BLOOD PLATELET BANK INVENTORY MANAGEMENT: AN APPROXIMATE DYNAMIC PROGRAMMING APPROACH

By

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A dissertation
presented to Ryerson University in partial
fulfillment of the requirements for the degree
of Doctor of Philosophy in the Program of
Mechanical and Industrial Engineering

Toronto, Ontario, Canada, 2015

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Approximate Dynamic Programming Model for Blood Platelets Inventory Problems

Doctor of Philosophy in Mechanical and Industrial Engineering (2015)
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Abstract

Blood platelets are precious and highly perishable; their supply and demand suffer from significant variation. Consequently, the inventory management of platelets is an actual, contemporary problem of considerable human interest. Although many researchers have solved a plethora of inventory models, their solutions have faced various challenges. This dissertation models some of these challenges, alongside expenses and stock levels. This dissertation is based on four key objectives: (1) to develop a blood platelet inventory model that can represent an actual blood bank inventory, while overcoming the problem's curse of dimensionality; (2) to look for the best issuing policy based on the proposed model that can serve different incoming blood platelet demands; (3) to analyze the effect of having a new, artificial blood platelet alongside the existing natural eight blood types; and (4) to enhance the proposed model for a dual-supplied regional blood platelet bank that serves a network of hospitals. Blood platelet inventory management model is a multi-period, multi-product model that considers the eight natural blood types with uncertain demand, and deterministic lead times, alongside the artificial platelet and patients right to refuse it.

The study is supported by both a review of literature and a testing data provided by the Canadian Blood Service. The findings show that modeling blood platelet inventory management, including the eight blood types and their ages, represents the actual-life model without any need for downsizing. It also leads to significantly reductions in shortages and outdates while increasing reward gained and maintaining minimal inventory levels. Compared to a single supply model, the dual supply model give less shortage and outdate rates. The regional blood bank inventory model considers the fact that patients have the right to refuse transfusion using artificial blood platelets. Finally, if the percentage of artificial supply in the inventory is more than 30% and the rate of patient acceptance is more than 30%, then both outdate and shortage percentages are below 1%.

Acknowledgements

Working as a PhD student at Ryerson University was a challenging and enthusiastic journey. During my PhD journey I met many brilliant and inspiring people who supported, encouraged and influenced me to reach my goals. I would like to thank those who helped me and made this part of my life a pleasant and a rich experience for me.

First, I am grateful to Dr. Mohammed Wahab Mohammed Ismail for enthusiastically supporting my work, sharing his knowledge, and guiding me throughout the program.

I am also thankful to the program director Dr. A. Ghasempoor for providing support, as well as to the members of my internal defense committee; Dr. C. Searcy and Dr. L. Fang, for providing valuable input to my research. I also thank the Ryerson MIE administrative staff for their valuable assistance.

In addition, my gratitude goes to Maha Farsi, my better half, for wholeheartedly supporting me in this endeavor. Special acknowledgments go to my brothers Dr. Sami and Dr. Ahmed, who were catalysts to my completion of this program.

Dedicated to the most wonderful people in my life:

Mom and Dad

Saleh Alabdulwahab

Fatima Mokhtar

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Nomenclature

i Blood platelet types removed from the inventory to serve demand, where i = 1, 2, . . . , 8, for AB-, AB+, A-, A+, B-, B+, O-, and O+, respectively; Blood type θ is indicated by nine.

j Blood platelet age, $j = 1, 2, \ldots, 6$, where one indicates new blood platelets and more than six means the blood platelets can no longer be used.

k Requested blood platelet types that are served by blood platelet types in the inventory, where $k = 1, 2, \ldots, 8$, for 1 = AB+, 2 = AB-, 3 = A+, 4 = A-, 5 = B+, 6 = B-, 7 = O+, and 8 = O-.

t Given day in a year; the process runs daily for a year, where $t = 1, 2, \ldots, 365$, then is repeated again for n years.

C_d Reward per dose of blood platelets used to satisfy the demand that don't match the type ordered, except θ.

C_g Penalty for each unit of outdated blood platelets.

C_h Penalty per day for holding one unit of blood platelets.

C_r Reward per dose of blood platelets used to satisfy the demand that match the blood type ordered.

C_u Penalty for failing to satisfy demand for each unit of blood platelets.

C_θ Reward per dose of artificial blood platelets used to satisfy the demand with artificial blood platelets.

$C_{\bar{\theta}}$ Penalty for refusing the assigned artificial platelets and replacing them with natural ones.

D_{92t} All unused artificial blood platelets (where 9 represents θ blood platelets) at the conclusion of day t are considered outdated and removed from the inventory.

D_{i6t} Blood platelets of type i with age $j > 6$ removed from inventory at the beginning of day t.

I_{ijt} Available inventory when day t commences; I_t^1 is the total beginning inventory for day $t = 1$, I_t^n is the total inventory on day t at replication n, where $I_t = \sum_i \sum_j I_{ijt}$.

I_t^x Daily inventory after updating it with the actual demand at the conclusion of day t.

n Replications per year, where $n = 1, 2, \ldots, 200$.

N_i Maximum inventory capacity for blood platelet type i.

p_{91t} Incoming artificial blood platelets, which are type θ (where blood type θ is indicated by nine) with age $j = 1$ received when day t commences.

p_{i1t} Donation of blood type i with age $j = 1$ received at the beginning of day t, plus donation received due to refusal of artificial blood platelets, where $i = 1, 2, \ldots, 8$.

Q_{it} Order-up-to level when day t begins, calculated using a newsvendor model.

u_t The total unsatisfied demand at the end of day t.

x_{91t} Total number of accepted artificial blood platelet doses (where blood type is indicated by nine) removed from inventory to satisfy part of y_t demand during day t.

x_{ijt} Amount of blood platelets units which are i type with age j removed from the inventory to satisfy demand y_{kt} during day t, and $x_t = \sum_i \sum_j x_{ijt}$.

y_{kt} Actual demand for blood type k on a given day t, and $y_t = \sum_k y_{kt}$.

z_{ijt} Actual unused blood platelets in the inventory that are type i with age j at the conclusion of day t.

$\bar{V}_t^n(I_t)$ Value function approximation at replication n on day t for I_t. When $n = 1$, $\bar{V}_t^1(I_t)$ is the initial value, and $\bar{V}_t(I_t)$ is the general form on day t.

v_t^n Dual variable for replication n at day t's end; v_t is the general form on day t. v_t^+, v_t^- and $v_t^{+,n}$, $v_t^{-,n}$ are the dual values for replication n from the left and right sides.

γ Discount factor utilized for the purpose of discounting the value function $\bar{V}_t^n(I_t)$.

λ Patient's acceptance percentage of assigned artificial blood platelets. $\lambda =$ is used as an acceptable percentage.

List of Acronyms

ABT Autologous blood transfusion

ADP Approximate Dynamic Programming

BC Buffy coat

CBS Canadian Blood Services

CRF Circular policy

CRFR Blood types ordered circular policy

CRN New blood policy

DP Dynamic Programming

FFP Fresh-frozen plasma

FIFO First in First Out

LIFO Last in First Out

PAS Platelet additive solution

PLT Platelet concentrate or Leukocyte concentrate

PRP Platelet rich plasma

RBC Red blood cells

WB Whole blood or red cell concentrate

WBC White blood cells or leukocytes

Glossary of Terms

Allogenic blood is blood collected from another person to serve any patient's needs.

Anemic person will only require RBC.

Aphaeresis is the way blood is gathered from a donor. It occurs after plasma, leucocytes, or platelets are removed for transfusion into a donor at the same time as this collection.

Autologous blood is a patient's own blood that they receives.

Blood is human whole blood; it is gathered from a volunteer who donates their resources, and is mixed with what is called an "anti-coagulant."

Blood bank is a location where donated blood and its parts are stored for later use. The blood bank's vital function is the ability to collect, store, distribute, and process a favourable amount of blood and its parts for transfusion purposes.

Blood Components are obtained, drug-prepared, and separated from or derived from whole blood that was gathered from a volunteer.

Blood Component Therapy can best be described as the utilization of components of blood instead of utilizing whole blood.

Blood distribution is the scheduled delivery of blood's parts to hospitals from a center.

Blood products are obtained from blood's pooled plasma or are drug manufactured. If from pooled plasma, they are obtained through fractionation or drawn from volunteer blood donors.

Blood substitution happens when a needed blood type is not available and is replaced with a suitable, acceptable blood type.

Blood transfusion occurs when blood or its parts are injected into a patient's blood system.

Donor is someone who willingly gives their blood after being declared healthy during a doctor's examination for donating blood; a donor does not accept any consideration in cash or kind from any source for their gift of blood.

Dose or unit of platelets is about 250ml.

General donor rules specify that one must have a minimum weight of 110 pounds, be seventeen years or older, and be healthy to donate blood. These rules are in addition to a health and physical test that must be passed before they are allowed to donate.

Hemophiliac person will require the clotting factors from plasma.

Hospital platelet banking policies focus on stock levels at individual healthcare facilities (specifically, hospitals) and their maintenance; in contradistinction, regional platelet banking policies focus on stock levels at hospitals within a region.

Leucapheresis is the process by which blood is drawn from a donor.

Plasma is best described as the part of blood that is fluid. It is a solution of protein and salt that suspends white and red cells of blood, as well as platelets, in its liquid.

Platelets are a minute cellular components of blood, they assist the process of blood clotting by affixing themselves to the inner layer of veins, capillaries, and arteries.

Plateletpheresis is the event whereby blood is collected form a donor after concentrates of platelets are separated and transfused into the donor at the same time.

Professional donors are people who give their blood for later use and receive consideration for it, in cash or otherwise. They do so for a specific patient and can also be described as paid or commercial donors.

Red Blood Cells (RBC)are easily recognizable. They are a part of whole blood, and have hemoglobin within them, which is a complicated protein with iron that carries oxygen through the blood stream to the body. RBCs give blood its crimson shade.

Replacement donors are people who are related to or who know the patient who will be receiving their blood.

Supply chains include the processes of return and a manufacturer's intent of improving value while combining all supply chain activities.

The ABO blood type system and the Rhesus system together give the eight major blood types that medical professionals care most about: AB+, AB–, A+, A–, B+, B–, O+, and O–.

The donation of blood is the event whereby a person willingly has their blood gathered from them to be stored in a blood bank to later be used for a transfusion.

The process of crossmatching is to match donor and recipient blood samples.

The regional blood center usually plans, collects, processes and distributes blood products to healthcare banks and others in the country.

The Rhesus (Rh) system is most commonly used aside from the ABO system. A person either has the Rhesus antigen or does not. If it is present, the blood is said to be Rh positive (denoted by a " + " sign); if not, it is called Rh negative (denoted by a " - " sign). The ABO blood type system and the Rhesus system together give the eight major blood types that medical professionals care most about: AB+, AB–, A+, A–, B+, B–, O+, and O–.

White Blood Cells (WBC) serve the purpose of defending the human body from attack; for example, they defend the body from viruses, bacteria, and fungi.

Chapter 1

INTRODUCTION

This chapter provides the reader with a short description of the dissertation's organization. It then provides an overview of the topics, ending with an explanation of the dissertation's purpose and goals.

