different industries, such as healthcare. The blood supply chain (BSC) is no different from any other industry in the sense that it can stand a lot to gain from its proper management.

The blood supply chain comprises the evolution and tracking of blood and blood components from donor to recipient. These blood products are transfused to patients in the context of surgical procedures, routine medical practices and in emergency situations. In this way, the blood supply chain encompasses several day-to-day activities, making it possible to provide the final blood products required for such tasks. These include the processes of collecting, testing and processing blood and blood products prior to their distribution (Osorio et al., 2015).

Blood and its derived components cannot be considered as conventional products. In fact, they are remarkable in the sense that the consequences of mishandling them may lead to catastrophic consequences, implicating human lives. A shortage in blood supply is likely going to hinder scheduled procedures or, more seriously, resulting in a patient's untimely death, therefore potentially having a negative impact in mortality rate. On the other hand, surplus may very well be proceeded by outdates which have significant repercussions society-wise, as it is ethically wrong to waste such a valuable and scarce commodity with increasingly lower do-

nation numbers (21,74 donors per 1000 inhabitants in 2016 in Portugal the lowest number in the last nine years) (Beliën and Forcé, 2012). Furthermore, we need to consider that the need for such products will never cease to exist, which is why this is such a worthy topic to be studied and its importance acknowledged.

The management of the blood supply chain, although crucial, is particularly challenging due to a variety of reasons, ranging from the perishability of the products, which is not only short, but also different between them; to the challenge of matching supply and demand, being the supply of donor blood irregular while the demand for blood products highly stochastic. Moreover, there is an array of blood products that can be derived from whole blood, with RBC requiring blood group compatibility, further increasing the complexity of the problem. Finally, it is also important to understand that an efficient blood supply chain planning should not only meet demand but at the same time reduce wastage and minimize costs (Osorio et al., 2015).

Literature on the topic exists, some focusing on each echelon of the supply chain and few in integrated views of the whole network. Notwithstanding, literature focusing on the Portuguese blood supply chain is non-existing. With this work, we intend to shed some light on the Portuguese case and mitigate fragilities of the system, closing this gap.

Hence, the aim of this work is to characterize the Portuguese blood supply chain and to improve the main identified sources of inefficiencies by proposing an optimization model to handle tactical and operational decisions.

2. Case Study

This paper addresses a real case-study conducted in collaboration with Instituto Portugus do Sangue e da Transplantao (IPST), responsible for the regulation and management of the Portuguese BSC. This entity has jurisdiction over the national territory, being subdivided in three regions of operation, each with a regional blood centre. In particular, this work was done in cooperation with Centro de Sangue e Transplantao de Lisboa (CSTL), the regional blood centre for the regions of Algarve, Alentejo and Lisboa e Vale do Tejo, restricting the focus of the study to the Southern region of Portugal. The objective is to characterize the Portuguese BSC identify the main sources of inefficiencies and propose adequate measures for the improvement of its operation.

The Portuguese BSC network is composed of donors, collection points, processing centres and demand zones. Donors donate whole blood at temporary collection facilities, fixed collection points or even at some processing centres. Collected blood is then shipped from both collection points to a processing centre, for instance, to the regional blood centre CSTL, where it is separated into its many components in order to produce the desired final products, which are then stored awaiting shipment to demand zones. Simultaneously, samples of the drawn blood are analysed for various viruses and diseases, which either clears the blood products for distribution or sentences them to disposal.

Based on this network, it is possible to establish the main echelons of the Portuguese BSC, which are depicted in figure 1.

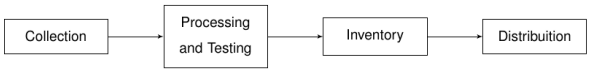

Figure 1: Portuguese Blood Supply Chain echelons.

Starting with collection, this is the stage of the BSC entailing the attainment of whole blood in order to satisfy demand, and there two main methodologies for collection, namely whole blood collection or aphaeresis, where only some components are collected. Follows processing, where collected whole blood is separation into components, mainly red blood cells (RBC), pools of platelets and plasma. Inventory management of these components is particularly challenging due to their short perishability, and the methodology adopted is First In First Out (FIFO). Minimum stock levels are also established at both processing centres and demand zones in order to respond to emergency situations that may arise. Finally, distribution of blood products from processing centres to demand zones is dependent on the allocation made daily by the on-call physician at the former location, considering distances, existing stocks, and hospitals' activities.

