



This document is the original author manuscript of a paper submitted to an IFIP conference proceedings or other IFIP publication by Springer Nature. As such, there may be some differences in the official published version of the paper. Such differences, if any, are usually due to reformatting during preparation for publication or minor corrections made by the author(s) during final proofreading of the publication manuscript.

# Inventory routing problem with transshipment and substitution for blood products using the case of the Belgian blood distribution

Christine Di Martinelly<sup>1</sup>[0000-0002-6615-9992], Nadine Meskens<sup>2</sup>[0000-0003-3717-0081], Fouad Riane<sup>3</sup>[0000-0002-4962-0919], and Imane Hssini<sup>4</sup>

<sup>1</sup>IESEG School of Management, Univ. Lille, CNRS, UMR 9221 - LEM - Lille Economie Management, F-59000 Lille, France, c.dimartinelly@ieseg.fr,

<sup>2</sup> Université Catholique de Louvain, Louvain School of Management, LOURIM, Chaussée de Binche 151, 7000 Mons, Belgique, nadine.meskens@uclouvain.be

<sup>3</sup> SCI Ecole Centrale de Casablanca, Casablanca, Morocco, LGI CentraleSupélec Paris Saclay University, LMMII Laboratory, FST Settlat, Hassan Premier University

<sup>4</sup> LSI, Ecole Nationale des Sciences Appliquées d'Oujda, Oujda, Morocco

**Abstract.** In this paper, we deal with a blood supply chain management problem. We focus in particular on blood distribution routes design and optimization. Blood is a scarce and perishable product, made of multiple components, each with specific compatibility rules. We would like to investigate the impact of compatible products substitution and transshipment between hospitals on blood demand satisfaction. We use the case of the blood supply chain in Belgium as an application. We model the case as an Inventory Routing Problem with transshipment and substitution for perishable products in a capacity constrained environment. We implement the model and conduct experimentations to evaluate the contribution of both transshipment and substitution with regards to shortages and distribution and inventory costs reduction. In a capacity constrained environment, at equivalent cost, mismatching/substitution is preferred to transshipment to satisfy the demand and avoid backorders.

**Keywords:** inventory routing, blood supply chain, sensitivity analysis.

## 1 Introduction

In this paper, we are interested in the Inventory Routing Problem (IRP) with transshipment and substitution for blood products in a capacity constrained environment. The IRP problem arises in several industries and services when decisions on inventory management, vehicle routing and delivery-scheduling decisions are integrated; it is encountered typically in the case of vendor managed inventory in which the supplier/vendor is given the responsibility of managing the customer's inventory [1]. As seen in the literature review of [2], the IRP has received considerable attention from researchers over the years and multiple variants, taken into account multiple attributes of the

problem, have been studied. Among those attributes, we focus on transshipment and substitution.

Transshipment occurs when products can be shipped between customers; this feature is interesting in a deterministic context when no lost sales occur as it is a way to reduce distribution and inventory costs [3]. Substitution may offer the opportunity to sell a substitute product in case a product is out-of-stock; it enables a company to satisfy the demand and reduce excess inventory; however, in a capacity constrained environment, products are competing for the space available and the advantages linked to substitution are dependent on the parameters of the model [4].

Both transshipment and substitution have a positive effect on the amount of inventory kept and are ways to avoid shortages, yet the trade-offs when both are taken into account are not clear. We aim to perform a sensitivity analysis to understand those and determine lines for future research.

To perform this analysis, we use the case of the Belgium blood supply chain, which is typically the case of an IRP for multiple perishable products with transshipment and substitution in a capacity constrained environment. Blood is a particular commodity, which is perishable and scarce, with an irregular supply, and whose shortage may be life-threatening. Blood, or whole blood, is made of 4 components (red blood cells, platelets, plasma and cryo), which are separated mechanically or by apheresis [5]. Those different components have each specific shelf-live and usage. Additionally, they are tested for blood groups and have their own rules for compatibility. The study of the blood supply chain focuses on various stages of the process from donors to patients, as it can be seen in the literature reviews made by [5], [6] and [7]. In this paper, we focus on the distribution and inventory management problem between the blood bank and the hospitals, on which the authors presented a state of art in [8]. Relevant papers to our research are summarized in Table 1, following the problem characterization proposed by [2]. The setting under study is close to the research of [9], in which the authors consider only one vehicle and of [10], in which the authors do not take into account inventory holding cost nor substitution.