1.1 Overview

Providing cost-effective delivery of public healthcare while sustaining or furthering its quality is a challenging journey across the globe. Collecting and sustaining a clean and safe blood supply through monitoring and removing collections that possibly carry harmful viruses or bacteria is expensive. In addition to ever-expanding liability and regulation issues, the costs of blood and its various products will continue to increase, varying from institution to institution. There are a number of contributors related to healthcare. These include: regularly ensuring that transfusions occur in a safe manner; collecting, preparing and transfusing of donor blood; and following up with patients (Shander 2005). For example, the Canadian Blood Services (CBS) recorded in 2009/2010 that its operation costs totaled $1B ($CAN). It has been estimated that 50 percent of that budget was in regards to gathering, producing, analyzing, and delivering blood and its transfusable products (Canadian Blood Services 2012).

In great demand, blood is a unique and precious resource. Its only acceptable sources are healthy, generous adults who are willing to donate their blood at a healthcare facility for their own or for others' use. Around the world, about 80 million blood units are donated by these adults yearly (World Health Organization 2001, American Blood Centers 2011a); about 15 million units were donated in the U.S alone (American Blood Centers 2011a). Only, about 60% of American population is able to donate blood due to age and health requirements (World Health Organization 2001, American Blood Centers 2011a). Currently, fewer than 5% of this percentage generously take advantage of their ability to donate (American Blood Centers 2011a). Consequently, allogenic transfusion (blood donated by others) is the primary source of blood. It is used to serve any patients.

Within America, transfusion services, blood donor banks, and blood banks account for approximately 88% of the national blood supply and more than 80% of blood transfusion;. Hospitals are responsible for collecting the remaining 12% of the supply (American Blood Centers 2011a). These collection facilities comprise healthcare facility systems, which have a variety of levels and are dependent upon a plethora of factors. For example, in a three-level facility, demand points or hospitals, blood clinics, and blood centers may exist (Pierskalla 2004, Sahina et al. 2007). Blood is collected from both blood clinics and hospitals; it is then sent to the blood production center to be tested and processed. Different blood products are then separated, labeled, and distributed to different blood centers and hospitals (American Blood Centers 2011a). Every day, every hour, administrators of blood banks receive orders from hospitals and prepare the blood products for delivery. Although regional blood centers have more complex operational functions than the hospital blood bank, their critical problems are the same. For example, concerns include predicting blood needs, filling needs, and monitoring stock levels to avoid wastages or stock-out problems (American Blood Centers 2011a)

Blood centers usually plan, collect, process and distribute blood products to hospitals and other blood banks in their country. Figure 1.1 shows the main blood bank process. From the figure, the process starts by collecting blood from donors. The collected blood is processed and saved in an inventory. The blood is either sent to other blood bank (transshipment policy), or sent to internal department (Issuance policy). After that, the blood assigned to serve incoming demand for transfusing. The Canadian regional blood center operates a network of 42 donation locations and three bloodmobiles (Canadian Blood Services 2012). This sizable network also includes 22,000 yearly donor clinics and 12 blood production centers: Halifax, Hamilton, St. John's, Saint John, Ottawa, Toronto, London, Regina, Edmonton, Calgary, Winnipeg, and Vancouver (Canadian Blood Services 2012). Demand points from across the country (except Quebec) order products from the CBS on a daily basis. The CBS center processes the blood products and schedules delivery to serve the daily needs of all demand points: the current demand fill rate is 97.6% (Canadian Blood Services 2012). In addition, the CBS will serve any emergency demands with an emergency shipment. Typically, the first step in blood banking is the collection process, which depends on the availability of qualified and willing blood donors. To be considered qualified, donors must satisfy various requirements imposed by the blood bank. Once the blood is removed from the donor, it is processed to extract different components. The World Health Organization (2001) and American Blood Centers (2011b) have reported that the donated whole blood unit is separated into different products such as plasma, red blood cells, and platelets (PLTs). Usually, each product is transfused to a different patient (American Blood Centers 2011b, World Health Organization 2001), according to his or her various needs.

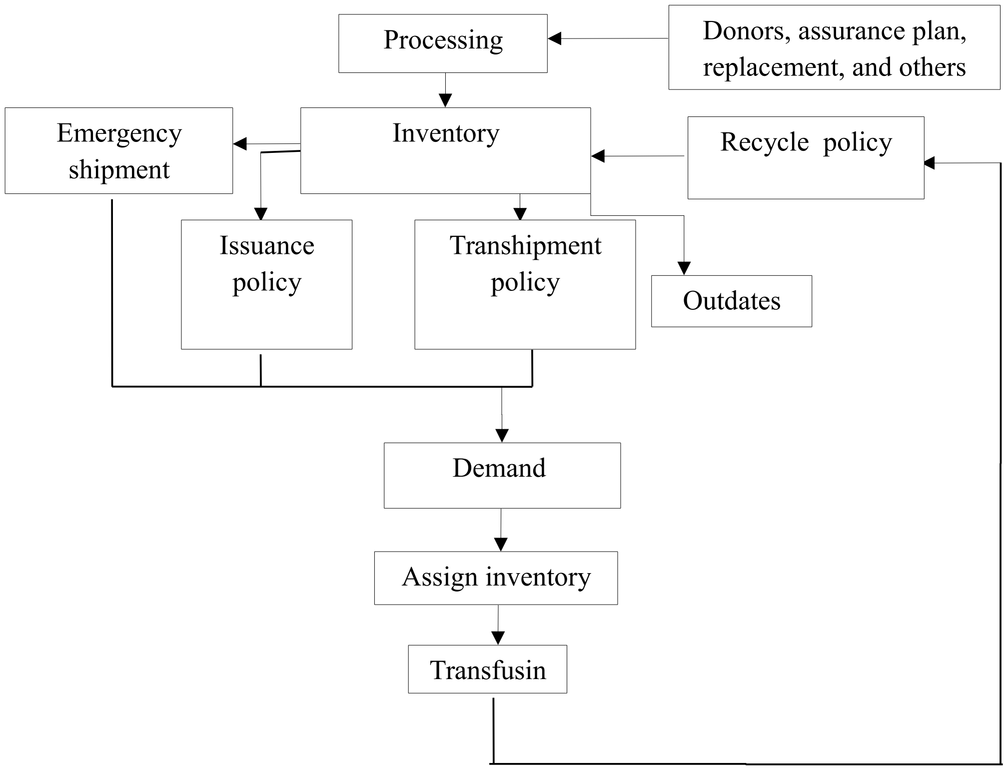

Figure 1.1: Main blood bank process

The purpose of transfusion of platelets is to assist healing or to prevent bleeding, usually during an operation or to help patients with medical conditions such as a platelet deficiency or function difficulties. Platelets can last up to seven full days before expiring; nonetheless, they need one day processing time and will be available for six days only. This leaves an extremely short shelf life compared to that of other products of blood. Consequently, managing them in bank systems can be difficult.

Blood platelet bank systems are complex; thus a need has risen for increasingly centralized locations of processing. As Greening et al. (2010) have reported that blood banks suffer from slow and costly blood delivery. This negatively impacts banks efficiency and economies of scale. Moreover, platelets cannot be stockpiled in large quantities due to their short shelf-life. As a result, the primary reserve is maintained within living blood donors. Donation and shortages are dependent upon these donors to assist when needed. Consequently, healthcare facilities, transfusion preparedness, and blood banks are wholly dependent upon these volunteers, due to the fact that these facilities rely upon clinics to administer and collect the much-needed blood. However, the clinics that gather this resource face a plethora of challenges, namely: analyzing transfusions for transmitted diseases, following complex regulations, experiencing supply stock-out, facing unstable demand, and working within tight budgets (Greening et al. 2010). Thus, speed is vital for the optimization of this system. This optimization can be most clearly defined as the best possible resource usage (employees, volunteers, budget, and donor population) that minimizes blood product shortages and outdates (Greening et al. 2010).

Clinics are not the only facilities that face a plethora of challenges, however. Some of the primary challenges blood platelet bank managing systems experience are: (1) inadequate government commitment; (2) lack of blood platelet donors; (3) poor organization of the blood platelet supply system; (4) high demand uncertainty; (5) traditional blood platelet issuance policies; (6) complex blood platelet delivery processes; and (7) inappropriate uses of blood platelets (Cumming 1976).

From these factors, an opportunity for new exploration has emerged. Multiple aspects are affected by blood platelet bank functionality. The most important factors are: short shelf-life of platelets, uncertain demand, balance of blood platelet demand and supply, outdated platelet percentages, blood bank costs, blood bank inventory levels, high blood platelet bank system complexities, and platelet inventory management. Any changes to these factors will affect the blood bank function and its inventory level, and may cause platelet shortages or outdates. Alleviating these functionality challenges will improve blood platelet bank managing systems.

1.2 Blood Basics

Blood is a specialized body fluid. It has four main components: plasma, red blood cells, white blood cells, and platelets.

1.2.1 Blood Usage

Whole blood is an extremely complex resource with many uses. When blood is donated at a blood center, it is typically separated into its various parts: platelets, red blood cells, white blood cells, and plasma. Every part serves a specific purpose. For example, platelets are useful for patients with bleeding disorders, which are often a result of leukemia, cancer therapy, and/or open-heart surgery (Canadian Blood Services 2012). As the products differ, each one's quantity fluctuates with the usable lifespan of each product once donated

1.2.2 Blood Types

Humans are the only relevant blood source. Several centuries ago, an attempt was made to replace animal blood with that of humans, but the results were anything but favourable. Further adding to the complexity of this is the fact that humans have a large array of blood types. As of today, over 20 blood-type classification systems are acknowledged and by the International Society of Blood Transfusion (ISBT) (National Blood Centers 2004). The most important of these is the ABO system, identified and established by Karl Landsteiner in the early 1900s (Blood Products 2011, Canadian Blood Services 2012). Under this system there are only a few varying classifications of blood: A, B, AB, and O. Currently, the ISBT has acknowledged and defined over 20 blood classification systems. It considers the Rhesus antigen that exists on red blood cells' exteriors. It either is or is not present in one's system. If it's present, one's blood is best described as Rh positive (denoted by a "+" sign); if not, it is called Rh negative (denoted by a "-" sign). Together the ABO and Rhesus systems give the eight major blood types that medical professionals find most relevant: AB-, AB+, A-, A+, B-, B+, O-, and O+, respectively. These types of blood exist in different percentages in different countries. Table 1.1 demonstrates a plethora of examples of this. For example, the table shows that O-, a universal blood type, is below 7% in North America but is below 5% in Finland (World Health Organization 2006, Blood Products 2011).

Table 1.1: Blood type percentage distributions in different countries

Country/Blood Types	AB+	AB–	A+	A–	B+	B–	O+	O–
Canada (Canadian Blood Services 2012)	2.5	0.5	36	6	8	1	39	7
Finland (Finnish Red Cross 2010)	7	1	38	6	15	2	27	4
Hong Kong (Hong Kong Red Cross 2011)	7	0	26	0	27	0	36	6
USA (American Blood Centers 2011a)	3	1	34	6	9	2	38	7

1.2.3 Blood Components

The process of withdrawing a donor's blood is known as apheresis. It is done with a plethora of complex machines and other components specifically made for this process. While volunteer donors are never paid, the collection locations may receive monetary compensation "equal to the production cost of the manufacturing processes" (Donate Blood Organization 2011, Blood Book 2011). Blood collection occurs around the world. The World Health Organization (2006) has stated that around 80 million blood units are donated yearly. 15 million units of this sum are known to have been donated in the United States (American Blood Organization 2013). Most often, every donated blood unit (otherwise known as whole blood (WB)) is divided into its parts; Whole blood is comprised of water, cells, hormones, enzymes, nutrients, and body waste (Donate Blood Organization 2011, Blood Book 2011). As aforementioned, the most relevant of these components that are separated after donation are plasma, platelets, white blood cells, and red blood cells. These different parts are usually delivered to healthcare facilities and transfused to different individuals, each with various requirements. At times, some of these products are discarded. This usually occurs due to problems with production process, inventories, or outdating (Donate Blood Organization 2011, Blood Book 2011). The components of blood can be described as follows:

- Red Blood Cells (RBCs): Arguably the most well-known, these cells fulfill the purpose of transporting oxygen throughout the blood stream in a process utilizing hemoglobin, a multi-faceted protein wherein iron resides. Hemoglobin is the component that causes whole blood to appear crimson.