The proper management of the BSC as a whole is critical in avoiding extra costs and inefficiencies and flows between the BSC chain echelons are crucial to this end. In the current paradigm, allocations are not well-defined, which may present a source of inefficiency and disorganization. This will, therefore, be the main issue addressed by the present study, with focus on problems and decisions at the tactical and operational levels. At the planning level, allocation decisions are studied, while at the operational level, production and inventory decisions are considered. Accordingly, the problems addressed are, given the existing infrastructures for the three echelons of the network (collection, production and demand facilities) as well as supply and demand, study blood flows, production and distribution, assuring demand satisfaction and with the objective of minimizing total costs. To do so, a two-stage approach was adopted, both resorting to an optimiza-

tion model that tries to accurately depict the BSC network. The first stage addresses allocation decisions at the planning level, using an aggregated and more simplistic model, whereas in the second stage, a more complex and time refined model is used to look in more detail into the more operational side of the BSC.

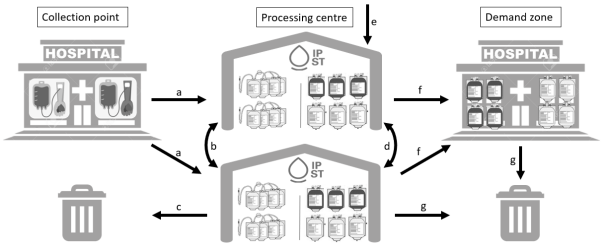

Figure 2: Model decisions.

3. Model description

The model developed to portray the BSC contemplates the last three echelons of the BSC represented in figure 1. The decision of not modelling the donor echelon lies primarily with the purpose of the work itself, which, at this point, is to study the flows within the network, considering collection as input.

The proposed model for the BSC is depicted in figure 2 and includes collection points, processing centres and demand zones, mostly hospitals. The flow starts at the collection points, where collected blood must be allocated to a processing centre and shipped there. All collected blood must be transferred to a processing centre within the same day it is collected, as it has a 24-hour period to be separated. Once at the processing centre, whole blood units are separated into its components, here under study are red blood cells (RBC) and platelet pools. Derived components that are cleared from previous testing must be conserved at specific conditions and present different shelf-lives. In this case, RBC can last up to 42 days, whereas pools have a time-span of only 5 to 7 days. Plasma has a much greater shelf-life, of approximately 3 years, which is why it is not considered in the proposed model. The blood products are kept stored in the processing centres until requested from demand zones. The allocation of these products is up to the processing centre, although there is an obvious tendency to dispatch products with shorter remaining shelf-lives first, following a FIFO policy. Processing centres also have the option of buying blood products from other regions within Portugal, which is why a purchase flow is introduced in the model, this option being discouraged by associating it with superior costs. Requests from demand zones arrive daily, according to hospital's needs and usage rates. Once at the demand zones, products are kept in inventory until needed for transfusion.

The decisions incorporated in the model are the following:

1. The amount of whole blood transported from collection points to processing centres at each period (a).
2. The amount of whole blood transported between processing centres at each period (b).
3. The quantity of blood products, produced by each processing centre at each period.
4. The quantity of wasted whole blood units by each processing centre at each period associated with not processing it (c).
5. The inventory level of each product in both processing centres and demand zones at the end of each period.
6. The amount of blood products transported between processing centres at each period (d).
7. The amount of purchased units of blood products at each processing centre at each period (e).
8. The amount of blood products transported from processing centres to demand zones at each period (f).
9. The units of blood products from inventory to be consumed by the demand zones at each period.
10. The quantity expired blood products in each processing centre and demand zone at each period (g).

Moreover, the following assumptions were taken into account to formulate the proposed model:

- The BSC is single product prior to processing (whole blood) and multi-product thereafter (RBC and pools).
- The perishability of the products, which is considered since they are produced until transfused. It is of 42 days for RBC and 5 days for pools.

