Blood Shortage Management with a Reactive Lateral Transshipment Approach in a Local Blood Supply Chain

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Abstract

The perishability of blood components and uncertainty in both donation and demand scale are two important reason that contributing to blood shortage. According to the WHO's global statistics, 107 out of 180 countries struggle with an insufficient amount of blood units to meet currently existing demand for blood products. This paper proposes a 2-stage location-allocation blood supply chain network which aims to optimize blood inventory level by minimizing the total related costs. Various ordering policies, lateral transshipment between hospitals, emergency orders from blood centers, limited capacity for each centers, and blood aging process have been considered in the form of constraints. The Greater Toronto Area (GTA) has been considered as the case study focus for this research, and all the further necessary actions and recommendations have been taken based on the case study's results.

Keywords
Blood supply chain, Lateral Transshipment, Perishability, Inventory Level, Shortage

1. Introduction

The high rate of blood components' perishability and the fact that humans are only resource of supplying these products make blood supply chain as one of the most crucial and complicated supply chains that exists in today's world. Due to blood's life-saving characteristic, the value of using an integrated model to prevent both shortage and wastage is undeniable. This paper discusses an integrated system of a blood supply chain on a real-world example. The main objective of the proposed supply chain is to minimize all the related cost in order to optimize inventory level in both hospitals and blood centers and set a balance between shortage and wastage amounts. To make the model closer to the real-world situation, ability to issue an emergency order in case of shortage has been accounted in the proposed model as well.

2. Literature Review

All over the world, blood supply chains are facing with various challenges like an increase in operating costs, rise in competition among blood centers, donors' motivation, seasonal shortages and blood components' perishability. (Dutta, 2019) An organized inventory management that achieved by understanding the complex interrelations of supply and demand, and other factors that affect them would be fruitful to discover the blood supply chain configuration that should be used in order to overcome this complexity. (Chapman el al, 2004) Moreover, Blood supply chain is considered as one of the key players in the healthcare system. Hence, any improvement in blood management can have a significant impact on the performance of the healthcare system. (Zahiri et al, 2015). Considering multi-period planning horizon, perishability of blood, uncertainty in demands and supplies, blood substitution transfusion, and blood delivery system framework are the elements that affect blood supply chain improvement. (Zahiri et al, 2015; Kaveh and Ghobadi, 2017).

2.1.Simulation Approach to Identify the System

Although forecasting method are mainly recognized as tools that can improve sales for the commercial companies, ability to forecast the amount of blood components' demands can be considered as an effective step which can both reduce the stress that exist in both blood centers and hospitals, and increase the efficiency. (Caulfield, 2013) In today's world, technology provides wide range of methods for anticipating products' demands, computer simulation approach is one of those methods that prepares a situation in which healthcare decision makers have the opportunity to make effective decision regarding all the blood supply chain's policies. (Rytilä & Spens, 2006) The simulation results reveal all the essential information about the existing concerns, potential impacts and value added activities that exist in the supply chain system. As a result, by studying all these results, the decision makers will decide whether to implement the proposed system into the real world or not. (AbuKhousa et al, 2014; Kopach et al, 2003). Due to the limited budget, most of the governments prefer to improve the existing blood supply chain rather than creating a new one. Hence, it is essential to realize that how major problems and their root causes in an existing blood supply chain can be identified. (Lowalekar and Ravi, 2017) proposed a TOC thinking process for India blood supply chain. The supply chain faced with various problems such as high shortage and wastage of blood products, large inventory levels, poor and erratic blood collection, high error rate and etc. Although the mentioned problems seemed to be unrelated to each other, applying the proposed TOC approach in a simulation model revealed that they were all inter-related and originated from a single root-cause.

2.2.Blood as a Perishable Product

In contrast to many traditional supply chains, due to the perishable nature of blood components, their supply chain should focus on both responsiveness and efficiency factors simultaneously. This is because, fresh products like blood have their own Marginal Value Time (MVT) which shows the change in value of product per unit time at a given point in the supply chain. Any change in MVT of the blood products causes an increase in the costs of the blood supply chain (Blackburn and Scudder, 2009), hence, managing blood inventories is a trade-off of shortages and lost sales against wastage (Stanger et al, 2012). (Katsaliaki et al, 2014) introduced a game-based empirical approach to decision making which has the two main characteristics: 1. Perishability, and 2. Limited product collection/production. The blood supply chain game that has been proposed in the paper gave the audience the ability to study the supply chain from different points of view. During the game, the participants have acquired knowledge about push/pull process in order to realize how they should set the inventory policies due to the existing conditions. Moreover, some other fields such as inventory control practices, transportation assignment techniques, costs management and bullwhip effect have been introduced and studied during the game either in order to make the game more realistic. The bullwhip effect is known to cause excess inventory (Lee et al. 1997) which in turn can increase the wastage rate of perishable products. (Rutherford et al, 2016) realized that inefficient management of the relationship that exists between blood operation centers and hospital blood banks was the main problem that caused the bullwhip effect in a blood supply chain system.

