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Blood Shortage Reduction by Deployment of Lateral Transshipment Approach

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Blood Shortage Reduction by Deployment of Lateral Transshipment Approach

By

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DECLARATION OF ORIGINALITY

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ABSTRACT

The healing effects of human blood make it one of the essential, life-saving components in a variety of medical procedures. However, assuring timely and sufficient blood supply for use in life-critical medical procedures is one of the major challenges that most health care networks around the world are persistently facing and trying to resolve. Based on the WHO's latest statistics, 107 out of 180 countries all around the world have an insufficient amount of blood units to meet their demands. For two years in the row (2018-19), Canadian Blood Services have called for 100,000 new donors to sign up in order to meet the anticipated demand for blood. The perishability of blood components and uncertainty in both donation and demand scale are two important reasons that contribute to the blood shortage. Due to the poor inventory planning, the high rate of discarded units is another worldwide issue that exists in the blood supply chain and needs to be urgently addressed.

Canadian blood supply chain network consists of several organizational entities and each of them impacts the blood units' inventory levels in its own, unique way. In this study, an integrated supply chain model has been considered, and it consists of three main networked organizations: 1. Mobile Collection Centers, 2. Blood Centers, and 3. Hospitals. The main goal of this research is to develop a mathematical optimization model that can improve the proposed supply chain's performance by reducing its related costs, and the currently existing shortage rate from about 25% to less than 15%. Lateral Transshipment and Emergency Ordering are two main approaches that have been implemented in the proposed model in order to improve both performance and efficiency.

The Greater Toronto Area (GTA) has been considered as the case study focus for this research, and both models have been applied in this case study. All the further necessary actions and recommendations would be taken based on the case study's results.

DEDICATION

It is my genuine gratefulness and warmest regard that I dedicate this work to my beloved family.

To my parents who unconditionally supported me during my studies and gave me a chance to prove and improve myself all my walks of life.

To my brother who always believed in me and were always there for me, who is very special.

To my fiancé who has been a constant source of support and encouragement during the challenges of graduate school and life.

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LIST OF ABBREVIATIONS/SYMBOLS

Sets and Indices			
$\boldsymbol{T}$	*Time Horizon $t\epsilon T$*	R	*Mobile Collection Centers $r \in R$*
$\boldsymbol{K}$	*Blood centers $k\epsilon K$*	I	*Hospitals $i, j \in I$*
$\boldsymbol{M}$	*Remaining shelf life of hospitals' blood units $m\epsilon M$*	N	*Remaining shelf life of blood centers' blood units $n\epsilon N$*
P	*Transportation Modes $p \in P$*	Q	*US blood centers $q \in Q$*

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*
θ	*Percentage of blood units which will be discarded due to environmental risk factors and test results*	HAD	*Maximum number of open mobile collection centers in each period*
ZAR_r	*Capacity of mobile collection center r*	MAX_p	*Maximum number of available transportation mode p*
SAN_k	*Capacity of blood center k for donating blood*	VC_p	*Transportation cost per distance for transportation mode p*
LB_{ki}	*Distance between blood center k to hospital i*	LH_{ij}	*Distance between hospital i to hospital j*

Parameters			
$AMCA_{qn}^{t}$	*Total inventory of US blood center q for blood units with shelf life n at period t*	Haz_n	*Cost of delivering one unit of blood with shelf life n from US blood centers to hospitals*

Variables			
Positive Variables			
y_i^t	*Order quantity at hospital i in period t*	S_{it}	*Target inventory level of hospital i at period t*
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*
HJM_{rk}^t	*Quantity of delivered blood from mobile collection center r to blood center k at period t*	EZ_k^t	*The whole emergency blood transferred from blood center k in period t*

Variables			
Positive Variables			
MIZ_{kn}^{t}	*Blood center's k usage of blood units with shelf life n in period t*	KOM_{qi}^{n}	*The amount of blood units that can be delivered from US blood center q to hospital i with shelf life n at period t*
Binary Variables			
OP_{rt}	*If mobile collection center r is open at period t 1 otherwise 0*	BTH_{ki}^{pt}	*If blood center k transfer blood units to hospital i by using transportation mode p at period t 1 otherwise 0*
HTH_{ij}^{pt}	*If hospital i to hospital j by using transportation mode p at period t 1 otherwise 0*	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*		

GLOSSARY

AABB	The American Association of Blood Bank
ARPs	Automatic Replenishment Programs
ASBP	Armed Service Blood Program
BJ	Box-Jenkins
CBS	Canadian Blood Services
DSS	Decision Support System
ERP	Enterprise Resource Planning
GDP	Gross Domestic Product
GTA	Greater Toronto Area
MDP	Markov Decision Process
MI	Michigan
MVT	Marginal Value Time
NBTC	National Blood Transfusion Committee
NY	New York
OH	Ohio
PA	Pennsylvania
RBCs	Red Blood Cells
RFID	Radio Frequency Identification
RSCCS	Refined Smart Cold Chain System
SCND	Supply Chain Network Design
STAT	Immediately

TCI	Toyota Canada Inc.
TOC	Theory of Constraints
TRC	Turkish Red Crescent
TSO	Transfusion Safety Officers
VMI	Vendor Managed Inventory
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1. Background & Motivation

Managing blood supply chain network has always been crucial for governments and organizations due to the blood's characteristics. Perishability of blood products, uncertainty in donation and demand sizes are the three main reasons that complicate the blood supply chain planning (National Health Expenditure Trends, 2018).

The most important reason is that blood is a perishable product and consists of various components each with different expiring dates. Therefore, all the needed actions should be taken in the shortest possible time in order to both save blood components from expiration and avoid having any blood discarding related costs. Based on the latest Canadian Blood Services (CBS) annual review, it has been realized that the rate of whole blood discards during the year 2017-2018 was almost near to 6% of the total blood donations (Year-End Review, CBS). Having a precise plan, which controls the flow of blood donations in a system, helps to reduce wasted units and their costs.

Hitherto only few substitutes have been introduced for blood products and humans are the main resource for supplying these component. Due to the fact that donation process deals with high uncertainty, these components are categorized as scarce products that are at risk of serious shortages. Various factors can affect the blood shortage issue:

- The number of donors who are willing to donate regularly.
- Seasonal factors affecting donation e.g. public holidays.

- The blood services ability to adequately predict the number of units of blood required throughout the year
- The clinicians' awareness of appropriate blood ordering and transfusion and the hospital laboratories ability to ensure sufficient stock (Chargé, 2019).

For instance, based on the statistics, there are seasonal shortages due to low blood donations during the winter and summer months (Annual Report, 2015; Glicher & McCombs, 2005).

Patients are the final customers of a blood supply chain network, and blood components are in a direct relation with human lives. These products are one of the main participants of organ transplants, cancer and anemia treatments, and major surgeries such as, for example open-heart surgery. So, it can be figured out that the request for blood by the patients drives the supply chain and determines the number of required blood donations (Chargé, 2019). However, since blood is a single-source product, in many countries, people still die because of inadequate supply of blood products (World Health Organization, 2012). Any shortage of these components can have serious consequences such as increasing the mortality rate especially in the time-sensitive situations. Having a precise plan can help to match the blood supplied and demands with each other.

A precise plan manages both inventory level and inventory flow in a way that not only improves the performance of the blood supply chain, but does it also have a significant impact on reducing the costs of the blood supply chain or generally the healthcare industry. Due to the latest statistics, healthcare spending in Canada is projected to reach $264.4 billion in 2019, representing 11.6% of Canada's gross domestic product (GDP). This amounts to $7,068 per Canadian. Figure 1.1 shows total health expenditure costs have grown 45 years in Canada (National Health Expenditure Database, Canadian Institute for Health Information).

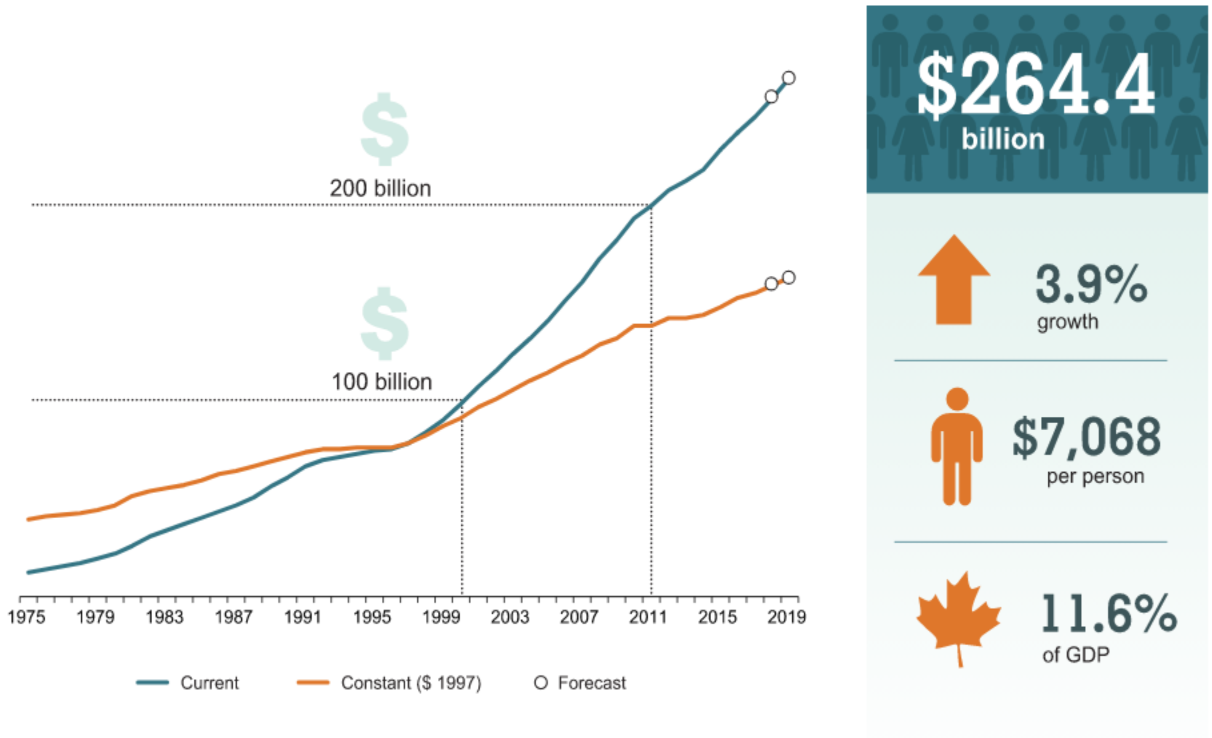


Figure 1.1- Total Health Expenditure Growth (*National Health Expenditure Database, Canadian Institute for Health Information*)

Besides the complex characteristic of blood components, the high global dependency on the US for applying blood product such as source platelets is another international concern about blood supply chain planning that is growing these days. According the latest statistics available, in 2016, Canada paid the US 512 million dollars to provide various types of blood components (Dinerstein, 2018). Hence, besides life-threatening problems, shortage raises concern about additional costs that governments have to pay if they cannot satisfy patients' demands by using their own blood collection resources.

In conclusion, the required actions to face blood shortage issue can be varied considering the existing shortage level in a blood supply chain system. (Daniel and Contreras, 2005). As an example, in August 2018, Canadian Blood Services was faced with a serious shortage issue. In an appeal to the public, the organization asked urgently for at least 22,000 blood donors in order to be able to deal with the shortage issue (Global News, 2018). Moreover, in March 2020, Canadian Blood Services Organization reported 20 percent dropped in the number of donations due to the COVID-19 pandemic resulted in a blood shortage issue (The Canadian Press, 2020).

1.2. Canadian Blood Supply Chain Configuration

A supply chain is the network of organizations that are involved, through upstream and downstream linkages, in the various processes and activities that produce value in the form of products and services delivered to the ultimate consumer (Christopher, 2016). In other words, a supply chain consists of multiple firms, both upstream (i.e., supply) and downstream (i.e., distribution), and the ultimate consumer (Mentzer et al, 2001).

Performance is one of the factors to measure how much the supply chain is well-organized. Supply Chain Network Design (SCND) is one type of strategic decision methods that are used to improve the supply chain’s performance. Generally, SCND consists of determining the optimal numbers, locations, and capacities of the required facilities and the aggregated material flows among them over a long and multi-period planning horizon (Zahiri et al, 2015). In addition, both shortage and surplus of a blood supply can cause serious problems such as an increase in the mortality rate or supply chain’s costs (Kuruppu, 2010). Therefore, understanding the configuration of the intended supply chain will help to identify the existing opportunities that are useful for improving the supply chain’s performance.

Canadian blood supply chain is a framework in which blood components collected from donors across Canada are delivered to the patients who are in need. Figure 1.2 shows the supply chain configuration. Each of the supply chain’s actors has its own role described in the following sections.

Figure 1.2- CBS Supply Chain *(Chargé, 2019)*

1.2.1. Donors

Since humans are the only source of the blood, blood donors can be considered as the main actor of the Canadian blood supply chain. The donor's suitability for donating blood is one of the greatest concerns in every blood supply chain. As stated in the World Health Organization's guidelines, "Blood transfusion services have the responsibility to collect blood only from donors who are at low risk for any infection that could be transmitted through transfusion and who are unlikely to jeopardize their own health by blood donation" (Public Health Agency of Canada, 2019). Blood operators have to follow the standard procedure provided for them in a way they can screen which donors are eligible for donating blood components. The standard procedure consists of several steps such as, for example donor questionnaires and required tests. The donor questionnaire includes several essential questions that should be answered by the donors. It should be noted donors should be completely honest during this process, and let operators know about any of their health hazards that may affect the safety of the blood components. Moreover, the required tests are conducted in a way that will notify the operators of the presence of any known transfusion-transmissible infectious (Blake and Hardy, 2014). If blood satisfies all the requirements regarding its safety, compatibility will be the next factor that makes the use of this scarce resource even more restricted. Figure 1.3 shows which blood types are compatible with each other. As has been shown in Figure 1.3, recipients with blood type AB+ can receive blood from all other types, while recipients with blood type O- can only receive blood from the same blood type. On the other hand, blood donation type AB+ can only be transfused to the patients with blood type AB+, while blood donation type O- can be transfused to patients with any blood type.

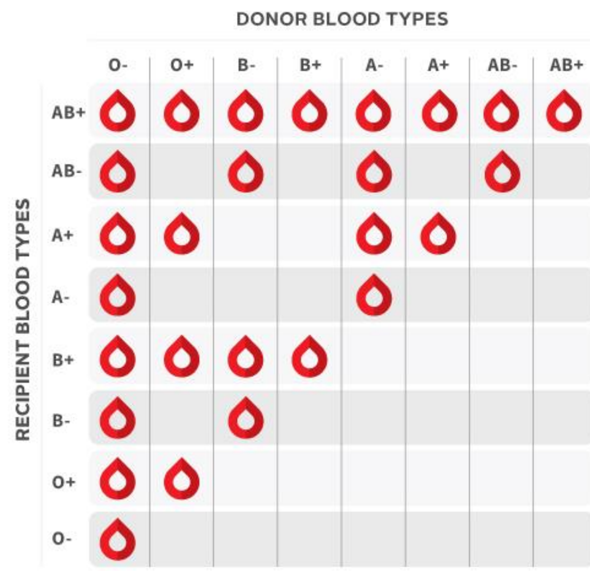


Figure 1.3- Blood Types Compatibility *(World Health Organization, 2012)*

Moreover, Figure 1.4 shows the breakdown of blood types in Canadian population.

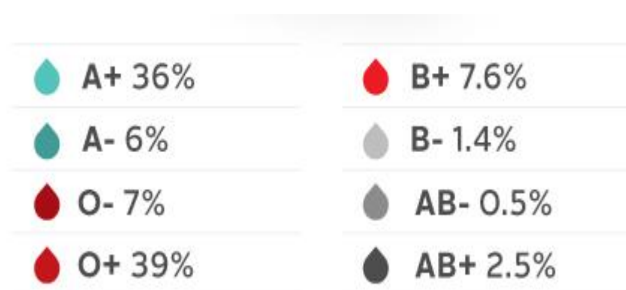


Figure 1.4– Frequency of Various Blood Types in Canada *(World Health Organization, 2012)*

As has been shown in Figure 1.4, some blood types (e.g. AB-, and B-) are more at risk of shortage than the others.

Ageing population phenomenon is another concern that is related to the donors. It has been estimated the blood components' demands will increase more than 10 % over the next decade while the number of available donors will most likely be reduced (Ghandforoush and Sen, 2010).

1.2.2. Canadian Blood Services(CBS)

There are two blood operators in Canada: Héma-Québec, serving hospitals in the province of Québec, and Canadian Blood Services, serving hospitals in all provinces and territories outside of Québec. Canadian Blood Services is incorporated as a not-for-profit organization. It is regulated as a biologics manufacturer by Health Canada and primarily funded by the provincial and territorial ministries of health, except Québec. The ministers of health appoint Canadian Blood Services' board of directors, approve Canadian Blood Services' annual budget and review its corporate plan. With its head office in Ottawa, Canadian Blood Services manages manufacturing sites, testing facilities and collection sites across Canada (except Québec) from both operations and quality assurance perspective. All sites undergo regular and extensive internal and external audits. CBS organization is responsible primarily for preparing fresh blood components from volunteer donations and managing their supply to hospitals for patients in need. As part of this responsibility, the blood operators select donors, collect and test donated blood, process donated blood into blood components, and store and transport blood components and products to hospitals. Qualified personnel with a wide range of skills and expertise (e.g. medical, nurses, laboratory technologists, regulatory, legal, finance, IT), supported by an extensive quality system and an appropriate infrastructure, ensure a supply of safe blood components and products of the highest quality (Blake and Hardy, 2014). CBS has a specific inventory level for each blood component. Based on the available blood component, the inventory level would be determined. For instance, platelet which is the rarest component of blood can have 3 main inventory levels' phase: 1. Green, 2. Amber and 3. Red. Table 1.1 defines each of these inventory level phases.

Table 1.1- Platelets Inventory Level *(CBS Report, 2016)*

Platelet Inventory Level	**% of National Requirement**
Green Phase (Minimal decrease to optimal)	80-100% of Daily National Requirement
Amber Phase (Serious)	25-79% of Daily National Requirement
Red Phase (Critical)	<25% of Daily National Requirement

Although Canada is one the main blood buyers from the US, and CBS invite more people to donate their blood components, based on the existing information, during the latest years, the inventory level of platelets in in the CBS is in the Amber phase which indicates that at least 20% and at most 75% of demands would not be satisfied (Dinerstein, 2018). On the other hand, Figure 1.5 shows that in April 2018, more than 10% of collected platelets have been discarded. Considering all these existing facts reveals that CBS is facing a serious management problem, and it needs an integrated plan which can reduce both shortage and outdated units, and optimize the blood components' flow.

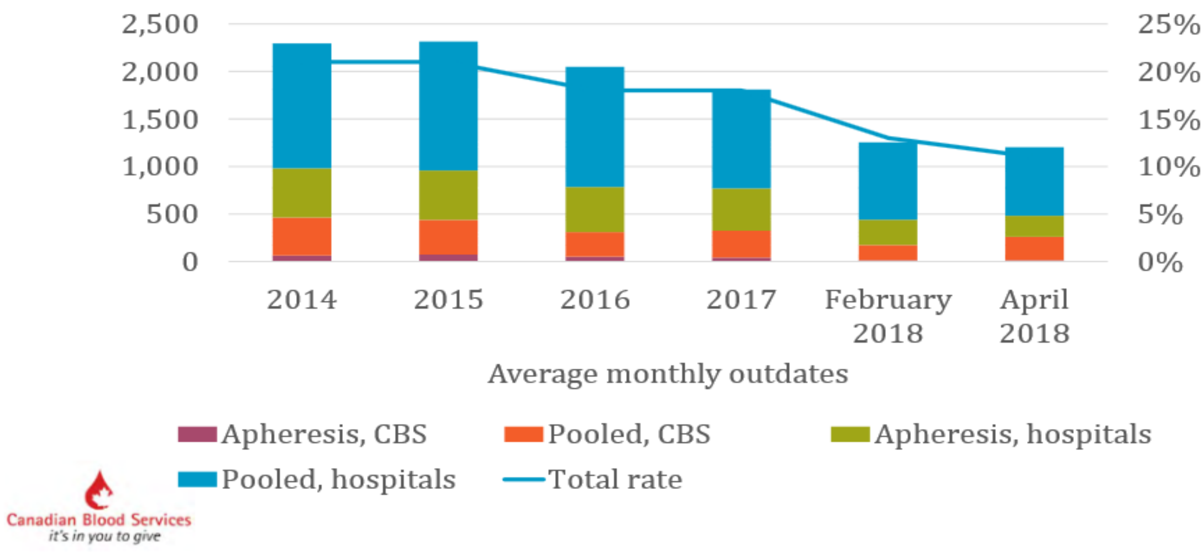


Figure 1.5- CBS Platelet Outdated Units' Issue *(CBS Annual Report, 2018)*

1.2.3. Hospitals

After collecting the blood components, CBS centers will send them to hospitals. Hospitals are the penultimate stage in the Canadian supply chain, and they are responsible for safe transfusion of the blood components to the patients. Although various frameworks have been adopted by Canadian hospitals, broadly all of them have three following structures in common with each other.

1. **Transfusion laboratory staff and medical directors** request blood products from the blood operator, as needed, and ensure their safe storage and distribution to clinical staff. This group is involved in blood products' compatibility testing to ensure an appropriate match between a blood product and a patient.

2. **Transfusion clinical staff**, in hospital units where blood is transfused, are responsible for developing and implementing transfusion policies approved by the hospital or regional transfusion committee.

3. **Transfusion recipients' physicians** order blood products for their patients in need. They are responsible for the optimal utilization of blood products and appropriate transfusion practices. It is noteworthy that most major hospitals in Canada are equipped with Transfusion Safety Officers (TSO) who are responsible for the quality and safety of transfusion within their institutions (Blake and Hardy, 2014).

1.2.4. Patients

Patients who are the ultimate actor in the Canadian blood supply chain depend on having blood components available to them on a daily basis for their specific treatment. Based on the statistics, in Canada, 52% of people say they or a family member have needed blood or blood products at some point in their lives (Dinerstein, 2018). Our country also needs organ and tissue donors, but not enough Canadians have made plans to donate. The need for blood components can be varied in various situation, although there is a constant demand for three following blood products:

- Platelets
- Blood Plasma
- Red Blood Cells

The amount of needed blood is calculated based on the situation that a patient is facing, for example:

- 5 donors to save someone who needs heart surgery
- 50 donors to help save just 1 person seriously hurt in a car crash
- 8 donors a week to help someone going through treatment for leukemia (Dinerstein, 2018)

1.2.5. Supporting Actors

1. AABB: The American Association of Blood Bank is an international, not-for-profit association representing individuals and institutions involved in the fields of transfusion medicine and cellular therapies (Blake and Hardy, 2014). As has been mention earlier, Canada is one of the main buyers of US blood components (Dinerstein, 2018). This information reveals that although CBS spent a major amount of its budget to supply blood components, the action does not have any beneficial effects on its performance.

2. Toyota Canada: Toyota Canada Inc.(TCI) is the exclusive Canadian distributor of Toyota and Lexus vehicles. Toyota and Canadian Blood Services are two organizations with vastly different products and services but a similar dedication to quality, efficiency and improving the lives of Canadians - an unlikely partnership has turned out to be a perfect match. The first collaboration of Toyota and CBS was in 2015 when Toyota helped CBS to figure out all the existing opportunities for improving the performances of its production and distribution facilities. The first step of the collaboration began with implementing the four fundamental philosophies of the Toyota Canada in the CBS organization:

1. The customer comes first
2. People are our most valuable resource
3. Continuous improvement
4. Shop floor focus- working alongside those closest to the process

As a result, CBS became able to make the following improvements:

1. Production and sorting improvements, to gain additional production time of 1 hour per day.
2. Standardized storage areas to improve workflow, creating additional benefits for employees such as less time in -20°C freezers.
3. 30% reduction in steps taken by employees as a result of reorganized workstations creating a better workflow for employees.

4. Packing time reduction by 40%. By reorganizing storage areas, making problems more visible and standardizing work processes, employees can find the right products quickly and accurately (Toyota Website, 2016).

As of 2017, Toyota Canada has extended its support to CBS with annual donations in order to make more people aware of blood and stem cells' donation, and invite them to participate in these donation processes (CBS and Toyota Websites, 2016). In conclusion, it can be realized that the collaboration between Toyota Canada and CBS mainly focuses on improving the performance of each Canadian Blood Supply Chain's process.

1.3. Canadian Blood Supply Chain Processes

Canadian blood supply chain carries four main processes out in order to safely deliver collected blood to the patients:

1. **Shipping and Delivery:** After blood components have been collected, CBS sends several samples to blood test centers to become sure about blood safety, and delivers the rest of them to the Canadian Blood Services production sites.

2. **Storing and Processing:** Three various procedures will be followed to store and process the donation. In the first procedure, the donations will be put into centrifuges and the whole blood will be separated into three layers:

   1. Plasma
   2. Buffy Coat
   3. Red Blood Cells(RBCs)

In the second procedure, the donations will be further processed based on the patients' needs. In the last procedure, donations will be kept in the interim storage before being labelled. It should be noted that considering Toyota Canada's recommendation to use sorting benches results in an 88% reduction in the sorting process steps, and gaining one hour of production time per day.

5. **Labelling and Storage:** If the test results show that the donations are suitable, they will be labelled and put into finished-product storage. All the components will be kept in storage sites until they are needed for a hospital order. Figure 1.6 shows the storage time and method that is required for each blood component. Rearranging storage areas and freezers was another Toyota Canada's recommendation that has been implemented in the storage sites and caused improvement in the workflow and employees' performance.

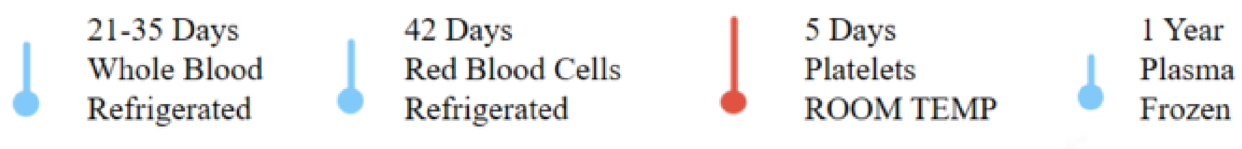


Figure 1.6 - Storage time and method for each blood component *(Ballem, 2018)*

6. **Distribution:** This is the last step in the Canadian Blood Supply Chain Process. As has been mentioned before blood components will be distributed based on the orders that CBS receives from hospitals. Hospitals' orders can be divided into the two main categories:

1. Routine Hospital orders
2. STAT(immediately) orders

Routine Hospital orders are regularly delivered to the hospitals to keep a constant supply of blood to the hospitals. STAT orders are only transferred during emergency situations when hospitals need a certain blood component quickly.

1.4. Blood Components

Blood is a living tissue that carries nutrients to and wastes away from all parts of the body. Blood consists of red and white blood cells, platelets, and plasma (Glicher and McCombs, 2005). Blood can be transfused to the patients as pint(s) of either whole blood or a specific blood component. Figure 1.7 shows the percentage breakdown of blood by component in one single unit of whole blood.

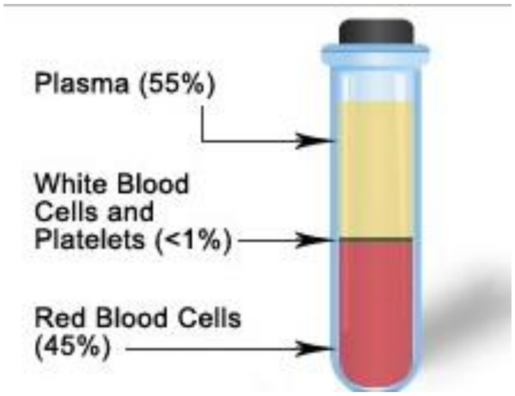


Figure 1.7- Blood Components Percentage in a Unit of Whole Blood *(Ballem, 2018)*

The blood components that are used in a blood transfusion process are Red Blood Cells(RBCs), Platelets, and Plasma. Each of these blood components should have its own supply chain network according its own specific characteristic and storing condition.