As additional characteristics, we consider multiple vehicles and if the demand cannot be satisfied, it is backordered. The problem is modeled as a mixed integer program; as the IRP in its basic version is NP-hard [2], a decomposition-based heuristic is developed and tested on multiple instances. The model is additionally used to lead extensive experimentations on key parameters of the model; this last part is presented in the present paper.

## **2 Problem description and assumptions**

In this section, we analyze an IRP with transshipment and substitution for the red blood cell products over a finite discrete time horizon, using multiple vehicles with limited capacity. We consider two echelons of the supply chain as products are delivered between the blood bank and the different hospitals. At each time period, the routing problem seeks to identify which hospitals to visit; multiple vehicles are required due to distances between hospitals and time limit on each tour. The inventory at each

hospital is managed under a Maximum Level (ML) policy meaning that the blood bank determines how much to deliver as long as the holding capacity is respected.

**Table 1.** Relevant papers to the IRP for blood products.

	Authors		Product number	Demand	Time horizon		Routing		Inventory decision			Fleet composition		Fleet size			Objectif				Solution method			Problem characteristics			
	Single	Multiple			Stochastic	Deterministic	Finite	Infinite	Direct	Multiple	Non negative	Lost sales	Back order	Homogeneous	Heterogeneous	Single	Multiple	unconstrained	Cost	Profit	Env. impact	other	Exact method	Heuristic	Meta-heuristic	Simulation	Transfer
[11]	*		*		*			*	*		*			*			*				*				*		
[12]	*		*		*			*					*		*		*	*	*		*		*				
[13]	*		*		*			*		*				*						*			*				
[14]	*		*		*			*	*	*	*			*			*			*		*		*			
[15]	*		*		*			*	-	-	-			*			*			*		*			*		
[16]	*		*		*			*	*	*	*			*			*			*		*					
[17]	*		*		*			*	-	-	*			*			*		*	*		*					
[18]		*	*		*			*			*		*	*		*				*		*					
[9]		*	*		*			*	-	*	-	*	*	*		*			*	*	*	*		*	*	*	*
[10]		*	*		*			*		*	-	*	*	*		*			*	*	*	*		*	*	*	*

The demand for blood cell products is considered deterministic, and is expressed in number of blood bags. As the supply of blood cell products at the blood bank may vary over the time period, there may be periods in which the blood supply is not sufficient to cover the demand. In this case, hospitals have the possibility to substitute the blood cell products (the term of mismatching can be encountered in place of substitution and describes the use of a compatible blood product when the patient's blood type is unavailable at the time of the request), use transshipment to get the product from another hospital or backorder the demand (meaning the surgical intervention requiring the blood is postponed). At each period, a percentage of the products hold on inventory becomes obsolete.

#### Notation

##### Set

$\mathcal{H}$	Set of hospitals only
$\mathcal{H}^+$	Set of hospitals and blood bank
$\mathcal{V}$	Set of vehicles
$\mathcal{S}$	Set of visited hospitals during a period
$\mathcal{T}$	Set of time periods over the planning horizon
$\mathcal{P}$	Set of blood products

## Parameters

$D_{irt}$	Demand of product $r$ during period $t$ at hospital $i$
$C_i$	Storage capacity at hospital $i$
$Z_{rt}$	Quantity of product $r$ available at the depot during each period $t$
$\theta_{ri}$	Outdating rate of product $r$ stored at each location $i$
$cap$	Vehicle capacity
$\varphi_{ij}$	Transportation time between 2 locations $i, j \in H^+$
$\tau_t$	Maximum working time during period $t$
$dist_{ij}$	Distance (in km) between 2 locations $i, j \in H^+$
$I_{ri0}$	Initial inventory of product $r$ at hospital $i$
$CST_{ri}$	Inventory holding cost of product $r$ at location $i$
$CTRAV$	Transportation cost, in €/KM
$CT_{ri}$	Transshipment penalty cost of product $r$ from location $i$
$CR_{ri}$	Backorder cost of product $r$ at location $i$
$CS_{ru}$	Substitution cost between products $r$ and $u$
$MC_{ur}$	Compatibility matrix; equal to 1 if product $u$ is compatible with product $r$ ; 0 otherwise
$e_r$	Blood type distribution per product $r$ in the Belgian population