2.3.Blood Transportation System

Due to the uncertain nature which exists in blood supplies and demands, a variety of emergency delivery options should also be implemented in the available models.
In most recent researches, Transportation planning of the blood supply chain is studied from two main perspectives:

1. Reliability: Blood supply chains are responsible to deliver blood components in a way that blood's discard rate will be minimized.
2. Efficiency: The total cost of the network should be minimized (Zahiri et al, 2018).

Also, from another point of view, manage blood delivery according to demand centers' needs and optimized internal management of the blood supply system besides cost efficiency and reliability are other factors that help to create an efficient planning for the blood supply chain network. (Ghandforoush and Sen, 2010).
Lateral transshipment is one of the common tools in the supply chain management in order to deal with shortage and wastage. There are two types of lateral transshipment: 1. Reactive Transshipment and 2. Proactive transshipment. Implementing lateral transshipment in a supply chain can be helpful to prevent any shortages and mitigate any wastage. Also, it has a great impact on cost reduction. (Larimi et al, 2019) presented a mathematical model in which both total costs, and maximum unsatisfied demands have been minimized for the platelets' supply chain. . Lateral transshipment in this study has been considered as a reactive transshipment. This means that platelets are transferred between hospitals and clinical centers only if they face with any platelets' shortage in their own inventory. On the other hand, (Dehghani et al, 2019) believed that proactive transshipment would be more useful in order to reach to be able to reduce costs, shortage and wastage in the best possible way. By applying the proactive transshipment in the hospitals' supply chain networks, the "order-up-to" rule (Dijk et al, 2009) in which the orders would take place at fixed points of time before observing the demand has been applied into the model. Moreover, by using Quasi-Monte Carlo sampling approach several scenarios have been generated in order to be able to deal with the uncertain nature of blood components' demands.

2.4.Platelets Supply Chain

Each blood component has its own specifications which may lead to create a more customized supply chain for that component. Due to the Short shelf life of platelets compared to other blood product, managing their inventory is one of the main challenges in the blood supplying system. (Fontaine et al, 2009) Establishing an inventory bank can have positive effects on the four main factors that are in a direct connection with blood supply chain's effectiveness: 1. Blood shortage, 2. Outdating, 3. Inventory level and 4. Reward gained. (Abdulwahab and Wahab, 2014) suggested a mathematical model to control the inventory level of blood platelets. The proposed blood platelet bank dealt with stochastic demand and supply, and deterministic lead time. By applying news-vendor model and dynamic programming it has been realized that by minimizing the first two mentioned factors, the inventory level would be optimized, therefore, the blood platelet band reward would be maximized. Some of the patients just have to receive fresh blood components, while others can be cured by old blood components either. Thus, blood substitution can be considered as an option in case of any emergency need, especially for type two patients. (Civelek et al, 2015) proposed a blood platelet inventory management model by following a Markov Decision Process (MDP) in order to show that shortage, wastage and holding costs are not the only factors that can affect the inventory planning. Introducing substation option and its related cost provided an opportunity for the model to satisfy a demand for a certain-aged item by using a different-aged item, if the substitution matches the need. The fact that the number of donors have significant effect on the blood supply chain performance is undeniable. In today's world, the limited number of donors, and the increasing rate of blood demands are the problems that make the blood supply chain planning even more complex. (Rajendran and Ravindran, 2019) proposed a stochastic mathematical model that considered the two aforementioned problems for a platelet supply chain. The wastage and shortage problem not only increase the costs dramatically, but also do they delay all the operational functions like surgeries or organ transplants. Therefore, having a precise ordering policy can improve the performance of both blood operators and hospitals.