1.4.1. Whole Blood

Whole Blood is the simplest, most common type of blood donation. It’s also the most flexible because it can be transfused in its original form, or processed further to be separated into its specific components of red cells, plasma and platelets. Whole Blood donations require minimal processing before it is ready to be transfused into a patient. (Ballem, 2018)

1.4.2. Red Blood Cells (RBCs)

Red blood cells account for 45% of whole blood consists. RBCs are prepared from whole blood by removing the plasma (the liquid portion of the blood) (Ballem, 2018). RBCs have 42 days of shelf life and they should be stored in a refrigerated condition. The common applications RBCs include trauma, surgery and blood disorders. "AB0" blood types are established on RBC surfaces, and according to blood types' specific demand and supply amounts, each of them has its own planning in the RBCs supply chain (Zahiri et al, 2018).

1.4.3. Platelets

Platelets (Figure 1.8) constitute less than 1% of whole blood and are considered as the rarest blood component. Platelets 5 days' usability period have the shortest shelf life among all blood components. Therefore, due to the limited available time, all the required actions to deliver these units to hospitals and transfuse them to patients should be the fastest. Platelets can be extracted by using a centrifuge process called platelet-rich plasma therapy to separate plasma and platelets from donated whole blood. Platelets from several different donors are then combined to make one transfusable unit.

Alternately, platelets can be obtained using an apheresis machine which draws blood from the donor's arm, separates the blood into its components, retains some of the platelets, and returns the remainder of the blood to the donor. If donors donate platelets units by using an apheresis medical technology, they can contribute about four to six times as many platelets as a unit of platelets obtained from a whole blood donation (Ballem, 2018). The obtained platelets should be stored in a room temperature condition. The common applications of platelets include cancer treatment, organ transplant and surgery.

1.4.4. Plasma

Plasma constitutes 55% of whole blood. Plasma has the longest shelf life between blood components, and it can be stored in a frozen condition for up to one year. Blood plasma serves several important functions in human body, despite being about 92% water. (Plasma also contains 7% vital proteins such as albumin, gamma globulin and anti-hemophilic factor, and 1% mineral salts, sugars, fats, hormones and vitamins). It helps maintain a satisfactory blood pressure and volume, and supplies critical proteins for preventing blood clotting and immunity. It also carries electrolytes such as sodium and potassium to the muscles and helps to maintain a proper pH (acid-base) balance in the body, which is critical to cell function (Ballem, 2018). In a transfusion process, plasma is used for burn patients, shock and bleeding disorders applications.

1.4.5. Conclusion

In conclusion, Table 1.2 shows a summary of all related information to the blood types which have been described.

Table 1.2- Summary of Blood Types Information *(Ballem, 2018)*

(See Figure 1.6)

Blood Types	**Color**	**Shelf Life**	**Storage Conditions**	**Key Users**
Whole Blood	Red	21/35 days	Refrigerated	Trauma, Surgery
Red Blood Cells (RBCs)	Red	Up to 42 days	Refrigerated	Trauma, Surgery, Anemia, Any blood loss, Blood disorders
Platelets	Colorless	5 days	Room temperature with constant agitation to prevent clumping	Cancer treatments, Organ transplants, Surgery

Blood Types	Color	Shelf Life	Storage Conditions	Key Users
Plasma	Yellowish	1 year	Frozen	Burn Patients, Shock, Bleeding disorders

1.5. Problem Statement

According to the WHO's recent statistics, 107 out of 180 countries around the world do not have a sufficient inventory of blood units to meet the demands of their population (McDonnell, 2019). Currently, CBS adopts two main approaches to deal with the blood shortage issue in Canada:

1. Invite new blood donors: For two years in the row (2018-19), CBS has been repeatedly calling for 100,000 new blood donors to sign up to meet the anticipated demand for blood.
2. Buy blood components from US: Buying blood from US is the second approach used by CBS organization to face the shortage issue. The amount of blood components in each order determines by using the forecasting approach and considering the existing shortage. In 2016, Canada paid the US 512 million dollars to provide blood components for unsatisfied demands (Dinerstein, 2018). This shows that Canada is heavily dependent on the US to satisfy the existing demands and avoid shortage.

At the same time, CBS has reported that more than 10% of platelets has been discarded in April 2018 (See Figure 1.5). Since both issues of shortage and outdated units are co-existing in the CBS organization at the same time, one can imply that the current blood management tactical planning at CBS are not effective to organize supply chain that can manage both shortage and outdated units' issues simultaneously. However, since blood supplying depends heavily on availability of donors, CBS should continue exploring other approaches such as, for example, lateral transshipment and emergency ordering methods to mitigate this dependency. Applying these approaches in the supply chain to redesign the process may provide a suitable condition for CBS to use the existing inventory in a way that the amounts of discarded units' and shortage rates, and the dependency on the US blood products will be reduced. These methods may enable CBS to effectively monitor the inventory level of all the internal actors and make a decision that help all the actors to improve both their performance and efficiency. This research aims to explore solution for a blood network supply chain redesign process in which CBS can be in the green phase (See Table 1.1), and satisfy at least 80% of the blood components' shortage.

1.6. Approach

This chapter reveals the importance of blood supply chain performance due to its life-saving product. With regarding the blood's nature and Canadian blood supply chain configuration, this study proposes to develop and explore a mathematical model that can be implemented in a local level of Canadian blood supply chain. It will help to understand (by studying various scenarios) how to achieve both inventory management and reduce all the costs..

Perishable nature of blood products and uncertainty of supply and demand expose concurrently Canadian blood supply chain to both shortage and expiration issues at the same time, therefore, the proposed model must be able to reduce both the shortage level and expired amount of the system together. By reviewing the available research, the currently existing gaps in the blood supply chain field and the direction of this research are to be determined. This study considers three main categories of actors in a blood supply chain:

1. Mobile Collection Centers
2. Blood Centers
3. Hospitals

In addition, available blood transportation modes can be expanded to offer the proposed centers more flexibility and help optimize the blood units' flow between every two centers.

Available information shows that the current actions such as, for example buying blood from US and inviting people to donate blood which CBS is under taking to deal with blood shortage and expiration problems are not highly effective and increase costs significantly. This research purposes and quantifies two additional approaches as possible enhancements to the blood supply chain performance:

1. Reactive Lateral Transshipment
2. Emergency Ordering

The reactive lateral transshipment approach is an option that allows hospitals to order blood units from other hospitals and clinical centers if the former faces shortage.

Emergency ordering approach also allows hospitals to order blood units from blood centers directly if they face shortages. The mobile collection centers in this research are temporary centers that can just collect the blood units and transfer them to the blood centers. Blood centers are the next stage of the proposed supply chain in which the blood units will be collected, tested and stored. Hospitals are the last stage of the suggested model, hospitals can order blood directly from blood centers in a normal situation, or ordering blood from blood centers or other hospitals during an emergency situation.

The fact that blood components are perishable and errors that can happen in the test results and by staff have been considered in the model as well. A limited capacity for all the centers and available transportation modes have been considered in order to make the proposed model closer to a real-world situation. Furthermore, to reduce outdated units, a FIFO (First in, first out) system has been applied in both hospitals and blood centers. Optimization modelling and applying a case study approaches have been used in this research to show how the proposed model would behave in the real world. The Greater Toronto Area(GTA) has been considered as the case study of this research, and all the further necessary actions and recommendations will be taken based on the case study's results.

1.7. Thesis Overview

The remainder of this study is organized as follows. In Chapter 2, the blood supply chain network's relevant research works, their approaches and achievements are described. In Chapter 3, necessary information to redesign a blood supply chain network has been introduced and a mathematical model has been developed by considering the assumptions. The research's case study has been introduced in Chapter 4, and all the required data to solve the proposed model has been explained. Chapter 5 shows the numerical results obtained by solving the model, and also demonstrates the model's sensitivity towards parameters' changes. In Chapter 6, a novel solution has been suggested to solve the infeasibility problem caused by unexpected changes in the parameters. Conclusions and recommendation for future research works are presented in Chapter 7.

1.8. Contributions

The following contributions have been implemented in this study.

1.8.1. Reactive Lateral Transshipment Approach

Reactive Lateral Transshipment approach provides an opportunity for hospitals to request blood components from other hospitals in case of need. Applying this approach in the proposed model is a novel contribution. If implemented, it would not only reduce hospitals' shortage level and save more lives, but also does it have positive effects on the reduction of outdated blood units' amount.

1.8.2. Emergency Ordering Approach

Emergency Ordering approach is another way that can be used by hospitals, if they face with any shortage. Considering this option in the suggested model is a new contribution. If applied, it provides an additional opportunity for hospitals in case of they cannot satisfy their shortage level by ordering blood units from other hospitals.

1.8.3. Transportation Modes

The proposed multimodal transportation framework is a novel contribution to this field. If implemented, both blood centers and hospitals have the opportunity to use various modes to deliver blood units from one nodes to another.

CHAPTER 2

LITERATURE REVIEW

2.1. Chapter Overview

This chapters shows some the most discussed issues over the past few years regarding healthcare and specifically blood supply chain. Figure 2.1 is a map stream that demonstrate the process of literature review in this research.

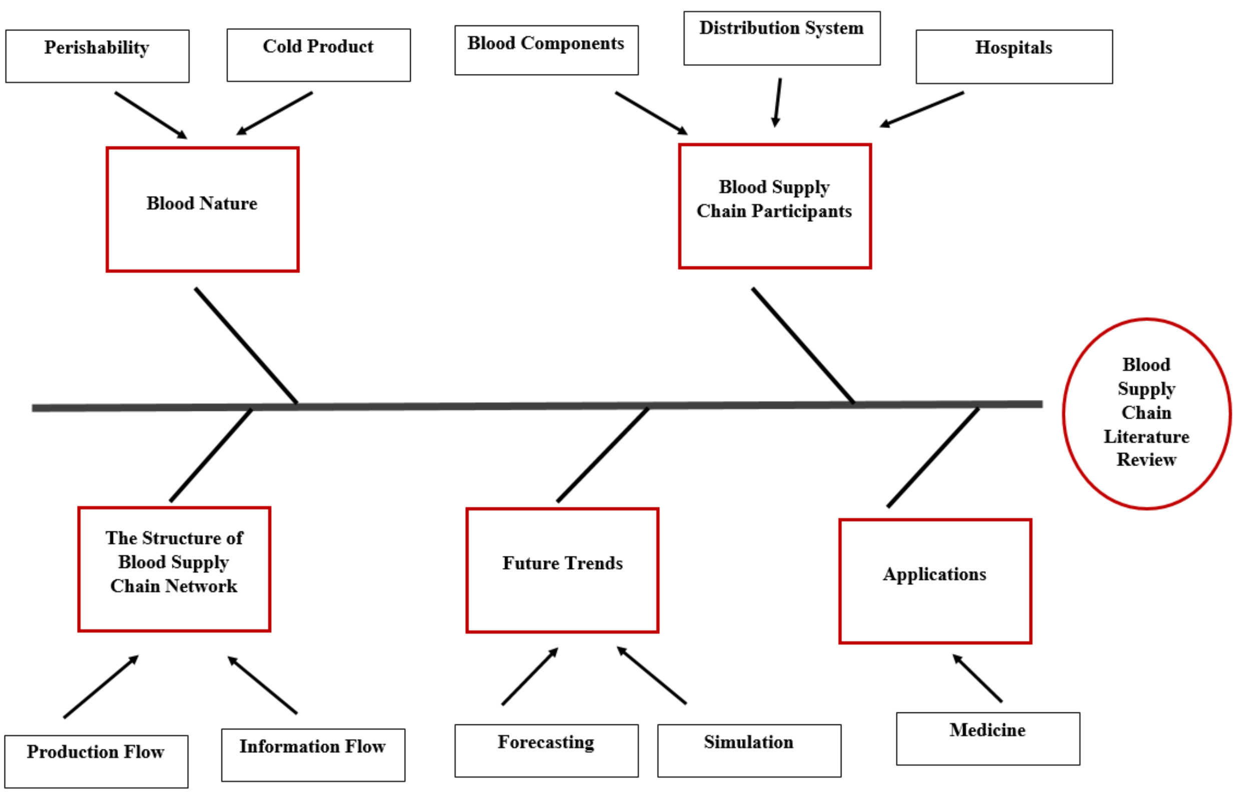


Figure 2.1- Literature Review Map Stream

2.2. Blood Supply Chain Network

The healthcare supply chain is recognized as one of the common area between both engineering and healthcare sciences fields (Aghazadeh et al, 2017). World changes constantly these days, and healthcare industry has to keep itself updated to be able to have both effective and efficient management. To achieve this goal, all the key elements of the healthcare system should first be identified, and then be optimized by considering all the new circumstances. The blood supply chain is considered as one of the critical elements of 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 a 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 performance, and also offer opportunities for improvement (Zahiri et al, 2015; Kaveh and Ghobadi, 2017).

Nowadays, blood availability is one of the major problems that developed countries are facing, and blood supply chains are dealing with various challenges such as, for example an increase in operating costs, a rise in competition among blood centers, donors' motivation, seasonal shortages and blood components' perishability (Dutta, 2019). Organized inventory management that is 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 detrimental effect of this complexity (Chapman et al, 2004). Choosing between centralized or decentralized structure is one of the ongoing debates among healthcare preferences. Each of these structures has its own advantages and disadvantages. For instance, it appears that hospitals see cost advantage in decentralized blood centers, while the centralized centers are more efficient when sharing and coordinating information (Carden & DelliFraine, 2006). Information flow in the supply chain is a key element that has a significant impact on both the supply chain's effectiveness and donors' satisfaction. An integrated supply chain in which information is shared across the entire system can be viewed as a successful framework leading to improve of the supply chain's performance (Grant, 2010). As an example, Enterprise Resource Planning (ERP) is known as a well-known tool to manage the information flow in manufacturing. The application of ERP in the blood supply chain field promises benefits from increased efficiency to improved quality, productivity, and profitability. Automatic Replenishment Programs (ARPs) is another tool that uses information sharing between supply chain members to discover how inventory should be managed. The application of these programs can reduce costs and lead times, and improve service level and productivity (Angulo et al, 2004). In conclusion, it can be realized that selection between centralized and decentralized structure or an in-between structure is highly dependent on the goals which blood supply chain are seeking. At first, it should be identified whether the main purpose is to minimize the total costs or to maximize the actors' satisfaction (Gupta et al, 2004).

2.3. Simulation Approach to Forecast Trends

Blood operation centers are responsible for a wide range of activities such as, for example blood collection from donors, blood processing and blood components distribution to hospitals and clinical centers. Usually, blood operation centers are focused on satisfying hospitals' demand in their own geographic area, but occasionally also provide blood for hospitals located sometimes even hundreds of miles away (Nagurney et al, 2012). Therefore, it can be realized that such centers are the critical nodes in a blood supply chain.

Although forecasting methods are mainly recognized as tools that are useful in manufacturing and commercial activities, the ability to forecast the amount of blood components' demands can be considered as an effective step which can both reduce the shortage stress, and increase efficiency (Caulfield, 2013). In today's world, technology provides a wide range of methods for anticipating products' demands, computer simulation approach is one of those methods that help managers prepare for a situation in which healthcare decisions can make an effective decisions regarding all of 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 a supply chain system. Consequently, by studying all these results, the decision-makers will decide about the effectiveness of the proposed model in the real-world situation (AbuKhousa et al, 2014). (Kopach et al, 2003) developed prototype simulation models to predict the likelihood and assess the subsequent medical consequences of blood product shortages. To make the model closer to reality, several factors such as uncertain supply and demand, suppliers' and consumers' policies and blood matching rules have been considered. The study was run in three different simulation environments, representing urban, semi-urban and rural areas.

A computational environment created by (Filho et al, 2013) in which using the Box-Jenkins (BJ) procedure has led to a forecasting method that can be used by blood centers during the blood components' demands estimation process instead of adopting traditional ordering policy methods.

Economic theory implies that the national blood supply can be increased either by increasing the level of resources used in the collection and production of blood components or by utilizing existing resources more efficiently (Pitocco & Sexton, 2005). Due to the limited budgets, most of the governments prefer to improve the existing blood supply chain rather than creating a new one.

Hence, it is essential to realize 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 the blood supply chain, in India. The supply chain faced various problems such as high shortage and outdated units' rates, large inventory levels, poor and erratic blood collection, high error rate and etc. Although the mentioned issues seemed to be independent, applying the proposed TOC approach in a simulation model revealed that they were all inter-related and originated from a single root-cause.

2.4. Blood as a Perishable Product

In contrast to many traditional supply chains, perishability of blood components, forces focus in blood supply chain 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 the value of product per unit time at a given point along the supply chain. Any change in MVT of the blood products drives up 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 the amount of outdated units (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
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 the push/pull process in order to understand how they should set the inventory policies due to the existing conditions. Moreover, some other concepts 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 used to forecast supply chain inefficiencies is known to cause excess inventory (Lee et al. 1997) which in turn can increase the outdated units' 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 responsible for the bullwhip effect in a blood supply chain system.

Knowing the fact that humans are the only resource for supplying blood components, and there is no other artificial substance that can be considered a good replacement for this scarce product, emphasizes the importance of having a precise planning in every stage of a blood supply chain especially hospitals and clinical centers who are responsible for blood transfusion. Najafi et al (2017) presented a mathematical model to manage blood ordering and issuing policies in hospitals. The ability to transshipment blood components between the nodes located within the same SC stage, and recognizing whether the patient can receive blood of any age or only fresh blood can be transfused made the model more realistic.

2.5. Blood Supply Chain Behavior in Uncommon Situations

Some supply chains maintain the same response policy in every situation, while others need to have various planning depending on the model scenario that is taking place. Blood supply chain belongs to the second group because blood components can be considered as one of the vital supplies in which their demands increase dramatically during an emergency situation. Moreover, a blood supply chain is an inseparable part of the healthcare system. Therefore, any disruption in this network would have some serious effects on the whole system. Between the years 1960 to

1990, natural disasters have claimed more than 3,000,000 people around the world, affecting 8,000,000 lives. (Schultz et al, 1996). After a series of earthquakes in 1999, Turkish Red Crescent (TRC) has engaged in restructuring for all of its activities, including the blood services, (Sahin et al, 2005) proposed a location-allocation mathematical model to increase the countrywide service level of the blood centers. The models' structure contains two main levels:

1. Upper-level: includes all the regional blood centers.
2. Lower-level: includes blood stations, mobile units and blood centers.

As a result, finding the proposed model helped TRC to increase the effectiveness of its current sites and find the optimal locations for establishing the new sites.

Similarly, after the Wenchuan earthquake in 2008 in China, the government realized that the lack of integrated scheduling for the transportation supply chain led to a shortage in some areas while other areas discard outdated blood units. To improve the uneven distribution, (Sha and Huang, 2012) presented a mathematical model in which all the decisions related to scheduling, location and allocation of blood components have been taken. The proposed model provided a framework in which cross-matching requirements over different regions have been satisfied. By reviewing these research works, it becomes clear that healthcare facilities' location problem has a significant impact on both minimizing the cost and maximizing the performance (Ghane & Tavakkoli-Moghaddam, 2018).

Research efforts in the area of an integrated blood supply chain network when disaster strikes have been increased dramatically over the past few years. This is because, due to climate change and all other related issues, frequency of natural disaster has increased more than ever before. It is anticipated that an integrated supply chain can offer ability to reduce the death rate and injuries. (Fahimnia et al, 2017) suggested a framework for the blood supply chain which consisted of blood donors, mobile blood facilities, local and regional blood centers and demand points. The aim of this 4-stages blood supply chain was to simultaneously improve both the efficiency (cost-minimizing) and effectiveness (delivery time minimizing).

To improve the accuracy of planning for blood distribution in an emergency situation, (Habibi et al, 2018) proposed a mathematical model that has two main objectives: to minimize both costs and blood shortages. The model considered several factors such as multi-period time horizon, robust uncertainty, and establishing permanent facilities to be more realistic. In the end, it has been realized that expanding the budget to a reasonable level will be helpful to be completely prepared for supplying the blood components' needs during an emergency situation like when a disaster strikes.

(Samani et al, 2017) suggested a blood supply chain network design that considered simultaneously efficiency, responsiveness and effectiveness, which are three major issues in any blood supply chain, simultaneously. Since some patients can only receive fresh blood, and any inadequacy in blood components can cause an increase in the death rate, the model aimed to minimize the time span between blood production in operation centers and consumption in demand zones in order to keep the blood components fresh besides the two previous objective functions.

The magnitude of disasters and their destruction level, various transportation modes, blood substitution, and reliability are other aspects that have been considered in the latest research work to make them closer to the real-world situation (Khalilpourazari & Arshadi, 2017; Fazli-Khalaf et al, 2017; Salehi et al, 2017).

Although the importance of supplying commodities such as water, food and shelter during the post-disaster phase is undeniable, the delivery of medicine such as blood is incomparable importance because blood components' transfusion has a direct impact on humans' lives, and even a slight delay may be fatal. Therefore, precise transportation planning is also critical. (Diabat et al,

2019) presented a mathematical model in which time and cost of delivering products have been minimized under various disaster scenarios. Moreover, disruption, which is an inseparable part of any disasters' scenario, has been implemented in the model to understand how blood transportation can be carried out when disruption affected the facilities or routes.

Responding to a disaster consists of three different phases:

1. Pre-disaster phase
2. Disaster phase
3. Post-disaster phase

(Jabbarzadeh et al, 2014) suggested a mathematical model that focused on improving the blood supply chain's performance during the post-disaster periods. Concerns regarding how all the operations should be managed to achieve the best responsiveness manner are at the highest level during the post-disaster phase. Thus, establishing a framework in which all the costs are minimized, and the blood inventory levels at each period have already been determined, can improve the performance level dramatically.

It is worthwhile to mention that during each phases of a disaster, there are various factors that affect the supply chain's performance. Hence, creating an integrated supply chain network in which all the phases have been considered will be a great help to increase the preparedness. (Eskandari et al, 2018) proposed a mathematical model that its main goal was to create a framework where the blood supply chain's efficiency can be increased during the disaster and post-disaster phases. The framework has been studied from three different perspectives:

1. Mitigating the environmental impacts that are caused by blood facilities' construction, and blood components' transportation.
2. Maximizing the blood supply chain's social impacts by providing various job opportunities in the communication that the supply chain has been constructed.

3. Minimizing the various costs that are associated with blood collection, preparation, transportation and transfusion.

Uncertainty has been applied in the model as well due to the nature of both blood and disaster.

The Military Blood Program called Armed Service Blood Program (ASBP) has a reach worldwide program. ASBP consists of several organizations, and all of them are committed to function together to assure that blood supply chain management can be run successfully during a man-made disaster, such as war. To have a better performance in all involved organizations, (Delen et al, 2011) proposed a hierarchical management structure by using data mining and GIS tools to be implemented in the ASBP's organizations.

Besides the disasters and emergency instances, there are some other times, as, for example religious events or statutory holidays (eg. Lunar New Year in China) in which the rate of blood donation decreases dramatically. In anticipations of such slowdown volumes of blood components' demands should be forecasted based on the previous data in order to prevent any shortages. (Haijema et al, 2009) suggested a stochastic dynamic programming to study ordering policies that should be set in a platelet supply chain to manage rate of both expiry and shortage. Furthermore, they conducted simulation studies to understand the effect of events such as, for example Easter and Christmas which break the production and lead to shortages. As a result, it has been concluded that during the production break events the management of the blood supply chain would be completely different.

2.6. Blood Transportation System

Perishability of blood products and uncertainty in both demands and supplies, make blood transportation planning as one of the major issues which managers deal with. (Hemmelmayr et al, 2010) presented a mathematical model, which goal was to minimize transportation time. To address the uncertain nature of blood supplies and demands, a variety of emergency delivery options were also implemented in the model.

In most recent research, transportation planning of the blood supply chain is studied from two main perspectives:

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

(Zahiri et al, 2018) proposed a mathematical model that focused on vehicle routing planning to improve both the reliability and efficiency of a blood supply chain. A stochastic programming approach has been implemented in order to cope with all the existing uncertainties. In addition, a combined scenario tree has been adopted to integrate collection, production, screening and distribution nodes in order to be able to manage all the necessary action which are helpful to achieve these goals.

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 efficient planning for the blood supply chain network. (Ghandforoush and Sen, 2010) presented an approach that contains Decision Support System (DSS) and non-convex integer optimization methods. In the first step, the DSS method has been used to support the supply chain of the blood production process. Optimization of the mobile scheduling system based on a non-convex integer programming model, led to a conclusion that removing utilized mobile centers is the optimal option to reduce maintenance expenses and improve transportation and staff time.

In some cases, the mobile blood collection centers have been designed to operate only the functions which are related to blood collection, and all other remaining functions such as blood tests and distribution, have to be done by other blood operation centers. Thus, mobile blood centers should deliver their collected blood to the blood centers on a regular basis. (Sahinyazan et al, 2015) created a mobile blood collection system in which collected blood should be transferred to the blood operator center at the end of each day in order to avoid the risk of blood spoilage. Increasing the amount of daily blood collection at a reasonable cost is the main goal of implementing mobile blood centers. However, if the mobile centers have to transfer the collected blood by themselves, some parts of their operational time would be wasted, and all related transportation costs would increase dramatically. Therefore, the model introduced a new vehicle called shuttle which has a job is to visit the mobile blood centers at the end of each day to deliver the collected blood to the blood operators. As a result, the optimal routing solution has been suggested for both mobile centers and shuttles to reduce all the related costs.

Lateral transshipment is one of the common tools in supply chain management deployed to deal with shortage and waste. Lateral transshipment occurs when a product must be transferred between the nodes in the same stage. There are two types of lateral transshipment:

1. Reactive Transshipment
2. Proactive transshipment.

Implementing lateral transshipment in a supply chain can be helpful to prevent any shortages and mitigate any waste. Also, it helps to reduce costs. Like any other supply chain, the blood supply chain is dealing with shortage and outdated units' issues, too. Hence, both transshipment methods have been applied in various blood supply chain networks in order to obtain desirable results in both inventory management and cost reduction fields. (Larimi et al, 2019) presented a mathematical model in which both total costs and maximum unsatisfied demand have been minimized for the platelets' supply chain. The fact that platelets' lifetime is only 5 days and a unit of blood contains less than 1% platelets shows the importance of having a separate organized supply chain for delivering this component. To overcome these obstacles and uncertainty issues, the model assumed lateral transshipment as an opportunity that provided a situation in which platelets can be transferred between all the clinical centers and hospitals. Lateral transshipment in this study was of a reactive kind, meaning that platelets were transferred between hospitals and clinical centers only when any platelets' shortage occured. The results showed that not only the proposed model reach its own goals, but it also improves demand satisfaction.

On the other hand, (Dehghani et al, 2019) believed that proactive transshipment would be more useful reaching reduction costs, shortage and outdated units 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 in to the model. Moreover, by using the Quasi-Monte Carlo sampling approach several scenarios have been generated to deal with the uncertain nature of blood components' demands.

2.7. Blood Components' Specific Supply Chain

As has been mentioned in Chapter 1, each blood component has its own specifications which may lead to creating a more customized supply chain for that particular blood component. (Ensafian et al, 2017) proposed a mathematical model in which the age of the platelets and ABO-Rh priority matching have been considered. The tactical and operational decisions in this model were obtained by considering a multi-period time horizon. To reduce uncertainty, the number of donors was forecasted by using a discrete Markov chain process. The platelet's demand was the only factor in this supply chain that deals with uncertainty and was a stochastic parameter. The main goals of the suggested model were to reduce all related costs and manage the existing risk in a way that both the expected value and variance of the costs would be reduced.

The short shelf life of platelets (compared to other blood products) 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 the blood supply chain's effectiveness:

1. Blood shortage
2. Outdating
3. Inventory level
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 eight blood types, stochastic demand and supply, and deterministic lead time. By applying the newsvendor model and dynamic programming it was verified that by minimizing the first two mentioned factors, the inventory level was optimized, therefore, the blood platelet bank reward was maximized.

While some of the patients have to receive fresh blood components, while others can be cured by old blood components. 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) to show that shortage, expiration and holding costs are not the only factors that can affect the inventory planning. Introducing a substitution 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 has a 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 outdated units' and shortage problems not only increase the costs dramatically, but also 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.