## Variables

$Q_{rit}$	quantity of product $r$ delivered to location $i$ during period $t$
$q_{rijt}$	quantity of product $r$ transported between location $i$ and $j$ at period $t$
$I_{rit}$	inventory of product $r$ at hospital $i$ at period $t$
$x_{ijt}$	Binary variable equal to 1 if during period $t$ the location $j$ is directly visited after location $i$
$S_{rit}$	quantity of product $r$ in backorder at location $i$ during period $t$
$T_{rit}$	quantity of product $r$ transshipped from location $i$ during period $t$
$SU_{urit}$	Quantity of product $u$ , substitute of product $r$ , from inventory of location $i$ at period $t$ (to satisfy demand $D_{irt}$ )

## 2.1 Mathematical modelling

$$\text{Min} \sum_{i \in \mathcal{H}} \sum_{\substack{j \in \mathcal{H} \\ i \neq j}} \sum_{t \in \mathcal{T}} CTRAV * dist_{ij} * x_{ijt} + \sum_{j \in \mathcal{H}} \sum_{r \in \mathcal{P}} \sum_{t \in \mathcal{T}} CST_{rj} * I_{rjt} \quad (1)$$

$$+ \sum_{j \in \mathcal{H}} \sum_{r \in \mathcal{P}} \sum_{t \in \mathcal{T}} CR_{rj} * S_{rjt}$$

$$+ \sum_{j \in \mathcal{H}} \sum_{t \in \mathcal{T}} \sum_{r \in \mathcal{P}} \sum_{u \in \mathcal{P}} CS_{ru} * SU_{rujt} + \sum_{j \in \mathcal{H}} \sum_{t \in \mathcal{T}} \sum_{r \in \mathcal{P}} CT_{rj} * T_{rjt}$$

Subject to :

$$\sum_{i \in \mathcal{H}} x_{ijt} \leq 1 \quad \forall j \in \mathcal{H}, t \in \mathcal{T} \quad (2)$$

$$\sum_{\substack{i \in \mathcal{H} \\ i \neq j}} x_{ijt} - \sum_{\substack{m \in \mathcal{H} \\ m \neq j}} x_{jmt} = 0 \quad \forall j \in \mathcal{H}, t \in \mathcal{T} \quad (3)$$

$$\sum_{i \in \mathcal{S}} \sum_{\substack{j \in \mathcal{S} \\ j \neq i}} x_{ijt} \leq |\mathcal{S}| - 1 \quad \forall \mathcal{S} \subset \mathcal{H}, \mathcal{S} \neq \emptyset, t \in \mathcal{T} \quad (4)$$

$$\sum_{i \in \mathcal{H}} \sum_{\substack{j \in \mathcal{H} \\ j \neq i}} x_{ijt} * \varphi_{ij} \leq \tau_t \quad \forall t \in \mathcal{T} \quad (5)$$

$$\sum_{j \in \mathcal{H}} x_{0jt} \leq |\mathcal{V}| \quad \forall t \in \mathcal{T} \quad (6)$$

$$\sum_{\substack{i \in \mathcal{H} \\ i \neq j}} q_{rijt} - \sum_{\substack{m \in \mathcal{H} \\ m \neq j}} q_{rjmt} = Q_{rjt} - T_{rjt} \quad \forall j \in \mathcal{H}, r \in \mathcal{P}, t \in \mathcal{T} \quad (7)$$

$$\sum_{r \in \mathcal{P}} q_{ri0t} = 0 \quad \forall i \in \mathcal{H}, t \in \mathcal{T} \quad (8)$$