- The blood group types, which are considered for whole blood and RBC. This is incorporated by considering the distribution of these blood types in the population, as well as demand distribution.
- The production rate, which means there is a ratio of 1:1 between whole blood and RBC, but to produce 1 unit of platelet pools it is requires 4 units of whole blood of the same group type.
- The storage capacity of the processing centres which is limited.
- The inventory levels, which are considered at both processing centres and demand zones, where minimum levels are defined.
- Shortages at demand zones are not allowed, which means the model is obliged to satisfy demand (demand zone consumption plus minimum inventory levels).
- The possibility of purchasing blood products, introducing a purchase flow at the processing centre level.
- Wastes are considered and have associated costs. There is whole blood waste associated with the decision to not produce (for example in cases of too much collection) and blood product waste, associated with unused expired blood products

4. Model formulation

4.1. Indices and sets

$i \in I$	set of existing collection points
$j, j' \in J$	set of existing processing centres
$h \in H$	set of existing demand zones
$t, t' \in T$	set of time periods
$p \in P$	set of derived products
$g \in G$	set of blood group types

4.2. Parameters

ai_{ij}	Transportation cost per blood pack unit between collection point i and processing centre j
$aj_{jj'}$	Transportation cost per blood pack unit between processing centre j and processing centre j' [$aj_{jj'} = 0$ if $j = j'$]
ah_{jh}	Transportation cost per unit of product between processing centre j and demand point h
b_{pj}	Unit production cost of product p at processing centre j
c_p	Unit holding cost of product p
cwb_j	Unit disposal cost per blood pack unit at processing centre j
cwp_p	Unit disposal cost per unit per unit of product p
cu_p	Purchase cost per unit of product p
d^t_{gh}	Total consumption in blood pack units for zone h for group type g of product RBC in period t
$dpool^t_h$	Total consumption in blood pack units for zone h of product PLT in period t
ilj^t_{gj}	Minimum inventory level in blood pack units of group type g of product RBC at processing centre j and in period t
$iljpool^t_j$	Minimum inventory level in blood pack units of product pool at processing centre j and in period t
s_{pj}	Storage capacity of product p at processing centre j
τ_p	Maximum time product p can be used before perishing
α	Percentage of wasted blood after processing
β_{RBC}	Minimum inventory factor for RBC
β_{pool}	Minimum inventory factor for pools
γ	Factor for number of days considered in the minimum inventory level calculus
cap_j	Production capacity of processing centre j
M	Very large number
δ_p	Production factor dependent on product p
ki^t_{gi}	Collected whole blood of group type g in blood pack units at collection point i in period t
kj^t_{gj}	Collected whole blood of group type g in blood pack units at processing centre j in period t
$isinicial^t_{gpjt'}$	Initial inventory of product p of group type g produced in perior t' in blood pack units at processing centre j in period t
$ihinicial^t_{gpht'}$	Initial inventory of product p of group type g produced in perior t' in blood pack units at demand zone h in period t
XI_{ij}	Allocation of collection centre i to processing centre j
XH_{jh}	Allocation of demand zone h to processing centre j

4.3. Variables

SI^t_{gij}	Quantity in blood pack units of group type g transported from collection point i to processing centre j in period t

$SJ^t_{gjj'}$	Quantity in blood pack units of group type g transported from processing centre j to processing centre j' in period t
$VJ^t_{gpjj't'}$	Quantity in blood pack units of group type g of product p produced in period t' transported from processing centre j to processing centre j' in period t
$VH^t_{gpjht'}$	Quantity in blood pack units of group type g of product p produced in period t' transported from processing centre j to demand zone h in period t
CO^t_{gpj}	Quantity in blood pack units of group type g of product p purchased by processing centre p in period t
BP^t_{gpj}	Quantity in blood pack units of group type g of product p produced in processing centre in period t
$IS^t_{gpjt'}$	Inventory level of group type g of product p produced in period t' at processing centre j at the end of period t
$IH^t_{gpht'}$	Inventory level of group type g of product p produced in period t' at demand zone h at the end of period t
ILH^t_{gh}	Minimum inventory in blood pack units of group type g of product RBC at demand zone h in period t
$ILHPLT^t_h$	Minimum inventory in blood pack units of product PLT at demand zone h in period t
$U^t_{gpht'}$	Quantity in blood pack units of group type g of product p produced in period t' used in demand zone h in period t
WB^t_{gj}	Waste quantity of group type g at processing centre j at the end of period t
WP^t_{gpj}	Waste quantity of group type g of product p at processing centre j at the end of period t
WH^t_{gph}	Waste quantity of group type g of product p at demand zone h at the end of period t