- White Blood Cells (WBC): These cells fulfill the purpose of defending the human body from substances that do not belong within it, such as viruses, fungi, and bacteria.

- Platelets (PLTs): Minute parts of whole blood, these fulfill the purpose of clotting injuries by affixing them-self to the interior of arteries, capillaries, and veins.

- Plasma: This product is extremely fluid; it fulfills the purpose of suspending red and white blood cells within itself. It is comprised of sodium and protein.

All of these components have a plethora of utilizations. Which part a patient needs is dependent upon his or her unique situation, decided by factors such as blood type and type of injury or illness. An example is a patient with iron deficiency, who will only need RBCs. In contradistinction, a patient who cannot stop bleeding will need plasma, as it clots. Use of the various parts of blood instead of the aggregate is called Blood Component Therapy. It allows a single portion of blood to meet the requirements of four patients, as each unit can be divided into the four above parts (Donate Blood Organization 2011).

1.2.4 Blood Donation

The donation of blood is a system wherein a person willingly allows a collection facility to gather his or her blood for transfusion or for a blood bank. This occurrence may correlate with a collection facility's "drive" to gather the resource, or may be planned by the donor to take place at a local center at the volunteer's convenience (American Blood Organization 2013). Volunteering to contribute this precious resource has a number of health benefits, such as an increased growth of the amount of red cells of blood within one's body or decreased likelihood that men will develop complications such as heart disease (Greening et al. 2010).

1.2.5 Blood Banks

It has been reported by the American Blood Centers (2011a) that collection of the resources is a national policy issue and is assigned to local blood banks, hospital blood banks, non-profit blood banks, or commercial organizations. Furthermore, blood collection, processing and distribution is centralized and handled by the Red Cross within various nations, including Canada, Australia, the United States of America and Finland. However, other involved institutes may coexist (Finnish Red Cross 2010, Canadian Blood Services 2011, American Blood Centers 2011a, Australian Red Cross 2013).

Blood banks are used to store these donations. The core function of these banks is the ability to acquire, test, store, distribute, and process collected blood and its components for the purpose of transfusion. The first step is collection, which depends on the availability of qualified and willing donors. The volunteers must satisfy a variety of requirements to qualify. Afterwards, the blood is processed to extract its products. These are kept in the inventory depending on storage requirements, temperature, expected shelf-life, and other factors. They are then distributed at a variety of levels. For example, a regional blood bank may serves all regional hospitals and other local blood banks (Pierskalla 2005, Blood Book 2011). Pierskalla (2005) has stated that there are significant problematic issues among these levels and their facilities in regards to structural relations. These conflicts include who the resource's parts belong to; what the affiliations between the agencies are; how the affiliations can be defined; how the relationships may be monetarily determined to provide a positive resolution for society; if there is equilibrium, and more.

1.2.6 Blood Delivery

Central blood banks have a number of problematic logistical issues. A contributing factor is the scheduled distribution of a multitude of blood parts from centers to public healthcare facilities. This includes consideration of the growing utilization of the products, their varying shelf lives, and the speed and efficiency of their arrival at intended destinations. At present, banking of blood within the United States warrants a careful analysis; it was stated in 2011 that the national need for blood would soon meet and possibly surpass the amount available (American Blood Centers 2011b). One critical aspect that must be studied to alleviate this is blood type substitution. Although demands are characterized by the blood type of the recipients, the requests may be filled with other blood types more readily available in the hospital's inventory. While not possible in all scenarios, blood type substitution offers incredible alternatives to filling demand when supply is constricted. Making a unit of one type more readily available has the potential to lead to many other substitutions (American Blood Centers 2011a). This may allow the filling of what would previously be characterized as unmet demand. This relationship can be seen in Table 1.2, where '1' indicates that substitution is allowed between two blood types and '0' means that substitution is not allowed.

Table 1.2: Blood platelet substitution relationships (American Blood Organization 2013)

Type	Demand							
Donor	AB+	AB-	A+	A-	B+	B-	O+	O-
AB+	1							
AB-	1	1						
A+	1	0	1					
A-	1	1	1	1				
B+	1	0	0	0	1			
B-	1	1	0	0	1	1		
O+	1	0	1	0	1	0	1	
O-	1	1	1	1	1	1	1	1

1.2.7 Blood Transfusion

Blood transfusion is best described as the event wherein one injects blood or one of its specific components into a patient's blood system. This process is meant to replace the whole blood or one of its parts in the event that the patient has lost one of them; specifically, when this disappearance is likely to severely disrupt some essential functions of blood (Cumming 1976). For example, platelets may be replaced in the event that a patient has a disease that hinders the development or utility of the product, such as leukemia. Most of these events are preventative, for example to hinder a patient's natural loss of blood or to cease a hemorrhage (Alice et al. 2011, Amornrat et al. 2012). Various factors that lead to prophylactic platelet transfusions have been explained in a plethora of works; these events are so varied that a sole platelet threshold is not applicable.

1.2.8 Crossmatching

A feature of gathering and using blood in patients is crossmatching, whereby donor and recipient blood samples are matched. While the ABO system decides what specific blood may be utilized for specific patients, the recipient's serum and the red blood cells of the donor are directly analyzed for harmony, ensuring the patient's existing antibodies will accept the donor's blood (Canadian Blood Services 2012). The crossmatching process is completed in approximately one hour. In the event that a healthcare professional asks for the resource for a patient, the person receiving the blood is analyzed; compatible blood units are then found within the existing blood inventory. Physicians always request more blood than is necessary in case of emergency. The blood that is initially asked for but remains unused is placed back within storage after a specific amount of time; the term that best describes this is crossmatch-release period (Canadian Blood Services 2012). However, crossmatching does not work for every recipient. The Canadian Blood Services (2012) has stated that some patients cannot accept any substitutions or stocked blood. For example, pregnant women and newborn babies may only take new and from the same blood types. The organization has further shown that specific events such as open heart surgery necessitate that the transfused blood be an exact match with that of the patient. Consequently, some demand situations are more flexible than others. As a result, the replacement of the resource, while extremely helpful in slowing decreasing collection inventories, does face a few challenges (Canadian Blood Services 2012).

1.3 Problem statement

Blood bank is responsible for collecting, processing, and delivering blood products to hospitals. A blood bank's manager starts the morning by reviewing the bank's blood inventory and removing any outdated blood platelets. Next, the previous day's order quantity is received and added to the inventory. The inventory is arranged by blood type and age, and the total inventory is counted. Then the manager must decide the order quantity off each blood type for the next day, based on scheduled and expected demand and supply, and the bank's historical data. After that, the manager should make a decision concerning which policy to use to serve the incoming hospital demands. Regional blood banks usually serve a chain of hospitals based on their needs on a daily basis. Each hospital usually serves her patients' based on the blood types they require. Moreover, blood demand occurs daily while supply only takes place six days a week, from Monday to Saturday, with a varied daily pattern. Therefore, the demand is satisfied with the same or a suitable substitutable blood type using predefined issuing policies. Demand types include are: any suitable platelets, a preference for new platelets, no allowable substitution, and more. The problem for blood platelet banks is a discrete event multi-period multi-product inventory model that serves different hospitals.

1.4 Research Objectives

A suitable approach needs to be taken to address inventory costs, blood platelet ages, the short shelf-life of blood platelets, and the eight blood types. This research is an attempt in that direction. The primary objective of this project is to study blood platelet inventory management systems while addressing the following four research goals:

I. Develop a model of a blood platelet bank inventory by using the Approximate Dynamic Programming (ADP) methodology, prevailing against the model's curse of dimensionality, and use various, suitable and common policies to test the proposed model. ADP is a modeling and algorithmic technique used to solve large scale problems. It can overcome the curse of dimensionality.

II. Look for the best issuing policy to serve varied incoming blood platelet demands, such as requests for same blood platelets, only new platelets, any suitable available platelets, no substitutions, or any combination. Ensure each policy has its own steps and methodologies.

III. Analyze the effect of adding the newly discovered artificial blood platelet to the model containing the natural eight blood types; furthermore, study the effect of patients accepting or refusing the assigned artificial blood platelet.

IV. Expand the previous model so that it can handle an inventory network model with a regional blood bank and different hospitals.

1.5 Expected Contribution

The contributions from this research project are expected in at least three ways: (a) develop an ADP approach to model the multi-period blood bank process with an aim to include the eight blood types and six-day age; (b) solve the developed model without any downsizing and overcome the curse of dimensionality; (c) study and develop policies that can handle different types of demands and incoming donations; (d) study the effect of having a dual-supply source blood bank inventory model with: eight natural blood types and one artificial blood type, as patients have the right to accept or reject the artificial blood type. The main objectives are to reduce blood platelet outdates and shortages, to keep inventory levels at a minimum, and to reduce overall costs for blood banks.

1.6 Research Methodology

Discrete representation of blood platelet banks often suffers from the following curses of dimensionality: (a) if the state space is a vector, the state space grows exponentially with the number of dimensions; (b) a multi–dimensional information variable makes the computation of the expectation intractable; and (c) when the decision variable is a high-dimensional vector, one has to rely on mathematical programming to solve the more complicated optimization problem in Bellman's equation (Powell 2007). Powell (2008) successfully uses ADP to solve different large scale problems. The ADP solution is a classical form of Bellman′s equation that breaks Bellman's equation to pre and post decision states and values. Once it does this, the pre-model is solved as an optimization problem with the available inventory information using linear programming. Next, at the end of the day the post-model is updated with the new exogenous information that has arrived and the model is simulated using the new updated information to expect the next period's inventory. This process continues until a final solution is reached.

1.7 Organization

This dissertation starts with an introduction in Chapter 1. Chapter 2 discusses relevant literature and summarizes literature gaps, research motivations, and research objectives. Chapter 3 summarizes an analysis of CBS data. Chapters 4 through 7 provide detailed analyses and findings of the dissertation's four objectives, while Chapter 8 provides conclusions, research contributions and limitations, and directions for future research. These sections are followed by an appendices, a list of acronyms, and a list of references.

Chapter 2

LITERATURE REVIEW

This chapter summarizes previous works and highlight the research gaps. The initial section reviews relevant papers while Section 2.2 summarizes various blood platelet statistics. Sections 2.3 to 2.14 discuss several solution methodologies including: simulation, Markov chain models, dynamic programming, inventory models, policies, artificial blood platelets, regional blood banking, and more. They are organized to address various objectives and to provide a short summary of relevant research. Section 2.15 then summarizes factors that may affect any blood bank, while Section 2.16 summarizes gaps in the relevant literature. The last section examines the motivation for this dissertation.