$$\sum_{r \in \mathcal{P}} q_{rijt} \leq Cap * x_{ijt} \quad \forall i \in \mathcal{H}^+, j \in \mathcal{H}, i \neq j, t \in \mathcal{T} \quad (9)$$

$$T_{rit} \leq (1 - \theta_{ri}) * I_{rit-1} \quad \forall i \in \mathcal{H}, r \in \mathcal{P}, t \in \mathcal{T} \quad (10)$$

$$I_{rit} = (1 - \theta_{ri}) * I_{rit-1} + Q_{rit} - S_{rit-1} - T_{rit} - \sum_{u \in \mathcal{P}} MC_{ru} * SU_{ruit} + S_{rit} \quad \forall i \in \mathcal{H}, r \in \mathcal{P}, t \in \mathcal{T} \quad (11)$$

$$D_{rit} = \sum_{u \in \mathcal{P}} MC_{ur} * SU_{urit} + S_{rit} \quad \forall i \in \mathcal{H}^+, r \in \mathcal{P}, t \in \mathcal{T} \quad (12)$$

$$I_{r0t} = (1 - \theta_{r0}) * I_{r0t-1} - \sum_{i \in \mathcal{H}} q_{roit} + Z_{rt} \quad \forall r \in \mathcal{P}, t \in \mathcal{T} \quad (13)$$

$$\sum_{r \in \mathcal{P}} (1 - \theta_{ri}) * I_{rit-1} + \sum_{r \in \mathcal{P}} Q_{rit} - \sum_{r \in \mathcal{P}} T_{rit} \leq C_i \quad \forall i \in \mathcal{H}^+, t \in \mathcal{T} \quad (14)$$

$$\sum_{r \in \mathcal{P}} I_{rit} \leq C_i \quad \forall i \in \mathcal{H}, t \in \mathcal{T} \quad (15)$$

$$x_{ijt} \in \{0,1\} \quad \forall i, j \in \mathcal{H}^+, i \neq j, t \in \mathcal{T} \quad (16)$$

$$Q_{rit}, I_{rit}, q_{rijt}, SU_{urit}, T_{rit} \geq 0 \quad \forall i, j \in \mathcal{H}^+, i \neq j, r, u \in \mathcal{P}, t \in \mathcal{T} \quad (17)$$

The objective function (1) minimizes the total cost (costs of transportation, inventory holding, backorder, substitution, and transshipment penalty). Constraints (2) assure that

each hospital is visited at most once during each period. Constraints (3) guarantee that the vehicle moves to the next hospital after serving the current one. Constraints (4) delete subtours. Constraints (5) ensure that the time to complete each tour does not exceed working hours. Also, during each period, the number of tours cannot be superior to the number of vehicles (as a vehicle completes maximum a tour during each period) (6). Constraints (7) determine the quantities delivered at each hospital and quantities transshipped. Constraints (8) make sure the vehicle is empty when returning to the depot. Constraints (9) are vehicle capacity constraints. Constraints (10) determine the maximum quantities of products that can be transshipped. Constraints (11) and (12) are inventory balancing constraints at the hospitals. Constraints (13) are inventory balancing constraints at the depot. Constraints (14) are capacity constraints for each hospital. Constraints (14) are capacity constraints for each time period. Constraints (16) and (17) define the domain of the variables.

### 3 Computational results

The mathematical model has been coded with CPLEX and implemented on a computer with Windows XP, 2,9 GHz Intel Core i5 and 8 Go RAM. The models are run with an optimality gap of 2%.

#### 3.1 Data set

The data set has been constructed following a similar approach to [9], mixing both real data and generated data. We consider hospitals located in the South part of Belgium. The number of hospitals considered for the computational experiment varies between 5 and 15. The distances between hospitals,  $dist_{ij}$  are estimated via a GIS software. There are 4 vehicles with the same capacity. The planning horizon is 7 days, considering 8 products, each one representing a blood type. Table 2 presents the percentages per product in the Belgian population.