4.3.1 Objective function and constraints

$$
\begin{aligned}
minZ = &\sum_i \sum_j \sum_g \sum_t SI^t_{gij} ai_{ij} + \sum_j \sum_{j'} \sum_g \sum_t SJ^t_{gjj'} aj_{jj'} + \sum_j \sum_{j'} \sum_g \sum_p \sum_{t'} \sum_t VJ^t_{gpjj't'} aj_{jj'} \\
&+ \sum_j \sum_h \sum_g \sum_p \sum_{t'} \sum_t VH^t_{gpjht'} ah_{jh} + \sum_p \sum_g \sum_j \sum_{t'} \sum_t IS^t_{gpjt'} c_p \\
&+ \sum_p \sum_g \sum_h \sum_{t'} \sum_t IH^t_{gpht'} c_p + \sum_p \sum_j \sum_g \sum_t BP^t_{gpj} b_{pj} + \sum_p \sum_g \sum_j \sum_t CO^t_{gpj} cu_p \\
&+ \sum_j \sum_g \sum_t WB^t_{gj} cwb_j + \sum_p \sum_g \sum_j \sum_t WP^t_{gpj} cwp_p + \sum_p \sum_g \sum_h \sum_t WH^t_{gph} cwp_p
\end{aligned} \tag{1}
$$

Subject to:

$$\sum_g SI^t_{gij} \leq cap_j \cdot XI_{ij} \qquad \forall i \in I, j \in J, t \in T \tag{2}$$

$$\sum_g \sum_p \sum_{t'} VH^t_{gpjht'} \leq M \cdot XH_{jh} \qquad \forall j \in J, h \in H, t \in T \tag{3}$$

$$ki^t_{gi} = \sum_j SI^t_{gij} \qquad \forall g \in G, i \in I, t \in T \tag{4}$$

$$BP^t_{gpj} \leq \delta_p (\sum_i SI^t_{gij} + \sum_{j' \neq j} SJ^t_{gj'j} - \sum_{j' \neq j} SJ^t_{gjj'} + kj^t_{gj}) \qquad \forall g \in G, p \in P, j \in J, t \in T \tag{5}$$

$$WB^t_{gj} \leq (\sum_i SI^t_{gij} + \sum_{j' \neq j} SJ^t_{gj'j} - \sum_{j' \neq j} SJ^t_{gjj'} + kj^t_{gj})\alpha \qquad \forall g \in G, j \in J, t \in T \tag{6}$$

$$\frac{1}{\delta_p} BP^t_{gpj} + WB^t_{gj} + \sum_{j' \neq j} SJ^t_{gjj'} = \sum_i SI^t_{gij} + \sum_{j' \neq j} SJ^t_{gj'j} + kj^t_{gj} \qquad \forall g \in G, p \in P, j \in J, t \in T \tag{7}$$

$$IS^t_{gpjt'} + \sum_h VH^t_{gpjht'} + \sum_{j'} VJ^t_{gpjj't'} = BP^t_{gpj}$$
$$+ \sum_{j'} VJ^t_{gpj'jt'} + CO^t_{gpj} \qquad \forall g \in G, p \in P, j \in J, t = t' \in T \qquad (8)$$

$$IS^t_{gpjt'} = IS^{t-1}_{gpjt'} - \sum_h VH^t_{gpjht'} - \sum_{j'} VJ^t_{gpjj't'}$$
$$+ \sum_{j'} VJ^t_{gpj'jt'} \qquad \forall g \in G, p \in P, j \in J, t, t' \in T, t > t' > t - \tau_p \qquad (9)$$

$$\sum_g \sum_{t-\tau_p < t' \leq t} IS^t_{gpjt'} \leq s_{pj} \qquad \forall p \in P, j \in J, t \in T \qquad (10)$$

$$\sum_{t-\tau_p < t' \leq t} IS^t_{g,RBC,jt'} \geq ilj^t_{gj} \qquad \forall g \in G, j \in J, t \in T \qquad (11)$$

$$\sum_g \sum_{t-\tau_p < t' \leq t} IS^t_{g,pool,jt'} \geq iljpool^t_j \qquad \forall j \in J, t \in T \qquad (12)$$

$$\sum_h \sum_{t' \leq t-\tau_p} VH^t_{gpjht'} = 0 \qquad \forall g \in G, p \in P, j \in J, t \in T \qquad (13)$$

$$\sum_{j'} \sum_{t' \leq t-\tau_p} VJ^t_{gpjj't'} = 0 \qquad \forall g \in G, p \in P, j \in J, t \in T \qquad (14)$$

$$IH^t_{gpht} = \sum_j VH^t_{gpjht} - U^t_{gpht} \qquad \forall g \in G, p \in P, h \in H, t, t' \in T \qquad (15)$$