Based on the latest report (Chargé, 2019) Canadian blood supply chain is categorized as a comprehensive supply chain that includes all the organizations involved in all the upstream and downstream flows of products, services, finances, and information from the ultimate supplier to the ultimate customer (Mentzer et al, 2001). Controlling these organizations requires an integrated plan in which all the necessary policies for operating the supply chain have been defined. (Blake et al, 2003) proposed three phases simulation model for the platelet supply chain that has been applied in the Nova Scotia region. The first phase of the model gathered all the necessary information. In the second phase, by applying a dynamic programming model on the obtained information, locally optimal ordering policies for both producer (CBS) and consumers (hospitals, and clinical centers) have been identified. The last phase runs the model in a simulation environment in order to realize its effectiveness.

RBC is another blood component that has its own specific supply chain. It has been discovered that during storage phase, RBCs undergo biochemical changes, which are referred to as "storage lesions" (Fontaine et al, 2010), hence, the inventory stock rate and holding time are the two topics that have been discussed in the most recent paper due to this nature of the RBCs. The frequency of scheduled shipments from the blood supplier, the average age and the volume of the shipped stocks are the factors that affect holding time and inventory rate (Pereira, 2005). (Katsaliaki, 2008) provided a risk-free environment by using a discrete event simulation model in order to both reduce the costs and increase safety. The simulation study has shown that taking some necessary actions like holding stock of rare blood groups of RBC, having a second routine delivery per weekday, adhering an age-based issuing of order, etc., would help blood banks to reach to the optimal level the outdated, group substitutions, shortages and deliveries.

Although various methods such as, for example encouraging people to donate blood by advertising and constructing permanent or mobile blood collection centers have been applied to improve balance between blood supply and demand, blood substitution option can be recognized as the most cost-effective one, especially for RBC and Plasma products that in the clinical practice, have longer shelf lives than the other blood components (Zahiri & Pishvaee, 2017). Considering blood group compatibility not only reduces the outdated units' rate, but also does decrease the cost. (Duan and Liao, 2014) suggested a simulation framework for the RBCs supply chain, where the main goal was to minimize the expected system outdated rate under a predetermined maximally allowable shortage level. Blood substitution is one of the most useful methods in order to manage both shortage and outdated units' amounts. Thus, three different scenarios have been considered in the simulation framework. The first scenario did not allow any blood substitution either at the hospital or the blood center. The second scenario considered blood substitution only at the hospital stage, while the third scenario let the blood components be replaced with their compatible at both hospital and blood center stages. In addition, all three scenarios have been tested with three levels of maximal shelf lives: 21, 14 and 7 days. In conclusion, it has been figured out that the third scenario by considering the lowest maximal shelf life would lead to the optimal result, however, if financial problems did not let to have blood substitution in both two stages, the second scenario should be considered.

Both shortage and outdated units' issues can threaten not only the supply chain, but also the whole environment. That is why, shortage can increase the rate of death rates, while outdated units' issue can put the environment's sustainability in danger. (Nagurney & Masoumi, 2012) Moreover, shortage and outdated units' amounts optimization are two conflicting goals because a large amount of stored products improves demands' satisfaction while it will increase the storage time for the blood components as well (Baesler et al, 2014). Thus, a flexible blood supply chain network can be useful in this kind of situation that some of the hospitals and clinical centers are facing shortage while others are dealing with a large amount of outdated units. Flexibility in a supply chain can be obtained from various ways. (Jafarkhan and Yaghoubi, 2018) proposed a mathematical model for an RBC supply chain network. By adding the possibility of lateral transshipment and using compatible blood types (substitution) in case of any shortages, the model became flexible. As a result, it has been realized that transshipment can be useful to reduce the shortage and the total costs, and substitution can be applied when the demand rate is high. In addition, (Ekici et al, 2018) realized that 1. Increasing donors; utilization, and 2. Tailoring the donations based on the demand can be considered as fruitful tools to deal with outdated units' and repeated blood donation problems.

Besides, lateral transshipment and blood substitution options, there are several other options that can affect the supply chain's flexibility. (Dillon et al, 2017) presented a mathematical model that aimed to minimize all the operational costs. Different planning horizons, various lead times and shorter or longer shelf lives have been considered in the model in order to expand the solution area and flexibility which leads to obtain an optimal solution that matches more with reality. Given to high rate of uncertainty that existed in both blood components' demands and supplies, a stochastic approach by considering various scenarios has been implemented in the model in order to reach to ordering policies that can be applied in the real world.

As it has been discussed before, to overcome the shortage problem, establishing mobile blood collection facilities is a way that can provide a convenient situation in order to encourage more people to donate their blood. (Hamdan and Diabat, 2019) suggested a two-stage mathematical model for the RBC supply chain that the first stage of the model focused on finding the optimal locations for mobile blood collection centers, and the second stage determined an integrated framework for both inventory and distribution decisions. Minimizing the number of outdated units, system costs, and blood delivery time were the fundamental factors that have been considered in these strategic and tactical decisions.

From another point of view, it can be considered that both RBCs and platelets have short lifetimes. Therefore, an integrated blood supply chain that can satisfy both components' requirements would be useful in the situation that blood operators have time and cost limitations which prevent them from having a separate supply chain for each of these components. (Gunpinar and Centeno, 2015) proposed a set of mathematical models in which various factors such as two patients' types, demands' uncertainty rate and crossmatch-to-transfusion ratio have been considered in order to provide a situation in which storage, outdated units' and production costs would be minimized. The obtained results not only reduced all the related costs, but also did they improve hospitals' services level.

2.8. Hospitals Management System

Hospitals are recognized as the largest customer of the blood components around the world, and it is their responsibility to ensure that donated blood is used efficiently and effectively (Perera et al, 2009). Therefore, it can be realized that managing hospital inventory in order to deal with nonstationary demand is a major issue for hospitals all around the world (Hemmelmayr et al, 2009). In 2004 the Chief Medical Officer's National Blood Transfusion Committee for England and North Wales (NBTC) issued guidance on how hospitals should prepare contingency plans to deal with a shortage of red cells for transfusion. (Britain, 2004; Galloway et al, 2008). After declaring the guidance, some research works have been conducted to realize whether the guidance was helpful for hospitals and clinical centers or not. (Stanger et al, 2012) analyzed the related data of 277 hospitals in England and North Wales to realize what methods have been used for reducing RBCs outdated amount. Interviewing with blood inventory managers in the top-performing hospitals revealed 6 key themes that together drive good performance in blood stocks inventory management. These themes are human resources and training, stock levels and order patterns, transparency of inventories, simple inventory procedures, focus on freshness, and internal collaboration within the hospital. All these factors revealed the importance of having high quality, trained and experienced staff. Hence, it would be realized that the proposed models should consider hospitals' staff as a factor that can make the models closer to reality. It also has been realized that for having successful inventory management in other stages of a blood supply chain, techniques from commercial supply chain management can be useful methods (Yates et al, 2017).

Reserving frozen blood in the hospitals and clinical centers' storage is another solution to deal with short-term shortages that can be caused by seasonal shortages, weather conditions, and increasing donors' deferrals. (Erickson et al, 2008) reviewed the option of using frozen blood in case of any shortages in RBCs, and it has been concluded that although the application of frozen blood had its own costs, its benefits far outweighed its cons.

In some cases, it has been realized that the application of some specific methods in the healthcare field cannot produce desirable results. For instance, (Stanger, 2013) conducted a study in which some of Germany's hospitals were involved in order to realize that whether the application of vendor managed inventory (VMI) in these hospitals was useful or not. Although VMI provided a situation in which suppliers controlled every detail related to blood components' flow in the supply chain, given to the obtained results, it has been discovered that hospitals were not satisfied with existing situation because they were completely dependent on the supplier, and they could not manage any of their blood products' inventory by themselves. Thus, this real case study reveals that however some inventory policies are really successful in the commercial fields, they can be implemented in non-commercial sections like the healthcare industry.

2.9. Blood as a Medicine

The main purpose of blood transfusion is to cure the various type of blood-related diseases 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 the pharmaceutical supply chain network. Nowadays, many countries heavily regulate their pharmaceutical supply chains because of the new challenges that are happening every day (Papageorgiou, 2001; Yu et al, 2010). Therefore, as the first step, it is essential to realize the main challenges that global health pharmaceutical supply chains are faced with. (Privett and Gonsalvez, 2014) conducted a series of interviews and surveys in order to identify and prioritize these issues. In conclusion, it has been recognized that there are 10 main obstacles that any pharmaceutical supply chain in the world is dealing with. Respectively, the challenges are 1. Lack of coordination, 2. Inventory management, 3. Absent demand information, 4. Human resource dependency, 5. Order management, 6. Shortage avoidance, 7. Expiration, 8. Warehouse management, 9. Temperature control and 10. Shipment visibility. All the mentioned challenges exist in the blood supply chain either, and lots of research works have been done in these fields to realize how each of these obstacles can be eliminated or at least how its effect could be mitigated.

Some of the research works try to find a solution that can deal with several challenges at the same time. During a midterm planning horizon, and by considering a robust stochastic approach, (Mousazadeh et al, 2015) suggested a mathematical model to reach tactical decisions about the location-allocation problems of a pharmaceutical supply chain network. During the decision phase, it has been considered that both total costs and unsatisfied demands should be minimized in order to improve the supply chain performance in order management, warehouse management and expiration fields.

From a technological perspective, it has been discovered that pharmaceutical supply chains are more production-centric rather than patient-centric delivery models. This issue can be recognized as a major problem because the first and foremost important goal of any pharmaceutical supply chain is to increase its responsiveness toward the patients. Thus, all the obstacles that exist in this field should be identified and eliminated in order to be able to improve the performance. (Settanni et al, 2017) employed a various range of operation research methods and understood four main challenges that should be removed from the pharmaceutical supply chain network to be more practical in today’s world.

Due to the high complexity of the pharmaceutical inventory management, pharmaceutical industries form a large portion of the costs in the healthcare inventory. (Kelle et al, 2012) proposed a mathematical framework which is a guideline to take all the ordering and inventory decisions at the operational, tactical and strategic levels. In the framework, the operational decisions focused on the reorder point and order up to level issues, while the tactical decisions tried to find the best balance between three key performance indicators that are: the expected number of daily refill workloads, the service level and the storage space utilization. The strategic decision provided the most appropriate condition for both operational and tactical decisions.

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 the 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 that has a direct impact on the performance of a pharmaceutical supply chain.

From hospitals' point of view that are the main consumer of blood components, there are various factors that affect the delivery time of blood components, and besides all the internal factors that have an effect on the inventory management, setting an optimized ordering policy for the hospitals depend on these factors as well. (Uthayakumar and Priyan, 2013) developed a pharmaceutical supply chain model in which various aspects such as multiple products, variable lead time, permissible payment delays and constraints on space availability have been considered in order to find the optimal way which led to both reducing the costs and improving the customer service level. The proposed solution can be applied to any blood supply chain either because the blood network is one example of a pharmaceutical network, and any circumstance that exists in a pharmaceutical supply chain can be recognized as a constraint for the blood supply chain either.

2.10. Blood as a Cold Fresh Product

Figure 1.6 shows that each of the blood components needs its own temperature setting to be transformed. Hence, the blood supply chain for some of the components like RBCs, and plasma should be considered as a cold supply chain either, and follow all the necessary procedures. (Chen et al, 2014) described the cold supply chain as a supply chain that usually is used for perishable items like blood during their storage, transport and sales in order to keep them fresh. Hence, it can be realized that one of the main concerns that exist regarding cold blood supply chains is about the freshness of the perishable items which determines whether they are safe to use or not. The inefficient results in the identification and tracking of blood products have been improved by using the RFID tags. (Chen et al, 2014) proposed a Refined Smart Cold Chain System (RSCCS) method which is equipped with RFID tags) in order to provide all the necessary information for both suppliers and customers to be sure about the safety and freshness of the perishable products which are delivered through a cold supply chain. Furthermore, (Coustasse et al, 2013) presented the application of RFID technology in the hospitals to improve patients' safety. Based on the results, it has been discovered that applying RFID tags in the blood supply chain framework not only decreases the cost dramatically, but also does it increase the ability to track and locate blood components. (Due to Davis et al, 2009) research work, it has been discovered that the RFID application process can recoup investment cost in a 4-year payback period.

Moreover, it also should be noted that any changes related to the time or temperature of a supply chain can cause an increase in the net present value of the cold supply chain. In the real world, various types of perturbation exist which leads to negative effects on the supply chain performance. (Bogataj et al, 2005) proposed a mathematical method in which the factors which cause the stability in a cold chain were studied. Since blood is a perishable item and its demand varies during different situation understanding the perturbations that exist in the real world, and the ways which can mitigate the former's harmful effects can be helpful to create a flexible blood supply chain.

Time Sensitivity is one of the main factors that managers would consider when they want to have a precise plan for perishable items. Transportation time and inventory levels are the main items that are in a direct relationship with time sensitivity, and any improvement in these items can mitigate the sensitivity dramatically. During the past few years, various options have been proposed for facing this issue. (Musavi and Bozorgi, 2017) suggested a sustainable hub location-vehicle scheduling model in order to find an optimal solution that improves both reliability and efficiency. Based on the results, it can be realized that establishing several hubs across a specific region can help to improve blood transfusion performance. That is why, some of the hospitals and clinical centers may be far from the blood collection centers, hence, considering an intermediate center that can store a specific amount of blood would be useful to overcome both shortage and outdated units' problems.

2.11. Conclusion

Tables 2.1 to 2.5 demonstrate a summary of most related papers to this study and existing gaps of the current research works.

Table 2.1- Literature Review Summary

No.	**Author(s)**	**Publication Year**	**Objective Function**		**Blood Component**			**Implementation**	
			Single	**Multi**	**Whole Blood**	**Red Blood Cells**	**Platelets**	**Case Study**	**Numerical Example**
1	Blake et al	2003	●				●	●	
2	Kopach et al	2003	●		●			●	
3	Dijk et al	2009	●		●		●	●	
4	Fontaine et al	2009	●				●	●	
5	Ghandforoush & Sen	2010	●				●		●
6	Fontaine et al	2010	●			●		●	
7	Hemmelmayr et al	2010		●	●				●
8	Nagurney et al	2012		●	●				●
9	Nagurney & Masoumi	2012		●	●				●
10	Abdulwahab & Wahab	2014		●	●		●	●	
11	Duan & Liao	2014		●		●			●
12	Zahiri et al	2015	●		●			●	
13	Sahinyazam et al	2015		●	●			●	
14	Civelek et al	2015	●				●		●
15	Rutherford et al	2016	●		●	●		●	
16	Najafi et al	2017		●	●				●
17	Kaveh & Ghobadi	2017	●		●			●	●
18	Lowalekar & Ravi	2017	●		●			●	
19	Fahimnia et al	2017		●	●				●
20	Zahiri et al	2017		●	●			●	
21	Habibi et al	2018		●	●			●	
22	Eskandari et al	2018		●			●		●
23	Jafarkhan & Yaghoubi	2018	●			●		●	
24	Ekici et al	2018		●	●				●
25	Zahiri et al	2018		●	●				●
26	Larimi et al	2019		●			●	●	
27	Rjandran & Rayindran	2019	●				●		●
28	Dehghani et al	2019	●		●			●	●
29	Hamdan & Diabat	2019		●		●		●	
30	This Study	2020	●				●	●	

Table 2.2- Literature Review Summary

No.	Author(s)	Publication Year	Approach				Optimization Model	
			Simulation	Optimization	Decision Making	Analysis	Linear	Non-Linear
1	Blake et al	2003	●	●			●	
2	Kopach et al	2003	●					
3	Dijk et al	2009	●	●			●	
4	Fontaine et al	2009				●		
5	Ghandforoush & Sen	2010		●	●			●
6	Fontaine et al	2010	●			●		
7	Hemmelmayr et al	2010		●			●	
8	Nagurney et al	2012		●			●	
9	Nagurney & Masoumi	2012		●			●	
10	Abdulwahab & Wahab	2014	●	●				●
11	Duan & Liao	2014	●	●				●
12	Zahiri et al	2015		●			●	
13	Sahinyazam et al	2015		●			●	
14	Civelek et al	2015		●	●		●	
15	Rutherford et al	2016	●					
16	Najafi et al	2017		●				●
17	Kaveh & Ghobadi	2017		●			●	
18	Lowalekar & Ravi	2017			●			
19	Fahimnia et al	2017		●			●	
20	Zahiri et al	2017		●			●	
21	Habibi et al	2018		●			●	
22	Eskandari et al	2018		●				●
23	Jafarkhan & Yaghoubi	2018		●			●	
24	Ekici et al	2018		●			●	
25	Zahiri et al	2018		●				●
26	Larimi et al	2019	●	●			●	
27	Rjandran & Rayindran	2019		●			●	
28	Dehghani et al	2019	●	●			●	
29	Hamdan & Diabat	2019		●			●	
30	This Study	2020		●			●	

Table 2.3- Literature Review Summary

No.	Author(s)	Publication Year	Solution			Condition	
			Heuristic	Metaheuristic	Exact	Normal	Emergency
1	Blake et al	2003			●	●	
2	Kopach et al	2003			●	●	
3	Dijk et al	2009		●		●	
4	Fontaine et al	2009			●	●	
5	Ghandforoush & Sen	2010	●			●	
6	Fontaine et al	2010	●			●	
7	Hemmelmayr et al	2010		●		●	
8	Nagurney et al	2012	●			●	
9	Nagurney & Masoumi	2012	●			●	
10	Abdulwahab & Wahab	2014	●			●	
11	Duan & Liao	2014		●		●	
12	Zahiri et al	2015			●	●	
13	Sahinyazam et al	2015		●			●
14	Civelek et al	2015	●			●	
15	Rutherford et al	2016			●	●	
16	Najafi et al	2017			●	●	
17	Kaveh & Ghobadi	2017		●		●	
18	Lowalekar & Ravi	2017			●	●	
19	Fahimnia et al	2017	●				●
20	Zahiri et al	2017			●	●	
21	Habibi et al	2018			●		●
22	Eskandari et al	2018		●			●
23	Jafarkhan & Yaghoubi	2018	●			●	
24	Ekici et al	2018			●	●	
25	Zahiri et al	2018		●			●
26	Larimi et al	2019			●	●	
27	Rjandran & Rayindran	2019		●		●	
28	Dehghani et al	2019	●			●	
29	Hamdan & Diabat	2019			●	●	
30	This Study	2020			●	●	●

Table 2.4- Literature Review Summary

No.	Author(s)	Publication Year	State				Delivery			
			Certain	Uncertain			Direct	Emergency	Lateral	
				Stochastic	Fuzzy	Robust		External	Reactive	Proactive
1	Blake et al	2003		●			●			
2	Kopach et al	2003		●			●			
3	Dijk et al	2009	●				●			
4	Fontaine et al	2009	●							
5	Ghandforoush & Sen	2010	●				●			
6	Fontaine et al	2010		●			●			
7	Hemmelmayr et al	2010		●		●	●			
8	Nagurney et al	2012	●				●			
9	Nagurney & Masoumi	2012	●				●			
10	Abdulwahab & Wahab	2014	●				●			
11	Duan & Liao	2014	●				●			
12	Zahiri et al	2015			●	●	●			
13	Sahinyazam et al	2015	●				●			
14	Civelek et al	2015	●				●			
15	Rutherford et al	2016	●				●			
16	Najafi et al	2017		●			●			
17	Kaveh & Ghobadi	2017	●				●			
18	Lowalekar & Ravi	2017	●				●			
19	Fahimnia et al	2017	●					●		
20	Zahiri et al	2017			●	●	●			
21	Habibi et al	2018		●		●	●			
22	Eskandari et al	2018		●		●	●			
23	Jafarkhan & Yaghoubi	2018		●		●	●			
24	Ekici et al	2018	●				●			
25	Zahiri et al	2018		●	●		●			
26	Larimi et al	2019		●		●	●		●	
27	Rjandran & Rayindran	2019		●			●			
28	Dehghani et al	2019		●			●			●
29	Hamdan & Diabat	2019		●			●			
30	This Study	2020	●				●	●	●	

After conducting the literature review, it has been realized that the available analytical supply chain models usually do not consider the following issues:

- Hospitals' connection (Lateral Transshipment Approach)
- Mobile collection centers during a normal situation
- Availability of various transportation modes and their specific planning
- Emergency ordering option from centers in a different stage
- The effect of test results and existing environmental errors on the amount of collected blood units
- Managing both outdated units' and shortage problems at the same time

Hence, by realizing the current gaps, this research aims to propose a mathematical model that can cover all the mentioned gaps and optimize the supply chain's performance.

CHAPTER 3

BLOOD SUPPLY CHAIN MATHEMATICAL MODEL

3.1. General Aim

Increasing the surplus is the main goal of every supply chain (Chopra and Meindl, 2016). Since in most countries blood donation is a voluntary process, a blood supply chain network will usually be recognized as a non-profitable supply chain. Hence, the blood supply chain network can increase its surplus only by decreasing all the related costs. This study aims to discover the actors of a blood supply chain network, and redesign the blood supply chain that to only increase the surplus, but also improve the performance by taking required actions to reduce shortage rate and outdated units' amount.

3.2. Design of Supply Chain

3.2.1. Structure

The blood supply chain structure includes the following stages:

1. Donors (Supplier)
2. Temporary and Permanent Blood Centers (Manufacturer and Distributor)
3. Hospitals (Retailer)
4. Patients (Customer)

Blood components (e.g. RBCs, platelets and plasma) are the main products of a blood supply chain, and all the details about the inventory level of these components and their distribution will be considered as the information flow of the blood supply chain. Donors are the first stage of every blood supply chain. Temporary and permanent blood centers are serving as collectors, manufacturers and distributors. After testing and processing the donated blood in these centers, they will distribute the blood components to the hospitals based on the latter demands. Hospitals have their own inventory for each blood component, and they are in a direct relationship with patients who are the customers of blood components. The stored blood components in the hospitals will either be transfused to the patients or be discarded due to their perishable nature.

Both blood centers and hospitals constantly update their product flows by monitoring the available information flow.

3.2.2. Objectives

Considering several perspectives during a supply chain design process will help to figure out how main objectives of the network should be defined. This research aims to improve both efficiency and performance of the blood supply chain. Efficiency is one of the main aspects of every supply chain. In this study, redesigning a blood supply chain that its main goal is to reduce all the related costs of actors and their interactions, helps to improve the blood supply chain's efficiency. Moreover, by reducing the shortage and outdated units' rates, the performance level of the proposed supply chain network will be improved.

3.2.3. Process

Usually, the blood donation process takes between eight to ten minutes. After collecting the blood from donors, it will be tested to make sure that it is safe for any further transfusion. Testing process has its own lead-time. The tested blood can either be stored as a whole blood or as blood components such as, for example red blood cells, platelets and plasma. The processed blood components can either be stored in the blood centers or the hospitals. It is noteworthy to mention that each blood component has its own storing condition that should be considered in the blood supply chain network. The delivery process from blood centers to hospitals or between hospitals depends on the situation, and the delivery time can be varied between normal and emergency situations. Blood centers and hospitals always monitor their inventory to discard outdated blood units. In situations that patients do not need blood components with specific age, hospitals try to use the older blood components in order to decrease the discarding rate.

3.2.4. Technology

Monitoring the inventory levels of the supply chain's actors by applying a suitable technology will help the network to increase its efficiency by reducing shortage and discarded units' rates. The applied technology constantly monitors both information and product flows to not only improve efficiency and performance, but also to save more lives.

3.3. The Purpose of the Study

By considering all the previous research efforts, and available statistics and information, it can be realized that improving blood supply chain management not only help responsible organizations to improve their performance and reduce costs, but also it helps to save more humans' lives. Hence, the importance of establishing an integrated blood supply chain in which all the activities aim to help more people is undeniable. Moreover, (Williamson and Devine, 2013) in their research work observed that demands for blood components are growing dramatically, and this increasing rate makes blood as one of the most crucial and complicated supply components that exist in today's world. Perishability of blood products, uncertainty in donation and demand sizes are the three main reasons that make the blood supply chain planning so challenging. This research aims to develop a mathematical model to reduce all the costs of the blood supply chain model. Life-saving and perishable nature of blood units, is a source of risks of shortage and expiration. Hence, an integrated supply chain, in which almost all the active actors are considered and organized, can be a great help in order to manage blood unit delivery in a way that both hospitals' satisfaction from overcoming shortage and expiration issues will be maximized and costs will be reduced. The proposed blood supply chain in this research consists of 3 stages:

1. Mobile Collection Centers
2. Blood Centers
3. Hospitals

The supply chain begins with mobile collection centers where blood units are collected. Since mobile centers are not able to test, process and store the blood units, they send all the collected units to the blood center at the end of each period. After receiving the blood units, blood centers test a specific percentage of these units to make sure that they are healthy and transferable. The testing process always takes one day. When the testing process confirms the blood units' health, they can be stored in the blood centers' inventory. In order to make the model closer to the real world, it has been assumed that some parts of blood units will be discarded due to test results, and environmental risk factors such as staffs' mistakes and device failure. The last stage of the proposed supply chain consists of hospitals that determine blood units' demand in each period. Due to demand uncertainty, hospitals can face with shortage, hence, lateral transshipment has been considered as a helpful tool in order to deliver blood units from other hospitals to the hospital that are in need. However, since other hospitals' inventory levels maybe not enough, blood centers can also send blood units to hospitals that are facing shortage. Blood centers are also responsible for delivering fresh blood units to the hospitals based on the lateral orders. The number of orders will be determined by considering the desired inventory level, and the existing amount of inventory level of each hospital. Both hospitals and blood centers can store blood units with various ages, but orders just include fresh blood units that are just received from blood collection centers. The lead time of ordering process is one day, and hospitals receive fresh blood units the day after their orders take place. Moreover, demand uncertainty can also cause having outdated units in both blood centers' and hospitals' inventory, thus, discarding option with its own specific cost is available in both stages. To reduce the expired amount, it has been assumed that patients can receive blood units of any age, and there is no difference between young and old blood units for the transfusion process. Furthermore, to make the model more realistic, various transportation modes have been considered in the model, which each of them has its own pace and cost.

3.4. Research Methods

For redesigning the blood supply chain in this study, two research methods have been used:

1. Mathematical Optimization Method: This method is one of the most common methods in the supply chain field, and it has been selected for implementing in this study because it provides a realistic framework to figure out how the optimum results for the assumed objective function(s)

can be obtained when there are various constraints that not only limit the solution area, but also have conflict between themselves that even make the situation infeasible.

2. Applying Case Study: This approach is used in this research work to show how proposed model can improve a real-world blood supply chain.

First by considering the optimization approach, a deterministic single objective mathematical model has been proposed in order to both reduce all the related costs and find the best policy to reduce both existing shortage and outdated units' rates. In the next step, the proposed model has been applied for a specific case study to be able to provide all the necessary information and data. The Greater Toronto Area (GTA) located in the Ontario province of Canada has been selected for this research. The required information and data of this study have been collated from considering multiple past research efforts and reports. In the end, the proposed model which has been coded in the GAMS software was be solved by applying all the gathered data in order to analyze how the model would improve the supply chain's performance, and develop potential practical strategies.

3.5. Problem Statement

The blood supply chain can be considered as one of the key actors of any healthcare supply chain. The blood supply chain of this research consists of three main stages, as explained in section 3.3. 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 orders from blood centers would satisfy the shortage amount (Equations 3 and 4).
- A specific amount of shortage should be covered in each period of time by applying both lateral transshipment approach and emergency delivery from blood centers (Equations 21 and 22).
- Each mobile collection center and blood collection center has a limited capacity for collecting blood from blood donors in each period of time (Equations 23 and 44).
- By considering the existing inventory level and the amount of demands, it would be decided to whether open a mobile collection center at a specific period or not (Equations 44 and 45).
- Given that blood is a life-saving product, both hospitals and blood centers are allowed to have inventory levels. Hence, both centers are allowed to discard the outdated units (Equations 13 and 15).
- The target inventory of hospitals will be calculated by considering both each period's demand and last period's shortage (Equations 24 to26).
- Each hospital's demand for each period of time has been estimated and specified based on existing information and the number of available beds.
- Only fresh blood components that has 2 days of shelf life would be delivered from blood centers to hospitals when the latter order and older blood components will be delivered in case of emergency (Equations 3, 8 and 9).
- The testing process has its own lead-time (Equation 20).
- Given that environmental risk factors such as test results' errors, staff errors, etc. exist in the blood centers, some parts of collected blood components from both mobile collection centers and donors would be discarded (Equation 20).
- Regular order has its own lead-time (Equation 17).
- Emergency order has its own lead-time (Equation 3).
- An initial inventory level for the beginning of the first period of time has been defined for each blood center and each hospital (Equations 2 and 10).
- Given the perishable nature of blood components, the ageing process affects blood transfusion decision, and blood units' delivery from blood centers to hospitals.