**Table 2.** Blood type distribution per product  $r$  in the Belgian population,  $e_r$

Product	O <sup>+</sup>	O <sup>-</sup>	A <sup>+</sup>	A <sup>-</sup>	B <sup>+</sup>	B <sup>-</sup>	AB <sup>+</sup>	AB <sup>-</sup>
%	36%	6%	37%	7%	9%	1%	3%	1%

- The demand  $D_{irt}$  is randomly generated in an interval  $[a * e_r * L_i, b * e_r * L_i]$  where  $L_i$  is the number of beds in the hospital  $i$  and  $e_r$  is the blood type distribution per product  $r$  in the Belgian.
- The quantity of products  $r$ , available at time  $t$ , at the blood bank,  $Z_{rt}$ , is uniformly generated in the interval  $[c * e_r * \sum_i L_i, d * e_r * \sum_i L_i]$ .

Different demand scenarios over the time horizon are considered and analyzed by varying the values of  $a$ ,  $b$  and  $c$ ,  $d$ . In this paper, we focus on a scenario where the demand is high compared to the blood supply, thus requiring the use of transshipment and mismatching to satisfy the demand of blood products. The values are set to  $a = 20$ ,  $b = 30$  and  $c = 30$ ,  $d = 35$ .

- The initial inventory at each hospital,  $I_{ri0}$ , is randomly generated in the interval  $[0, \dots, 50]$ .
- The maximum working time during period  $t$ ,  $\tau_t$ , is fixed at 10 hours/day.
- The capacity of each vehicle,  $cap$ , is fixed at a total of 5000 products.
- The outdated rate,  $\theta_{ri}$ , is 1%.
- The holding cost,  $CST_{ri}$ , is fixed at 1€/product, the transportation cost,  $CT_{RAV}$ , at 0,5 €/KM, and the transshipment penalty cost,  $CT_{ri}$ , at 1.5€/product.
- The backorder cost,  $CR_{ri}$ , is set at 5€/product and the substitution cost,  $CS_{ru}$ , at 2€/product.

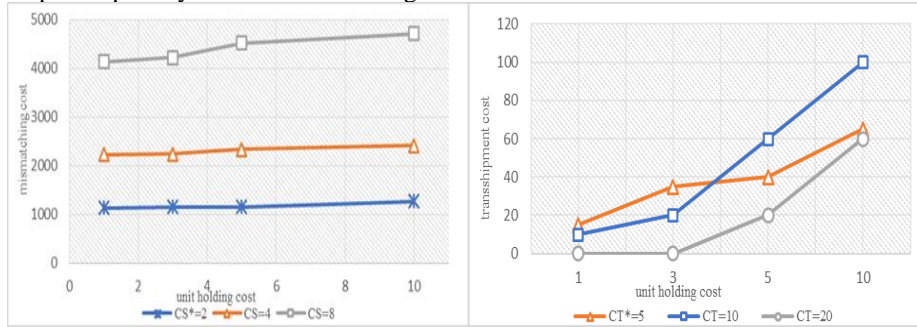
### 3.2 Sensitivity analysis

A sensitivity analysis is conducted on some key parameters of the objective function with the aim of testing their influence on the elements under study: mismatching cost, transshipment penalty and backorder cost.

The holding cost is an important element of an inventory management model. One would expect that if the holding cost increases, hospitals will use mismatching and transshipment to keep inventory as low as possible.

The holding cost has an impact on mismatching; when the holding cost increases, hospitals use more mismatching to satisfy the demand (chart on the left in **Fig. 1**) and avoid shortages. Obviously, if the holding cost is superior to the mismatching cost, there is more mismatching.