$$IH^t_{gpht'} = IH^{t-1}_{gpht'} - U^t_{gpht'} + \sum_j VH^t_{gpjht'} \qquad \forall g \in G, p \in P, h \in H, t, t' \in T, t - \tau_p < t' < t \qquad (16)$$

$$ILH^t_{gh} = \beta_{RBC} \sum_{t-\gamma}^{t+\gamma} d^t_{gh} \qquad \forall g \in G, h \in H, t \in T \setminus \{1, ..., \gamma, \mid T \mid -\gamma + 1, ..., \mid T \mid\} \qquad (17)$$

$$ILHPLT^t_h = \beta_{pool} \sum_{t-\gamma}^{t+\gamma} dpool^t_h \qquad \forall h \in H, t \in T \setminus \{1, ..., \gamma, \mid T \mid -\gamma + 1, ..., \mid T \mid\} \qquad (18)$$

$$\sum_{t-\tau_p < t' \leq t} IH^t_{g,RBC,ht'} \geq ILH^t_{gh} \qquad \forall g \in G, h \in H, t \in T \qquad (19)$$

$$\sum_g \sum_{t-\tau_p < t' \leq t} IH^t_{g,pool,ht'} \geq ILHPLT^t_h \qquad \forall h \in H, t \in T \qquad (20)$$

$$WP^t_{gpj} = \sum_{t'=t-\tau_p} IS^{t-1}_{gpjt'} \qquad \forall g \in G, p \in P, j \in J, t \in T \qquad (21)$$

$$WH^t_{gph} = \sum_{t'=t-\tau_p} IH^{t-1}_{gpht'} \qquad \forall g \in G, p \in P, h \in H, t \in T \qquad (22)$$

$$\sum_{t-\tau_p < t' \leq t} U^t_{g,RBC,ht'} = d^t_{gh} \qquad \forall g \in G, h \in H, t \in T \qquad (23)$$

$$\sum_g \sum_{t-\tau_p < t' \leq t} U^t_{g,pool,ht'} = dpool^t_h \qquad \forall h \in H, t \in T \qquad (24)$$

$$SI^t_{gij}, SJ^t_{gjj'}, VJ^t_{gpjj't'}, VH^t_{gpjht'}, CO^t_{gpj}, BP^t_{gpj}, IS^t_{gpjt'}, IH^t_{gpht'},$$
$$ILH^t_{gh}, ILHPLT^t_h, U^t_{gpht'}, WB^t_{gj}, WP^t_{gpj}, WH^t_{gph} \geq 0 \;\&\; int \qquad \forall i \in I, j, j' \in J, h \in H, g \in G, p \in P, t, t' \in T \qquad (25)$$

The objective function (1) minimizes total costs of the chain, including transportation, inventory, production and waste. The first four terms are related with transportation costs, namely between the three types of facilities adopted, so between collection points and processing centres and the later and demand zones, for both unprocessed and processed blood. The two following terms, five and six, are holding costs associated with inventory of blood products at both processing centres and hospitals. Term seven refers to production costs while term eight represents the costs of purchasing blood products. Finally, the final three terms depict waste disposal costs, being the first representative of whole blood waste associated with the decision of not processing it, and the two later represent waste of blood products from outdating.

On the set of constraints, equations (2) and (3) ensure flows of blood and its derived products only occur when there is an allocation between the two facilities in question, being valid for the allocation of collection centres to processing centres and demand zones to processing centres. Furthermore, equation (2) ensures processing centres only receive whole blood units up to their daily production capacity. Equation (4) assures flow balance by ensuring all collected whole blood is transferred to processing centres at the end of each period.

At the processing centre, equation (5) defines whole blood decomposition into blood products (RBC and pools), incorporating a production ratio. In the production process there is also intrinsic waste associated with the process of blood separation into components and, therefore, equation (6) establishes a maximum waste of whole blood for each period and processing centre. This is explained as this waste may vary between centres and units to be produced, as they must be a multiple of 4 or else the excess must be discarded. Furthermore, this approximates the reality imposed by the centres which is to produce all that is collected. Equation (7) is a conservation constraint, ensuring all whole blood received at processing centres is either produced or discarded at the end of every period.

Equation (8) and (9) are inventory conservation constraints for each processing centre in every period. They define inventory at the processing centres based on inventory from the previous period, the transferred inventory to demand zones, new inventory due to production and purchases. Equation (10) is a capacity constraint for all processing centres, so inventory levels do not surpass maximum capacity of the centres. Equations (11) and (12) are minimum stock definition at processing centres, ensuring availability of products to response in emergency situations. In turn, equations (13) and (14) guaranty no expired products are sent to either demand zones or other processing centres.