2.5.Blood as a Medicine

The main purpose of blood transfusion is to cure the various type of blood-related conditions such as trauma, anemia, cancer treatments, organ transplants, etc., and blood is considered as a medicine in these transfusions. Hence, blood supply chain management can be recognized as a subset of pharmaceutical supply chain network. In every pharmaceutical supply chain, time, quality and cost are three main factors that are in a direct relationship with customers' satisfaction. (Imran et al, 2018) called these three factors in their paper "Business Triad". By considering fuzzy programming method, a mathematical model has been suggested to minimize all the related complaints to the business triad. The proposed model tried to offer customer satisfaction as another perspective which has direct impact on the performance of a pharmaceutical supply chain.

2.6.Existing Gaps

After conducting literature review, it has been realized that available analytical supply chain models usually do not consider lateral transshipment approach and emergency ordering option from available blood centers as solution which can be helpful not only to reduce the shortage amount, but also do they reduce the wastage amount and balance inventory levels of hospitals. The focus of this research is to show how applying these options would affect both costs and inventory levels.

3. Problem Statement

Blood supply chain can be considered as one of the key participants of any healthcare supply chain. The aim of this research is to develop a mathematical model in order to minimize all the related costs of the blood supply chain model and optimize inventory level. Due to the life-saving and perishable nature of blood units, they are in danger of both shortage and wastage. Hence, an integrated supply chain can be a great help in order to manage blood unit delivery in a way that both satisfaction will be maximized and costs will be minimized. The proposed blood supply chain in this research consists of two main stages:

1. Blood centers
2. Hospitals

In addition, to make the model more realistic, a few additional assumptions have been implemented:

- Given that blood components' demands are unpredictable; shortage is allowed in the hospitals. Lateral transshipment between hospitals and emergency order from blood centers would satisfy the shortage amount.

- Each blood collection center has a limited capacity for collecting blood from blood donors.
- Each hospital’s demand has been estimated and specified based on existing information.
- There would be a specific lead time for both regular and emergency orders.
- An initial inventory level for the beginning of first period of time has been defined for each blood center and each hospital.
- Given the perishable nature of blood components, ageing process affects blood transfusion decision, and blood units’ delivery from blood centers to hospitals.
- Figure 1 shows the proposed model, consisting of two stages. There are multi blood centers that deliver blood units to the hospitals whenever the lateral issue an order. Although both shortage and wastage are allowed in hospitals, blood centers cannot face with any shortage.

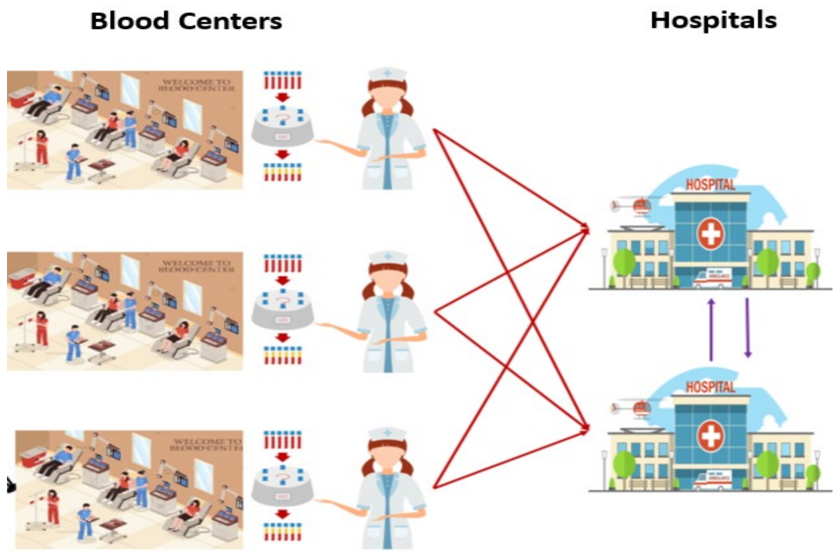

Figure 1: Schematic view of the blood supply chain network

4. Mathematical Model

In this section the deterministic mathematical model is presented. Notations used in the model and their definitions are outlined in Table 1 in the Appendix 1.