2.1 Literature Overview

Research associated with blood and blood inventories has been performed for years. Despite this long history, the focus on blood platelet inventory is relatively new in comparison to other areas of blood bank research. Nonetheless, this study of blood banks has generated increasing interest among a number of supply chains. Different of review papers have been written on perishable inventory theory (Nahmias 1975a, Nahmias 1980, Prastacos 1984a, Pierskalla 2004, Karaesmen et al. 2011, Belien & Force 2012). Nahmias (1975a) provided general discussions concerning inventory that can expire; some of these examined random- and fixed-life perishability and recommended future systems. While Nahmias (1980) primary concern was on adjusting management of stocked products that may become waste, Prastacos (1984a) primarily focused on discussing issues banks of blood face on a regular basis, including gathering, ordering, and delivering the resource while experiencing challenges of implementation. In addition, Pierskalla (2004) studied different blood bank issues such as: blood bank structure, blood bank supply and demand optimization, optimal inventory levels, transportation and transshipment, and blood issuing policies. In contradistinction, Karaesmen et al. (2011) briefly summarized the blood bank system of supply, they focused on the products of whole blood. Belien & Force (2012) provided a discussion of literature concerning the management of this system. They did so for the purpose of assisting research in following texts that have been published in various fields on this topic; they also intended to assist with identifying trends to further subsequent research. The authors presented findings that showed that a large portion of their research was completed in settings of a stochastic nature; they featured various ways to realistically implement their work.

There also exists a body of research on blood bank optimization through different modeling approaches. Some of the methodologies used to solve this problem in the past are as follows: simulation (e.g., Elston & Pickrel 1963, Abbot 1977, Haijema et al. 2007, De Kort et al. 2011, Hess & Grazzini 2011, Perkins et al. 2011, Ying 2011), the Markov chain model (e.g., Chazan & Gal 1977, Haijema et al. 2008, Alfonso et al. 2012, Stanger et al. 2012), dynamic programming (e.g., Fries 1975, Nahmias 1975b, Blake et al. 2003, Sarode et al. 2009, Edder & Maroff 2010, Nguyen et al. 2010, Parazzi et al. 2010, Romphruk & Paupairoj 2010, Zubair 2010, Stanger et al. 2011, Zhou et al. 2011), inventory model (e.g., Frankfurter et al. 1974, Jagannathan et al. 1991, Fontaine et al. 2010, Alice et al. 2011, Amornrat et al. 2012). Researchers have examined different policies at blood banks, such as hospital blood banking policies (e.g., Elston & Pickrel 1963, Elston & Pickrel 1965, Prastacos 1978, Prastacos 1979, Flornes et al. 2010, Goodnough 2011, Neurath et al. 2012), and regional blood banking policies (e.g., Cohen & Pierskella 1975, Deniz et al. 2010, Ghandforoush & Sen 2010), time series models (e.g., Critchfield et al. 1985, Sirelson & Brodheim 1991), and regression (e.g., Brodheim et al. 1975, Cohen & Pierskella 1975). Furthermore, literature reviews on artificial blood platelets and blood bank networks have been discussed.

2.2 Blood Platelet Statistics

The production cost of a platelet dose, which involves resource gathering, analysis, processing, and distribution, is best described as expensive (approximately \$500 USD for single-donor blood or \$165 USD for platelets derived from whole-blood units) (National Blood Centers 2004). In Canada, dose (250ml) costs dropped from \$375 CAD in 2007 to \$365 CAD in 2011 (Canadian Blood Services 2012), platelets' outdate rates significantly increase dose cost. The loss of a unit of platelets leads to significant monetary difficulties for collection centers. An additional challenge is the demand trend. As multiple studies have found, platelet necessity has demonstrated an inclination to expand (Critchfield et al. 1985, Sullivan & Wallace 2005). With this general upward demand for platelets, one can simultaneously see an increase in waste. A three-year statistical data analysis demonstrated a notably large increase in outdated or wasted platelets (National Blood Centers 2004). This is unfortunate as outdating significantly impacts blood bank costs and credibility, not to mention human lives. In 2004, almost 17% (974,000 of 5,729,000) of American processed doses became outdated, never have been utilized for transfusions. These percentages translated to almost $156 million dollars in losses (National Blood Centers 2004). Moreover, the number of transfused American single-donor platelets increased by 26% from the year 1999 to the year 2001. As Sullivan et al. (2007) concluded, about 10.2 million platelets were transfused, a 12.6% more than the transfusions that occurred in 1999.

Kelly et al. (2012) reported in their study in New York that the outdate percentage from October 2003 to March 2005 was 5.4%. It increased to 5.6% from June 2005 to October 2006. Furthermore, Novis et al. (2002) reported that over 25% of platelets from random volunteers outdate, while over 10% of collected aphaeresis platelets also become waste; this is out of every tenth collected bank of blood of 1,639 United States hospitals studied. Moreover, as much as 20% of produced platelet concentrates have been reported outdated. In the 2003-2004, Veihola et al. (2006) found that the annual rate of platelet outdates fluctuated between 3.9% and 31%. The mean rate of waste (13%) maintained a similar range, coinciding with this increase. Platelets expired across the supply chain, but the majority of wastage was due to outdates. However, the annual platelet production volumes were also to some extent associated with these outdate rates. Table 2.1 shows more recent statistics of platelets derived from whole-blood or aphaeresis. Notice in Table 2.1 that the total outdated and wasted is 19.9%, which is very high and must be reduced. A 2011 United States survey found that platelet production increased by 13% (to 4,277 thousand doses) from 2008-2011. Blood centers collected 92.1% of platelets (Whitaker 2012). Through aphaeresis the Canadian Blood Services (CBS) gave about 850,000 red blood cell doses (RBCs) and 110,000 platelet (PLT) doses to healthcare facilities in Canada in 2009/2010 (Whitaker 2012). The budget for its operations during this time-frame totaled $1B (CAN). Appendix 1 shows the list of used acronyms and Appendix 2 describes glossary of terms used in the dissertation.

In its 2012 annual report, the CBS states that shipments of platelets increased to 119,528 doses in 2011/2012 from 114,193 doses in the previous year; total shipments were 91,600 doses in 2004/2005. The percentage of 2012 orders filled was 97.6%, while demand was expected to increase by approximately 4.6% (Canadian Blood Services 2012). In an ongoing effort, CBS works with hospitals for the purpose of minimizing inventory-management system product loss as a consequence of expiry (Canadian Blood Services 2012).

The growing demand for platelets is similar in Europe. Fourteen nations have shown that approximately 44% of platelets came from buffy coat (BC), 49% came from aphaeresis and 7% came from platelet-rich plasma (PRP) (Murphy 2005). Switzerland's need for platelets grew to twice its size between 1991 and 1995 (Nydegger & Schneider 1997); the demand in Wales grew by 450% from the year 1980 to the year 1992 (Booth et al. 1992). Furthermore, the Finnish Red Cross

Table 2.1: Outdated components in Canada, as a percentage of the total of transfusion platelets in 2011 (Canadian Blood Services 2012)

Type	Whole-Blood Platelets	Aphaeresis Platelets
Processed/Produced	1,762,163	2,515,696
Total Outdate	301,724 (17.1%)	321,070 (12.8%)
Reported Wasted	48,697 (2.8%)	24,724 (1.0%)
Transfused	993,000	1,973,000
Unaccounted	418,742	196,901

has stated that its own need for platelets has consistently increased (Finnish Red Cross 2011). In 2013 the Australian Red Cross (2013) needed over 1.35 million donations, while the platelets collected in 2012-2013 were 1.34 million, despite owning 83 blood centers and 38 mobile units that collect blood products from volunteer donors by visiting over 1000 sites yearly. Marwaha (2010) stated that in Southeast Asia blood requirements are 15 million doses while the collection is 9.3 million doses. This large gap must be filled.

Working to alleviate this issue is challenging, as donors constitute an extremely small group. Moreover, when platelets are obtained they cannot be exchanged for alternative blood parts, or stored at freezing temperatures for later utilization. Consequently, this discord between supply and demand leads to too many stored resources, and many "extras" go to waste. Although it is always best for patients to receive blood platelets of the same type, blood platelet substitution is possible between certain blood types. It needs to be considered as a way to fill this problematic discord.

2.3 Simulation

This section provides a brief summary of research concerning inventory modeling and simulation of blood banks. Cohen & Pierskella (1975) also simulated a model for the purpose of discovering the "pros and cons" of using FIFO and LIFO policies. They worked to discover how these policies may be used so that shortages and expiries within healthcare facilities may decrease. The most significant work on this topic by Abbot (1977); he focused on managing blood supply with a simulation. He was the first researcher to include the AB blood type, despite the fact that previous researchers had included whole blood or calculated each individual case. As a consequence, Abbot was able to include blood substitution in his simulation. This decreased shortages and presented a more realistic model of true operating systems in public healthcare facilities. In addition, Abbot (1977) showed that older blood is more likely to be used if it is transported to a larger location, thus reducing waste. Jagannathan et al. (1991) used a simulation; as well; however, their focus was on discovering perfect inventory amounts at each facility (dependent upon periods of crossmatching) to eliminate outdates and shortages. Furthermore, to understand the blood bank process Katsaliaki et al. (2014) proposed the blood supply chain game, which aimed to translate qualitative aspects of a sensitive supply chain into quantitative economic consequences. They simulated platelet movement from donors to blood banks to patients based on the UK blood supply chain, testing fluctuation in supply and order quantities between 0% and 30%.

2.4 Markov Chain Models

This section provides a short discussion of research concerning Markov Chain modeling. Chazan & Gal (1977) implemented the Markov chain to study inventory blood age distribution and to analyze the maximum average blood inventory that will not increase blood outdating. Most recently, Blake et al. (2003) and Broyles et al. (2013) discussed Markov chain models; they utilized the most likely regression in an effort to predict “discrete distributions of transient inpatient inventories” and expectations. The authors provided quality-of-fit and statistical importance analyses specifically for this Markov chain. They demonstrated that it was significantly more predictable than other, seasonal models. Haijema et al. (2007) utilized Markov dynamic programs alongside simulations and data provided by a blood bank in Holland. Once the dimension was downsized, researchers demonstrated that it is successful to use an order-up-to policy. Additionally, they claimed that a policy that is double order-up-to (young platelets and any platelets) is nearly optimal for patients needing younger platelets. Markov Dynamic Programming was combined with a simulation method for blood platelets. They applied the combined approach to the Dutch blood bank and the model was too large to solve. By down-sizing the model dimensions and implementing direction, they demonstrated that order-up-to replacement guidelines can succeed (Van Dijk et al. 2009).

2.5 Time Series Models

Critchfield et al. (1985) investigated time series capabilities in forecasting next-day platelet need. Time series implementation decreased the number of platelets wasted and reduced labor costs for the platelet inventory. Moreover, a computer model for platelet inventory management was built by Sirelson & Brodheim (1991). The model was based on average platelet demand. Changes in average need forecasted the shortage and outdate rates of platelets in the inventory. They also adjusted the platelets’ residual shelf-life for their variation in everyday needs.