- To reduce both outdated units' rate and its related costs, FIFO (First in, First Out) system has been applied for the hospitals' usage (Equations 27 to 43).
- Although both shortage and discarding outdated units are allowed in hospitals, blood centers are not allowed to face any shortage.
- Several modes of transportation at their own pace, fuel efficiency and planning would be available to deliver blood from blood centers to hospitals and between hospitals (Equation 1).
- A limited number of each transportation mode would be available in each period of time (Equation 46).
- Figure 3.1 shows the proposed model, consisting of three stages. There are multi mobile collection centers that deliver collected blood units to blood centers, blood centers will deliver blood units to the hospitals whenever the lateral issues an order, and keep the remaining amounts as inventory. Hospitals are the last stage that receives fresh blood units from blood centers and requests extra amount in case of shortage from other hospitals, or blood centers.

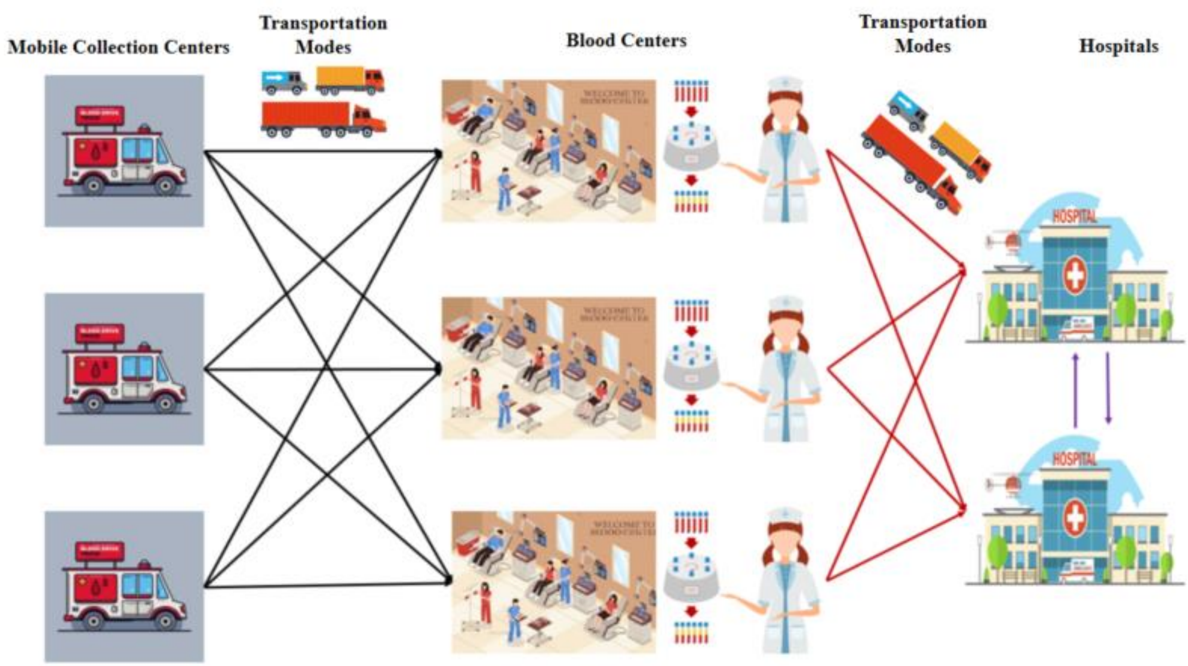


Figure 3.1- The 3-stage blood supply chain model

3.6. Mathematical Model

In this section, the deterministic mathematical model is presented. Notations used in the model and their definitions are outlined in Table 3.1.

Table 3.1- Notations used in the mathematical model

	Sets and Indices		
$\boldsymbol{T}$	*Time Horizon* $t \epsilon T$	R	*Mobile Collection Centers* $r \in R$
$\boldsymbol{K}$	*Blood centers* $k \epsilon K$	I	*Hospitals* $i, j \in I$
$\boldsymbol{M}$	*Remaining shelf life of hospitals' blood units* $m \epsilon M$	N	*Remaining shelf life of blood centers' blood units* $n \epsilon N$
P	*Transportation Modes* $p \in P$		

	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*
θ	*Percentage of blood units which will be discarded due to environmental risk factors and test results*	HAD	*Maximum number of open mobile collection centers in each period*

Parameters			
ZAR_r	Capacity of mobile collection center r	MAX_p	Maximum number of available transportation mode p
SAN_k	Capacity of blood center k for donating blood	VC_p	Transportation cost per distance for transportation mode p
LB_{ki}	Distance between blood center k to hospital i	LH_{ij}	Distance between hospital i to hospital j

Variables			
Positive Variables			
y_i^t	Order quantity at hospital i in period t	S_{it}	Target inventory level of hospital i at period t
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

Variables			
Positive Variables			
HJM_{rk}^{t}	*Quantity of delivered blood from mobile collection center r to blood center k at 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*		

Variables			
Binary Variables			
OP_{rt}	*If mobile collection center r is open at period t 1, otherwise 0*	BTH_{ki}^{pt}	*If blood center k transfer blood units to hospital i by using transportation mode p at period t 1, otherwise 0*
HTH_{ij}^{pt}	*If hospital i to hospital j by using transportation mode p at period t 1, otherwise 0*	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*		

3.6.1. Objective Function

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

$$min \sum_{k}\sum_{i}\sum_{n\geq 3}\sum_{t} ES_{kin}^{t} * CE_{ki}^{n} + \sum_{k}\sum_{i}\sum_{t} Z_{ki}^{t} * SN_{ki} \tag{1}$$

$$+ \sum_{k}\sum_{t}(FV_{k}^{t} * HB_{k} + DW_{k}^{t} * CW) + \sum_{i}\sum_{j\neq i}\sum_{m}\sum_{t} X_{ijm}^{t} * C_{ij}^{m}$$

$$+ \sum_{i}\sum_{t}(V_{i}^{t} * H_{i} + \sigma_{i}^{t} * E + f_{i}^{t} * G + y_{i}^{t} * SEF)$$

$$+ \sum_{r}\sum_{k}\sum_{t} TES *(HJM_{rk}^{t} + DON_{k}^{t})$$

$$+ \sum_{k}\sum_{i}\sum_{p}\sum_{t} BTH_{ki}^{pt} * VC_{p} * LB_{ki} + \sum_{i}\sum_{j\neq i}\sum_{p}\sum_{t} HTH_{ij}^{pt} * VC_{p} * LH_{ij}$$

3.6.2. Constraint

The problem is subject to a variety of constraints that would be mentioned in the following.

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

Equation (2) indicates that there is a given inventory level for blood units with a 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 an equilibrium between initial 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, hospitals may only be able to satisfy a part of demand and the unsatisfied part would be considered as shortage.

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

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 initial inventory level of the blood center for the blood units should be considered since each blood center has a specific capacity in each period of time.

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

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

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

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

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

Equation (8) sets an equilibrium between initial 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 an equilibrium between initial 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 a given inventory level for blood units with a 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 blood units with M days' shelf life 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 with M days' shelf life 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.

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

Equation (18) indicates that in each period of time, fresh blood units that have been collected from all the blood centers will be delivered to each hospital based on its order amount.

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

Equation (19) indicates that the number of each hospital's orders will be determined based on its target inventory level and the initial inventory level of all blood units of various ages in each period of time.

$$Invs_{kn}^{t+1} = (1-\theta) * [\sum_{r} HJM_{rk}^{t} + Don_{k}^{t}]\ \forall k, n = 2, t \neq T \tag{20}$$

Equation (20) indicates that it takes one day to test the collected blood units from both mobile collection centers and blood centers and to make sure they are safe for future transfusion. It also shows that $\theta\%$ of collected blood will be discarded due to existing environmental errors and test results.

$$\sum_{j \neq i} \sum_{m} X_{jim}^{t} + \sum_{k} \sum_{n \geq 3} ES_{kin}^{t} \geq \beta f_{i}^{t}\ \forall i, t \tag{21}$$

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

$$\sum_{j \neq i} \sum_{m} X_{jim}^{t} + \sum_{k} \sum_{n \geq 3} ES_{kin}^{t} \leq f_{i}^{t}\ \forall i, t \tag{22}$$

Equation (22) indicates that in each period, 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 and each blood center, the number of collected blood units should be less than its capacity.

$$S_{i(t+1)} \leq D_{i}^{t}\ \ \forall i, t \neq T \tag{24}$$

Equation (24) indicates that for reducing the outdated blood units, each period's demand should be considered for planning the next period's target inventory level.

$$S_{i(t+1)} \geq (1-\beta) * f_{i}^{t}\ \ \forall i, t \neq T \tag{25}$$

Equation (25) indicates that by considering each period's shortage and shortage coverage rate and for reducing the shortage rate, the next period's target inventory level should be more than $(1-\beta)\%$ of the current shortage.

$$S_{it} \geq (1-\beta) * D_i^t \;\; \forall i, t \neq T \tag{26}$$

Equation (26) indicates that the target inventory level of each period should be more than $(1-\beta)\%$ of the period's demand to reduce the shortage.

$$\sum_i \sum_{n\geq 3} ES_{kin}^t = EZ_k^t \; \forall k, t \tag{27}$$

$$MIZ_{kn}^t \leq EZ_k^t \; \forall k, t, n = M \tag{28}$$

$$MIZ_{kn}^t \leq Invs_{kn}^t \; \forall k, t, n = M \tag{29}$$

$$EZ_k^t - MIZ_{kn}^t \leq \acute{M} b_{kn}^t \; \forall k, t, n = M \tag{30}$$

$$Invs_{kn}^t - MIZ_{kn}^t \leq \acute{M}(1 - b_{kn}^t) \; \forall k, t, n = M \tag{31}$$

$$MIZ_{kn}^t \leq EZ_k^t - MIZ_{k(n+1)}^t \; \forall k, t, 3 \leq n \leq M-1 \tag{32}$$

$$MIZ_{kn}^t \leq Invs_{kn}^t \; \forall k, t, 3 \leq n \leq M-1 \tag{33}$$

$$EZ_k^t - MIZ_{k(n+1)}^t - MIZ_{kn}^t \leq \acute{M} b_{kn}^t \; \forall k, t, 3 \leq n \leq M-1 \tag{34}$$

$$Invs_{kn}^t - MIZ_{kn}^t \leq \acute{M}(1 - b_{kn}^t) \; \forall k, t, 3 \leq n \leq M-1 \tag{35}$$

Equations (27-35) indicate the FIFO system for each period and in each blood center.

$$a_{im}^t \leq D_i^t \; \forall i, t, m = M \tag{36}$$

$$a_{im}^t \leq is_{im}^t + \sum_{j\neq i} X_{jim}^t - \sum_{j\neq i} X_{ijm}^t + \sum_k ES_{kin}^t \;\; \forall i, t, m = n = M \tag{37}$$

$$D_i^t - a_{im}^t \leq \acute{M} g b_{im}^t \; \forall i, m = 5, t \tag{38}$$

$$is_{im}^{t} + \sum_{j \neq i} X_{jim}^{t} - \sum_{j \neq i} X_{ijm}^{t} + \sum_{k} ES_{kin}^{t} - a_{im}^{t} \leq \acute{M}(1 - gb_{im}^{t})\ \forall i, t, m = n = M \tag{39}$$

$$a_{im}^{t} \leq D_{i}^{t} - a_{i(m+1)}^{t}\ \forall i, t, 3 \leq m \leq M - 1 \tag{40}$$

$$a_{im}^{t} \leq is_{im}^{t} + \sum_{j \neq i} X_{jim}^{t} - \sum_{j \neq i} X_{ijm}^{t} + \sum_{k} ES_{kin}^{t}\ \ \forall i, t, 3 \leq m \leq M - 1, n = m \tag{41}$$

$$D_{i}^{t} - a_{i(m+1)}^{t} - a_{im}^{t} \leq \acute{M} gb_{im}^{t}\ \forall i, t, 3 \leq m \leq M - 1 \tag{42}$$

$$is_{im}^{t} + \sum_{j \neq i} X_{jim}^{t} - \sum_{j \neq i} X_{ijm}^{t} + \sum_{k} ES_{kin}^{t} - a_{im}^{t} \leq \acute{M}\left(1 - gb_{im}^{t}\right)\ \forall i, t, 3 \leq m \leq M - 1, n = m \tag{43}$$

Equations (36-43) indicate the FIFO system for each period and in each blood center.

$$\sum_{k} HJM_{rk}^{t} \leq ZAR_{r} * OP_{rt}\ \ \forall r, t \tag{44}$$

Equation (44) indicates that in each period of time, a mobile collection center can deliver collected blood units to all the blood centers only if it would be open in that period of time.

$$\sum_{r} OP_{rt} \leq HAD\ \ \forall t \tag{45}$$

Equation (45) indicates that in each period of time, only a limited number of mobile collection centers can be open.

$$\sum_{k} \sum_{i} \mathrm{BTH}_{\mathrm{ki}}^{\mathrm{pt}} + \sum_{i} \sum_{j \neq i} \mathrm{HTH}_{\mathrm{ij}}^{\mathrm{pt}} \leq \mathrm{MAX}_{\mathrm{p}}\ \forall p, t \tag{46}$$

Equation (46) indicates that in each period of time, a limited number of each transportation mode would be available to transfer blood units from blood centers to hospitals, and between hospitals.

$$y_{i}^{t} \geq 0\ \forall i, t \tag{47}$$

$S_i \geq 0 \; \forall i$ (48)

$is_{im}^t \geq 0 \; \forall i, m, t$ (49)

$ie_{im}^t \geq 0 \; \forall i, m, t$ (50)

$a_{im}^t \geq 0 \; \forall i, m, t$ (51)

$f_i^t \; \geq 0 \; \forall i, t$ (52)

$V_i^t \geq 0 \; \forall i, t$ (53)

$\sigma_i^t \geq 0 \; \forall i, t$ (54)

$X_{ijm}^t \geq 0 \; \forall i, j \neq i, m, t$ (55)

$ES_{kin}^t \geq 0 \; \forall k, i, t, n$ (56)

$Z_{ki}^t \geq 0 \; \forall k, i, t$ (57)

$FV_k^t \geq 0 \; \forall k, t$ (58)

$DW_k^t \geq 0 \; \forall k, t$ (59)

$Invs_{kn}^t \geq 0 \; \forall k, t, n$ (60)

$Inve_{kn}^t \geq 0 \; \forall k, t, n$ (61)

$Don_k^t \geq 0 \; \forall k, t$ (62)

$HJM_{rk}^t \geq 0 \; \forall r, k, t$ (63)

$San_k \geq 0 \; \forall k$ (64)

$EZ_k^t \geq 0 \; \forall k, t$ (65)

$MIZ_{kn}^t \geq 0 \; \forall k, t, n$ (66)

$b_{kn}^t \epsilon \{0,1\} \; \forall k, n, t$ (67)

$gb_{im}^t \epsilon \{0,1\} \; \forall i, m, t$ (68)

$OP_{rt} \epsilon \{0,1\} \; \forall r, t$ (69)

$$BTH_{ki}^{pt} \epsilon \{0,1\} \; \forall k, i, p, t \tag{70}$$

$$HTH_{ij}^{pt} \epsilon \{0,1\} \; \forall i, j \neq i, p, t \tag{71}$$

Equations (47-71) indicate the type of decision variables that have been used in the model.

In the next chapter, the proposed model will be applied to a real-world case study so that its behavior can be tested, verified and understood. The optimal setting obtained will be analyzed and studied.

CHAPTER 4

CASE STUDY

4.1. Introduction

As mentioned in Chapter 1, the platelet is one of the blood components which has only 5 days' shelf life, and it has broad range of applications such as, for example surgery, cancer treatments and organ transplants. Hence, to both save more lives while increasing system efficiency at the same time, this research aims to improve the blood supply chain's performance and reduce the platelet supply chain's costs. By considering the proposed model in the previous chapter and to be able to reach the mentioned goals, the Greater Toronto Area(GTA) has been considered as the case study of this research, as a lot of data were publicly available.

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 (Population and Dwelling Count Highlight Tables, 2016). Figure 4.1 shows the map of the GTA.

Figure 4.1- The map of the GTA *(Greater Toronto Area. (2020, January 23). Retrieved from https://en.wikipedia.org/wiki/Greater_Toronto_Area)*

In this study, we try to reduce all the related costs of the platelet supply chain in the GTA area during a 7 days' period (a week). In the following, all the necessary information regarding the name and location of mobile collection centers, blood centers and hospitals has been presented. In the GTA, blood network includes 7 mobile collection centers, 12 blood centers and 20 hospitals are operating to realize how the proposed model would behave under a real-world condition. Table A.1 to A.3 show the information of GTA blood network's actors. Figures 4.2 to 4.4 demonstrate the locations of selected mobile collection centers, blood centers and hospitals in this research work.

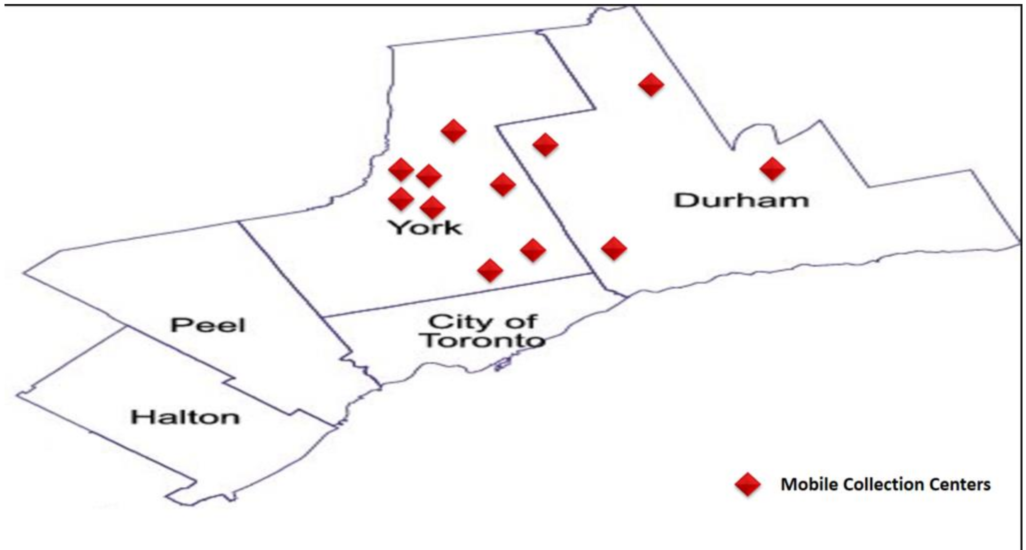


Figure 4.2- Mobile Collection Centers' Locations

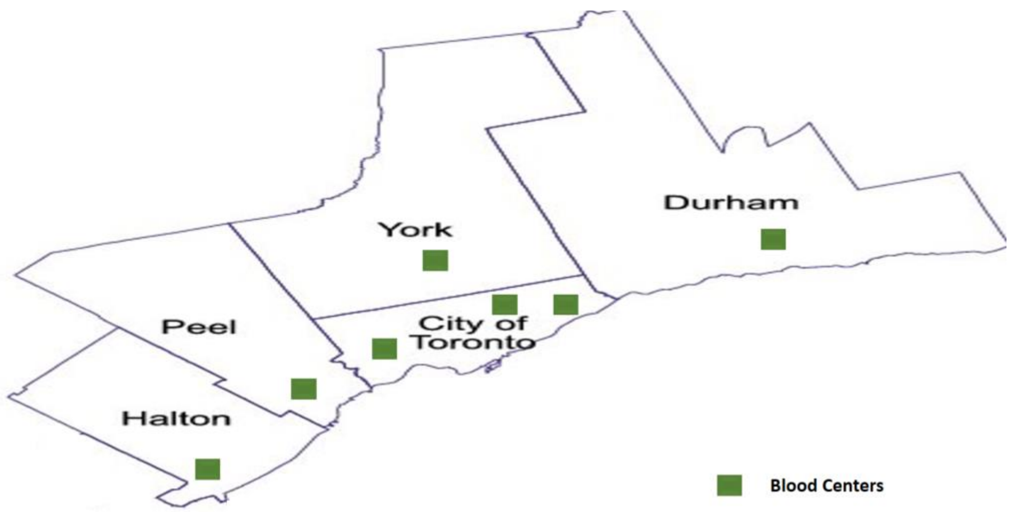


Figure 4.3- Blood Centers' Locations

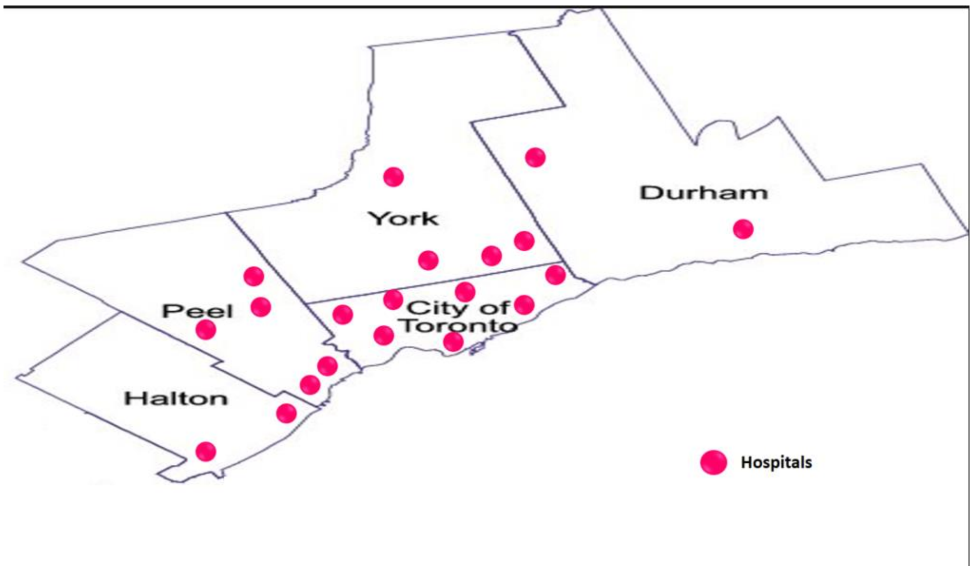


Figure 4.4- Hospitals' Locations

4.2. Demand

Table A.4 shows hospitals' demands based on their number of beds. It has been assumed that due to the emergency department and surgery operations which exist in each period of time, from 10% to 15% of patients in each hospital demand blood units. Moreover, on average, each blood transfusion process needs 3 pints of blood units to be injected into patients.

4.3. Inventory Level

4.3.1. Hospitals

Based on the obtained data from Canadian Blood Services, it has been realized that the current system is in the amber phase which means each hospital's inventory level satisfies only 55% to 79 % of its daily requirement. Hence, due to the first period's demand in each hospital, Table A.5 Shows the initial inventory level of blood units with shelf life from 3 to 5 in each hospital. Since, the blood units which 3 days' shelf life are the most desirable units, it has been assumed that 55% of the initial inventory level contains blood units which 3 days' shelf life, 30% of initial inventory level contains blood units which 4 days' shelf life, and 15% of initial inventory level contains blood units which 5 days' shelf life.

4.3.2. Blood Centers

Since the main goal of this model is to reduce the shortage level, it has been assumed that the blood centers are in the green phase of inventory level which means they can satisfy 80-100% of the daily national requirement. Hence, due to the first period's demand in each hospital, Table A.6 Shows the initial inventory level of blood units with shelf life from 2 to 5 days in each blood center. Since, the blood units which 2 days' shelf life are the most desirable units, it has been assumed that 60% of the initial inventory level contains of blood units which 2 days' shelf life, 25% of initial inventory level contains blood units which 3 days' shelf life, 10% of initial inventory level contains blood units which 4 days' shelf life and 5% of initial inventory level contains blood units which 5 days' shelf life.

4.3.3. Mobile Collection Centers

Mobile collection centers are in the first stage of the proposed supply chain. Each of the existing mobile collection centers has its own capacity, Table A.7 shows the capacity of the mobile collection center. It has been assumed that in each period of time only 10 mobile collection blood centers can be open.

4.4. Costs

4.4.1. Hospitals

Hospitals should order fresh blood units at the beginning of each period. In this problem, it has been assumed that ordering cost is the same for all the hospitals, and it is equal to $22.70 per ordered blood units. Moreover, as it has been mentioned before, if hospitals face with shortage, they should order blood units from blood centers and other hospitals to satisfy their needs. In order to prevent hospitals from dealing with shortage, it has been assumed that reordering cost is 20% more than ordering cost. Hence, the reordering cost for each of the hospitals in this problem is equal to $27.24.

Each hospital has its own holding cost which has been determined based on the size of the hospital. (Number of beds). Table A.8 shows the holding cost for each hospital.

In this study, it has been assumed that expiry cost is 40% less than reordering cost, as blood is a vital product, and deals with human lives. Therefore, the expiry cost for all the hospitals in this problem is equal to $16.34.

In this research, it has been assumed that in each period of time, at least 85% of hospitals' shortage should be satisfied. Moreover, since this research aims to reduce both outdated units and shortage amounts, if a hospital requests blood units from another hospital, the latter first should send the older blood units. Hence, blood units with 5 days' shelf life have the cheapest transshipping cost. Blood units with 4 days' shelf life are 20% more expensive than blood units with 5 days' shelf life, and blood units with 3 days' shelf life are 25% more expensive than blood units with 5 days' shelf life. In this problem, it has been assumed that one blood unit with 5 days' shelf life costs $1.35. Moreover, if both hospitals are not in the same region but have a common border, the cost would be 10% more than the way that they both are in a same region, and if a blood center and a hospital are not in the same region and do not have a common border, the cost would be 15% more than the way that they both are in the same region. Table A.9 shows the cost of transshipping one blood unit with its own shelf life from one hospital to another one.

4.4.2. Blood Centers

In case of shortage, hospitals can also request blood units from blood centers. Table A.10 shows the cost of transshipping one blood unit with its own shelf life from a blood center to a hospital. Like hospitals' transshipping cost, blood units with 5 days' shelf life have the cheapest blood center hospital's transshipping cost. Blood units with 4 days' shelf life are 20% more expensive than blood units with 5 days' shelf life, blood units with 3 days' shelf life are 25% more expensive than blood units with 5 days' shelf life, and blood units with 2 days' shelf life are 30% more expensive than blood units with 5 days' shelf life. As it has been mentioned earlier, one blood unit with 5 days' shelf life costs $1.35. Since in the proposed supply chain, blood centers and hospitals are in two different stages, the blood center hospital's transshipping cost is 20% more expensive than hospitals' transshipping cost. Furthermore, if a blood center and a hospital are not in the same region but have a common border, the cost would be 15% more than the way that they both are in the same region, and if a blood center and a hospital are not in the same region and do not have a common border, the cost would be 25% more than the way that they both are in the same region.

Blood centers also deliver fresh blood products to the hospital based on their demands. The lead time of delivering blood units is one day, and the hospital receives their orders the day after they issue the orders. Table A.11 shows the cost of delivering one unit of blood from one blood center to one hospital. All the mentioned conditions have an effect on the fresh blood delivery cost as well.

In order to encourage hospitals to increase their own inventory level, it has been assumed that in each region, the blood center's holding cost is 15% more than the average of hospitals' holding costs. Table A.12 shows the blood centers' holding Costs.

Since Blood Centers are the main source of providing blood units, they should always be prepared to handle hospitals' shortage. Therefore, the expiry cost of the blood center is 25% less than the expiry cost of the hospital and is equal to $12.25.

The cost of testing one unit of blood in each blood center would be equal to $ 89.04.