4.1.Objective

The objective of the model is to minimize all related costs which includes regular and emergency order costs, holding and discarding costs in blood centers, holding, discarding, shortage and ordering costs in hospitals and testing costs in blood centers.

$$\min \sum_{k}\sum_{n\geq 3}\sum_{i}\sum_{t} ES_{kin}^{t} CE_{ki}^{n} + \sum_{k}\sum_{i}\sum_{t} Z_{ki}^{t} SN_{ki} + \sum_{k}\sum_{t}(HB_k FV_k^t + CWDW_k^t) + \sum_{i}\sum_{j\neq i}\sum_{m}\sum_{t} X_{ijm}^{t} C_{ij}^{m} + \sum_{i}\sum_{t}(H_i V_i^t + E\sigma_i^t + GF_i^t + SEFy_i^t) + \sum_{k}\sum_{t} TesDON_K^t \quad (1)$$

4.2.Constraints

The problem is subject to a variety of constraints which have been previously mentioned.

$$is_{im}^{t} = B_{im}^{1} \ \forall i, m, t = 1 \quad (2)$$

Equation (2) indicates that there is an initial inventory level for blood units with specific age at the beginning of the first period in each hospital.

$$is_{im}^{t} + \sum_{j \neq i} X_{jim}^{t} - \sum_{j \neq i} X_{ijm}^{t} + \sum_{k} ES_{kin}^{t} - a_{im}^{t} = ie_{im}^{t} \; \forall i, m, n = m, t \tag{3}$$

Equation (3) sets balance between beginning inventory level and final inventory level of a hospital's blood units in each period of time.

$$\sum_{m} a_{im}^{t} + f_{i}^{t} = D_{i}^{t} \; \forall i, t \tag{4}$$

Equation (4) indicates that in each period of time, although all the blood units with various ages that exist in a hospital are used to satisfy its demand, there might be a chance that the hospital faces with shortage.

$$\sum_{i} ES_{kin}^{t} \leq Invs_{kn}^{t} \; \forall k, n \geq 3, t \tag{5}$$

Equation (5) indicates that in each period of time and in case of shortage, for delivering blood units with specific age from a blood center to a hospital, the beginning inventory level of the blood center for the blood units should be considered.

$$\sum_{i} Z_{ki}^{t} \leq Invs_{kn}^{t} \; \forall k, n = 2, t \tag{6}$$

Equation (6) indicates that in each period of time, for delivering fresh blood units from a blood center to a hospital the beginning inventory level of the blood center for the fresh blood units should be considered.

$$\sum_{j \neq i} X_{ijm}^{t} \leq is_{im}^{t} \; \forall i, m, t \tag{7}$$

Equation (7) indicates that in each period of time, for transshipping blood units with specific age from a one hospital to another one, the beginning inventory level of the transmitter for the blood units should be considered.

$$Invs_{kn}^{t} - \sum_{i} ES_{kin}^{t} = Inve_{kn}^{t} \; \forall k, t, n \geq 3 \tag{8}$$

Equation (8) sets balance between beginning inventory level and final inventory level of a blood center's blood units which have more than 3 days of shelf life in each period of time.

$$Invs_{kn}^{t} - \sum_{i} Z_{ki}^{t} = Inve_{kn}^{t} \; \forall k, t, n = 2 \tag{9}$$

Equation (9) sets balance between beginning inventory level and final inventory level of a blood center's fresh blood units in each period of time.

$$Invs_{kn}^{t} = Cap_{kn}^{1} \; \forall k, n, t = 1 \tag{10}$$

Equation (10) indicates that there is an initial inventory level for blood units with specific age at the beginning of the first period in each blood center.

$$Inve_{kn}^{t} = Invs_{k(n+1)}^{t+1} \; \forall k, t \neq T, n \neq M \tag{11}$$

Equation (11) indicates the ageing process of stored blood units in a blood center.

$$\sum_{n \neq M} Inve_{kn}^{t} = FV_{k}^{t} \; \forall k, t \tag{12}$$

Equation (12) indicates that in each blood center, by aggregating the final inventory level of blood units with various age, the total inventory level of the blood center will be determined.

$$DW_{k}^{t} = Inve_{kn}^{t} \; \forall k, t, n = M \tag{13}$$

Equation (13) indicates that in each blood center, the final inventory of M days' blood units will be discarded at the end of each period.

$$\sum_{m\neq M} ie_{im}^{t} = V_i^t \ \forall i,t \tag{14}$$

Equation (14) indicates that in each hospital, by aggregating the final inventory level of blood units with various ages, the total inventory level of the hospital will be determined.

$$\sigma_i^t = ie_{im}^t \ \forall i,t,m=M \tag{15}$$

Equation (15) indicates that in each hospital, the final inventory of M days' blood units will be discarded at the end of each period.