2.6 Dynamic Programming (DP)

This part briefly discusses research concerning dynamic programming and blood banks. Fries (1975), Nahmias (1975a), Nahmias (1982), and Nahmias (1980) each applied dynamic programming to the perishable inventory management problem. Their studies did not specifically pertain to blood, and thus particular shelf-life and substitution patterns are not incorporated into their research. Nonetheless, their analyses had many valuable conclusions regarding perishable inventory in general. Their models were very similar; the main difference appears in the fact that Nahmias applied outdating costs for a specific decision as part of a one-period cost, whereas Fries included costs after a number of transitions equal to the lifetime of blood. Increasing current inventory by a single portion decreases the optimal quantity of ordered blood by less than one portion; the best order quantity was not as sensitive to fluctuations in the older stock as it was in the newer stock (Nahmias 1982, Nahmias 1980). This age sensitivity requires that for an accurate model, all ages presented in the inventory must be taken into account. A vector with a dimension equal to the shelf-life of the product was thus required. Nahmias concluded that working with inventory that has an expected lifetime greater than three periods is extremely difficult. Additionally, Brodheim et al. (1975) examined decreasing shortages and outdates as much as possible in the blood bank of a healthcare facility, and determined the likelihood of discord between demand and supply, average inventory age, and average wasted units. Blake et al. (2003) studied a model for blood platelet suppliers with the assumption of a market-free supply chain of blood. They concluded that a dynamic programming approach is feasible and may lower costs by 18% while decreasing outdate and shortage rates. Furthermore, research by Haijema et al. (2008) considered inventory control of platelets as a multi-dimensional Markov decision problem (MDP). As the model was too large to be optimally solved, an approximate solution was obtained using stochastic dynamic programming (SDP).

2.7 Approximate Dynamic Programming (ADP)

Discrete Dynamic Programming (DP) is a recursive, step-by-step relationship between two value functions in current and next periods. DP breaks a multi-period planning problem or decision into sub-problems at different points in time. It then solves all possible sub-problems and uses their results to efficiently calculate the solution to a larger problem.

DP is used to solve different problems such as Markov decision problems with finite and reasonable state and action spaces. However, DP suffers from the curse of dimensionality with higher dimensional states or action space problems. In addition, DP assumes the model information is perfect. Unlike DP, ADP uses approximations to overcome computational difficulties. An ADP solution is best described as a traditional version of Bellman's equation. It breaks the original model into pre- and post-decision states and values. In order to simulate moving the ADP process forward in time, two needs arise as shown below. The first is the need for a way to randomly generate a sample of what might happen. The second is the need for a way to make decisions. (1) Making Decisions (approximately): When we use exact DP, we step backwards in time, exactly computing the value function, we then use it to produce the optimal decisions. When we step forward in time, we have not computed the value function. Consequently, we have to turn to an approximation in order to make decisions. (2) Stepping Forward through Time: We are now going to step forward in time from the current state to the next state. As a result, $t = 0$'s model information is unknown, and random. The strategy will simply be to pick a sample realization from the given data at random. Thus, in the current period the missing information is randomly generated. Next the decision rule of the current state is implemented, which we are going to do using our approximate value function. Given our decision, what we need to know next is the information that arrived between the current and the next period or between time $t = 0$ and $t = 1$. At the end of the current period, the states are updated accordingly with the known information. Then the states for the next period are calculated. The process is repeated using the next state as the input for linear programming model (Powell 2007).

The curse of dimensionality is best described as a variety of events that occur when testing and organizing high-dimensional spaces, most likely with thousands of various dimensions, including: (1) the state space; (2) the space of outcome; and (3) the space of action (feasible region). ADP has three main characteristics: (1) real-time control; (2) near-term tactical planning; and (3) strategic planning. ADP can be viewed from four very different perspectives. Depending on the problem one is trying to solve, ADP can be viewed as a way to improve an observable, physical process; an algorithmic strategy for solving complex dynamic programs; a way of making classical simulations more intelligent; and a decomposition technique for large-scale mathematical programs (Powell 2007).

Different factors influence ADP's functionality as it requires substantial tuning. This can be avoided by considering the following issues: (a) Also, ADP is a powerful modeling and algorithmic methodology, it does not suite all problems. It works well when acceptable solutions cannot be obtained through using available simple methodologies. (b) When building a value function approximation, be sure that it shows the expected model characters. Moreover, the initial value should represent the model behavior. (c) The value function approximation should suit the problem structure and can be easily derived to take advantage of derivative information when needed. (d) The wrong stepsize formula can ruin an ADP algorithm. The selected stepsize should helps the value function approximation to converge. These points have to be carefully studied (Powell 2007, Powell 2011).

In a series of papers, Powell (2007, 2008a,b, 2011a,b,c) described ADP algorithm suites for extremely large problems experiencing the curse of dimensionality. Specifically, Powell (2007) proposed applying ADP methods to a blood bank inventory model and showed that ADP could cater to various blood bank model state variables. This is while overcoming both dimensionality and time parameters, thereby removing the need to downsize. Moreover, Powell & Roy (2005), Topaloglu & Powell (2005), George & Powell (2006), Topaloglu & Powell (2006), George et al. (2008), Ma & Powell (2008), Nascimento & Powell (2008) and Nascimento & Powell (2009) have presented research that successfully utilizes ADP to solve large-scale problems.

2.8 Comparison between DP and ADP

ADP and DP are compared and discussed based on various aspects of the two methods. Katanyukul (2010) compared Look-Ahead, a DP method, with some ADP methods, namely: RBF, Sarsa(A), Direct Credit Back, Residual Gradient, learning-based ADP Generalized Autoregressive Conditional Heteroscedasticity GARCII(1, 1), and the simulation-based ADP methods: Rollout and Hindsight Optimization (HO). Look-Ahead provided less favourable results than all other approaches using ADP. The design of experimental results showed that: (a) RBF, with evenly distributed centers and half midpoint effect scales, is an approximate cost-to-go ADP method that is efficient; (b) the Sarsa learning scheme is more favourable than Residual Gradient or Sarsa(A); (c) Direct Credit Back is significantly more favourable than the benchmark Look-Ahead, however, it is not more favourable than Residual Gradient in lead time problems of either zero or one-period; and (d) the performances of learning-based ADPs are inferior to that of simulation-based ADPs, such as Hindsight Optimization or Rollout. It was shown that the learning strategy that is most favourable is Sarsa, over Residual Gradient for both zero- and one-period inventory problems. Additionally, the ADP simulation-based approach, Rollout, is superior to Sarsa, the ADP learning-based approach. In another paper Katanyukul et al. (2011) examined simulation-based ADP and learning-based approaches to an inventory management model using GARCH model. A learning-based ADP approach, Sarsa, with a GARCH(1,1) demand model was studied, and compared to two simulation-based ADP methods: Rollout and Hindsight Optimization (HO). The results were based on various problem settings, such as demand correlations, cost parameters, and variances in demand. The Look-Ahead method is a DP model used to solve MDP. Look-Ahead was used to compare its performance to the other ADP methods. It was found that as the demand correlation decreases, all ADP methods appear to be significantly better than Look-Ahead. It appears that their improvement settles at approximately 55% for zero to negative correlation. In fact, the ADP Rollout method is far more favourable than Look Ahead, Sarsa, and HO in most cases. It was also found that HO has lower costs (total costs in Periods 13 to 60) than Sarsa in most cases, but only a few cases (demand correlation = 0 and 0.8) of significance tests can confirm the differences.

Medina et al. (2011) compared the performance of the ADP approaches using a "post-decision" state variable and a simple Genetic Algorithm (GA) for solving traffic signal timings in a small symmetric network with over saturated conditions. The comparison is founded upon throughput delay and the number of stops and on measures that considered the efficiency of green time utilization and queue occupancy of the links. Even thought both methods showed similar performance, the ADP solution is different than the GA solution. They both used green time efficiently thus preventing queue backups, and they both served all approaches according to current demands.

Reinforcement learning (RL) is an ADP version that powerfully solves complicated sequential decision-making control theory problems and suffers from the curse of dimensionality. RL directly confronts this issue which gives it the ability to solve problems that were previously considered intractable via classic DP. RL's success is because of its strong mathematical DP roots (Gosavi 2009). Moreover, Gabillon et al. (2011) applied a policy iteration based on ADP, to the game of Tetris. They showed and reported in the literature that an ADP algorithm obtains the best results for Tetris in both small 10×10 and large 10×20 boards. Although similar results were given by other optimization methods such as DP, ADP uses considerably fewer (almost 1/6) iterations than DP.

In summary, DP is used to solve different problems with finite, reasonable state and action spaces. However, It is expensive to solve a problem that has a large state and action spaces using DP. ADP is a powerful modeling and algorithmic technology. Not all problems need ADP. It uses approximations to overcome computational difficulties. It is is designed to solve large-scale problems (Powell 2007).

2.9 Artificial Blood Platelets

Medical laboratories have succeeded in extracting blood platelets from human cells (Sarteschi 2006, Dietz 2009, Edwards 2010, Lasky et al. 2010, Hess & Grazzini 2011). These platelets have the characteristic of the O- group and can be used as a universal artificial blood type substitution, which can be used on all patients regardless of their blood type. Thus, resources should be allocated to the development of artificial blood substitutes; these products will generate a large, reliable source of inventory for blood banks. They offer universal compatibility, lower probability of disease contamination, and large-scale supply (Sarteschi 2006). They may also be used on the battle-field and in hospitals to account for shortages of blood. However, many of the products under development still face multiple problems regarding safety and efficiency, so further research is required before these products may be fully accepted into medical practice (Reid & Kim 2006). Edwards (2010) made the note that human trials of the artificial blood were expected to commence in 2013, while Reid & Kim (2006) expected that artificial blood platelets will be available in 2016. Modery Pawlowski et al. (2013) presented a comprehensive review of these approaches; the basis of their argument regarded future directions of synthetic blood.

The existence of synthetic blood platelets in the bank provides a better and more effective service (Modery Pawlowski et al. 2013, Duan & Warren 2014); it will save soldiers' lives on the battlefield, decrease transportation mileage, reduce fuel consumption, and decrease cost and lead times to patients. The availability of artificial blood platelets will also help balance the demand and supply behavior, addressing the gap. Additionally, their short lead time can offset donor shortages.

Although the synthetic platelet will overcome different blood bank inventory problems, some patients will still refuse it. Berend & Levi (2009), Rajtar (2013) studied the refusal of transfusion of blood and its components for religious or other personal reasons - for example, by Jehovah's Witnesses. They suggest a working procedure to help those patients. Bingham (2012) explored the refusal of healthcare for legal and ethical reasons, done by patients who are adults. It was concluded that comprehension of these ethical and legal reasons is extremely important and will help nurses make decisions that protect the interests of vulnerable patients.

2.10 Blood Bank Issuance and Replenishment Policies

Hospital blood banking policies indicate how inventory levels at a single healthcare facility should be sustained while regional blood banking policies are focused on stock levels at hospitals in a region. Blood policies are related to blood platelet movement between regional blood banks, blood banks, collection sites and hospitals. For example, replenishment policy is concerned with how to increase inventory levels, while issuance policy is concerned with how to serve different blood demands. Others have different concerns. Prastacos (1978) used First In, First Out (FIFO) and Last In, First Out (LIFO) policies to reduce blood wastage or shortages. It was concluded that keeping a rotation system for aggregated blood can considerably decrease loss of units (due to outdating or shortages) at each healthcare facility assisted by banks in their regions.