4.4.3. Mobile Collection Centers

Mobile collection blood centers deliver fresh blood units to blood centers based on their orders. The blood units would be delivered on the same day, but the testing process in blood centers takes one day, so in each period, the inventory level of blood centers contains the delivered blood units which have been received during the previous period. Table A.13 shows the cost of delivering one unit of blood from one mobile blood collection center to one blood center. All the mentioned conditions have an effect on the fresh blood delivery cost as well.

4.4.4. Transportation Modes

Based on the existing information, it has been realized that cargo vans and trucks are the most common transportation modes that are used in the Canadian blood supply chain system. Hence, in this problem, Table A.14 shows the vehicles which have been used to distribute blood from blood centers to hospitals, and between hospitals:

By considering the fact that the gas price in GTA area is almost $\$\ 1.179/_{Km}$, and based on the fuel efficiency of each vehicle, Table A.15 shows the transshipment cost for each vehicle.

Moreover, Table A.16 shows the maximum available number of each vehicle.

4.5. Distance

Tables A.17 and A.18 show the distance between two hospitals and between each blood center and each hospital which have been obtained by using Google Maps online service.

4.6. Risk Factors

In (Larimi et al, 2019) research work, the platelets' discarded rate due to the existing risk factors and environmental errors can be varied between 5% to 55%. However, since the location of proposed case study in this research is different from the location of (Larimi et al, 2019) case study, it has been assumed that because of the existing staff errors and environmental risks in the blood centers, 15% of blood units that have been delivered to the blood centers would be discarded.

CHAPTER 5

RESULTS & ANALYSIS

5.1. Introduction

This chapter will demonstrate how the proposed model would help the blood supply chain's actors to both reduce their related costs and manage their inventory level. In the next step and by considering the obtained results, some sensitivity analysis will be conducted to realize how the model would behave if any changes happen in the system. In the last step, a simulation model will be adopted to perform validation process in order to make sure that the proposed model is valid for any further application.

5.2. Results

By considering previous research works and existing information, a base blood supply chain model without considering the lateral transshipment approach and emergency ordering option has been solved to show how the current situation is. In the next step, both lateral transshipment approach and emergency ordering options have been added to the model to demonstrate how these approaches will improve the results. Both based and proposed models have been implemented in GAMS win32 27.1.0 using Intel ® Core™ i5-2320 CPU 3 GHz processor with 8 GB of RAM. A summary of the results has been provided in Table 5.1.

Table 5.1- Summary of the results

Objective Value($)	
Base	**Proposed**
1191989.51	1031777.97
Total Shortage Amount(Units)	
Base	**Proposed**
16144.70	10746.05
Percent of Satisfied Demand(%)	
Base	**Proposed**
53	79
Total Outdated Units Amount	
Base	**Proposed**
538	0

Table 5.2-Summary of the improvements

Total Costs Improvement (%)	**Total Shortage Improvement (%)**	**Total Discarding Improvement (%)**
13	33	100

The first row of Table 5.1 shows the total costs of both based and proposed model, the next two rows show the total shortage amount in each model, and the percentage of satisfied demand in each model. The last two row shows the number of outdated units in each model.

By considering the obtained results, Table 5.2 provides a summary of improvements after applying the proposed approach. The first column shows that replacing the based model with the proposed model will decrease the costs by 13%. The next column demonstrate that the total shortage amount will reduce by 33% in the proposed model. The last column shows that there would be no wastage in the proposed model.

Figures 5.1 to 5.3 graphically display how the application of lateral transshipment and emergency ordering approaches will improve the results of the model.

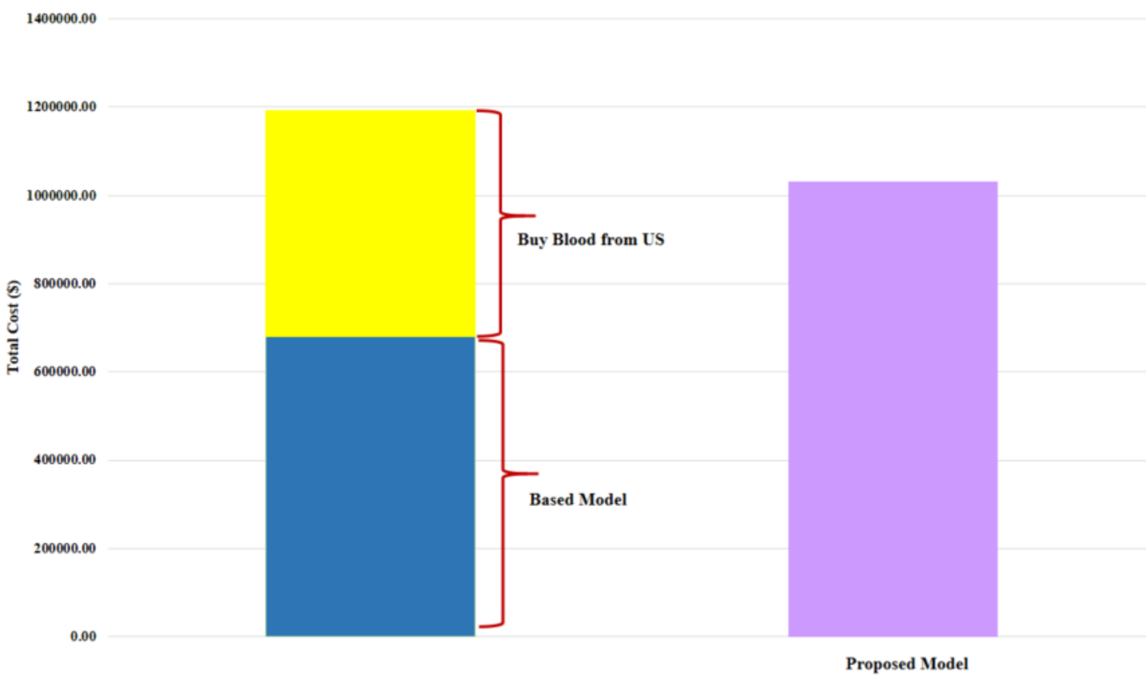


Figure 5.1- Models' Total Costs

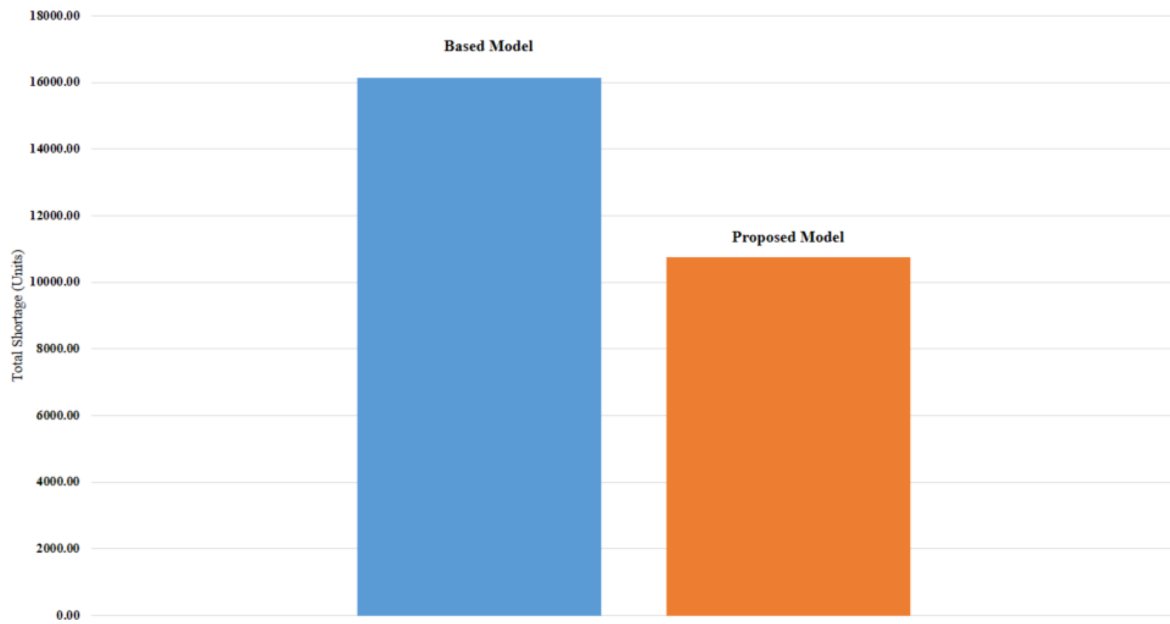


Figure 5.2- Models' Total Shortage

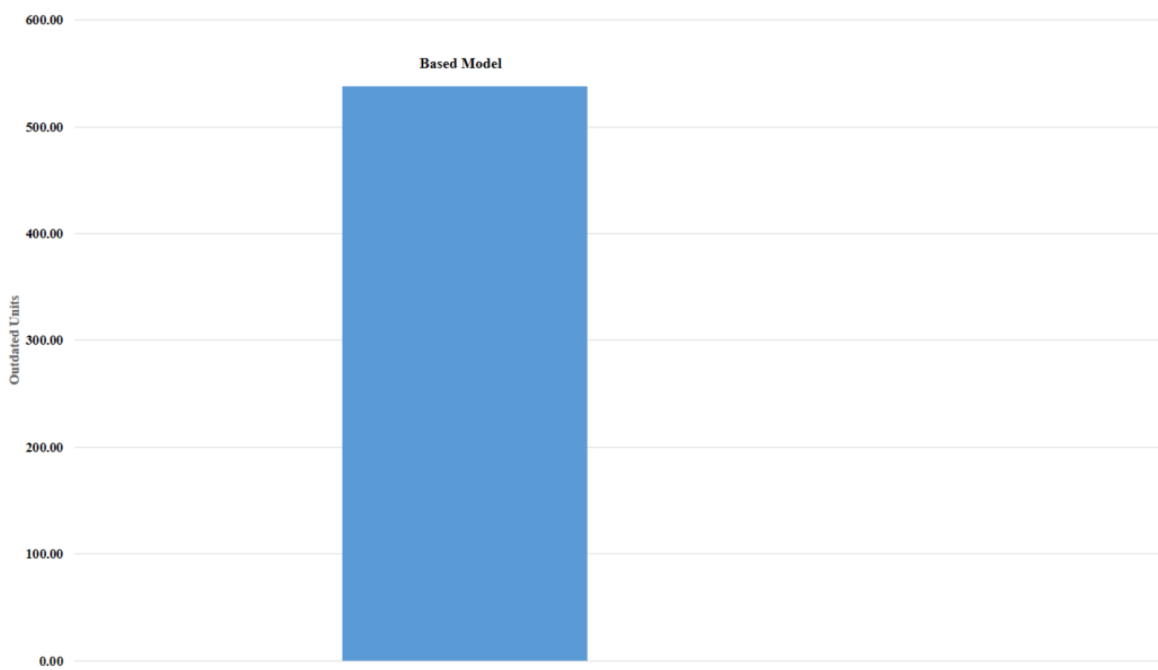


Figure 5.3- Models' Outdated Units

As has been shown in Figure 5.3, there would be no outdated units' amount in the proposed model.

5.3. Sensitivity Analysis

The amount of demand, initial inventory level of blood centers and hospitals, risk factor and shortage coverage are the parameters that can be changed due to some unforeseen circumstances. Hence, this section will show how the final result would change if any unexpected changes happen to the mentioned parameters, and how the model should behave in order to deal with these changes.

5.3.1. Demand

To realize how the proposed model would behave if the hospitals' demands change, the demand amount has been decreased up to -5% and increased up to +10%. More than 5% decrease or 10% increase in the demands' amount makes the proposed model infeasible. Therefore, it can be realized that if abruptly the demands' amount increase by 15%, the proposed model cannot respond, and the shortage amount would not be satisfied. Figure 5.4 shows how the final result will change if any changes happen to the demands' amount.

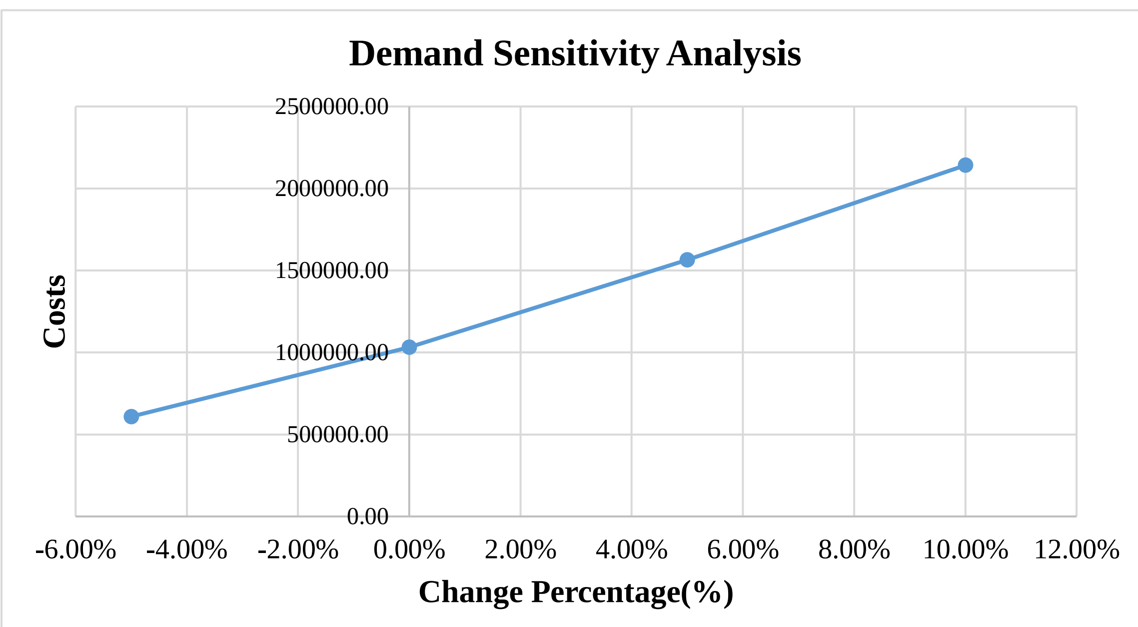


Figure 5.4- Demand Sensitivity Analysis

The trend of the plot shows that the total cost will increase if the demands' amount increase. This is a normal behavior since the model has to use more resources for satisfying the extra amount of demands.

5.3.2. The First Period's Inventory Level of Blood Centers

To realize how the proposed model would behave if the first period's inventory levels of blood centers change, their inventory level has been decreased up to -20% and increased up to 10%. Figure 5.5 shows how the final result will change if the blood centers' initial inventory level change.

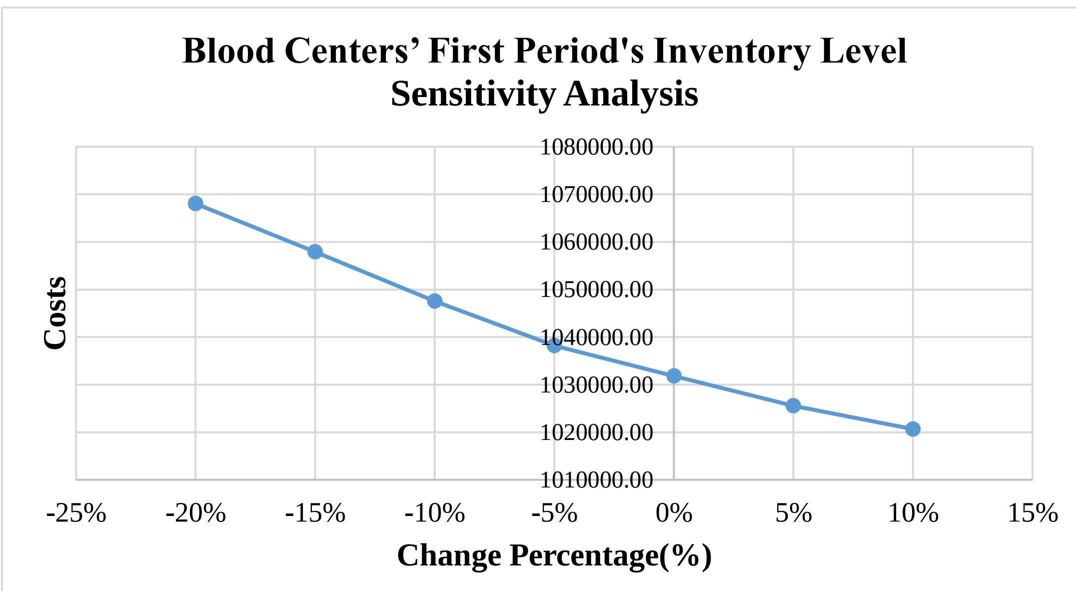


Figure 5.5- Blood Centers' First Period's Inventory Level Sensitivity Analysis

As Figure 5.5 shows decreasing in the amount of blood centers' first period's inventory level will increase the total costs. That is why, the system should use other more expensive resources. Figure 5.5 also demonstrate that due to the existence of lateral transshipment approach the model would not become infeasible even if the first period's inventory levels of blood centers decrease by 20%.

It is noteworthy to mention that since blood centers are the main stage that can provide fresh blood units for hospitals, they should always have initial inventory level in order to be able to satisfy the demands.

5.3.3. The First Period's Inventory Level of Hospitals

To realize how the proposed model would behave if the first period's inventory levels of hospitals change, their inventory level has been decreased up to -20% and increased up to 20%. Figure 5.6 shows how the final result will change if the hospitals' first period's inventory level change.

As Figure 5.6 shows decreasing in the amount of hospitals' first period's inventory level will increase the total costs. That is why, the system should use other resources to satisfy the demand. Figure 5.6 also demonstrate that due to the existence of lateral transshipment approach the model would not become infeasible even if the first period's inventory levels of blood centers decrease by 20%.

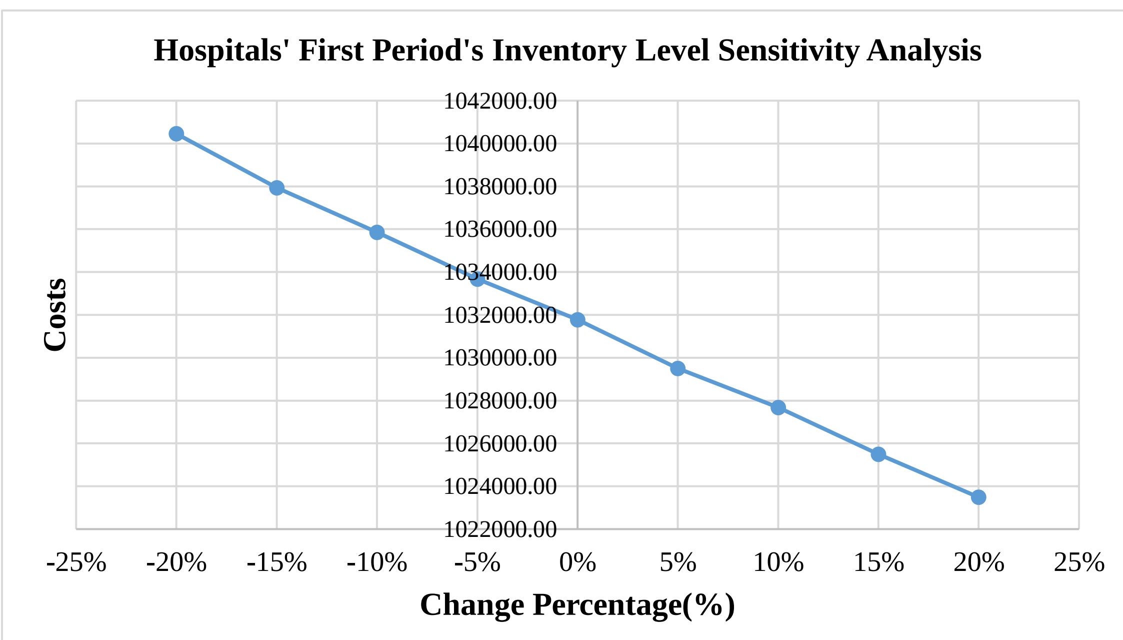


Figure 5.6- Blood Centers' First Period's Inventory Level Sensitivity Analysis

Although storing blood units in hospitals seems to be costly, Figure 5.7 show that a system with having first period's inventory level is more cost effective than a system with no first period's inventory level in its hospitals. It can be realized from Figure 5.7 that storing first period' inventory level in the hospitals would decrease the total cost of the system by 4%.

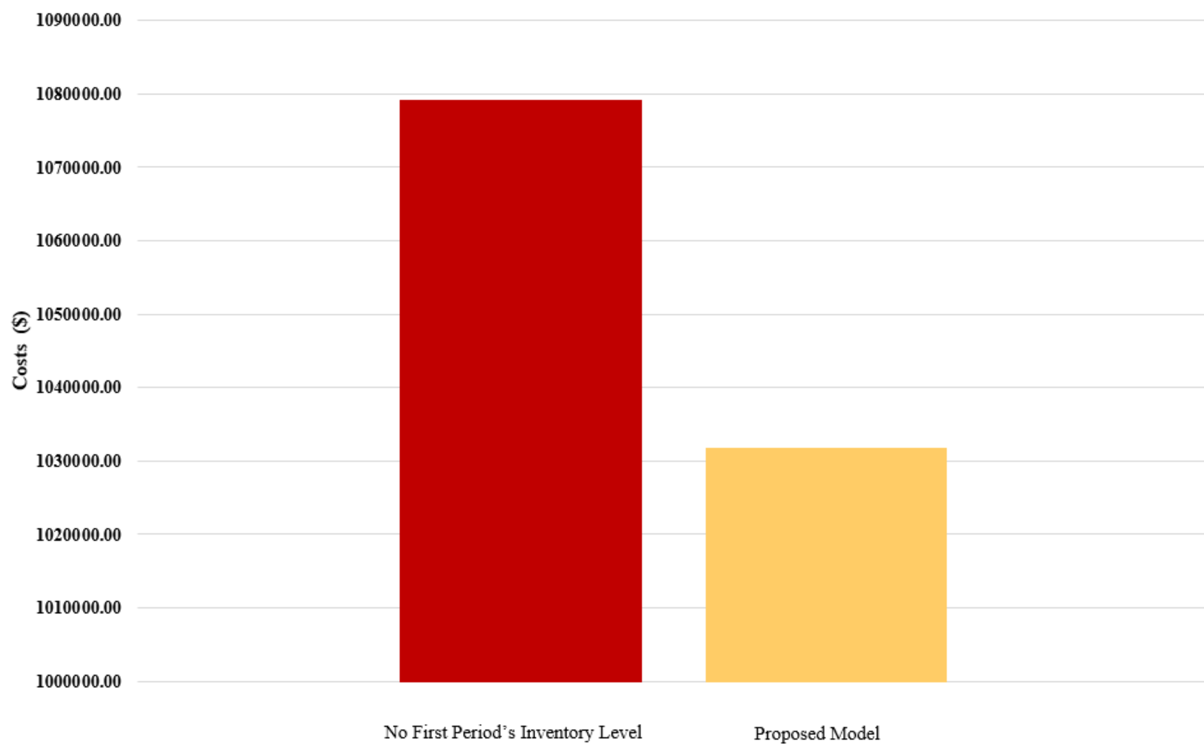


Figure 5.7- Hospitals' First Period's Inventory Level's Effect on the Total Costs

Moreover, Figure 5.8 shows that storing initial inventory level in the hospitals not only reduce the costs, but also does it decrease the total shortage amount by 2%.

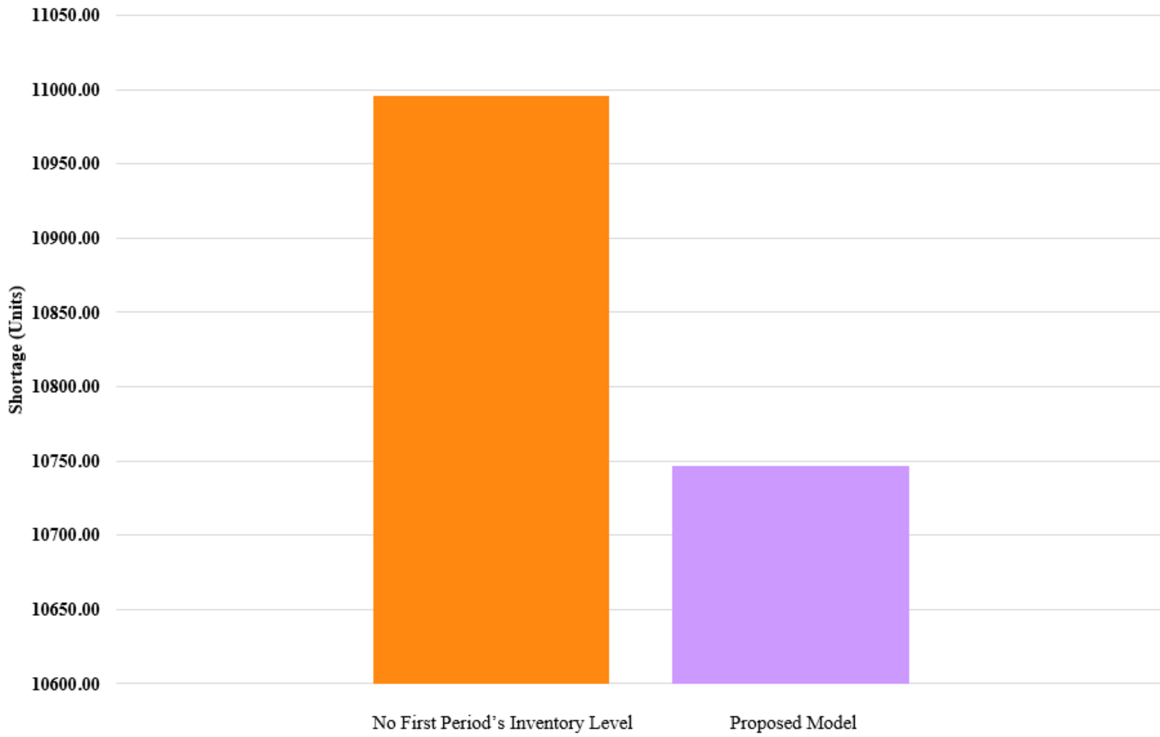


Figure 5.8- Hospitals' First Period's Inventory Level's Effect on the Total Shortage Amount

5.3.4. Risk Factor

The existing environment can always affect the level of risk factors. Hence, in order to realize how any changes in the risk factor would affect the final results, the risk factor of the model has been decreased up to -15% and increased up to 15%. Figure 5.9 shows that if the risk level decreases, the total costs will decrease too. This is a reasonable result because by decreasing the existing risk factor, more blood units would be available for transfusion and the emergency ordering amount would decrease. In addition, Figure 5.9 demonstrates that if the risk factor level increases, the system should provide more financial support to be able to satisfy hospitals' demand.

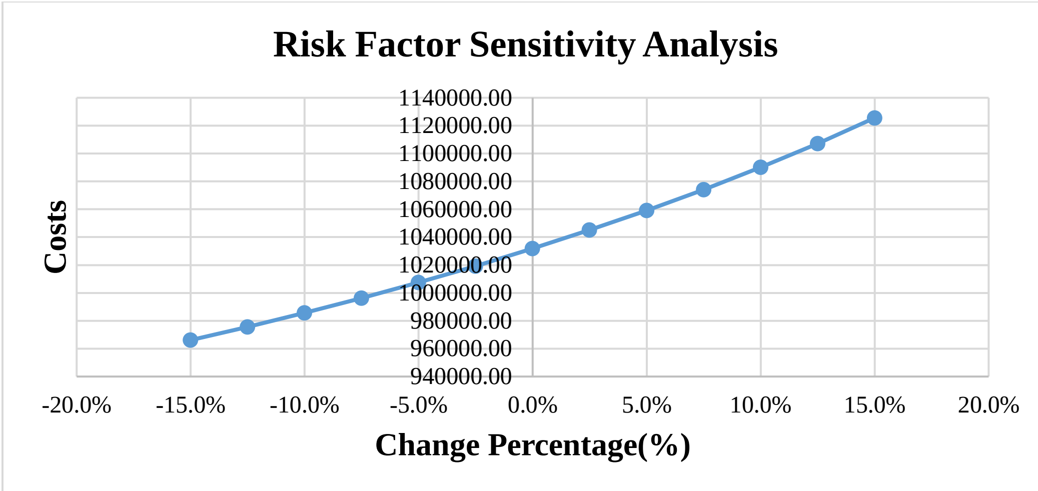


Figure 5.9- Risk Factor Sensitivity Analysis

5.3.5. Shortage Coverage

In order to examine the readiness of the proposed system, its shortage coverage has been decreased by up to -15% and increased up to +15%. The current system would satisfy at least 85% of the existing shortage, Figure 5.10 shows how the total costs would change if there are any changes in the shortage coverage rate. As has been shown in Figure 5.10, by decreasing the shortage coverage amount, the total costs would decrease as well. This is because the model is allowed to contain more unsatisfied demands. Similarly, by increasing the shortage coverage rate, the total cost would increase too, and that is why the model is more forced to satisfy all the existing shortage. Figure 5.10 also demonstrates that the proposed model can completely satisfy the existing shortage. This result shows that the proposed lateral transshipment and emergency ordering approaches are effectively useful.