$$ie_{im}^t = is_{i(m+1)}^{t+1} \ \forall i,t\neq T,m\neq M \tag{16}$$

Equation (16) indicates the ageing process of stored blood units in a hospital.

$$y_i^t = is_{im}^{t+1} \ \forall i,t,m=3 \tag{17}$$

Equation (17) indicates the lead time of delivering orders to a hospital is one day, and orders just include fresh blood units.

$$y_i^t = \textstyle\sum_k Z_{ki}^t \ \ \forall i,t \tag{18}$$

Equation (18) indicates that a hospital can receive fresh blood units from all blood centers.

$$S_i - \sum_m is_{im}^t = y_i^t \ \forall i,t \tag{19}$$

Equation (19) indicates that the amount of each hospital's orders will be determined based on its target inventory level and the beginning inventory level of all blood units with various ages.

$$Invs_{kn}^{t+1} = Don_k^t \ \forall k,n=2,t\neq T \tag{20}$$

Equation (20) indicates that it takes one day to test the collected blood units, and to make sure they are safe for future transfusion.

$$\textstyle\sum_{j\neq i}\sum_m X_{jim}^t + \sum_k \sum_{n\geq 3} ES_{kin}^t \geq \beta f_i^t \ \forall i,t \tag{21}$$

Equation (21) indicates that in each period of time at least β percent of each hospital's shortage should be satisfied.

$$\textstyle\sum_{j\neq i}\sum_m X_{jim}^t + \sum_k \sum_{n\geq 3} ES_{kin}^t \leq f_i^t \ \forall i,t \tag{22}$$

Equation (22) indicates that in each period of time, the received blood units in each hospital should not be more than its shortage.

$$Don_k^t \leq San_k \ \forall k,t \tag{23}$$

Equation (23) indicates that in each period of time and in each blood center, the amount of collected blood units should be less than its capacity.

$$\sum_i \sum_{n\geq 3} ES_{kin}^t = EZ_k^t \ \forall k,t \tag{24}$$

$$MIZ_{kn}^t \leq EZ_k^t \ \forall k,t,n=M \tag{25}$$

$$MIZ_{kn}^t \leq Invs_{kn}^t \ \forall k,t,n=M \tag{26}$$

$$EZ_k^t - MIZ_{kn}^t \leq \acute{M} b_{kn}^t \ \forall k,t,n=M \tag{27}$$

$$Invs_{kn}^t - MIZ_{kn}^t \leq \acute{M}(1-b_{kn}^t) \ \forall k,t,n=M \tag{28}$$

$$MIZ_{kn}^t \leq EZ_k^t - MIZ_{k(n+1)}^t \ \forall k,t,3\leq n\leq M-1 \tag{29}$$

$$MIZ_{kn}^t \leq Invs_{kn}^t \ \forall k,t,3\leq n\leq M-1 \tag{30}$$

$$EZ_k^t - MIZ_{k(n+1)}^t - MIZ_{kn}^t \leq \acute{M} b_{kn}^t \ \forall k,t,3\leq n\leq M-1 \tag{31}$$

$$Invs_{kn}^t - MIZ_{kn}^t \leq \acute{M}(1-b_{kn}^t) \ \forall k,t,3\leq n\leq M-1 \tag{32}$$

Equations (24-32) indicate FIFO system for each period of time and in each blood center.

$$a_{im}^t \leq D_i^t \ \forall i,t,m=M \tag{33}$$

$$a_{im}^t \leq is_{im}^t + \sum_{j\neq i} X_{jim}^t - \sum_{j\neq i} X_{ijm}^t + \sum_k ES_{kin}^t \ \ \forall i,t,m=n=M \tag{34}$$

$$D_i^t - a_{im}^t \leq \acute{M} gb_{im}^t \ \forall i,m=5,t \tag{35}$$

$$is_{im}^t + \sum_{j \neq i} X_{jim}^t - \sum_{j \neq i} X_{ijm}^t + \sum_k ES_{kin}^t - a_{im}^t \leq \acute{M}(1 - gb_{im}^t)\ \forall i, t, m = n = M \quad (36)$$

$$a_{im}^t \leq D_i^t - a_{i(m+1)}^t\ \forall i, t, 3 \leq m \leq M - 1 \quad (37)$$

$$a_{im}^t \leq is_{im}^t + \sum_{j \neq i} X_{jim}^t - \sum_{j \neq i} X_{ijm}^t + \sum_k ES_{kin}^t\ \ \forall i, t, 3 \leq m \leq M - 1, n = m \quad (38)$$

$$D_i^t - a_{i(m+1)}^t - a_{im}^t \leq \acute{M} gb_{im}^t\ \forall i, t, 3 \leq m \leq M - 1 \quad (39)$$

$$is_{im}^t + \sum_{j \neq i} X_{jim}^t - \sum_{j \neq i} X_{ijm}^t + \sum_k ES_{kin}^t - a_{im}^t \leq \acute{M}(1 - gb_{im}^t)\ \forall i, t, 3 \leq m \leq M - 1, n = m \quad (40)$$