Prastacos (1979) built a two-stage multi-echelon model based on a predicted blood rotation under the First In, First Out (FIFO) policy, this causes stock out and is shared equally. As a result, the model helped decrease the number of expired and stock out units at each hospital. Kopach (2004) built a model that had two-stages and was a two-stage multi-echelon, with dual rotation levels using the FIFO policy. His approach meant that the likelihood of a resource shortage was divided evenly amongst hospitals. As a result, the model succeeded in reducing the amount of shortages and expired portions at each location. Furthermore, Berk & Gurler (2008) proposed a control policy for perishables. This control policy introduced an effective shelf-life where decisions are based on a new suggested policy: a (Q, r) decision model, a review model with order quantity Q, and a reorder point r that is continuous. They showed that the developed policy succeeded in reducing both outdate and shortage rates. Katsaliaki & Brailsford (2009) developed and analyzed seven policies for blood stock system management in a general United Kingdom hospital that received its blood and components from a regional center. The blood types were varied to study their effect on the blood bank inventory.

Furthermore, perishable inventory problems were studied by Karaesmen et al. (2010) alongside suggested policies for substitution and order quantity. Blake et al. (2010) developed a model for consumer institutions. It attempted to find a platelet ordering policy that met defined bounds on outdates and shortages, while minimizing the overall number of orders issued.

2.11 Inventory Models

This section provides insights into literature on hospitals and blood bank inventory management. Blood platelet age is about seven days (available for only six-days with a lead time of one-day). Platelet stock is managed with a review on a daily basis. Satisfying need depends on the demand type, the available inventory, and the issuing policy used to satisfy the request. When the available stock cannot fill it, the excess demand is gone. Replacement orders arrive with a fixed one-day lead time. When this stock is delivered, it is all added to the shelf. As aforementioned, due to the mismatch of supply and demand (and the shrinking gap between them) there is a future cause for concern. Additionally, the shrinking margin between available and requested blood is causing actual problems in present-day hospitals. The facilities categorize surgeries based upon urgency; if there is an inadequate supply of blood, then various surgeries must be canceled or postponed. Elective surgeries are the first to be delayed due to the fact that they are the least critical.

Managing stock with speed is complicated. Reducing waste by using as many blood resources as possible necessitates understanding the relationship between supply and demand, and this must occur through cooperation of the parties involved. Furthermore, networks and computer systems need to be redesigned to work with actual blood supply and usage data so all parties can see it; this way they may work towards as few shortages and outdates as possible (Blake 2009, Perera et al. 2009, Zhou et al. 2011, Stanger et al. 2012).

Jennings (1968) reduced expired or unavailable blood units, emphasizing that the shortage-expiry system should be the initial point for stock levels. Furthermore, Graf et al. (1972) discussed the constant stock out of Rh negative blood faced by the Red Cross. Due to it, many hospitals kept (and still keep) an emergency quantity. This causes increased wastage percentages. Their analysis consequently aimed to reduce this surplus. Frankfurter et al. (1974) had a similar goal; they created a stock level prediction system meant to forecast short-term. The purpose of this creation was to completely remove shortages and outdates by scheduling blood collection. Brodheim et al. (1975) worked to discover the likelihood of a shortage happening, the stock age that is average, and the amount of expired portions that is average. They studied how a hospital blood bank reduce both shortages and outdates. Moreover, Graves (1982) utilized a theory wherein units were queued during his research to discover the predicted amount of expired units, shortages, stock ages, and stock levels. In addition, Fontaine et al. (2010) investigated the effect of RBC shelf lives on availability and outdate rates. They explained six different situations wherein red blood cell donations have varying shelf lives. It was found that at delivery shelf-lives had an average age of 10.2 days; at their issue for transfusion the average age was 18.8 days. They also noticed a shortfall in the accessibility of red blood units between 51% and 0%, alongside the fact that there was a growth in the rate of expiry between 0.4% and 4.5%.

Organizing and sustaining an acceptable stock of platelets with ABO/Rh-typed portions of blood clearly depends upon better forecasting of platelet need; for example, for elective surgeries or for longer platelet shelf-lives. While working to decrease the expiry of platelets is a significant monetary issue, a focus on managing inventory assures speedy provision of blood products for transfusion. A multitude of methods have been used to study inventory levels (primarily of platelets) to meet supply and need. Katz et al. (1983) built a simulation model that describes platelet manufacturing and delivery. Based on 24 months of platelet orders, it was found that the model was successful wherein a five-day platelet life exists, despite fluctuating platelet creation and delivery logistics. Furthermore, Ledman & Groh (1984) built a committee to plan platelet production, with respect to daily evaluations of platelets needed in 60 hospitals. They reduced the wastage percentage from 20% to 3% over a six-month demand period.

Accordingly, blood platelet supply is traditionally estimated based on the supplier's skills at monitoring variation in demand. However, platelets may not be sufficiently available due to different reasons, such as: donor shortages, sudden increases in demand, or product recalls (Sullivan et al. 2007, Fontaine et al. 2009, ORBCON 2010) Most recently, Duan & Warren (2014) formulated a red blood cell supply chain inventory model for multiple blood types with substitutions. This was the first model that considered a red blood cell supply chain with shortened permissible shelf-lives of 21, 14, and 7 days. The authors summarized the trend of type O blood usage while the shelf-life of blood decreased to a length of 7 days. It was shown that as shelf-life decreases, type O demand increases to substitute for other compatible blood types.

2.12 Newsvendor Model

The newsvendor model determines the optimal level of blood platelet availability in a way that expects both demand forecasting and reward maximization. The "newsvendor problem" is the problem of deciding the size of each blood type order that must be placed each morning. It must be done before observing the incoming blood platelets' random demand and while trying to balance both shortages and outdates. Blake et al. (2003) used the newsvendor model to calculate inventory's replenishment quantity. Furthermore, Tomlin & Wang (2005) showed expedited orders that were calculated using the newsvendor model. An easy order-up-to level that is time-invariant has been demonstrated to be singular.

2.13 Inventory Models with Dual Supply Sources

Typically in dual sourcing there is a cost effective, lower lead time supplier and an expensive, efficient lead time (responsive) supplier. The key notion in dual sourcing literature is to fill the base demand from the cost efficient supplier, and to source the excess demand from the expensive, yet responsive supplier. Moreover, Lardinois et al. (2010) solved an inventory problem with two supply sources. The first supplier needed a longer lead time, while the second supplier had a shorter lead time but an extra cost. Lardinois et al. (2010) showed that dual supply can lead to significant outdate decreases when compared to a single supply policy.

Furthermore, prior work on dual-sourcing inventory problems has closely examined the trade-off between normal and time efficient replacements. Optimal dual-sourcing policies have been commonly described as dependent upon state, necessitating a dynamic programming model with multi-dimensions. Challenges of these types are typically complex and need to be solved heuristically. It has been shown by Ramasesh et al. (1991) that the solution for a model with two sources is best described as an extension of the regular policy (Q, R) to a variable lead time and to two different reorder levels. Scheller-Wolf & Tayur (2003) worked to create a Markovian production-inventory model that utilizes dual-source supply. Moreover, Ferguson & Koenigsberg (2007) analyzed quantity and cost choices of a firm that provides perishable goods to end consumers. In their model, internal competition arises between the old and the young units when the old units are believed to have a lesser quality than the young units. Lamme et al. (2010) described the design, input, and results of a model that explored the possible benefits of a dual sourcing strategy with emergency shipments for perishables, compared to a single sourcing strategy. Overall, they found that there are situations in which the dual supply strategy outperforms single supply while taking into account lost sales, outdating, and emergency supply costs. They varied the emergency supply between 0% and 59%, and varied the shelf-life between 2 and 9 days. It was found that the product with a longer shelf-life with the suggested emergency shipment led to an outdate rate of zero.

In addition, Arts et al. (2011) studied the stock management of one product in a single location with dual suppliers with stochastic need. They used the dual-index policy to control the inventory model with regular and emergency orders. They showed that the developed policy gives "excellent" results for fixed lead times, and 'good' results for variable lead times. Furthermore, Rossi et al. (2012) studied the dual sourcing impact on food supply chain networks, where products were exported from a cheap but faraway source or from an expensive local source. The model was affected by three factors: quality at consumption, age at consumption, and waste. The acceptance limit, which decides at what time a unit becomes expired, was set to 5% of food afflicted. They found that the product age was affected by the product wastage.

2.14 Inventory Network Models

Blood bank and hospital network is a vast subject. Prastacos (1984b) outlined different management problems at the operational, tactical, and strategic levels. These issues have been faced by hierarchical (coordinated) structures. Facility systems most often exist in the manner of hierarchical systems. An example of this is a system with a variety of interacting location types. However, challenges regarding location have primarily been researched for one-level systems. An example of this is a single facility type. Owen & Daskin (1998) viewed this challenge concerning location as a crucial aspect in planning strategically. Owen & Daskin (1998) classified these models in regards to dynamic, stochastic and static natures of time. Furthermore, Rahman & Smith (1999), (1999b) explained that in publications related to locating healthcare facilities, two model categories have been presented.

In addition, a modicum of research surrounded component locations of a healthcare system in which facilities were viewed as a single type in regards to the service level that was provided. Additionally, Taylor et al. (2006) built a discrete-event supply chain model simulating the UK National Blood Service (NBS). It showed the healthcare supply chain relationship between the NBS production, testing, and delivery facility and its assigned hospitals. When the amount of healthcare facilities increases, the amount of time that the simulation is working becomes cumbersome due to its grandiose size. The NBS chain of supply model was thus broken into many lesser models. Research found that this version worked more successfully than its single, traditional counterpart, as the amount of hospitals grows. Their model included a myriad of blood products moving back and forth between a center of supply and one hospital of medium size. Networks on a more grandiose scale can be simulated, but necessitate distributed computing capabilities.

2.15 Factors Affecting Blood Platelet Banks

A blood bank's primary concern is to effectively manage its platelet inventory (i.e., to minimize costs and the total outdate rate of platelets while satisfying most of the demand from the hospitals it serves). Perera et al. (2009) and Harris (2012) summarized that the most critical performance objectives are to build a high service and low cost network and to design a network that can outperform competitors. Becoming a more mature supply chain means becoming more effective and providing higher quality service. Stanger et al. (2011) and Stanger et al. (2012) studied blood bank inventory management performance and concluded that effective performance is motivated by the success and experience level of staff in the transfusion lab, who are required to be experienced, properly and regularly trained, and skilled. Crossmatching electronically, inventory visibility, and uncomplicated management systems facilitate a positive performance as well. It can be summarized that inventories succeed at their top levels with effective service and inexpensive capital (Sarin & Giani 2003).

Various models have been extensively utilized for the purpose of solving issues managing blood. In particular, Carter et al. (2012) explored the impact of blood collection issues and considered what it means for the next ten years of blood services, donation management, and recruitment. They discussed significantly strategic issues such as: maintaining an adequate blood group mixed donor system; having a smart inventory control policy; using a flexible, efficient system that reflects the current global economic climate; and redesigning the donor experience. They concluded that the potential challenges and possibilities for the next ten years are: influences and changes in demographics, the influence of up-and-coming technologies, trends of need, demand trends, and expectations of blood donors. Sherman & MacIvor (2012) studied the culture of blood utilization and suggested different strategies for improving. These include good assessments of risk, optimization of inventory baseline, expected transfusion problems, policies to reduce blood wastage, blood conservation technologies, transfusion instructions and targeted therapy, testing aspects, and extensive transfusion protocols. In contradistinction, Grant (2013) presented an investigation with a different purpose from obtaining and retaining loyal donors; he explored how to be more time efficient and successful in delivering blood and other products to customers. It was concluded that a national blood service can support information flow and integration throughout the blood inventory supply chain to achieve good inventory management, resource optimization, and good communication with input and output stakeholders. This increases transfusion safety and reduces cost.