At demand zones, inventory is defined by equations (15) and (16) in each period as previous inventory plus received products minus used units. Equation (17) and (18) calculate the minimum inventory level for both blood products considered for each hospital, which must correspond to a number of days established by β worth of consumption for RBC and pools. Equations (19) and (20) enforce this minimum levels.

Waste associated with outdating is defined at both processing centres and hospitals by equations (21) and (22), respectively. Equations (23) and (24) define consumption at each hospital for both products considered. These equations ensure all demand must be fulfilled, meaning satisfying transfusion needs in each period of time for the for each blood product. Finally, equation (25) defines the domain of the decision variables.

The model built by equations (1) to (25) is of type Mixed Integer Program (MIP) and models a generic planning problem of a blood supply chain network with a set of collection centres, processing centres and demand zones, where there must be at least a connection between both the former and the later with a processing centre, ensuring all collected blood reaches a processing centre and all demand is satisfied. The model presented is a generic one, however it was used at two different levels, with some adaptations. Stage one presents an aggregation of time and blood group type of this model; while stage two is the disaggregated version. The first one deals with a six month horizon, and flows obtained are then turned into allocations which are used as input for the second stage, with a time horizon of 45 days.

5. Results

The proposed two stages of the approach are applied to the case study of the Southern region of Portugal, obtaining the following results.

5.1. Aggregated Stage

5.1.1 General Indicators

Table 1 shows the results for the aggregated stage as well as the corresponding extrapolated real values. Comparing whole blood waste, this is reduced in the model as there it is modelled for a maximum waste in order to enforce the policy of all collected blood arriving at processing centres must be produced. As for production, the model presents higher values for both products, likely due to the approximations used to obtain both this indicator and collection data.

Moving on to distributed units, this metric refers

Table 1: General results comparison

		Real	Model
Whole Blood Waste		756	121
Produced Units	**RBC**	53905	63452
	pool	11713	15863
Distribuited Units	**RBC**	75663	77804
	pool	12109	13324
Received Units	**RBC**	61488	77698
	pool	9046	12977
Purchased Units	**RBC**	21632	15503
	pool	3410	1587
Outdates	**RBC**	1409	0
	pool	2556	8924

to units distributed from processing centres to either demand zones or other processing centres, with values very similar between model and reality. However, some discrepancies are noticeable in the received units indicator, which refers to units received by demand zones from processing centres. In fact, these only account for 81% of total transfused RBC. The explanation for this lies with units assigned to demand zones which originated from coinciding processing centres (e.g. IPO to IPO) not being accounted for in received units. Furthermore, this is also related with the conversion of RBC units to smaller ones used in paediatric transfusions.

Regarding the purchased units indicator, the model values are lower than the ones presented in reality, which is one of the goals, to decrease dependency on other regions. This may, however, be associated with the increase in production. As for outdates, there is a decrease in RBC, which supports the correct allocation of these. Platelets pools, however, show an increase in values, likely associated with their shorter shelf-life.

These indicators are of extreme importance, for example, the purchases flow indicates the number of units that are missing from production in order to satisfy demand, being a great indicator of the dependency of the Southern region to the other existing two. Outdates, in turn, are key in validating the optimal allocation of products to demand zones.

5.1.2 Processing Centre Indicators

Figure 3 shows, in percentages, the distribution and purchase activities of the processing centres. The first two bars of each processing centre correspond to the model results, whereas the last two represent real extrapolated data. This data is only for RBC, however, the same tendencies apply to platelets pools. Production activity is not represented as there is no real data to compare it with.

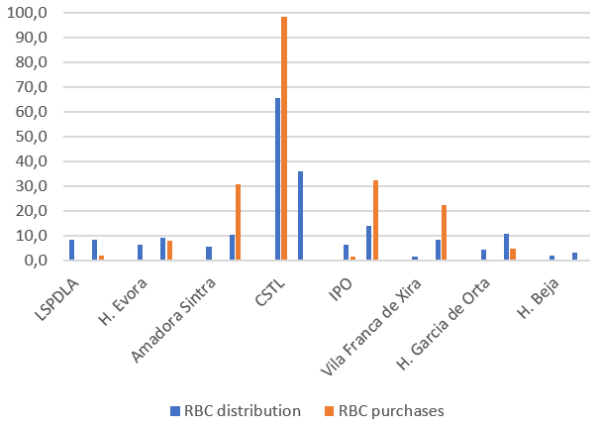

Figure 3: Distribution and purchases activities of processing centres.