Equations (33-40) indicate FIFO system for each period of time and in each blood center.

$y_i^t \geq 0\ \forall i, t$ (41)
$S_i \geq 0\ \forall i$ (42)
$is_{im}^t \geq 0\ \forall i, m, t$ (43)
$ie_{im}^t \geq 0\ \forall i, m, t$ (44)
$a_{im}^t \geq 0\ \forall i, m, t$ (45)
$f_i^t \geq 0\ \forall i, t$ (46)
$V_i^t \geq 0\ \forall i, t$ (47)
$\sigma_i^t \geq 0\ \forall i, t$ (48)
$X_{ijm}^t \geq 0\ \forall i, j \neq i, m, t$ (49)
$JB_{ki}^{pt} \geq 0\ \forall k, i, p, t$ (50)
$JT_{ij}^{pt} \geq 0\ \forall k, i, p, t$ (51)
$ES_{kin}^t \geq 0\ \forall k, i, t, n$ (52)
$Z_{ki}^t \geq 0\ \forall k, i, t$ (53)
$FV_k^t \geq 0\ \forall k, t$ (54)
$DW_k^t \geq 0\ \forall k, t$ (55)
$Invs_{kn}^t \geq 0\ \forall k, t, n$ (56)
$Don_k^t \geq 0\ \forall k, t$ (57)
$San_k \geq 0\ \forall k$ (58)
$EZ_k^t \geq 0\ \forall k, t$ (59)
$MIZ_{kn}^t \geq 0\ \forall k, t, n$ (60)
$b_{kn}^t \epsilon \{0,1\}\ \forall k, n, t$ (61)
$gb_{im}^t \epsilon \{0,1\}\ \forall i, m, t$ (62)

Equations (41-62) indicate the type of decision variables which have been used in the model.

5. Case Study

Platelet is one of the blood components which has 5 days' shelf life, and it has various application such as surgery, cancer treatments and organ transplants. Hence, in order to both save more lives and increase the system efficiency, this research aims to minimize platelet supply chain's costs. In order to achieve the mentioned goal, the Greater Toronto Area (GTA) has been considered as the case study of this study:

- The Greater Toronto Area (GTA) is the most populous metropolitan area in Canada. It consists of the central city, Toronto, along with 25 surrounding cities and towns distributed among four regional municipalities: Durham, Halton, Peel, and York.(OECD Territorial Reviews, 2010) According to the 2016 census, the Greater Toronto Area has a population of 6,417,516. (Statistics Canada, 2016). Figure 2 shows the map of the GTA.
- The supply chain design aims to minimize all related costs for both hospitals and blood centers and optimize the platelet allocation in a way that both shortage and wastage would be minimized.

In order to reach to the mentioned goals and by considering existing information, 7 blood centers and 20 hospitals have been selected all around the GTA. Figure 3 shows the location of blood centers and selected hospitals.

Figure 2: The map of the Greater Toronto Area (GTA)