2.15.1 Platelet Characteristics

While each blood component is extremely important for the various aforementioned reasons, platelets are the most critical. They are derived from donors, directly through aphaeresis, or from whole-blood. A standard adult treatment has between four and six units of blood and it may reach to 100 units. Each unit is a 250 ml. The component initially had a shelf-life of five-days, but recent advances in blood technology have increased this shelf-life to six-days, with a lead time of one-day (Modery Pawlowski et al. 2013). Thus, a prepared platelet portion is preserved for 5-7 days, between 20^oC and 24^oC. The viability of this product depends upon the maintenance of these conditions. Plasma or other solutions are utilized as the primary liquid for platelet storage (Booth et al. 1992, Edder & Maroff 2010). Blood platelets expire, and this resource's replenishment through voluntary, regular, and non-remunerated donations has created cause for concern. For example, questions have been raised concerning the age of blood donors or concerning the use of automated technology in gathering multiple units from a volunteer at once (Sloand et al. 1996). The amount of gathered doses is forecasted by the healthcare facility's need for them. As a result, blood banks set the goal to gather donations in direct relation to clinical necessity. Equilibrium with the population's various blood types is also wished for. To achieve this stochastic need, supplementary processes may be utilized - for example, aphaeresis may be used to collect more than one portion of platelets at a time (American Blood Centers 2011b, American Blood Organization 2013). Timely and successful organization of the supply chain (primarily focused on stock) would ensure that the best possible supply of resources is reached while decreasing outdating.

2.15.2 Supply

Robinson et al. (2008) and the Canadian Blood Services (2012) have summarize that donor recruitment, qualification, and collection are critical. However, the number of volunteers is decreasing due to "socio-demographic changes in population and increasingly strict screening requirements" (Robinson et al. 2008). This increases the gap between supply and demand. If the changes in blood donation and demand were to be matched, then future blood shortages would not be an issue.

Canadian blood is gathered from a multitude of donors that meet a variety of requirements, such as meeting a specific weight and age or only having traveled to certain locations. These volunteers have different options when providing this previous resource; there are many collection locations (Canadian Blood Services 2012). However, rules and regulations define who is eligible to be a blood donor. In general, one must be seventeen years or older, must be healthy, must be a minimum of 110 pounds, and successfully pass an exam verifying one's health. This ensures that the blood is safe to be transfused to others. There are many reasons that the resource could be deemed unsafe. Some examples include having recently been in jail, having had one's ears pierced in unsanitary conditions, having recently had acupuncture, or having one of many disorders and/or diseases. While the regulations seem extensive, they actually don't inhibit or lower the number of eligible donors (National Blood Centers 2004, Canadian Blood Services 2012, Whitaker 2012).

The gap between supply and demand is exacerbated in a number of ways. The first source of lost blood is in pre-donation deferrals. When a blood drive is conducted, roughly 75% to 80% of the scheduled appointments attend, thus resulting in an initial loss of expected blood from the drive. Of the people who do attend, approximately 15 to 20% are deferred because of failed health and physical exams. Additionally, a significant element of blood donation is the process of analyzing it for infectious diseases. Once blood has been donated, it is sent to testing labs that perform 11 to 12 tests, 9 of which are required by the World Health Organization. If any diseases are identified in the blood, the sample is immediately discarded, thus reducing the supply of blood to a level lower of total donations. Testing procedures are not generally time consuming as about 95% of donations are tested within 24 hours of arriving at the facility; thus the major effect is in the slight reduction of supply, not in the time delay. Additionally, Canada has a multitude of ethnic groups (Canadian Blood Services 2009). Each ethnic group has its own distribution of blood types. There is a discrepancy between ethnic groups donating and receiving blood. Thus a distribution mismatch exists between supply and demand. Furthermore, blood donors are all volunteers. They do not receive any sort of payment for their donation and donate purely for altruistic reasons. Recruitment is encouraged through blood bank brochures, presentations, telephone calls, or community and business groups. Supply is open six-days a week from Monday to Saturday. Quantity ordered is available early the following day (National Blood Centers 2004, Canadian Blood Services 2012, Whitaker 2012).

Supply is dependent upon various elements such as density of populations, transportation infrastructure, regional blood bank organization, and amount of hospitals. This limits processing the resources at banks or capacities for receiving blood from volunteers with limited mobility, time, or other constraints. Supply is variable because it relies on demand uncertainty; its quantity and type, hospital location, the fact that there is no supply on week-ends, and primary dependence on the availability of volunteer donors are all contributing factors. As the amount of eligible volunteers decreases due to a largely aging population, regulations for donating, and an increased need for operative procedures, additional work needs to be done to recruit new donors and to replace those who are no longer eligible. These efforts will result in a growing expense for each portion of blood gathered (American Blood Centers 2011b, American Blood Organization 2013).

2.15.3 Demand

As aforementioned, there is an upward trend in platelet demand and utilization. A number of studies have shown that necessity for platelets has demonstrated an inclination to continuously grow (Critchfield et al. 1985, Sullivan & Wallace 2005). However, it has been shown that the amount of transfusions is also increasing, contributing to an ever-chronic lack of available platelets (Marwaha 2010, Canadian Blood Services 2012).

Eight natural blood platelet types exist: AB-, AB+, A-, A+, B-, B+, O-, and O+, respectively. Thus eight stochastic demand types exist, coming in sequence twenty-four hours a day, seven days a week with a varied daily pattern. There are four different demand levels: (1) blood type demand is satisfied by the same type (no-substitution); (2) new blood demand is filled with new blood; (3) demand for old items is filled with any compatible item; (4) substitution is applied for any demand (National Blood Centers 2004, Canadian Blood Services 2012, Whitaker 2012).

2.15.4 Shortage of Platelets

There is a worldwide lack of available blood, including in America. For example, in a number of nations less than 5% of the population suitable to volunteer actually donates. Blood shortages mean there is either less than one-day's stock of blood accessible or the nations do not have enough accessible to meet hospital needs.

The cause of this chronic lack of availability is due to increased need, primarily a result of the growth of complex therapies; they necessitate a significant portion of whole blood and its products. The shortage can be attributed to fewer walk-ins donors and an expected number of cancellations and no-shows. Blood shortages also have a tendency to occur during hotter months when companies and educational facilities are less likely to organize volunteer drives. As a result, hospitals have largely moved towards autologous infusion, where patients donate blood to themselves, instead of using allogenic blood (donated by others). A critical lack of available blood may force elective surgeries to be canceled or may put human-lives at risk (American Blood Organization 2013, American Blood Centers 2011b).

2.15.5 Outdating of Platelets

Further costs that blood locations experience are due to platelets' low shelf-life of five to seven days and the significantly fluctuating necessity for them. Once a platelet portion is analyzed for safety, released, and delivered, what is left of the shelf-life may be less than a week. Sullivan & Wallace (2005) have stated that based on platelet dose sizes assigned per patient (for example, four platelet units per adult dose), more packages may be spoiled at this time. Around a fifth of assigned platelets are outdated.

Quick expiry may not occur if inventory levels and production could find an equilibrium with stochastic need - for example, by scheduling production and managing stock more effectively (Critchfield et al. 1985)). Disassociated from the basic process of production, a fluid platelet system of production could improve its ability to meet stock needs through enhanced responsiveness. Methods allowing prolonged platelet survival or synthetic platelets are highly desirable (Reid & Kim 2006, Parazzi et al. 2010, Modery Pawlowski et al. 2013).

2.15.6 Cost

Blood bank cost sources include blood recruitment, collection, testing, preparation, inventory, production, and distribution. Delivering healthcare in a cost-effective manner while sustaining or improving the level and value of the care is a difficult worldwide task. Society and those providing the funds view gathering blood and keeping it healthy and free of infectious viruses and bacteria as expensive. As aforementioned, blood donors are decreasing as a result of an aging population, donor eligibility controls, and increased blood testing. Policies to attract blood donors are needed to overcome this problem. This will result in an increase in donated blood cost (Taylor et al. 2006, Shander et al. 2007, Sarode et al. 2009, Nagurney et al. 2012). Expenses should consider, the following list, which may include additional items:

1. Expenses placed on blood donors
2. Cost of extracting products of blood for the purpose of transfusion
3. Expense of the logistics and the preparation of hospital transfusions
4. Expense giving and monitoring patient transfusions
5. Expense of unfavourable transfusion situations
6. Expense of assisting patients who develop diseases due to transfusions
7. Expense of legal situations (claims made by patients who were contaminated)
8. Expense of lost production
9. Expense of sustaining and organizing continental or national systems of haemovigilance.

2.16 Literature Summary and Research Gaps

Contemporary blood bank chains of supply have become increasingly complicated with new developments. Blood platelet need and blood bank complexity require that both hospitals and banks be increasingly innovative and cost-effective in collecting, producing, and delivering blood products and services (Ghandforoush & Sen 2010, Belien & Force 2012). Regardless of a multitude of important developments, blood platelet supply chain organization and control demonstrates unfavourable levels of discipline; actual and practical difficulties are often addressed in an unsatisfactory manner. The operating objectives for a blood platelet bank may be stated as: (1) minimizing platelet shortage rates; (2) minimizing the outdating of blood platelets; (3) maximizing blood bank rewards; and (4) keeping inventory at a minimum. Addressing these issues and objectives is critical for any successful blood bank.

It should be noted that models often have limitations and weaknesses. Due to their nature, models are based on assumptions. Consequently, systems based on them will not fulfill the expectation of performing as well as initially expected. This was confirmed by Hodgson (1986) and Smaros et al. (2003). It has been noted that the imposition of strict assumptions causes results that are distorted. As a result, it must be remembered that actuality is not depicted by models and cannot be accurately applied. In addition, there are a multitude of models primarily focused on blood supply chain management's operational elements, but these models scale with difficulty and do not present general results. Some of these models need a large computing time or are based on cost minimization as opposed to inventory needs. Moreover, some are too complex with too many assumptions.

In hospitals and blood banks across the world, economic considerations are becoming increasingly important - and are therefore being used to control precious resources such as blood (Isbister 1996). Using blood platelet units before their time expires benefits patients and hospitals, hence reducing unnecessary costs and losses due to time expiry. As stated by Cobain (2004) successful inventory management performance entails carrying enough stock to guarantee 100% availability while minimizing time expiry. Platelet usage will steadily increase due to different reasons. A low platelet shelf-life presents a critical difficulty healthcare facilities and centers need to overcome. The allocation of blood needs to be managed as the supply amount fluctuates throughout the year and demand is unpredictable. In addition, blood platelet are perishable and must be used within a short time period. Blake (2009) suggested that there is a need to develop fast and robust models to study the platelet inventory problem. Since the optimal solution should consider blood types and their ages, it is "computationally expensive to find the optimal solution using optimization tools, such as dynamic programming" in a short period of time (Haijema et al. 2007).

The problem has a very large number of state variables, outcome spaces, and action spaces. For example, the blood bank inventory contains eight blood types each with six different ages. In addition, demand can be for eight blood types with no substitution, substitution is allowed, or only new blood is needed. The demand dimension will be 8 $\times$ 3. Demand is served from inventory with

162 substitution possibilities (27×6). Therefore, if there is a demand for 100 units of A+ and on the same day 20 units donation is received. The demand dimension is 100^{16}, and donation dimension is 20^{48}. Thus, most researchers have attempted to downsize, simulate, or partially approximate the current problem, but this does not reflect all aspects of the actual-life model (Blake et al. 2003, Haijema et al. 2008). Moreover, Haijema et al. (2007) assumed that four donors were needed to meet one patient's need, while other countries take six to eight whole-blood donors to meet one patient's needs (Donate Blood Organization 2011).