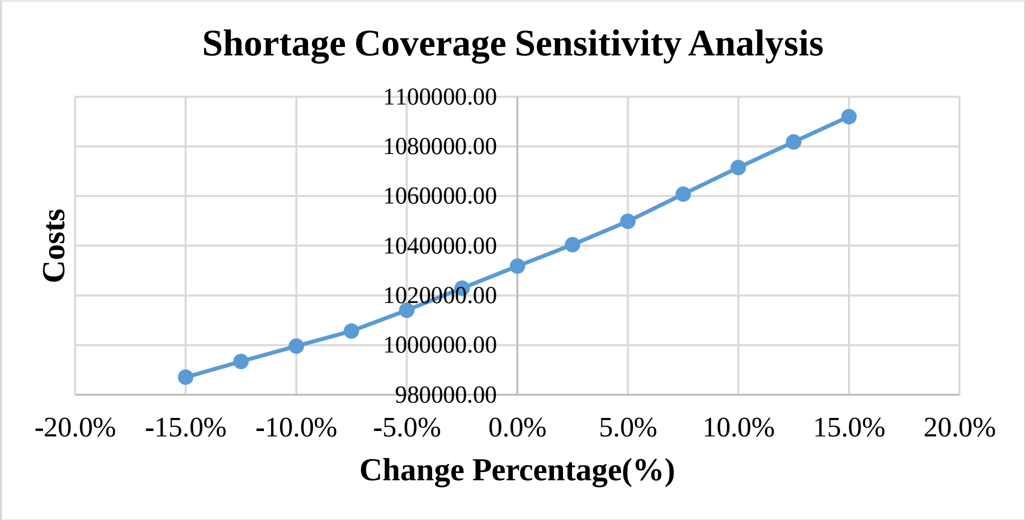


Figure 5.10- Shortage Coverage Sensitivity Analysis

5.4. Validation

The validation of the proposed model has been obtained by using a simulation approach. In this approach, the proposed model has been run for 100 times, and each run's final result has been calculated individually. Based on the obtained results from demand sensitivity analysis, and to run the proposed model in this simulation approach, it has been assumed the demand of this simulation process has a uniform distribution between -5% and +10% of its primary amount. Table 5.2 shows the final result of both the primary model and the simulated model. As has been shown in Table 5.2, although the final result of the primary model is better than the simulated model, both results are really close to each other and the value of the standard deviation is inconsiderable. Hence, by considering all these facts, it can be realized that the proposed model is valid.

Table 5.3-Validation Results

Final Result($)		**Standard Deviation($)**
Primary Model	**Simulated Model**	
1031777.97	1031895.69	165.16

5.5. Conclusion

By considering all the obtained information in this chapter, it can be realized that by applying the lateral transshipment and emergency ordering approaches, the model's results will improve and both inventory level and related costs will reduce. Moreover, after conducting sensitivity analysis, the obtained results demonstrate that although unexpected changes may affect the final result, in most cases the proposed model would be able to respond to these changes. This shows that the proposed model has enough flexibility to deal with any unexpected shifts. In the end, after 100 runs, the simulation process demonstrates that the proposed model has validation for any further use and application.

CHAPTER 6

FURTHER INVESTIGATION

6.1. Introduction

As has been mentioned in Chapter 1, currently, the Canadian blood supply chain buys blood units from the US to satisfy both its demand and shortage. In this research, the primary model proposed replacing the mentioned approach with using lateral transshipment and emergency ordering approaches in order to both save time and costs. Moreover, However, it has been realized that if the demand's amount increases by more than 15%, the proposed model would not be able to satisfy the needs. Hence, an updated model by considering buying blood units from the US beside lateral transshipment and emergency ordering approaches has been proposed in this chapter. The unexpected increasing rate in the demand's amount can be occurred due to some emergency situations. Thus, the updated model has been investigated as both non-profitable and profitable models to realize how this external help can affect the Canadian blood supply chain performance.

6.2. Updated Model

Considering an external help beside the two previous approaches will aid the system to increase its readiness for confronting any unexpected changes. For applying the external help into the model, some modifications in the primary proposed model are required. Therefore, this section will introduce all the new required parameters and decision variables. It is noteworthy to mention that all the previous parameters, decision variables and information that has been shown in Chapter 3 are going to be used in the updated model as well. Tables 6.1 to 6.3 show both new notations, parameters and decision variables that are going to be added to the model.

Table 6.1- New notation used in the updated mathematical model

	Sets and Indices
Q	*US blood centers* $q \in Q$

Table 6.2- New parameters used in the updated mathematical model

	Parameters
$AMCA_{qn}^{t}$	*Total inventory of US blood center q for blood units with shelf life n at period t*
Haz_n	*Cost of delivering one unit of blood with shelf life n from US blood centers to hospitals*

Table 6.3- New decision variable used in the updated mathematical model

	Variables
	Positive Variables
KOM_{qi}^{nt}	*The amount of blood units that can be delivered from US blood center q to hospital i with shelf life n at period t*

By considering new parameters and the decision variable, the updated model can be generated from the primary model. The updated model can be either non-profit or commercial. Due to the new circumstances, the objective function and some of the constraints which have been explained in Chapter 3 will change to prepare the system for responding to unexpected changes in demand's amount. The following two sections will demonstrate how the primary will change due to the new condition.

6.2.1. Non-Profit Blood Supply Chain

If during the unexpected changes, US blood centers deliver the blood units with no costs, there would be no effect on the primary model's objective function. However, given the limited capacity of blood centers, and the extra amount of blood units that are going to be delivered to the hospitals, some constraint of the primary model would change.

In the updated model, it has been assumed that if hospitals face shortage, they not only could get help from blood centers and hospitals, but also can they receive an extra amount of blood units from US blood centers. US blood centers can also deliver fresh blood units. Thus, in the updated model, hospitals can order fresh blood from both Canadian and US blood centers. However, the limited capacity of US blood centers will restrict the delivered amount from these centers to hospitals. By considering all the mentioned assumption, it would be realized that equations (18), (21) and (22) of Chapter 3 would change. The equations (1-3) are the updated version due to the new circumstances.

$$y_i^t = \sum_k Z_{ki}^t + \sum_q KOM_{qi}^{nt} \ \ \forall i,t \tag{1}$$

$$\sum_{j\neq i}\sum_m X_{jim}^t + \sum_k\sum_{n\geq 3} ES_{kin}^t + \sum_q\sum_{n\geq 2} KOM_{qi}^{nt} \geq \beta f_i^t \ \ \forall i,t \tag{2}$$

$$\sum_{j\neq i}\sum_m X_{jim}^t + \sum_k\sum_{n\geq 3} ES_{kin}^t + \sum_q\sum_{n\geq 2} KOM_{qi}^{nt} \, f_i^t \quad \forall i,t \tag{3}$$

Equation (1) indicates that in each period of time, hospitals' orders can be satisfied by both Canadian and US blood centers.

Equations (2) and (3) indicate that the US blood centers can deliver blood directly to the hospitals. It should be mentioned that since blood units are delivered from the US, it has been assumed that they are already processed and tested, and no lead time would be needed for testing and delivering these units.

6.2.2. Commercial Blood Supply Chain

If US blood centers sell their blood units to the Canadian blood supply chain during an unexpected change, some additional costs like cost of testing, preparation, storing and delivery will be added to the primary model. In this case, not only the mathematical model's constraints will change, but also will the model's objective function be affected. The constraints of the commercial blood supply chain model are the same as the constraints of the non-profit blood supply chain model. Hence, in this system, the equations (18), (21) and (22) of Chapter 3 should again be replaced with equations (1-3) that have been described in the previous section. Furthermore, the objective function of the primary model (equation (1) of Chapter 3) will be replaced with the following equation.

$$
\begin{aligned}
min \sum_{k}\sum_{i}\sum_{n\geq 3}\sum_{t} ES_{kin}^{t} * CE_{ki}^{n} + \sum_{k}\sum_{i}\sum_{t} Z_{ki}^{t} * SN_{ki} \\
+ \sum_{k}\sum_{t}(FV_{k}^{t} * HB_{k} + DW_{k}^{t} * CW) + \sum_{i}\sum_{j\neq i}\sum_{m}\sum_{t} X_{ijm}^{t} * C_{ij}^{m} \\
+ \sum_{i}\sum_{t}(V_{i}^{t} * H_{i} + \sigma_{i}^{t} * E + f_{i}^{t} * G + y_{i}^{t} * SEF) \\
+ \sum_{r}\sum_{k}\sum_{t} TES * (HJM_{rk}^{t} + DON_{k}^{t}) \\
+ \sum_{k}\sum_{i}\sum_{p}\sum_{t} BTH_{ki}^{pt} * VC_{p} * LB_{ki} + \sum_{i}\sum_{j\neq i}\sum_{p}\sum_{t} HTH_{ij}^{pt} * VC_{p} * LH_{ij} \\
+ \sum_{q}\sum_{i}\sum_{n}\sum_{t} KOM_{qi}^{nt} * \mathrm{Haz}_{\mathrm{n}}
\end{aligned}
\qquad (4)
$$

Equation (4) indicates that besides all the previously mentioned costs, delivering fresh and emergency blood units from blood centers to hospitals has its own specific cost which would affect the final result.

6.2.3. Conclusion

In conclusion, it can be realized that delivering an extra amount of blood units from US blood centers to the hospitals can be considered as a great help that can assist the latter to deal with any abrupt changes. However, since in the commercial supply chain, US blood centers have their costs, the Canadian blood supply chain has to consider all aspects to decide whether the extra amount should be delivered from US blood centers or some other actions have to be taken.

6.3. Implementation

As has been described in Chapter 4, the Greater Toronto Area (GTA), which located in Southern Ontario, has been selected as the case study of this research. By considering the location of the case study and in order to minimize both travel time and costs, it has been realized that the US blood centers that are going to deliver extra blood units should be located in the US states which have a common border with Southern Ontario. Therefore, 4 states have been selected, namely Michigan (MI), Ohio (OH), Pennsylvania (PA) and New York (NY). Based on the available statistic, 37% percent of the US population is eligible to donate blood, and from this population, only near 7% donate blood annually. (National Blood Collection, 2007) Regarding the demographic analysis of 4 mentioned states, Table B.1 shows the total inventory level of US blood centers in each period. It is noteworthy to mention the inventory level of blood units depends on their shelf life which is from 2 to 5 days. The fresh blood units with 2 days of shelf life form the largest part of the inventory level, and the blood units with 5 days of shelf life have the least part of the inventory level.

Moreover, Table B.2 shows the total cost of transporting one unit of blood with a specific shelf life from US blood centers to the hospitals. (Forbes et al, 1991) The total cost includes testing and processing cost, storing cost and transshipping cost. The total cost has been obtained based on the available information. It has been assumed that the total cost would be the same for all the states and all periods.

Table B.2 shows that in order to reduce the outdated units' amount, as blood units become older, their transporting cost becomes cheaper as well.

6.4. Results and Analysis

This section aims to demonstrate the results of both mentioned supply chains. Both commercial and non-profit models have been implemented in GAMS win32 27.1.0 using Intel ® Core™ i5-2320 CPU 3 GHz processor with 8 GB of RAM. A summary of the results has been provided in Table 6.6.

Table 6.4- Summary of the results

Objective Function($)	
Commercial	**Non-Profit**
2915093.50	1614295.71
US Blood Centers' Delivery Amount(Units)	
Commercial	**Non-Profit**
875	14804

Given Table 6.6, it can be realized that if the Canadian blood supply chain wants to buy blood units from the US, not only its cost will increase by almost 80%, but also does its purchasing power decrease by almost 94%. This is because the cost of buying blood units from US blood centers is expensive, and in the commercial blood supply chain, hospitals prefer to choose lateral transshipment and emergency ordering from Canadian blood centers approaches over buying blood units from the US. On the other hand, based on the results, if the blood units will be delivered from the US blood centers with no costs, hospitals would prefer to deliver blood units from US blood centers, and store these units in their inventory rather than ordering from other hospitals or Canadian blood centers.

Figures 6.1 and 6.2 show how respectively total costs and delivery amount from US are different between Commercial supply chain and Non-Profit Supply Chain.

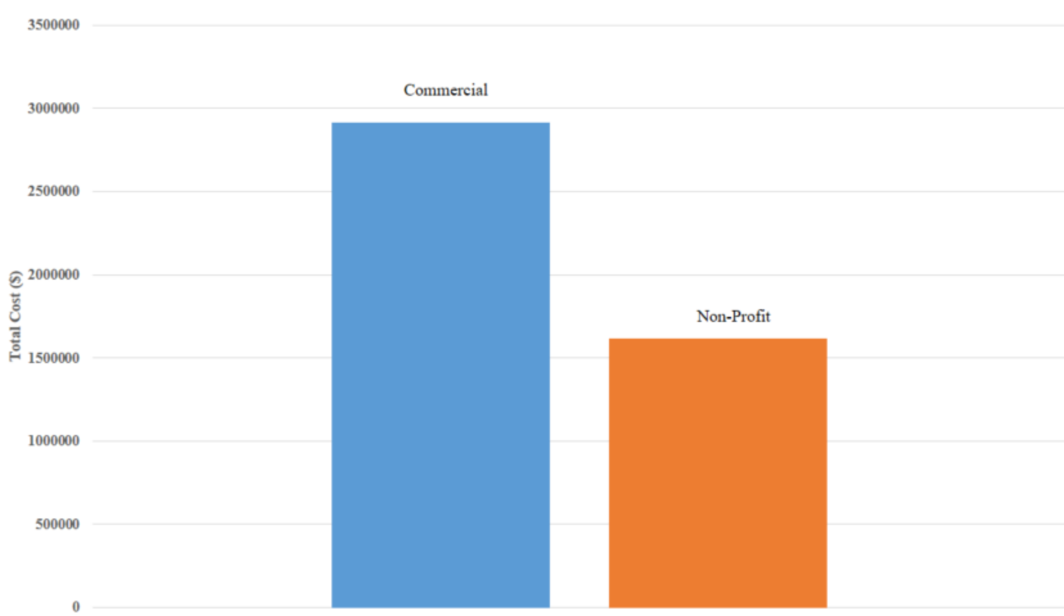


Figure 6.1- CBS's Total Cost in The Commercial and Non-profit Supply Chain

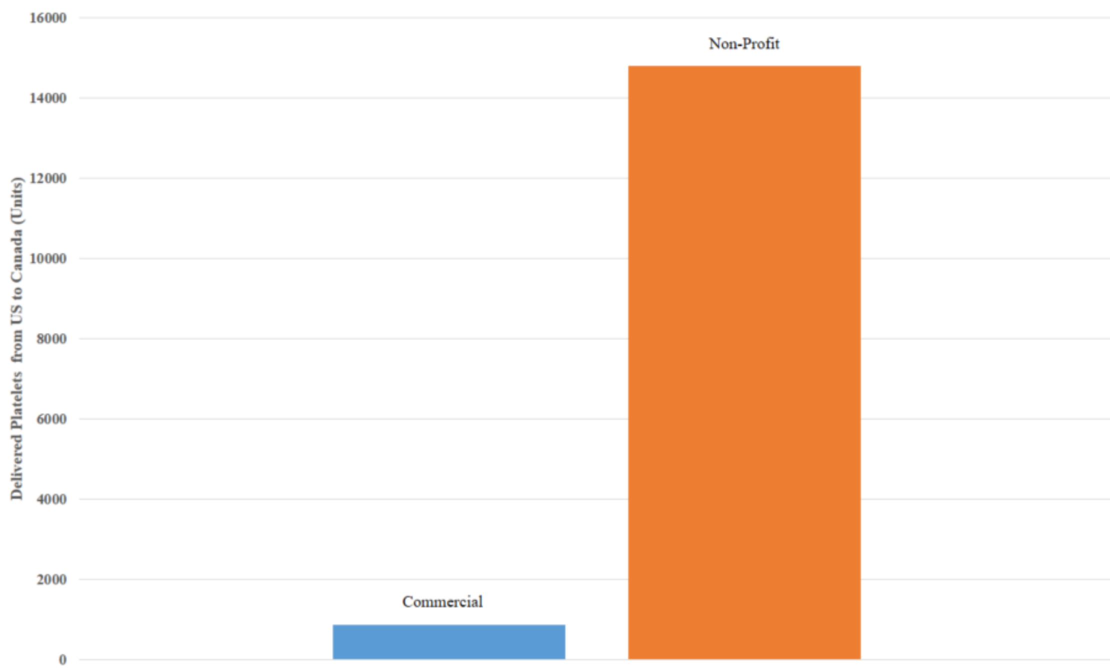


Figure 6.2- The Amount of Delivered Platelets' Units from US to Canada

6.5. Conclusion

The obtained results and analysis demonstrate that when blood units' demand increase dramatically in an emergency situation, the Canadian blood supply chain should either find a non-profit organization that can satisfy the extra amount of hospitals' demand, or allocating a specific amount of budget to buy blood units from available US blood centers. Otherwise, adopting a commercial blood supply chain system would not be worthy for the Canadian blood supply chain. That is why, in a commercial blood supply chain, the cost would increase and the delivered amount from US blood centers would decrease greatly. In conclusion, it can be realized that an external help during an abrupt change would be useful and satisfy demands, however, it would be a decisive decision for Canadian blood supply chain to determine its priorities and set a plan that can assist it to reach to its determined goals.

CHAPTER 7
CONCLUSIONS & RECOMMENDATIONS

7.1. Conclusions

In this research an integrated blood supply chain framework with adopting a reactive lateral transshipment and emergency ordering approaches under a certain condition to reduce the related costs and optimize the inventory level has been proposed. Reactive lateral transshipment approach allows hospitals to request for extra amount of blood units from other hospitals whenever they face with shortage, and emergency ordering option allows blood centers to deliver extra amount of blood units to hospitals in case of shortage. Since the existence of humans' errors is an undeniable fact, a specific amount of collected blood units of the proposed supply chain will be discarded due to these errors and tests' results. To eliminate all the unnecessary costs, various transportation modes with specific fuel efficiency have been considered to realize how allocation should be in order to both satisfy the demands, and prevent units be outdated. Several parameters such as specific capacity, travel distance, fuel efficiency, existing errors rate, etc. have been used to improve the model reality. The decision variables of the model relate to the inventory level of both blood centers and hospitals, the outdated units' and shortage amounts of hospitals, the outdated units' amount of blood centers, the fresh blood delivery amount, the quantity of transferred blood from hospitals or blood center during a shortage, and selecting the location of mobile blood centers. The proposed mathematical model has been applied to a real case study (Greater Toronto Area), and platelet as the rarest blood component with the least shelf life has been studied in this research. The obtained results reveal that by applying two mentioned approaches the shortage amount of Canadian blood supply chain will decrease by almost 60% while its cost will increase up to 52%. Moreover, there would be no outdated units' amount in the proposed supply chain which means that compared to the current situation, the outdated units' amount will decrease 100%.

In the next step, the sensitivity of the model to the demand's amount has been analyzed, and it has been figured out that by increasing the demand more than 15%, the proposed model would not be able to reach to the optimized solution. Therefore, a further action has been taken to prepare the model for any abrupt changes. By considering an external help from US, the infeasibility of the model has been solved. Two approaches have been considered in the updated model. In the first approach, a non-profit supply chain has been considered to deliver blood units from US to Canada while in the second approach, the supply chain would be commercial and there would be a cost for delivering blood units from US to Canada. By shifting the supply chain model from non-profit to commercial the cost will increase by almost 80% and the delivery amount will decrease by 94%. These results shows that how extra costs will affect the final results. In conclusion, it can be realized that if any unexpected change happens in the Canadian blood supply chain system, the CBS organization either should ask for non-profit donation or find a way in which buying blood components from outside resource would be more cost-effective than lateral transshipment and storing blood approaches.

7.2. Recommendations

The proposed model of this study can be extended from various perspective. The following actions can be implemented in the future research works.

7.2.1. Uncertainty

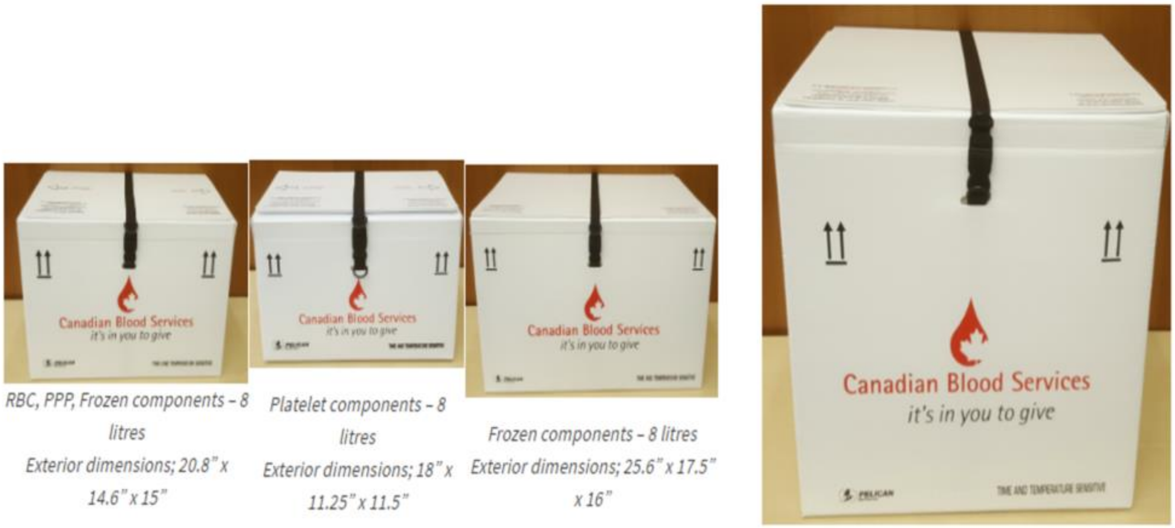
Uncertainty is an inseparable part of any system. For future research works uncertainty in demand amount and costs can be considered in the model in order to realize how fluctuations would affect the final results.

7.2.2. Patients' Condition

Patients' condition will be determined by considering several factors such as the type of disease, the amount of needed blood units, the type of needed blood units. Applying patients' condition in the model can have effect on hospital demand and the amounts of shortage and outdated units.

7.2.3. Transportation Modes' Capacity

Limited capacity of transportation modes can affect both the costs and the amount of delivered amount between two centers. Moreover, considering a specific capacity for transportation mode will affect the selection of these modes for travelling between two centers. It should also be noted that delivering blood components requires specific packaging process in order to provide the appropriate storage condition. Figure 7.1 shows various packages which are used by CBS for delivering blood components to the hospitals (Toyota and CBS websites, 2016).



RBC, PPP, Frozen components – 8 litres
Exterior dimensions; 20.8" x 14.6" x 15"

Platelet components – 8 litres
Exterior dimensions; 18" x 11.25" x 11.5"

Frozen components – 8 litres
Exterior dimensions; 25.6" x 17.5" x 16"

Plasma Protein Products (PPP) – 16 litres
Refrigerated or 2-25o C temperature products. The option exists to pack both refrigerated PPP and RBCs in the same box.
Exterior dimensions; 20.6" x 18.5" x 20.6"

Figure 7.1 - Various Packages for blood components (*Receipt of products: https://blood.ca/en/hospital-services/inventory-ordering/receipt-products*)

7.2.4. Monitoring Travel Time

Today's world technology provides a situation in which everything can be monitored online. Applying this technology in proposed model to monitor travel time will make the system closer to the real-world situation. This application will change the costs and delivery blood units' amount of the supply chain.

7.2.5. Enterprise Resource Planning System(ERP)

ERP system is an integrated system that manage a business process by using software and recent technology. The proposed model creates a framework in which an ERP system can be applied for managing any blood supply chain.