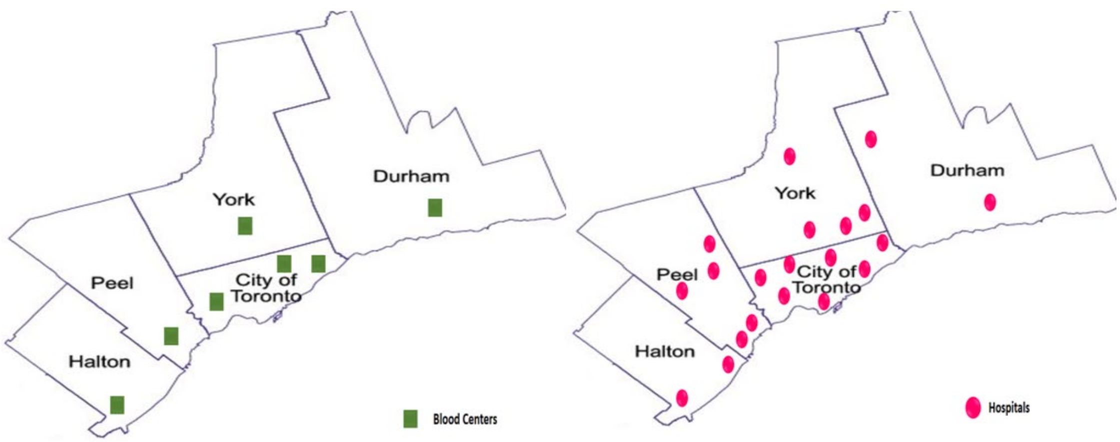

Figure 3: Blood centers and hospitals location

Also, to make the model closer to the real-world situation it has been assumed that the lead time for regular order would be one day while there would be no lead time for emergency order from blood center or lateral transshipment from other hospitals.

The needs of each demand center has been calculated by considering its available number of beds.

The time period that the proposed model should response to the hospitals' demands is 7 days (a week), and it has been assumed that in this period of time more than 85% of each hospital's shortage should be satisfied either.

6. Results and Analysis

This section will demonstrate how proposed model would help hospitals to reduce their shortage amounts. To make the results more understandable and by considering previous research works and existing information, a general blood supply chain model without considering the lateral transshipment approach and emergency ordering option has been solved to show the current situation. In the next step, both lateral transshipment approach and emergency order option have been added to the model to show how much they would affect the results. Both general model and proposed model have been implemented in GAMS win64 24.1.2 using Intel ® Core™ i3-3110M CPU 2.4 GHz processor with 4 GB of RAM. Summary of the results have been provided in both Table 2.

The first two columns show the costs of both general and proposed models, the next two columns show the cumulative shortage amount in both columns and the last two columns show the effects of lateral transshipment approach and the emergency ordering options.

Table 2. Summary of the results

Objective Value ($)		Total Shortage Amount (Units)		Cost Change (%)	Shortage Change (%)
General	Proposed	General	Proposed	31.71	55.33
589,862	776,937	5,983	3,310		

As it has been shown in the last two columns of Table 1, although applying these methods would increase the total cost almost 30%, the shortage amount would decrease more than 55%. These results demonstrate that the proposed model can be considered as a helpful solution to save more lives. Figures 4 and 5 show graphically how proposed model would affect the results.

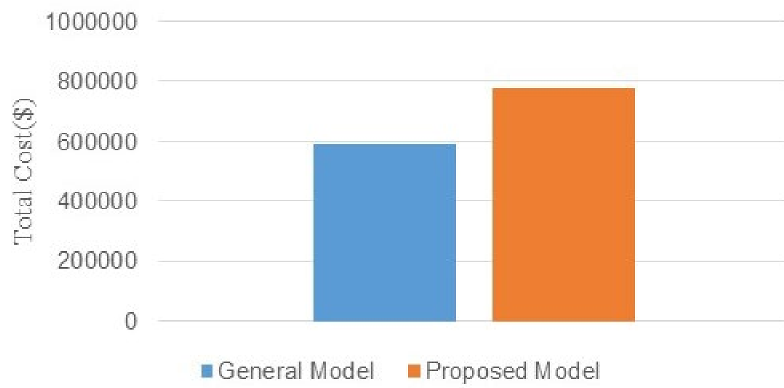

Figure 4: Models' Total Costs

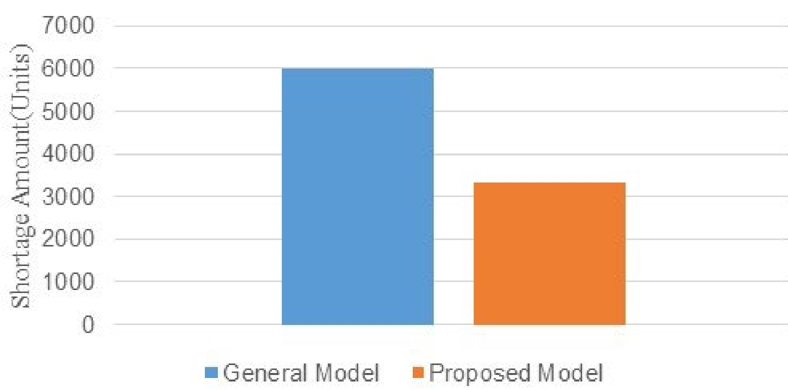

Figure 5: Models' Shortage Amount

In comparative analysis of both supply chain models, it has become apparent that in the general supply chain model on average 55% of the total demand encounters shortages, while applying lateral transshipment method and emergency ordering option decreases this rate to 31% in the proposed supply chain model. 24% improvement rate implies that the proposed methods are helpful to resolve significant part of shortage issue, although not eliminate if fully.