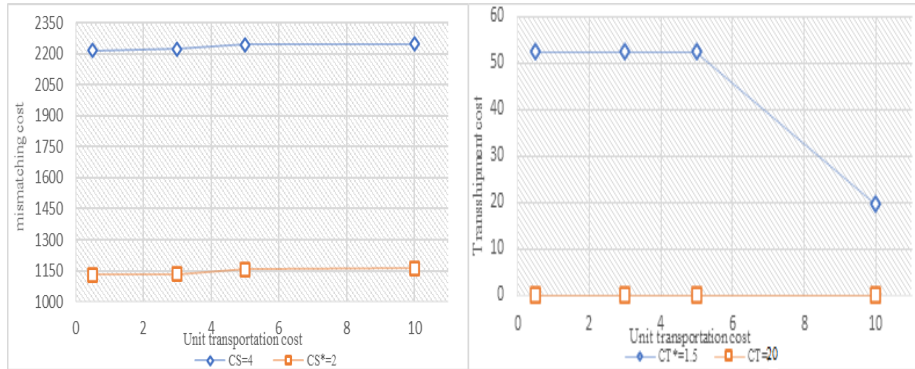
The quantities transshipped are in comparison very limited. Transshipment is used to satisfy the demand and avoid shortage in complement of mismatching when transshipment penalty is inferior to holding cost.



**Fig. 1.** Impact of holding cost on transshipment and mismatching (CT: unit transshipment penalty and CS: unit mismatching cost)

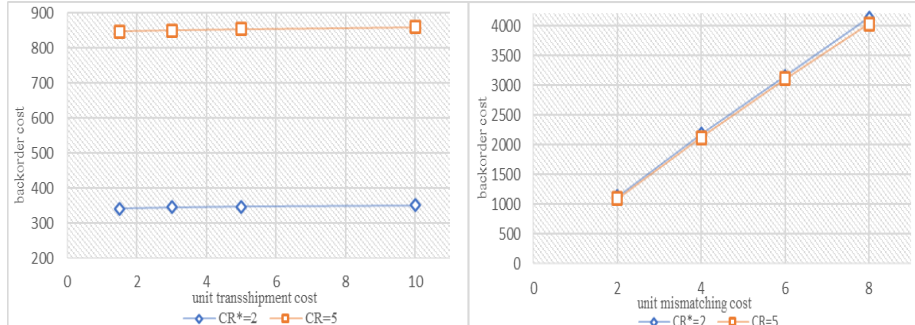
The impact of transportation cost on mismatching is very limited (chart on the left in **Fig. 2**). When transportation cost increases, the number of units mismatched slightly increases. When transshipment penalty is high (20€), there is no transshipment, whatever the transportation cost. Transshipment penalty is adding up to the cost of transportation and thus hospitals will try to minimize distribution costs as much as possible to satisfy the demand. Similar results were put forward by [3].





**Fig. 2.** Impact of unit transportation cost on transshipment and mismatching (CT: unit transshipment penalty and CS: unit mismatching cost)

Interestingly, the transshipment penalty has little impact on the quantities backordered. There is however a clear link between an increase in mismatching cost and the number of items that are backordered (chart on the right in **Fig. 3**). Interestingly, the 2 lines representing the total backorder costs are nearly superimposed meaning that there is nearly a direct relation between mismatching and backorder. If the mismatching cost doubles, the number of backorders doubled; this relation remains stable when the backorder cost increases.



**Fig. 3.** Impact of transshipment and mismatching on backorder cost (CR: backorder cost)

In the computational experiments led, at an equivalent cost per unit, mismatching/substitution is preferred to transshipment to satisfy the demand and avoid backorders. This will increase the demand for products with the highest mismatching rate (blood product type O can be a substitute for any product demand). This also raises the question of how to properly estimate substitution and transshipment unit cost in order to avoid bias in the derived inventory and routing policy. As blood products are vital, it pleads in favor of a multi-objective approach allowing the decision maker to give priority to the components of the objective function.

## 4 Conclusion and perspectives

In this paper, we studied the IPR with transshipment and substitution for multiple products in a capacity constrained environment. Due to the complexity of the problem, a decomposition-based heuristic was developed; this heuristic solved the problem in 3 phases, based on the complexity induced by the characteristics of the problem: the routing problem, the classical IRP and then the transshipment and substitution. The focus of this paper is on the sensitivity analysis led on the key components of the objective function of the IRP. This study put forward that mismatching is preferred to transshipment to satisfy the demand and avoid backorder. Mismatching and backorder quantities are also directly linked.