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APPENDICES

Appendix A

Table A.1- Mobile collection centers' information

No.	Location	Address
1	Canadian Mar Thorma Church	(York Region) 159 Sandiford Dr., Stouffville, ON
2	Uxbridge Seniors' Center	(Durham Region) 75 Marietta Street, Uxbridge, ON
3	Holiday Inn Express & Suites, Newmarket.	(York Region) 100 Pony Dr, Newmarket, ON
4	East Gwillimbury Sports Complex	(York Region) 1914B Mount Albert Road, Sharon, ON
5	The Church St. Patrick-Markham	(York Region) 5633 Highway #7 East, Markham, ON
6	Aurora Region	(York Region) 105 Industrial Parkway North, Aurora, ON
7	Newmarket Community Center	(York Region) 200 Doug Duncan Drive (formerly 221 Cedar St.), Newmarket, ON
8	Scugog Community Center	(Durham Region) 1655 Reach Street, Port Perry, ON
9	St. Thomas' Anglican Church	(Durham Region) 101 Winchester Rd. E., Brooklin, ON
10	York Region Administrative Center	(York Region) 17250 Young Street, Newmarket, ON
11	Pickering Recreation Complex- East Salon	(Durham Region) 1867 Valley Farm Rd, Pickering, ON
12	Markham Convention Center	(York Region) 2901 Markham Rd, Toronto, ON

Table A.2-Hospitals' information

No.	Location	Address
1	Credit Valley Hospital Site	2200 Eglinton Avenue West, Mississauga, ON
2	Halton Healthcare Services Corporation	3001 Hospital Drive, Oakville, ON
3	Hospital for Sick Children	555 University Avenue, Toronto, ON
4	Brampton Civic Hospital Site	2100 Bovaird Drive East, Brampton, ON
5	Joseph Brant Hospital	1245 Lakeshore Rd, Burlington, ON
6	MacKenzie Health	10 Trench Street, Richmond Hill, ON
7	Markham-Stouffville Hospital	381 Church Street, P.O. Box 1800, Markham, ON
8	The Cottage Hospital Site	4 Campbell Dr., Uxbridge, ON
9	Southlake Regional Health Centre	596 Davis Drive, Newmarket, ON
10	Etobicoke General Site	101 Humber College Blvd, Etobicoke, ON
11	Lakeridge Health Oshawa	1 Hospital Ct, Oshawa, ON
12	Toronto General Hospital	200 Elizabeth Street, Toronto, ON
13	Peel Memorial Centre for Integrated Health and Wellness Site	20 Lynch St., Brampton, ON
14	Bridgepoint Hospital Site	14 St. Matthews Road, Toronto, ON
15	Baycrest Hospital	3560 Bathurst Street, Toronto, ON
16	Mississauga Hospital Site	100 Queensway West, Mississauga, ON
17	Salvation Army Toronto Grace Hospital	650 Church Street, Toronto, ON
18	Toronto East Health Network - Michael Garron Hospital	825 Coxwell Avenue, Toronto, ON
19	Mount Sinai Hospital Site	600 University Avenue, Toronto, ON
20	West Park Healthcare Centre	82 Buttonwood Avenue, Toronto, ON

Table A.3- Blood centers' information

No.	Location	Address
1	Richmond Hill	9350 Young Street, Richmond Hill, ON
2	Toronto (College Street)	67 College Street, Toronto, ON
3	Toronto (King Street)	163 King Street West, Main Floor, Toronto, ON
4	Toronto (Young & Bloor)	2 Bloor Street East, Hudson's Bay Centre, Toronto, ON
5	Burlington	1250 Brant Street, Burlington, ON
6	Mississauga	756 Britannia Rd. West, Unit 2, Mississauga, ON
7	Oshawa	1300 Harmony Road North, Oshawa, ON

Table A.4- Hospitals' demands

No.	Hospital	Number of Beds	Demand						
			t=1	t=2	t=3	t=4	t=5	t=6	t=7
1	Credit Valley Hospital Site	382	69	79	62	83	67	74	60
2	Halton Healthcare Services Corporation	457	83	95	74	99	80	88	71
3	Hospital For Sick Children	453	82	94	73	99	80	88	71
4	Brampton Civic Hospital Site	608	110	126	98	132	107	118	95
5	Joseph Brant Hospital	245	44	51	40	53	43	47	38
6	MacKenzie Health	506	92	105	82	110	89	98	79
7	Markham-Stouffville Hospital	309	56	64	50	67	54	60	48
8	The Cottage Hospital Site	20	4	4	3	4	4	4	3
9	Southlake Regional Health Centre	400	73	83	65	87	70	77	62
10	Etobicoke General Site	262	48	54	42	57	46	51	41
11	Lakeridge Health Oshawa	363	66	75	59	79	64	70	57
12	Toronto General Hospital	417	76	86	68	91	73	81	65
13	Peel Memorial Centre for Integrated Health and Wellness Site	367	67	76	59	80	64	71	57
14	Bridgepoint Hospital Site	464	84	96	75	101	81	90	72
15	Baycrest Hospital	472	86	98	76	103	83	91	74
16	Missisauga Hospital Site	751	136	155	122	163	132	145	117
17	Salvation Army Toronto Grace Hospital	119	22	25	19	26	21	23	19
18	Toronto East Health Network - Michael Garron Hospital	515	93	107	83	112	90	100	80
19	Mount Sinai Hospital Site	442	80	91	72	96	78	86	69
20	West Park Healthcare Centre	314	57	65	51	68	55	61	49
Total			**1428**	**1628**	**1274**	**1711**	**1380**	**1522**	**1227**

Table A.5- Hospitals' initial inventory level for each shelf life

No.	Hospital	Initial Inventory Level of Each Shelf Life			Total Initial Inventory Level
		m=3	m=4	m=5	
1	Credit Valley Hospital Site	30	16	8	55
2	Halton Healthcare Services Corporation	30	16	8	55
3	Hospital For Sick Children	33	18	9	60
4	Brampton Civic Hospital Site	44	24	12	80
5	Joseph Brant Hospital	15	8	4	27
6	MacKenzie Health	39	21	11	71
7	Markham-Stouffville Hospital	23	13	6	42
8	The Cottage Hospital Site	2	1	0	3
9	Southlake Regional Health Centre	30	16	8	54
10	Etobicoke General Site	18	10	5	33
11	Lakeridge Health Oshawa	27	15	7	49
12	Toronto General Hospital	30	16	8	55
13	Peel Memorial Centre for Integrated Health and Wellness Site	26	14	7	47
14	Bridgepoint Hospital Site	34	18	9	61
15	Baycrest Hospital	33	18	9	60
16	Missisauga Hospital Site	59	32	16	107
17	Salvation Army Toronto Grace Hospital	8	4	2	15
18	Toronto East Health Network - Michael Garron Hospital	40	22	11	73
19	Mount Sinai Hospital Site	34	18	9	62
20	West Park Healthcare Centre	24	13	6	42.75

Table A.6- Initial inventory level of blood centers

No.	Blood Centers	Initial Inventory Level of Each Shelf Life				Total Initial Inventory Level
		n=2	n=3	n=4	n=5	
1	Richmond Hill Blood Center	244	101	41	20	813
2	Toronto Blood Center (College St.)	523	218	87	43	1743
3	Toronto Blood Center (King St.)	523	218	87	43	1743
4	Toronto Blood Center (Yonge & Bloor)	523	218	87	43	1744
5	Burlington Blood Center	183	76	31	15	611
6	Mississauga Blood Center	601	130	105	52	2109
7	Oshawa Blood Center	96	40	16	8	322

Table A.7- Mobile collection centers' capacity

No	Mobile Collection Centers	Capacity(Pint of blood)
1	Canadian Mar Thoma Church.	125
2	Uxbridge Seniors' Centre	140
3	Holiday Inn Express & Suites, Newmarket.	125
4	East Gwillimbury Sports Complex	125
5	The Church of St. Patrick – Markham	125
6	Aurora Legion	125
7	Newmarket Community Centre	125
8	Scugog Community Centre	140
9	St. Thomas' Anglican Church	140
10	York Region Administrative Centre	125
11	Pickering Recreation Complex - East Salon	140
12	Markham Convention Centre.	125

Table A.8- Hospitals' holding cost *(Lagerquist et al,2017)*

No.	Hospital	Holding Cost($)
1	Credit Valley Hospital Site	21.92
2	Halton Healthcare Services Corporation	20.18
3	Hospital For Sick Children	20.27
4	Brampton Civic Hospital Site	16.67
5	Joseph Brant Hospital	25.1
6	MacKenzie Health	19.04
7	Markham-Stouffville Hospital	23.62
8	The Cottage Hospital Site	30.34
9	Southlake Regional Health Centre	21.5
10	Etobicoke General Site	
11	Lakeridge Health Oshawa	22.36
12	Toronto General Hospital	21.11
13	Peel Memorial Centre for Integrated Health and Wellness Site	22.27
14	Bridgepoint Hospital Site	20.01
15	Baycrest Hospital	19.83
16	Mississauga Hospital Site	13.34
17	Salvation Army Toronto Grace Hospital	28.03
18	Toronto East Health Network - Michael Garron Hospital	18.83
19	Mount Sinai Hospital Site	20.53
20	West Park Healthcare Centre	23.5

Table A.9- Transshipping cost between hospitals *(Lagerquist et al,2017)*

No	Hospitals	Hospitals														
		Credit Valley Hospital Site			Halton Healthcare Services Corporation			Hospital For Sick Children			Brampton Civic Hospital Site			Joseph Brant		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
1	Credit Valley Hospital Site	0	0	0	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
2	Halton Healthcare Services	1.86	1.78	1.49	0	0	0	1.94	1.86	1.55	1.86	1.78	1.49	1.69	1.62	1.35
3	Hospital For Sick Children	1.86	1.78	1.49	1.94	1.86	1.55	0	0	0	1.86	1.78	1.49	1.94	1.86	1.55
4	Brampton Civic Hospital Site	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49	0	0	0	1.86	1.78	1.49
5	Joseph Brant Hospital	1.86	1.78	1.49	1.69	1.62	1.35	1.94	1.86	1.55	1.86	1.78	1.49	0	0	0
6	MacKenzie Health	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
7	Markham-Stouffville Hospital	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
8	The Cottage Hospital Site	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
9	Southlake Regional Health Centre	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
10	Etobicoke General Site	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49	1.94	1.86	1.55	1.94	1.86	1.55
11	Lakeridge Health Oshawa	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49	1.94	1.86	1.55	1.94	1.86	1.55
12	Toronto General Hospital	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55
13	Peel Memorial Centre for Integrated Health and Wellness Site	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
14	Bridgepoint Hospital Site	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
15	Baycrest Hospital	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55

No	Hospitals	Hospitals														
		Credit Valley Hospital Site			Halton Healthcare Services Corporation			Hospital For Sick Children			Brampton Civic Hospital Site			Joseph Brant		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
16	Mississauga Hospital Site	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
17	Salvation Army Toronto Grace Hospital	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55
18	Toronto East Health Network - Michael Garron Hospital	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55
19	Mount Sinai Hospital Site	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55
20	West Park Healthcare Centre	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55

No	Hospitals	Hospitals														
		MacKenzie Health			Markham-Stouffville Hospital			The Cottage Hospital Site			Southlake Regional Health Centre			Etobicoke General Site		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
1	Credit Valley Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
2	Halton Healthcare Services	1.94	1.86	1.55	1.94	1.86	1.55	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49
3	Hospital For Sick Children	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49
4	Brampton Civic Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
5	Joseph Brant Hospital	1.94	1.86	1.55	1.94	1.86	1.55	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49
6	MacKenzie Health	0	0	0	1.69	1.62	1.35	1.69	1.62	1.35	1.69	1.62	1.35	1.86	1.78	1.49
7	Markham-Stouffville Hospital	1.69	1.62	1.35	0	0	0	1.69	1.62	1.35	1.69	1.62	1.35	1.86	1.78	1.49
8	The Cottage Hospital Site	1.69	1.62	1.35	1.69	1.62	1.35	0	0	0	1.69	1.62	1.35	1.86	1.78	1.49
9	Southlake Regional Health Centre	1.69	1.62	1.35	1.69	1.62	1.35	1.69	1.62	1.35	0	0	0	1.86	1.78	1.49
10	Etobicoke General Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	0	0	0
11	Lakeridge Health Oshawa	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.94	1.86	1.55
12	Toronto General Hospital	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49
13	Peel Memorial Centre for Integrated Health and Wellness Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
14	Bridgepoint Hospital Site	1.69	1.62	1.35	1.69	1.62	1.35	1.69	1.62	1.35	1.69	1.62	1.35	1.86	1.78	1.49
15	Baycrest Hospital	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49
16	Mississauga Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
17	Salvation Army Toronto Grace Hospital	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49

No	Hospitals	Hospitals														
		MacKenzie Health			Markham-Stouffville Hospital			The Cottage Hospital Site			Southlake Regional Health Centre			Etobicoke General Site		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
18	Toronto East Health Network - Michael Garron Hospital	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49
19	Mount Sinai Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49
20	West Park Healthcare Centre	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49

No	Hospitals	Hospitals														
		Lakeridge Health Oshawa			Toronto General Hospital			Peel Memorial Centre for Integrated Health and Wellness Site			Bridgepoint Hospital Site			Baycrest Hospital		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
1	Credit Valley Hospital Site	1.94	1.86	1.55	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49
2	Halton Healthcare Services	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49	1.94	1.86	1.55	1.94	1.86	1.55
3	Hospital For Sick Children	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
4	Brampton Civic Hospital Site	1.94	1.86	1.55	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49
5	Joseph Brant Hospital	1.94	1.86	1.55	1.94	1.86	1.55	1.86	1.78	1.49	1.94	1.86	1.55	1.94	1.86	1.55
6	MacKenzie Health	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
7	Markham-Stouffville Hospital	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
8	The Cottage Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
9	Southlake Regional Health Centre	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49
10	Etobicoke General Site	1.94	1.86	1.55	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49
11	Lakeridge Health Oshawa	0	0	0	1.86	1.78	1.49	1.94	1.86	1.55	1.86	1.78	1.49	1.86	1.78	1.49
12	Toronto General Hospital	1.86	1.78	1.49	0	0	0	1.86	1.78	1.49	1.86	1.78	1.49	1.69	1.62	1.35
13	Peel Memorial Centre for Integrated Health and Wellness Site	1.94	1.86	1.55	1.86	1.78	1.49	0	0	0	1.86	1.78	1.49	1.86	1.78	1.49
14	Bridgepoint Hospital Site	1.86	1.78	1.49	1.86	1.78	1.49	1.86	1.78	1.49	0	0	0	1.86	1.78	1.49
15	Baycrest Hospital	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55	0	0	0
16	Mississauga Hospital Site	1.94	1.86	1.55	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.86	1.78	1.49
17	Salvation Army Toronto Grace Hospital	1.86	1.78	1.49	1.69	1.92	1.35	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35

No	Hospitals	Hospitals														
		Lakeridge Health Oshawa			Toronto General Hospital			Peel Memorial Centre for Integrated Health and Wellness Site			Bridgepoint Hospital Site			Baycrest Hospital		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
18	Toronto East Health Network - Michael Garron Hospital	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35
19	Mount Sinai Hospital Site	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35
20	West Park Healthcare Centre	1.86	1.78	1.49	1.69	1.62	1.35	1.86	1.78	1.49	1.94	1.86	1.55	1.69	1.62	1.35

No	Hospitals	Hospitals														
		Mississauga Hospital Site			Salvation Army Toronto Grace Hospital			Toronto East Health Network - Michael Garron Hospital			Mount Sinai Hospital Site			West Park Healthcare Centre		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
1	Credit Valley Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
2	Halton Healthcare Services	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.94	1.86	1.55	1.94	1.86	1.55
3	Hospital For Sick Children	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	1.69	1.62	1.35
4	Brampton Civic Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
5	Joseph Brant Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.94	1.86	1.55	1.94	1.86	1.55
6	MacKenzie Health	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
7	Markham-Stouffville Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
8	The Cottage Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
9	Southlake Regional Health Centre	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
10	Etobicoke General Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
11	Lakeridge Health Oshawa	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
12	Toronto General Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	1.69	1.62	1.35
13	Peel Memorial Centre for Integrated Health and Wellness Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
14	Bridgepoint Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49
15	Baycrest Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	1.69	1.62	1.35
16	Mississauga Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.86	1.78	1.49	1.86	1.78	1.49

No	Hospitals	Hospitals														
		Mississauga Hospital Site			Salvation Army Toronto Grace Hospital			Toronto East Health Network - Michael Garron Hospital			Mount Sinai Hospital Site			West Park Healthcare Centre		
		Shelf Life(m)														
		3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
17	Salvation Army Toronto Grace Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	1.69	1.62	1.35
18	Toronto East Health Network - Michael Garron Hospital	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	1.69	1.62	1.35
19	Mount Sinai Hospital Site	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	0	0	0	1.69	1.62	1.35
20	West Park Healthcare Centre	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.69	1.62	1.35	0	0	0

Table A.10-Transshipping cost between blood centers and hospitals *(Lagerquist et al,2017)*

Transshipping Cost Between Blood Centers and Hospitals($)																	
No.	Hospitals	Blood Centers															
		Richmond Hill Blood Center				Toronto Blood Center (College St.)				Toronto Blood Center (King St)				Toronto Blood Center (Young & Bloor)			
		Shelf Life(n)															
		2	3	4	5	2	3	4	5	2	3	4	5	2	3	4	5
1	Credit Valley Hospital Site	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
2	Halton Healthcare Services	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02
3	Hospital For Sick Children	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
4	Brampton Civic Hospital Site	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
5	Joseph Brant Hospital	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02
6	MacKenzie Health	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
7	Markham-Stouffville Hospital	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
8	The Cottage Hospital Site	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
9	Southlake Regional Health Centre	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
10	Etobicoke General Site	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
11	Lakeridge Health Oshawa	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
12	Toronto General Hospital	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
13	Peel Memorial Centre for Integrated Health and Wellness Site	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86

Transshipping Cost Between Blood Centers and Hospitals($)																	
No.	Hospitals	Blood Centers															
		Richmond Hill Blood Center				Toronto Blood Center (College St.)				Toronto Blood Center (King St)				Toronto Blood Center (Young & Bloor)			
		Shelf Life(n)															
		2	3	4	5	2	3	4	5	2	3	4	5	2	3	4	5
14	Bridgepoint Hospital Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
15	Baycrest Hospital	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
16	Mississauga Hospital Site	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
17	Salvation Army Toronto Grace Hospital	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
18	Toronto East Health Network - Michael Garron Hospital	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
19	Mount Sinai Hospital Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62
20	West Park Healthcare Centre	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62	2.1	2.03	1.94	1.62

Transshipping Cost Between Blood Centers and Hospitals($)													
No.	Hospitals	Blood Centers											
		Burlington Blood Center				Mississauga Blood Center				Oshawa Blood Center			
		Shelf Life(n)											
		2	3	4	5	2	3	4	5	2	3	4	5
1	Credit Valley Hospital Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.62	2.54	2.42	2.02
2	Halton Healthcare Services	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.62	2.54	2.42	2.02
3	Hospital For Sick Children	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
4	Brampton Civic Hospital Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.62	2.54	2.42	2.02
5	Joseph Brant Hospital	2.1	2.03	1.94	1.62	2.41	2.33	2.23	1.86	2.62	2.54	2.42	2.02
6	MacKenzie Health	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
7	Markham-Stouffville Hospital	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
8	The Cottage Hospital Site	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
9	Southlake Regional Health Centre	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
10	Etobicoke General Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.62	2.54	2.42	2.02
11	Lakeridge Health Oshawa	2.62	2.54	2.42	2.02	2.62	2.54	2.42	2.02	2.1	2.03	1.94	1.62
12	Toronto General Hospital	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
13	Peel Memorial Centre for Integrated Health and Wellness Site	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.62	2.54	2.42	2.02
14	Bridgepoint Hospital Site	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
15	Baycrest Hospital	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86

Transshipping Cost Between Blood Centers and Hospitals($)													
No.	**Hospitals**	**Blood Centers**											
		Burlington Blood Center				**Mississauga Blood Center**				**Oshawa Blood Center**			
		Shelf Life(n)											
		2	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**
16	**Mississauga Hospital Site**	2.41	2.33	2.23	1.86	2.1	2.03	1.94	1.62	2.62	2.54	2.42	2.02
17	**Salvation Army Toronto Grace Hospital**	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
18	**Toronto East Health Network - Michael Garron Hospital**	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
19	**Mount Sinai Hospital Site**	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86
20	**West Park Healthcare Centre**	2.62	2.54	2.42	2.02	2.41	2.33	2.23	1.86	2.41	2.33	2.23	1.86

Table A.11- Delivering Fresh Blood Cost from Blood Centers to Hospitals *(Lagerquist et al,2017)*

Delivering Cost from Blood Centers to Hospitals($)								
No.	**Hospitals**	**Blood Centers**						
		Richmond Hill Blood Center	**Toronto Blood Center (College St.)**	**Toronto Blood Center (King St)**	**Toronto Blood Center (Young & Bloor)**	**Burlington Blood Center**	**Mississauga Blood Center**	**Oshawa Blood Center**
		n=2	**n=2**	**n=2**	**n=2**	**n=2**	**n=2**	**n=2**
1	**Credit Valley Hospital Site**	2.41	2.41	2.41	2.41	2.41	2.1	2.62
2	**Halton Healthcare Services Corporation**	2.62	2.62	2.62	2.62	2.1	2.41	2.62
3	**Hospital For Sick Children**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
4	**Brampton Civic Hospital Site**	2.41	2.41	2.41	2.41	2.41	2.1	2.62
5	**Joseph Brant Hospital**	2.62	2.62	2.62	2.62	2.1	2.41	2.62
6	**MacKenzie Health**	2.1	2.41	2.41	2.41	2.62	2.41	2.41

Delivering Cost from Blood Centers to Hospitals($)								
No.	**Hospitals**	**Blood Centers**						
		Richmond Hill Blood Center	**Toronto Blood Center (College St.)**	**Toronto Blood Center (King St)**	**Toronto Blood Center (Young & Bloor)**	**Burlington Blood Center**	**Mississauga Blood Center**	**Oshawa Blood Center**
		n=2	**n=2**	**n=2**	**n=2**	**n=2**	**n=2**	**n=2**
7	**Markham-Stouffville Hospital**	2.1	2.41	2.41	2.41	2.62	2.41	2.41
8	**The Cottage Hospital Site**	2.1	2.41	2.41	2.41	2.62	2.41	2.41
9	**Southlake Regional Health Centre**	2.1	2.41	2.41	2.41	2.62	2.41	2.41
10	**Etobicoke General Site**	2.41	2.41	2.41	2.41	2.41	2.1	2.62
11	**Lakeridge Health Oshawa**	2.41	2.41	2.41	2.41	2.62	2.62	2.1
12	**Toronto General Hospital**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
13	**Peel Memorial Centre for Integrated Health and Wellness Site**	2.41	2.41	2.41	2.41	2.41	2.1	2.62
14	**Bridgepoint Hospital Site**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
15	**Baycrest Hospital**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
16	**Mississauga Hospital Site**	2.41	2.41	2.41	2.41	2.41	2.1	2.62
17	**Salvation Army Toronto Grace Hospital**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
18	**Toronto East Health Network - Michael Garron Hospital**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
19	**Mount Sinai Hospital Site**	2.41	2.1	2.1	2.1	2.62	2.41	2.41
20	**West Park Healthcare Centre**	2.41	2.1	2.1	2.1	2.62	2.41	2.41

Table A.12- Blood centers' holding cost *(Lagerquist et al,2017)*

No.	Blood Centers	Holding Cost($)
1	Richmond Hill Blood Center	28.18
2	Toronto Blood Center(College St.)	26.47
3	Toronto Blood Center(King St.)	26.47

No.	Blood Centers	Holding Cost($)
4	Toronto Blood Center(Young & Bloor)	26.47
5	Burlington Blood Center	26.04
6	Mississauga Blood Center	22.75
7	Oshawa Blood Center	25.71

Table A.13- Transshipping cost between mobile collection centers and blood centers *(Lagerquist et al,2017)*

No	Mobile Collection Centers	Blood Centers						
		Richmond Hill Blood Center	Toronto Blood Center (College St.)	Toronto Blood Center (King St.)	Toronto Blood Center (Young & Bloor)	Burlington Blood Center	Mississauga Blood Center	Oshawa Blood Center
1	Canadian Mar Thoma Church.	1.62	1.86	1.86	1.86	2.02	1.86	1.86
2	Uxbridge Seniors' Centre	1.86	1.86	1.86	1.86	2.02	2.02	1.62
3	Holiday Inn Express & Suites, Newmarket.	1.62	1.86	1.86	1.86	2.02	1.86	1.86
4	East Gwillimbury Sports Complex	1.62	1.86	1.86	1.86	2.02	1.86	1.86
5	The Church of St. Patrick – Markham	1.62	1.86	1.86	1.86	2.02	1.86	1.86
6	Aurora Legion	1.62	1.86	1.86	1.86	2.02	1.86	1.86
7	Newmarket Community Centre	1.62	1.86	1.86	1.86	2.02	1.86	1.86
8	Scugog Community Centre	1.86	1.86	1.86	1.86	2.02	2.02	1.62
9	St. Thomas' Anglican Church	1.86	1.86	1.86	1.86	2.02	2.02	1.62
10	York Region Administrative Centre	1.62	1.86	1.86	1.86	2.02	1.86	1.86
11	Pickering Recreation Complex - East Salon	1.86	1.86	1.86	1.86	2.02	2.02	1.62
12	Markham Convention Centre.	1.62	1.86	1.86	1.86	2.02	1.86	1.86

No	Mobile Collection Centers	Blood Centers						
		Richmond Hill Blood Center	Toronto Blood Center (College St.)	Toronto Blood Center (King St.)	Toronto Blood Center (Young & Bloor)	Burlington Blood Center	Mississauga Blood Center	Oshawa Blood Center

Table A.14- Vehicles' information

No.	Name	Fuel Efficiency (MPG)
1	2019 Ford Transit Van	16
2	2019 Ram Pro-Master Van	15.5
3	Kenworth T370	14

Table A.15-Vehicles' transshipment cost

No.	Name	Transshipment Cost ($/Km)
1	2019 Ford Transit Van	5.77
2	2019 Ram Pro-Master Van	5.60
3	Kenworth T370	5.05

Table A.16- Maximum available number of each vehicle

No.	Name	Maximum Available Number
1	2019 Ford Transit Van	12

2	2019 Ram Pro-Master Van	16
3	Kenworth T370	7

Table A.17- Distance between hospitals

No	Hospitals	Distance(Km)				
		Hospitals				
		Credit Valley Hospital Site	Halton Healthcare Services Corporation	Hospital For Sick Children	Brampton Civic Hospital Site	Joseph Brant
1	**Credit Valley Hospital Site**	0	19	35.3	39.7	32.5
2	**Halton Healthcare Services**	19.4	0	45.1	48.3	19.9
3	**Hospital For Sick Children**	36.2	48.1	0	47.4	59.1
4	**Brampton Civic Hospital Site**	30.2	47.8	47.4	0	61.3
5	**Joseph Brant Hospital**	33	20.9	59.9	61.8	0
6	**MacKenzie Health**	53.3	71.1	40	36.5	84.6
7	**Markham-Stouffville Hospital**	68.1	85.9	39.5	51.3	99.4
8	**The Cottage Hospital Site**	102	120	73.5	85.2	133
9	**Southlake Regional Health Centre**	84.3	102	55.5	67.5	166
10	**Etobicoke General Site**	29.6	45.6	30.9	18	66.1
11	**Lakeridge Health Oshawa**	89.9	106	63.1	87	135
12	**Toronto General Hospital**	36.8	48.6	0.7	47.9	59.5
13	**Peel Memorial Centre for Integrated Health and Wellness Site**	24.6	44	43.6	8.70	53.9
14	**Bridgepoint Hospital Site**	45.1	57	3.6	60.8	67.8
15	**Baycrest Hospital**	36.4	52.4	10	36.6	65.9
16	**Mississauga Hospital Site**	12.3	28.2	24.6	26.6	37.4
17	**Salvation Army Toronto Grace Hospital**	44.3	56.2	2.4	60	67.2
18	**Toronto East Health Network - Michael Garron Hospital**	46.5	58.4	8.3	57.1	69.3

No	Hospitals	Distance(Km)				
		Hospitals				
		Credit Valley Hospital Site	Halton Healthcare Services Corporation	Hospital For Sick Children	Brampton Civic Hospital Site	Joseph Brant
19	Mount Sinai Hospital Site	36.5	48.3	0.24	47.6	59.4
20	West Park Healthcare Centre	28	44	13.2	30.9	57.5

No	Hospitals	Distance(Km)				
		Hospitals				
		MacKenzie Health	Markham-Stouffville Hospital	The Cottage Hospital Site	Southlake Regional Health Centre	Etobicoke General Site
1	Credit Valley Hospital Site	62.5	66	101	81.8	44.4
2	Halton Healthcare Services	26.6	85.9	120	101	53
3	Hospital For Sick Children	29.9	39.4	74.5	55.1	31.9
4	Brampton Civic Hospital Site	35	49.8	84.3	65.3	16.9
5	Joseph Brant Hospital	84.6	99.4	133	114	66.6
6	MacKenzie Health	0	26	45.2	29.5	25.4
7	Markham-Stouffville Hospital	26.8	0	36.7	42.2	40.2
8	The Cottage Hospital Site	45.3	37.6	0	30.7	74.1
9	Southlake Regional Health Centre	30.5	38.7	30.6	0	56.4
10	Etobicoke General Site	25.4	40.2	74.1	55.1	0
11	Lakeridge Health Oshawa	59.9	39.4	40	77.9	75.9
12	Toronto General Hospital	34.7	38.1	72.2	53.3	31.6
13	Peel Memorial Centre for Integrated Health and Wellness Site	38.2	53	90.1	67.7	19.9
14	Bridgepoint Hospital Site	37.1	35.5	71.5	51.9	49.7
15	Baycrest Hospital	36.7	31.2	67.2	46.8	17.2
16	Mississauga Hospital Site	49.3	62.3	98	79	20.6
17	Salvation Army Toronto Grace Hospital	32.6	34.7	70.7	51.1	48.9
18	Toronto East Health Network - Michael Garron Hospital	37.7	33.6	67.7	48.2	46
19	Mount Sinai Hospital Site	36.4	36.9	72.8	53.3	31.4

No	Hospitals	Distance(Km)				
		Hospitals				
		MacKenzie Health	Markham-Stouffville Hospital	The Cottage Hospital Site	Southlake Regional Health Centre	Etobicoke General Site
20	West Park Healthcare Centre	38.1	41.5	75.4	56.3	12.8

No	Hospitals	Distance(Km)				
		Hospitals				
		Lakeridge Health Oshawa	Toronto General Hospital	Peel Memorial Centre for Integrated Health and Wellness Site	Bridgepoint Hospital Site	Baycrest Hospital
1	Credit Valley Hospital Site	103	44.2	35.1	46.8	36.1
2	Halton Healthcare Services	122	48.1	43.8	51	50.8
3	Hospital For Sick Children	63.2	0.75	43.1	3.2	10.6
4	Brampton Civic Hospital Site	86.1	47.4	8.8	50	36.2
5	Joseph Brant Hospital	120	59.8	57.3	62.7	86
6	MacKenzie Health	61.7	40	42.8	35.5	30.7
7	Markham-Stouffville Hospital	38.5	39.2	57.6	38.7	31.8
8	The Cottage Hospital Site	39.1	73.2	91.5	69.8	65.7
9	Southlake Regional Health Centre	77.6	55.1	73.8	54.7	47.7
10	Etobicoke General Site	75.9	30.9	24.3	33.5	18.3
11	Lakeridge Health Oshawa	0	63.4	93.3	54.3	67.5
12	Toronto General Hospital	60.9	0	43.4	2.9	10.6
13	Peel Memorial Centre for Integrated Health and Wellness Site	91.8	43.6	0	46.2	39.5