7. Conclusions and Future Work

7.1. Conclusion

In this paper, the blood supply chain design has been represented in the form of a deterministic optimization model. The proposed model has been applied to specific data and deterministic condition in the Greater Toronto Area (GTA). Decision variables of this model include the beginning and final inventory level of each hospital and each blood center in each period of time, shortage and wastage amount of each hospital due to its demand, wastage amount of each blood center due to the amount of collected platelet and delivered platelet units, and the platelets amount which will be transferred in emergency situation from hospitals and blood centers.

7.2. Future Recommendations

Considering uncertainty in both platelet supply and demands, various transportation modes and their specific capacity, ability to establish temporary blood centers in case of need, the effects of existing environmental errors such as test results' errors, staffs' errors, etc., and changing the condition of the proposed model to stochastic can be considered as the potential future research directions.

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Appendix 1 Notations used in the mathematical model

Sets and Indices

T	*Time Horizon* $t\epsilon T$	N	*Remaining shelf life of blood centers' blood units* $n\epsilon N$
N	*Hospitals* $i, j \in N$	K	*Blood centers* $k\epsilon K$
M	*Remaining shelf life of hospitals' blood units* $m\epsilon M$		

Parameters

B_{im}^{1}	*Initial inventory of blood units with shelf life m at hospital i*	M	*Maximum shelf life*
G	*Penalty order cost per unit at hospitals*	H_i	*Holding cost per unit at hospital i*
E	*Expiry cost per unit at hospitals*	SEF	*Ordering cost per unit at hospitals*
C_{ij}^{m}	*Cost of transshipping one unit of blood with shelf life m from hospital i to hospital j*	D_i^t	*Total demand of hospital i in period t*
CE_{ki}^{n}	*Cost of transshipping one unit of blood with shelf life n from blood center k to hospital i*	SN_{ki}	*Cost of delivering one unit of fresh blood from blood center k to hospital i*
HB_k	*Holding cost at blood center k*	CW	*Expiry cost per unit at blood centers*
TES	*Testing cost at blood centers*	CAP_{kn}^{1}	*Initial inventory of blood units with shelf life n at blood center k*
β	*Minimum shortage coverage*	$\acute{M}$	*Very large number*

Variables			
y_i^t	*Order quantity at hospital i in period t*	S_i	*Target inventory level at hospital i*
is_{im}^t	*Inventory level of hospital i for blood units with shelf life m at the beginning of period t*	ie_{im}^t	*Inventory level of hospital i for blood units with shelf life m at the end of period t*
a_{im}^t	*Quantity of blood unit with shelf life m used to fulfil demand at hospital i in period t*	f_i^t	*Quantity of shortage amount at hospital i in period t*
V_i^t	*Total inventory of hospital i at the end of period t*	σ_i^t	*Quantity of outdated blood units in hospital i at the end of period t*
X_{ijm}^t	*Quantity of blood units with shelf life m will be delivered from hospital i to hospital j in case of shortage in period t*	ES_{kin}^t	*Quantity of blood units with shelf life n will be delivered from blood center k to hospital i in case of shortage in period t*
Z_{ki}^t	*Quantity of fresh blood units will be delivered from blood center k to hospital i in period t*	FV_k^t	*Total inventory of blood center k at the end of period t*
DW_k^t	*Quantity of outdated blood units in blood center k at the end of period t*	$Invs_{kn}^t$	*Inventory level of blood center k for blood units with shelf life n at the beginning of period t*
$Inve_{kn}^t$	*Inventory level of blood center k for blood units with shelf life n at the end of period t*	DON_k^t	*Amount of donated blood units at blood center k in period t*
EZ_k^t	*The whole emergency blood transferred from blood center k in period t*	MIZ_{kn}^t	*Blood center's k usage of blood units with shelf life n in period t*
b_{kn}^t	*If blood center k uses blood units with shelf life n in period t 1 otherwise 0*	gb_{im}^t	*If hospital i uses blood units with shelf life m in period t 1 otherwise 0*