From the graph it is visible a clear decrease in the results for CSTL's contribution in distribution when compared to reality, which is offset by an increase in activity of every other centre, in particular H. Garcia de Orta with the highest growths. In this way, there a more homogeneous distribution of this activity between all available centres, however, CSTL maintains its place with the biggest contribution. Regarding purchases, in reality the majority of this purchases were done by CSTL, having these values steeply decreased in the model results, making IPO the centre with the highest purchases contribution.

5.1.3 Planning Indicators

From the planning decisions carried out in the model, allocations were attributed to flows of whole blood and blood products between collection points and demand zones to processing centres. These can are depicted in figure 4.

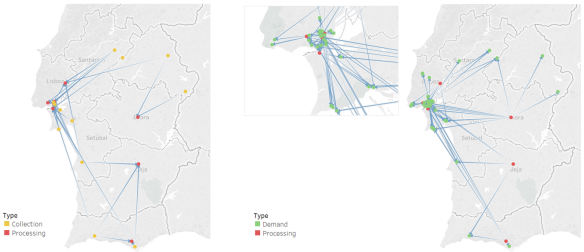

Figure 4: Allocation of collection points (left) and demand zones (right) to processing centres in the 1st semester of 2015.

From figure 4 it is visible that collection points are, in their majority, allocated to the nearest processing centres, which is line with the goal of costs minimization, favouring the validity of the model. There are, however, some collection points that are

also allocated to the LVT region and not only to the nearest processing centre, this is due to this region not collecting enough for its consumption. The allocations of blood products are quite more complex, which is mainly due to the contribution of pools. This is due to the reduced shelf life of this product, making its management more problematic and resulting in a more chaotic allocation.

These planning decisions are indeed the main goal of the application of this stage. They indicate the flows that should be opened in order to make the best distribution and management of the BSC, and will be used as input for the following study with the disaggregated stage. Their application is pivotal in several aspects, starting with better planning at tactical and operational levels, for example, on transportation arrangements.

5.1.4 Adjusted Scenarios

Two scenarios are built to achieve a more reliable comparison with extrapolated real data, by trying to approximate collection and consumption with this data. By doing so, although some assumptions have to be made, validation of the model can be achieved.

Both scenarios use collection input only from the haemovigilance report, with annual values that were distributed monthly by applying the monthly distribution already used for some collection centres previously. The difference between these scenarios lies with consumption data, as to obtain the two different hypothesis behind real data discrepancies. Scenario 1 considers consumption to be the real transfusion data, by assuming the hypothesis that received units do not account for the units received by the six simultaneous demand zones and processing centres. On the other hand, scenario 2 considers consumption approximately the number of real received units, assuming in this way the difference between received units and the transfused in reality was attributed to the paediatric units transfusion.

Results obtained for these scenarios are depicted in table 2. There, it is visible how much closer is production of RBC is with real results. The difference in scenarios is visible in the distribution and received units indicators, with scenario 1 presenting closer values in the former and scenario 2 in the later, as expected by the scenarios differences. For pools of platelets, the same discrepancies as before are observed due to the increased production imposed by the model's assumption of producing all.

Considering similar production and transfusions at demand zones for RBC, purchases are decreased in both scenarios, with particular emphasis for scenario 2, meaning there is room for improving the dependency of the Southern region under study. Furthermore, RBC outdates also present a very significant decrease, also supporting the capacity of improvement in reducing outdate waste.

Table 2: Comparison between scenarios 1 and 2.

		Real	S1	S2
Whole Blood Waste		756	115	119
Produced Units	**RBC**	53905	56868	56864
	pool	11713	14217	14216
Distribuited Units	**RBC**	75663	73790	61809
	pool	12109	12194	12342
Received Units	**RBC**	61488	73789	61712
	pool	9046	11967	12062
Purchased Units	**RBC**	21632	17878	5941
	pool	3410	2169	2171
Outdates	**RBC**	1409	0	35
	pool	2556	7914	7917

Further results show an agreement on most distribution of RBC units to demand zones, with variations under 4%, except for scenario 1's six facilities that are simultaneously demand zones and processing centres, which was expected. This supports the validation of a correct distribution and allocation made by the model.