No	Hospitals	Distance(Km)				
		Hospitals				
		Lakeridge Health Oshawa	Toronto General Hospital	Peel Memorial Centre for Integrated Health and Wellness Site	Bridgepoint Hospital Site	Baycrest Hospital
14	Bridgepoint Hospital Site	60.2	3	67.1	0	14.3
15	Baycrest Hospital	55.9	10.6	42.9	14.1	0
16	Mississauga Hospital Site	83.2	24.5	22.1	27	30.6
17	Salvation Army Toronto Grace Hospital	59.4	1.9	66.3	3.9	9.7
18	Toronto East Health Network - Michael Garron Hospital	56.4	7.7	63.4	5	20.6
19	Mount Sinai Hospital Site	61.5	0.7	43.7	3.1	11
20	West Park Healthcare Centre	65.9	13.5	26.4	20.2	13.2

No	Hospitals	Distance(Km)				
		Hospitals				
		Mississauga Hospital Site	Salvation Army Toronto Grace Hospital	Toronto East Health Network - Michael Garron Hospital	Mount Sinai Hospital Site	West Park Healthcare Centre
1	Credit Valley Hospital Site	12.1	37.3	46.1	35.1	27
2	Halton Healthcare Services	25.9	49.4	58.5	47.5	44.4
3	Hospital For Sick Children	24.8	2.4	12.9	0.25	17.1
4	Brampton Civic Hospital Site	26.3	49	56.5	46.8	29.8
5	Joseph Brant Hospital	37.6	61.5	70.3	59.8	57.9
6	MacKenzie Health	49.2	34.3	32	39.7	27
7	Markham-Stouffville Hospital	64	37.5	32.4	40	41.8
8	The Cottage Hospital Site	97.9	71.5	66.3	73.4	75.7
9	Southlake Regional Health Centre	80.1	53.5	48.3	55.5	58
10	Etobicoke General Site	22.3	32.5	41.3	30.6	13.5

No	Hospitals	Distance(Km)				
		Hospitals				
		Mississauga Hospital Site	Salvation Army Toronto Grace Hospital	Toronto East Health Network - Michael Garron Hospital	Mount Sinai Hospital Site	West Park Healthcare Centre
11	**Lakeridge Health Oshawa**	84	60.8	68.1	56.9	77.5
12	**Toronto General Hospital**	25.3	1.8	7.5	0.45	17.6
13	**Peel Memorial Centre for Integrated Health and Wellness Site**	22.5	45.2	54	42	25.2
14	**Bridgepoint Hospital Site**	33.7	3.9	5.3	3	25.9
15	**Baycrest Hospital**	30.6	9.8	13.5	10.4	12.3
16	**Mississauga Hospital Site**	0	26.3	35.1	23.8	21.4
17	**Salvation Army Toronto Grace Hospital**	32.8	0	6	2.4	12.1
18	**Toronto East Health Network - Michael Garron Hospital**	35.1	6	0	7.9	31.3
19	**Mount Sinai Hospital Site**	25	2.3	8.2	0	17.3
20	**West Park Healthcare Centre**	21.5	12.9	28	13	0

Table A.18- Distance between blood centers and hospitals

No	Hospitals	Distance(Km)						
		Hospitals						
		Richmond Hill Blood Center	Toronto Blood Center (College St.)	Toronto Blood Center (King St.)	Toronto Blood Center (Young& Bloor)	Burlington Blood Center	Mississauga Blood Center	Oshawa Blood Center
1	**Credit Valley Hospital Site**	51.1	44.2	33.9	36.8	30.1	8.3	104
2	**Halton Healthcare Services**	70.1	48	46.3	49.2	17.5	27.9	123
3	**Hospital For Sick Children**	34.2	1	1.6	2.1	55.5	36.4	77.5
4	**Brampton Civic Hospital Site**	34.6	47.3	45.6	55.7	58.9	21.4	87.6
5	**Joseph Brant Hospital**	83.6	59.8	58.1	68.2	4.3	40.6	137
6	**MacKenzie Health**	2.9	38.1	40.2	36.5	82.2	44.5	63.1

No	Hospitals	Distance(Km)						
		Hospitals						
		Richmond Hill Blood Center	Toronto Blood Center (College St.)	Toronto Blood Center (King St.)	Toronto Blood Center (Young& Bloor)	Burlington Blood Center	Mississauga Blood Center	Oshawa Blood Center
7	**Markham-Stouffville Hospital**	21.6	38.5	40.6	36.9	97	59.3	39.9
8	**The Cottage Hospital Site**	55.6	72.4	74.5	70.8	131	93.2	40.5
9	**Southlake Regional Health Centre**	31.4	54.4	56.5	52.8	113	75.5	79.1
10	**Etobicoke General Site**	24.4	30.9	29.2	39.3	49.2	21.5	77.4
11	**Lakeridge Health Oshawa**	57.4	61.9	63.9	60.3	113	95	5.7
12	**Toronto General Hospital**	31.9	0.14	2.5	1.5	55.7	37.1	66.1
13	**Peel Memorial Centre for Integrated Health and Wellness Site**	40.2	43.5	41.8	51.9	55.1	17.6	93.3
14	**Bridgepoint Hospital Site**	31.2	2.9	4.8	3.9	64.4	45.2	65.4
15	**Baycrest Hospital**	15.9	10.2	12.1	9.2	63.4	28.6	61.1
16	**Mississauga Hospital Site**	47.4	24.6	22.9	26.6	33.9	10.3	96.1
17	**Salvation Army Toronto Grace Hospital**	30.4	1.6	4.20	0.3	57.4	44.4	64.6
18	**Toronto East Health Network - Michael Garron Hospital**	27.4	7.4	13.2	6.20	65.8	46.6	70.8
19	**Mount Sinai Hospital Site**	32.4	0.55	2.10	2	55.8	21.4	68.6
20	**West Park Healthcare Centre**	25.7	17.6	15.9	12.2	55.1	19.9	78.6

Appendix B

Table B.1- US Blood Centers' Inventory Level

No.	Blood Center	Time																											
		1				**2**				**3**				**4**				**5**				**6**				**7**			
		Shelf Life(Days)																											
		2	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**
1	**MI**	227	124	41	21	205	112	37	19	250	136	45	23	273	149	50	25	307	168	56	28	182	194	33	17	148	81	27	13
2	**OH**	266	145	48	24	240	131	44	22	293	160	53	27	319	174	58	29	359	196	65	33	213	127	39	19	173	94	31	16
3	**PA**	291	159	53	26	262	143	48	24	320	175	58	29	349	191	64	32	393	214	71	36	233	116	42	21	189	103	34	17
4	**NY**	444	242	81	40	400	218	73	36	489	267	89	44	533	291	97	48	600	327	109	55	356	99	65	32	289	158	53	26

Table B.2- Total Cost of Delivering Blood Units from US to Canada (Forbes, 1991)

Shelf Life (Days)	Cost($)
2	298
3	223
4	186
5	155

Appendix C

```
IS.fx(i,m,"1")=B1(i,m);
INVS.fx(k,n,"1")=CAP1(k,n);
ES.fx(k,"2",i,t)=0;
obj .. L=e=sum((k,n,i,t)$(ord(n)>=2),ES(k,n,i,t)*CE(k,n,i))+sum((k,i,t),Z(k,i,t)»
*SN(k,i))+sum((k,t),HB(k)*FV(k,t))+sum((k,t),CW*DW(k,t))+sum((i,m,j,t)$(ord(i) n»
e ord(j)),C(i,m,j)*X(i,m,j,t))+sum((i,t),H(i)*V(i,t))+sum((i,t),E*SIGMA(i,t))+su»
m((i,t),G*F(i,t))+sum((i,t),SEF*Y(i,t))+sum((r,k,t),TES*HJM(r,k,t))+sum((k,t),TE»
S*DON(k,t))+sum((k,i,p,t),LB(k,i)*VC(p)*BTH(k,i,p,t))+sum((i,j,p,t)$(ord(i)ne or»
d(j)),LH(i,j)*VC(p)*HTH(i,j,p,t));
cons1(i,m,n,t)$((ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(j,»
m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=e=IE(i,»
m,t);
cons2(i,t) .. sum(m,a(i,m,t))+F(i,t)=e=D2(i,t);
cons3(k,n,t)$(ord(n)>=2) .. sum(i,ES(k,n,i,t))=l=INVS(k,n,t);
cons4(k,n,t)$(ord(n)=1)  .. sum(i,Z(k,i,t))=l=INVS(k,n,t);
cons5(i,m,t) .. sum(j$(ord(i) ne ord(j)),X(i,m,j,t))=l=IS(i,m,t);
cons6(k,n,t)$(ord(n)>=2) .. INVS(k,n,t)-sum(i,ES(k,n,i,t))=e=INVE(k,n,t);
cons7(k,n,t)$(ord(n)=1) .. INVS(k,n,t)-sum(i,Z(k,i,t))=e=INVE(k,n,t);
cons8(k,n,t)$(ord(n)<>4 and ord(t)<>7) .. INVE(k,n,t)=e=INVS(k,n+1,t+1);
cons9(k,t) .. sum(n$(ord(n)<>4),INVE(k,n,t))=e=FV(k,t);
cons10(k,t,n)$(ord(n)=4) .. DW(k,t)=e=INVE(k,n,t);
cons11(i,t) .. sum(m$(ord(m)<>3),IE(i,m,t))=e=V(i,t);
cons12(i,t,m)$(ord(m)=3) .. SIGMA(i,t)=e=IE(i,m,t);
cons13(i,t,m)$(ord(t)<>7 and ord(m)<>3) .. IE(i,m,t)=e=IS(i,m+1,t+1);
cons14(i,m,t)$(ord(m)=1) .. Y(i,t)=e=IS(i,m,t+1);
cons15(i,t) .. Y(i,t)=e=sum(k,Z(k,i,t));
cons16(i,t) .. S(i,t)-sum(m,IS(i,m,t))=e=Y(i,t);
cons17(k,n,t)$(ord(n)=1) .. INVS(k,n,t+1)=e=(1-TETA)*(sum(r,HJM(r,k,t))+DON(k,t)»
);
cons18(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))=»
g=BETA*F(i,t);
cons19(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))=»
L=F(i,t);
cons20(r,t) .. sum(k,HJM(r,k,t))=l=ZAR(r)*OP(r,t);
cons21(t) .. sum(r,OP(r,t))=l=HAD;
cons22(k,t) .. DON(k,t)=l=SAN(k);
cons23(i,t)$(ord(t)<>7) .. S(i,t+1)=g=(1-beta)*F(i,t);
cons24(i,t)$(ord(t)<>7) .. S(i,t+1)=l=D2(i,t);
cons25(i,t) .. S(i,t)=g=(1-beta)*D2(i,t);
cons26 .. KF=e=sum((i,t),F(i,t));
cons27(p,t) .. sum((k,i),BTH(k,i,p,t))+sum((i,j)$(ord(i) ne ord(j)),HTH(i,j,p,t)»
)=e=MAX(p);
cons28(k,t) .. EZ(k,t)=e=sum((i,n)$(ord(n)>=2),ES(k,n,i,t));
cons30(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=EZ(k,t);
cons31(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=INVS(k,n,t);
cons32(k,t,n)$(ord(n)=4)..  EZ(k,t)-MIZ(k,n,t)=l=MP*b(k,n,t);
cons33(k,t,n)$(ord(n)=4).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t));
cons34(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=EZ(k,t)-MIZ(k,n+1,t);
cons35(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=INVS(k,n,t);
cons36(k,t,n)$(ord(n)>=2 and ord(n)<=3).. EZ(k,t)-MIZ(k,n+1,t)-MIZ(k,n,t)=l=MP*b»
(k,n,t);
cons37(k,t,n)$(ord(n)>=2 and ord(n)<=3).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t»
));
cons38(i,t,m)$(ord(m)=3) .. a(i,m,t)=l=D2(i,t);
cons39(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. a(i,m,t)=l=IS(i,m,t)+sum(j$(ord(i) ne»
 ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t));
```

Figure C.1-Primary Model’s Code

```
cons40(i,t,m)$(ord(m)=3) .. (D2(i,t))-a(i,m,t)=l=MP*gb(i,m,t);
cons41(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(»
j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=l=MP»
*(1-gb(i,m,t));
cons42(i,t,m)$(ord(m)<=2) .. a(i,m,t)=l=(D2(i,t))-a(i,m+1,t);
cons43(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. a(i,m,t)=l=IS(i,m,t)+su»
m(j$(ord(i) ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES»
(k,n,i,t));
cons44(i,t,m)$(ord(m)<=2) .. (D2(i,t))-a(i,m+1,t)-a(i,m,t)=l=MP*gb(i,m,t);
cons45(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) »
ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a»
(i,m,t)=l=MP*(1-gb(i,m,t));
cons46 .. tagh=e=sum((i,t),d2(i,t));
model thesis /all/;
solve thesis using MIP minimising L;
loop((r,t),
if(sum(k,HJM.l(r,k,t))>=1,
OP.l(r,t)=1));
loop((r,t),
if(sum(k,HJM.l(r,k,t))=0,
OP.l(r,t)=0));
display L.l,Y.l,sigma.l,S.l,IS.L,IE.L,A.L,F.L,V.L,X.L,ES.L,Z.L,FV.L,DW.L,INVS.L,»
INVE.L,HJM.L,DON.L,KF.l,BTH.L,HTH.L,op.l,es.l,MIZ.l,tagh.l;
```

Figure C.2-Primary Model’s Code

```
IS.fx(i,m,"1")=B1(i,m);
INVS.fx(k,n,"1")=CAP1(k,n);
ES.fx(k,"2",i,t)=0;
obj .. L=e=sum((k,n,i,t)$(ord(n)>=2),ES(k,n,i,t)*CE(k,n,i))+sum((k,i,t),Z(k,i,t)»
*SN(k,i))+sum((k,t),HB(k)*FV(k,t))+sum((k,t),CW*DW(k,t))+sum((i,m,j,t)$(ord(i) n»
e ord(j)),C(i,m,j)*X(i,m,j,t))+sum((i,t),H(i)*V(i,t))+sum((i,t),E*SIGMA(i,t))+su»
m((i,t),G*F(i,t))+sum((i,t),SEF*Y(i,t))+sum((r,k,t),TES*HJM(r,k,t))+sum((k,t),TE»
S*DON(k,t))+sum((k,i,p,t),LB(k,i)*VC(p)*BTH(k,i,p,t))+sum((i,j,p,t)$(ord(i)ne or»
d(j)),LH(i,j)*VC(p)*HTH(i,j,p,t))+sum((q,i,n,t),kom(q,i,n,t)*has(n));
cons1(i,m,n,t)$((ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(j,»
m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=e=IE(i,»
m,t);
cons2(i,t) .. sum(m,a(i,m,t))+F(i,t)=e=D2(i,t);
cons3(k,n,t)$(ord(n)>=2) .. sum(i,ES(k,n,i,t))=l=INVS(k,n,t);
cons4(k,n,t)$(ord(n)=1)  .. sum(i,Z(k,i,t))=l=INVS(k,n,t);
cons5(i,m,t) .. sum(j$(ord(i) ne ord(j)),X(i,m,j,t))=l=IS(i,m,t);
cons6(k,n,t)$(ord(n)>=2) .. INVS(k,n,t)-sum(i,ES(k,n,i,t))=e=INVE(k,n,t);
cons7(k,n,t)$(ord(n)=1) .. INVS(k,n,t)-sum(i,Z(k,i,t))=e=INVE(k,n,t);
cons8(k,n,t)$(ord(n)<>4 and ord(t)<>7) .. INVE(k,n,t)=e=INVS(k,n+1,t+1);
cons9(k,t) .. sum(n$(ord(n)<>4),INVE(k,n,t))=e=FV(k,t);
cons10(k,t,n)$(ord(n)=4) .. DW(k,t)=e=INVE(k,n,t);
cons11(i,t) .. sum(m$(ord(m)<>3),IE(i,m,t))=e=V(i,t);
cons12(i,t,m)$(ord(m)=3) .. SIGMA(i,t)=e=IE(i,m,t);
cons13(i,t,m)$(ord(t)<>7 and ord(m)<>3) .. IE(i,m,t)=e=IS(i,m+1,t+1);
cons14(i,m,t)$(ord(m)=1) .. Y(i,t)=e=IS(i,m,t+1);
cons15(i,n,t)$(ord(n)=1) .. Y(i,t)=e=sum(k,Z(k,i,t))+sum(q,kom(q,i,n,t));
cons16(i,t) .. S(i,t)-sum(m,IS(i,m,t))=e=Y(i,t);
cons17(k,n,t)$(ord(n)=1) .. INVS(k,n,t+1)=e=(1-TETA)*(sum(r,HJM(r,k,t))+DON(k,t)»
);
cons18(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))+»
sum((q,n)$(ord(n)>=2),kom(q,i,n,t))=g=BETA*F(i,t);
cons19(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))+»
sum((q,n)$(ord(n)>=2),kom(q,i,n,t))=L=F(i,t);
cons20(r,t) .. sum(k,HJM(r,k,t))=l=ZAR(r)*OP(r,t);
cons21(t) .. sum(r,OP(r,t))=l=HAD;
cons22(k,t) .. DON(k,t)=l=SAN(k);
cons23(i,t)$(ord(t)<>7) .. S(i,t+1)=g=(1-beta)*F(i,t);
cons24(i,t)$(ord(t)<>7) .. S(i,t+1)=l=D2(i,t);
cons25(i,t)$(ord(t)<>7) .. S(i,t)=g=(1-beta)*D2(i,t);
cons26(t) .. KF(t)=e=sum(i,F(i,t));
cons27(p,t) .. sum((k,i),BTH(k,i,p,t))+sum((i,j)$(ord(i) ne ord(j)),HTH(i,j,p,t)»
)=e=MAX(p);
cons28(k,t) .. EZ(k,t)=e=sum((i,n)$(ord(n)>=2),ES(k,n,i,t));
cons30(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=EZ(k,t);
cons31(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=INVS(k,n,t);
cons32(k,t,n)$(ord(n)=4)..  EZ(k,t)-MIZ(k,n,t)=l=MP*b(k,n,t);
cons33(k,t,n)$(ord(n)=4).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t));
cons34(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=EZ(k,t)-MIZ(k,n+1,t);
cons35(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=INVS(k,n,t);
cons36(k,t,n)$(ord(n)>=2 and ord(n)<=3).. EZ(k,t)-MIZ(k,n+1,t)-MIZ(k,n,t)=l=MP*b»
(k,n,t);
cons37(k,t,n)$(ord(n)>=2 and ord(n)<=3).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t»
));
cons38(i,t,m)$(ord(m)=3) .. a(i,m,t)=l=D2(i,t);
cons39(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. a(i,m,t)=l=IS(i,m,t)+sum(j$(ord(i) ne»
 ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t));
```

Figure C.3- Updated Model's Code(Commercial)

```
cons40(i,t,m)$(ord(m)=3) .. (D2(i,t))-a(i,m,t)=l=MP*gb(i,m,t);
cons41(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(»
j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=l=MP»
*(1-gb(i,m,t));
cons42(i,t,m)$(ord(m)<=2) .. a(i,m,t)=l=(D2(i,t))-a(i,m+1,t);
cons43(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. a(i,m,t)=l=IS(i,m,t)+su»
m(j$(ord(i) ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES»
(k,n,i,t));
cons44(i,t,m)$(ord(m)<=2) .. (D2(i,t))-a(i,m+1,t)-a(i,m,t)=l=MP*gb(i,m,t);
cons45(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) »
ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a»
(i,m,t)=l=MP*(1-gb(i,m,t));
cons46(q,n,t)..sum(i,kom(q,i,n,t))=l=amca(q,n,t);
cons47 .. komak=e=sum((q,i,n,t),kom(q,i,n,t))
model thesis /all/;
solve thesis using MIP minimising L;
loop((r,t),
if(sum(k,HJM.l(r,k,t))>=1,
OP.l(r,t)=1));
loop((r,t),
if(sum(k,HJM.l(r,k,t))=0,
OP.l(r,t)=0));
display L.l,Y.l,sigma.l,S.l,IS.L,IE.L,A.L,F.L,V.L,X.L,ES.L,Z.L,FV.L,DW.L,INVS.L,»
INVE.L,HJM.L,DON.L,KF.l,BTH.L,HTH.L,op.l,es.l,MIZ.l,kom.l,komak.l;
display D2;
```

Figure C.4- Updated Model’s Code(Commercial)

```
INVS.fx(k,n,"1")=CAP1(k,n);
ES.fx(k,"2",i,t)=0;
obj .. L=e=sum((k,n,i,t)$(ord(n)>=2),ES(k,n,i,t)*CE(k,n,i))+sum((k,i,t),Z(k,i,t)»
*SN(k,i))+sum((k,t),HB(k)*FV(k,t))+sum((k,t),CW*DW(k,t))+sum((i,m,j,t)$(ord(i) n»
e ord(j)),C(i,m,j)*X(i,m,j,t))+sum((i,t),H(i)*V(i,t))+sum((i,t),E*SIGMA(i,t))+su»
m((i,t),G*F(i,t))+sum((i,t),SEF*Y(i,t))+sum((r,k,t),TES*HJM(r,k,t))+sum((k,t),TE»
S*DON(k,t))+sum((k,i,p,t),LB(k,i)*VC(p)*BTH(k,i,p,t))+sum((i,j,p,t)$(ord(i)ne or»
d(j)),LH(i,j)*VC(p)*HTH(i,j,p,t));
cons1(i,m,n,t)$((ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(j,»
m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=e=IE(i,»
m,t);
cons2(i,t) .. sum(m,a(i,m,t))+F(i,t)=e=D2(i,t);
cons3(k,n,t)$(ord(n)>=2) .. sum(i,ES(k,n,i,t))=l=INVS(k,n,t);
cons4(k,n,t)$(ord(n)=1)  .. sum(i,Z(k,i,t))=l=INVS(k,n,t);
cons5(i,m,t) .. sum(j$(ord(i) ne ord(j)),X(i,m,j,t))=l=IS(i,m,t);
cons6(k,n,t)$(ord(n)>=2) .. INVS(k,n,t)-sum(i,ES(k,n,i,t))=e=INVE(k,n,t);
cons7(k,n,t)$(ord(n)=1) .. INVS(k,n,t)-sum(i,Z(k,i,t))=e=INVE(k,n,t);
cons8(k,n,t)$(ord(n)<>4 and ord(t)<>7) .. INVE(k,n,t)=e=INVS(k,n+1,t+1);
cons9(k,t) .. sum(n$(ord(n)<>4),INVE(k,n,t))=e=FV(k,t);
cons10(k,t,n)$(ord(n)=4) .. DW(k,t)=e=INVE(k,n,t);
cons11(i,t) .. sum(m$(ord(m)<>3),IE(i,m,t))=e=V(i,t);
cons12(i,t,m)$(ord(m)=3) .. SIGMA(i,t)=e=IE(i,m,t);
cons13(i,t,m)$(ord(t)<>7 and ord(m)<>3) .. IE(i,m,t)=e=IS(i,m+1,t+1);
cons14(i,m,t)$(ord(m)=1) .. Y(i,t)=e=IS(i,m,t+1);
cons15(i,n,t)$(ord(n)=1) .. Y(i,t)=e=sum(k,Z(k,i,t))+sum(q,kom(q,i,n,t));
cons16(i,t) .. S(i,t)-sum(m,IS(i,m,t))=e=Y(i,t);
cons17(k,n,t)$(ord(n)=1) .. INVS(k,n,t+1)=e=(1-TETA)*(sum(r,HJM(r,k,t))+DON(k,t)»
);
cons18(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))+»
sum((q,n)$(ord(n)>=2),kom(q,i,n,t))=g=BETA*F(i,t);
cons19(i,t) .. sum((j,m)$(ord(i) ne ord(j)),X(j,m,i,t))+sum((k,n),ES(k,n,i,t))+»
sum((q,n)$(ord(n)>=2),kom(q,i,n,t))=L=F(i,t);
cons20(r,t) .. sum(k,HJM(r,k,t))=l=ZAR(r)*OP(r,t);
cons21(t) .. sum(r,OP(r,t))=l=HAD;
cons22(k,t) .. DON(k,t)=l=SAN(k);
cons23(i,t)$(ord(t)<>7) .. S(i,t+1)=g=(1-beta)*F(i,t);
cons24(i,t)$(ord(t)<>7) .. S(i,t+1)=l=D2(i,t);
cons25(i,t)$(ord(t)<>7) .. S(i,t)=g=(1-beta)*D2(i,t);
cons26(t) .. KF(t)=e=sum(i,F(i,t));
cons27(p,t) .. sum((k,i),BTH(k,i,p,t))+sum((i,j)$(ord(i) ne ord(j)),HTH(i,j,p,t)»
)=e=MAX(p);
cons28(k,t) .. EZ(k,t)=e=sum((i,n)$(ord(n)>=2),ES(k,n,i,t));
cons30(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=EZ(k,t);
cons31(k,t,n)$(ord(n)=4).. MIZ(k,n,t)=l=INVS(k,n,t);
cons32(k,t,n)$(ord(n)=4)..  EZ(k,t)-MIZ(k,n,t)=l=MP*b(k,n,t);
cons33(k,t,n)$(ord(n)=4).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t));
cons34(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=EZ(k,t)-MIZ(k,n+1,t);
cons35(k,t,n)$(ord(n)>=2 and ord(n)<=3).. MIZ(k,n,t)=l=INVS(k,n,t);
cons36(k,t,n)$(ord(n)>=2 and ord(n)<=3).. EZ(k,t)-MIZ(k,n+1,t)-MIZ(k,n,t)=l=MP*b»
(k,n,t);
cons37(k,t,n)$(ord(n)>=2 and ord(n)<=3).. INVS(k,n,t)-MIZ(k,n,t)=l=MP*(1-b(k,n,t»
));
cons38(i,t,m)$(ord(m)=3) .. a(i,m,t)=l=D2(i,t);
cons39(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. a(i,m,t)=l=IS(i,m,t)+sum(j$(ord(i) ne»
 ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t));
cons40(i,t,m)$(ord(m)=3) .. (D2(i,t))-a(i,m,t)=l=MP*gb(i,m,t);
```

Figure C.5- Updated Model’s Code(Non-Profit)

```
cons41(i,t,m,n)$(ord(m)=3 and ord(n)=4) .. IS(i,m,t)+sum(j$(ord(i) ne ord(j)),X(»
j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a(i,m,t)=l=MP»
*(1-gb(i,m,t));
cons42(i,t,m)$(ord(m)<=2) .. a(i,m,t)=l=(D2(i,t))-a(i,m+1,t);
cons43(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. a(i,m,t)=l=IS(i,m,t)+su»
m(j$(ord(i) ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES»
(k,n,i,t));
cons44(i,t,m)$(ord(m)<=2) .. (D2(i,t))-a(i,m+1,t)-a(i,m,t)=l=MP*gb(i,m,t);
cons45(i,t,m,n)$(ord(m)<=2 and (ord(m)+1) eq ord(n)) .. IS(i,m,t)+sum(j$(ord(i) »
ne ord(j)),X(j,m,i,t))-sum(j$(ord(i) ne ord(j)),X(i,m,j,t))+sum(k,ES(k,n,i,t))-a»
(i,m,t)=l=MP*(1-gb(i,m,t));
cons46(q,n,t)..sum(i,kom(q,i,n,t))=l=amca(q,n,t);
cons47 .. komak=e=sum((q,i,n,t),kom(q,i,n,t))
model thesis /all/;
solve thesis using MIP minimising L;
loop((r,t),
if(sum(k,HJM.l(r,k,t))>=1,
OP.l(r,t)=1));
loop((r,t),
if(sum(k,HJM.l(r,k,t))=0,
OP.l(r,t)=0));
display L.l,Y.l,sigma.l,S.l,IS.L,IE.L,A.L,F.L,V.L,X.L,ES.L,Z.L,FV.L,DW.L,INVS.L,»
INVE.L,HJM.L,DON.L,KF.l,BTH.L,HTH.L,op.l,es.l,MIZ.l,kom.l,komak.l;
display D2;
```

Figure C.6- Updated Model’s Code(Non-Profit)

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