Our future work is on a multi-objective approach to solve the problem under study and give different priorities to the components of the objective function.

Also, currently the outdateding of the products is considered through an outdateding rate applied to the products on inventory at the hospitals. The age of the products will be included.

## References

1. Disney, S.M. and D.R. Towill, *The effect of vendor managed inventory (VMI) dynamics on the Bullwhip Effect in supply chains*. International Journal of Production Economics, 2003. **85**(2): p. 199-215.
2. Coelho, L.C., J.-F. Cordeau, and G. Laporte, *Thirty Years of Inventory Routing*. Transportation Science, 2014. **48**(1): p. 1-19.
3. Coelho, L.C., J.-F. Cordeau, and G. Laporte, *The inventory-routing problem with transshipment*. Computers & Operations Research, 2012. **39**(11): p. 2537-2548.
4. Schlapp, J. and M. Fleischmann, *Technical Note—Multiproduct Inventory Management Under Customer Substitution and Capacity Restrictions*. Operations Research, 2018. **66**(3): p. 740-747.
5. Beliën, J. and H. Forcé, *Supply chain management of blood products: A literature review*. European Journal of Operational Research, 2012. **217**(1): p. 1-16.
6. Osorio, A.F., S.C. Brailsford, and H.K. Smith, *A structured review of quantitative models in the blood supply chain: a taxonomic framework for decision-making*. International Journal of Production Research, 2015. **53**(24): p. 7191-7212.
7. Pirabán, A., W.J. Guerrero, and N. Labadie, *Survey on blood supply chain management: Models and methods*. Computers & Operations Research, 2019. **112**: p. 104756.
8. Hssini, I., N. Meskens, and F. Riane, *Optimisation du stockage des produits sanguins labiles: revue et analyse de la littérature*. Génie industriel et productique, 2019. **2**(Numéro 1).
9. Jafarkhan, F. and S. Yaghoubi, *An efficient solution method for the flexible and robust inventory-routing of red blood cells*. Computers & Industrial Engineering, 2018. **117**: p. 191-206.

10. Zahiri, B., et al., *A multi-stage stochastic programming approach for blood supply chain planning*. Computers & Industrial Engineering, 2018. **122**: p. 1-14.
11. Bashiri, M. and E. Ghasemi, *A Selective Covering-Inventory- Routing problem to the location of bloodmobile to supply stochastic demand of blood*. International Journal of Industrial Engineering & Production Research, 2018. **29**(2): p. 147-158.
12. Eskandari-Khanghahi, M., et al., *Designing and optimizing a sustainable supply chain network for a blood platelet bank under uncertainty*. Engineering Applications of Artificial Intelligence, 2018. **71**: p. 236-250.
13. Hemmelmayr, V., et al., *Vendor managed inventory for environments with stochastic product usage*. European Journal of Operational Research, 2010. **202**(3): p. 686-695.
14. Hemmelmayr, V., et al., *Delivery strategies for blood products supplies*. OR Spectrum, 2009. **31**(4): p. 707-725.
15. Hendalianpour, A. *Mathematical Modeling for Integrating Production-Routing-Inventory Perishable Goods: A Case Study of Blood Products in Iranian Hospitals*. in *Dynamics in Logistics*. 2018. Cham: Springer International Publishing.
16. Kazemi, S.M., et al., *Blood inventory-routing problem under uncertainty*. Journal of Intelligent & Fuzzy Systems, 2017. **32**(1): p. 467-481.
17. Kochan, C.G., S.S. Kulkarni, and D.R. Nowicki, *Efficient Inventorying and Distribution of Blood Product During Disasters*, in *Advances in Managing Humanitarian Operations*, C.W. Zobel, N. Altay, and M.P. Haselkorn, Editors. 2016, Springer International Publishing: Cham. p. 185-204.
18. Federgruen, A., G. Prastacos, and P.H. Zipkin, *An Allocation and Distribution Model for Perishable Products*. Operations Research, 1986. **34**(1): p. 75-82.