5.1.5 Scenarios Analysis

It is extremely important to study the effects of data variability in the results, which is why a scenarios analysis was conducted, using four different scenarios that represent the four combinations of extreme situations regarding collection and demand. These are described in table 3.

Table 3: Scenarios' description.

	Collection	Demand
Scenario 3	Max	Max
Scenario 4	Min	Max
Scenario 5	Max	Min
Scenario 6	Min	Min

The most important results from this scenarios analysis are the flows obtained, which are then converted in allocations. In the allocations of collection centres to processing centres, 19 of 96 do not remain unchanged, corresponding to 17%. On the allocations of demand zones to processing centres, 63 in 360 flows are not in agreement in the four scenarios, corresponding to 18%. This shows that, as ex-

pected, there is some dependency of allocation with collection and demand data, however it is a small one, as with extreme situations, more than 80% of the allocations remain unchanged. This supports the these allocations can, therefore, be adopted regardless of the values for each period under study, meaning they can likely be employed even if demand and collection are not precisely known with minimum impact in optimality.

5.2. Disaggregated Stage

This is the second stage employed in the present work, with a bigger emphasis in the operational side, obtained more time refined results. Table 4 shows the general indicators for the disaggregated stage.

Table 4: General indicators for RBC of the disaggregated model.

Whole Blood Waste	5 302
Produced Units	12 728
Distribuited Units	23 973
Received Units	23 500
Purchased Units	9 406
Outdates	1 731

These results show the effects of blood group type incorporation, which can be seen in the purchases and outdates indicators, both with higher values. The former represented about 23% of consumption in the aggregated model, having this value risen to 47%; while the later used to be 0% for the aggregated model, now representing 8% of production plus purchases. This changes are due to the blood type compatibility requirement, indicating that collection is likely not adjustment to consumption. By existing groups with higher needs than the ones satisfied by collection, this increases the purchases required for consumption satisfaction. On the other hand, if consumption of some blood group types is lower than collection, than this leads to waste associated with excess product, that inevitably spoils.

Figure 5 depicts the main activities per blood group type, which will be helpful in assessing the adjustment of collection to consumption.

Two opposite situations are present in figure 5. The first, where collection is not enough to satisfy consumption, with high production, low whole blood waste, high purchases and low outdates, such as the cases of O+,B+ and O-. On the other hand, there is the case when collection exceeds consumption, presenting low production, high whole blood waste, low purchases and high outdates. This is the case of AB+ for example.

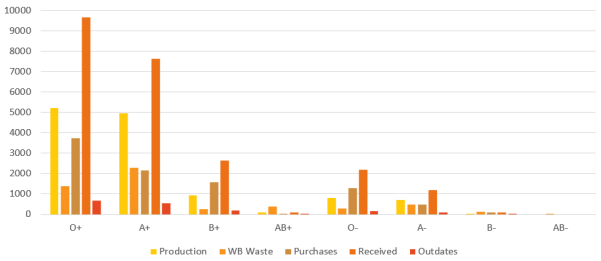

Figure 5: Comparison of activities per blood group type.

6. Conclusion

Given the data analysed, a couple of recommendations can be put together. Firstly, rethinking the distribution of activities between the available processing centres, namely a more even distribution of distribution and purchases. Secondly, the results show there is room for improvement in distribution of mainly RBC units, with lower outdate values supporting this. This allocation may even also allow for a reduction in dependency of the other two national regions, as shown in scenarios 1 and 2, with similar production and consumption and obtaining less purchased units. Finally, scenarios 3 to 6 analysis shows relatively acceptable margins of non-optimality for the use of the model, in terms of obtaining allocations.

On the disaggregated stage, results point to an added strictness from the blood group type incorporation, with higher purchases and outdates. Furthermore, the analysis of this approach allows for a better insight in the adjustment of collection to consumption.

Further work should be developed based on this issue, with emphasis on the Portuguese BSC, and some future directions could be considering collection as a decision variable, allowing for a geographical study of the needs in order to satisfy demand and reduce dependency of the region. Furthermore, incorporating blood type compatibility in the disaggregated model and understanding the differences it introduces would also be extremely helpful.

In conclusion, the approaches presented show promise in addressing a better planning for the Portuguese BSC. Its potential for providing more efficient decisions in allocations is critical, given their importance in waste reduction and dependency decrease, which could potentially lead to very favourable outcomes if implemented.

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