In addition, previous statistics show that the blood platelet demand is increasing while donations are decreasing (Canadian Blood Services 2012). Keeping loyal donors is not easy (Grant 2013). Additionally, the cost of platelet production is high (Canadian Blood Services 2012). Thus, blood banks and hospitals need to reduce their cost without affecting patient services. Blood management and optimization of the supply to match the demand is a critical factor (Carter et al. 2012, Grant 2013). Because of costly production and short shelf-lives, it is impractical to fill stock on a large scale when it is not needed or there is a significantly large pool of donors. The production of platelets must follow levels of need closely; large centers must work to decrease production expenses of platelets as much as possible (Ghandforoush & Sen 2010).

A summary of the important factors that make this problem a challenge for research are as follows: (1) shelf-life of platelets is short; they are perishable items and are of eight blood types, each with different demand. The preparation of platelets involves significant costs; (2) the blood platelet inventory replenishment policy is critical and needs more effort to determine; (3) the platelet supply at a donor-drawing center is an important factor, but is affected by demand uncertainty. Supply is also impacted by the need to test the suitability of donor blood and to analyze and remove an increasing number of diseases and viruses prior to platelets being transfused; (4) the need for blood platelets at healthcare facilities is uncertain; (5) the blood platelet inventory issuance policy is critical and demand types are becoming more complex. More effort is needs to serve different platelet demand types; (6) a number of related choices must be decided upon at the policy, inventory, and blood order quantity; all are subject to the necessity for reductions in expenses, decreased expiry rates, and decreased shortage rates; and (7) the entire regional blood bank network, including blood banks, hospitals, and more can be evaluated as an entire system. In conclusion, current limited studies paired with problems such as the curse of dimensionality, high increase of platelet demands, decrease in platelet donation, balanced inventories, low capital, and high model complexity, need additional research for solutions. In addition, the artificial blood platelet supply needs to be investigated within the inventory model and the regional blood bank network.

2.17 Research Motivations

ADP methodology is used for analyzing blood platelet types and their associated ages in the blood bank inventory model. The methodology is logical and powerful, though relatively simple, in solving the actual sized blood platelet bank inventory problem. Furthermore, the methodology is extendable to other fixed lead time perishable products. The uniqueness and usefulness of this framework is in application at various levels, which include formulating and solving the blood bank inventory model without any downsizing; developing a blood bank issuance policy to serve different types of incoming demand; expanding the framework to add the artificial blood platelet beside the eight natural supplied blood types; studying the effect of patients accepting or refusing the artificial platelet; and developing a regional blood platelet bank inventory network model that can serve a local blood bank network. The purposes of this dissertation are: (1) to build a typical blood platelet bank inventory model while attempting to overcome the model's curse of dimensionality in addition to working to solve the developed model; (2) to develop the inventory replenishment policy; (3) to look for the best issuance policies to serve different incoming blood platelet demands; (4) to analyze the effect of having an extra new, artificial, universal blood type alongside the existing eight blood types; and (5) to implement the new model on chain of supply of a single regional bank and varying hospitals. Four objectives were developed to support these purposes; they are as follows:

I. Developing an inventory model of a typical blood platelet bank.

II. Looking for the best issuing policy for different incoming blood platelet demands.

III. Analyzing the effect of having an extra, new, artificial, universal blood platelet alongside the existing natural blood platelets.

IV. Enhancing the dual supply chain model on a network of one regional blood bank and different hospitals.

2.17.1 Developing an Inventory Model of a Typical Blood Platelet Bank Using Approximate Dynamic Programming

The key factor in the blood bank inventory process is blood type. The manager starts the morning by reviewing the inventory and removing any outdated blood platelets. Next, the previous day's order is received and added to the inventory. The inventory is arranged by blood type and age, and the total inventory is counted. Then managers must decide how much to order from each blood type based on the scheduled and expected demand and the history data. Afterwards, the manager should decide which policy should be used to serve the incoming demand. Notice that the blood platelet age is about six-days and demand is uncertain; demand occurs 24/7 while donation takes place only six-days a week, from Monday to Saturday. A blood bank inventory contains eight natural blood types that have a shelf-life between one and six-days. In Table 1.2, 27 natural supply rules are available to serve the demand. 162 (27 $\times 6$ possible ages) blood type supply arcs exist. They are used to represent all possible movements of inventory to satisfy different demand types. The inventory has 48 natural cells (8 blood types $\times 6$ possible ages). The 48 arcs are used to represent all possible movements from the present day's inventory to the next day's inventory. Any blood platelet dose that is more than six-days old must be discarded. Therefore, if the problem is expanded to add different probabilistic demand, it will be too large to solve because of the curse of dimensionality. Because this problem has a large state variables and a large action spaces . This will create a huge outcome spaces, thus, DP is a challenging computational problem. Therefore, most researchers have attempted to downsize, simulate, or partially approximate the current problem, but this does not reflect all aspects of the real-life model.

Powell (2007) proposed the application of approximate dynamic programming (ADP) methods for a blood bank inventory model, but a complete implementation of his model was never reported. ADP can cater to various model state variables while overcoming both dimensionality and time parameters, thereby removing the need to downsize. The purpose is to develop an ADP approach to model the blood bank inventory process with an aim to include the eight blood types and ages. Then it will successfully solve the developed model without any downsizing and overcome the curse of dimensionality as suggested by Powell (2007). Different common policies are discussed on how to satisfy the incoming demand from the available blood platelet inventory. Figure 2.1 describes the proposed model, where a single blood platelet bank with an eight-blood type supply serves a single hospital's demand.

Based on ADP, the problem is solved in two-phases: linear programming model and ADP model. When the process starts on the morning of day t, all the previous day's inventory is aged by one-day. Any blood platelets that are more than six-days old are removed from the inventory because they are outdated. In addition, the pre-ordered blood platelets on the morning of day t-1 with age one are received and added to the inventory on the morning of day t. Next, a combination of the newsvendor model and the current inventory are used to determine the next day's order quantity. After the order quantity is placed, the model is solved to serve the incoming demand and the reward function is maximized. Linear programing is used to solve the first phase, and therefore returns the optimum solution with its dual variables. At the day's conclusion when the actual demand is known, the inventory is updated accordingly. ADP then uses the linear programming output to determine the next day's inventory. This inventory will be the linear programming input for day t+1. The system's performance was evaluated with an attention to four measures of success:

shortage of platelets, expiry, inventory level, and reward gained. This paper was published in Computers and Industrial Engineering, Vol. 78 (12), pp. 259-270, 2014 (Abdulwahab & Wahab 2014).

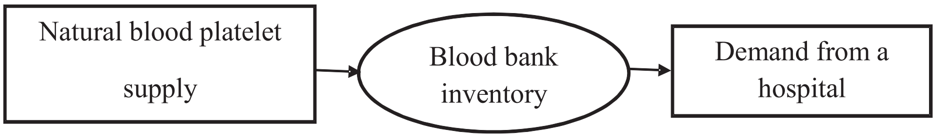

Figure 2.1: Phases I and II

2.17.2 Looking for the Best Issuing Policy for Different Incoming Blood Platelet Demands

The annual platelet production volumes were, to some extent, associated with outdate rates. Platelets are wasted throughout supply chains, and a majority of the losses are a result of outdates. Both a limited shelf-life and unanticipated fluctuations in platelet need emphasize the significance of organizing and controlling monetary and human resources at locations. The challenge of blood platelets is an actual issue of perishable inventory and has three major complicating factors: distinction of blood groups, uncertain demand, and short shelf-lives. Hence these factors should be carefully planned. In addition, hospitals can significantly reduce outdates and shortages by ordering more meticulously. Furthermore, fluctuating need, weekend production stops, and lead time of production all affected any solution. Moreover, there is a lack of production on Saturdays and Sundays, and the lead time of production will affect any solution. Finally, factors such as short shelf-life, high production costs, shortages in donors, a high shortage percentage, and a high outdate percentage are critical and will affect any solution.

The focus of this objective is to develop a blood bank issuing policy based on the model developed by Objective I. A combined Approximate Dynamic Programming (ADP), linear programming, and newsvendor model approach is presented and applied to a blood platelet inventory. This objective considers different issuance policies to serve hospital demand, and tries to give insight on possible beneficial parameters of order strategies. A special interest lies in finding a practical policy that can serve all demands with minimum shortage and outdate percentages. The proposed policies were developed based on a mix of FIFO (First In First Out), LIFO (Last In First Out), and circular policy to satisfy different demand types while complementing research (Prastacos 1984a, Haijema et al. 2007, Blake et al. 2010, Karaesmen et al. 2010). Unfortunately, some models are intractable due to a lack of scalability. Thus, Approximate Dynamic Programming is used to optimize various policies. Finally, data obtained from the CBS was used for testing.

The proposed issuance policies serve different incoming demand types, such as: requests for same blood platelets, any suitable available platelets, high priority new platelets, or low priority platelet substitutions. Each policy has its own steps and methodologies. While working to serve the incoming demand, the policy will attempt to keep shortage, outdate, and inventory levels at a minimum, while maximizing rewards. Later, a comparison will be drawn between all policies to select the best one that achieves the research goals. Figure 2.2 describes the detailed process. The first box on the left shows the inventory node, which is used to service the incoming demands. All used blood will leave the system. The end-of-day inventory will be the next day's inventory, plus the newly arrived blood.

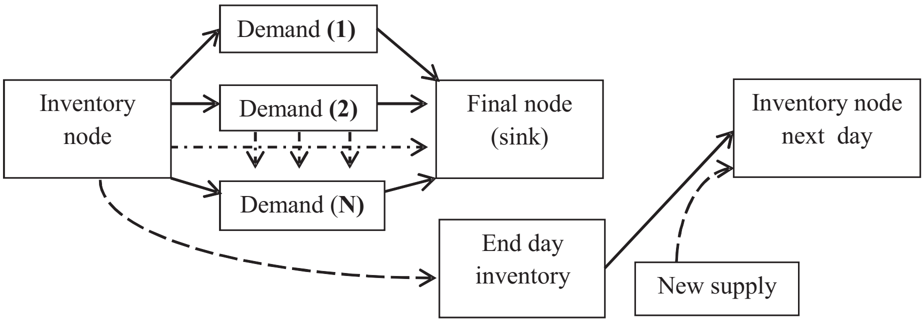

Figure 2.2: Detailed blood bank process

2.17.3 Analyzing the Effect of Having an Additional New, Artificial, Universal Platelet alongside the Existing Natural Platelet Types

Currently, blood bank supply chains of supply are becoming increasingly complicated. As aforementioned, needs for blood platelets and blood bank complexity requires that both hospitals and blood banks be increasingly innovative and cost-effective in collecting, producing, and delivering blood products and services. Regardless of a multitude of developments, blood platelet supply chain management lacks discipline; unsatisfactory addresses have been made concerning actual and practical difficulties.

The only acceptable source of platelets is a healthy human who is willing to donate. This dissertation assumes that the artificial blood will compensate for O- shortages and will improve Canada's blood bank supply chain. As a result, significant interest exists in a synthetic platelet that can mimic natural blood platelet functionality with no side effects. In January 2009 Lasky et al. (2010) succeeded in producing blood platelets from human cells. This enabled blood platelet banks to continually grow platelets in quantities that can ease the tight supply of these critical, short-life blood components. cd

The model is described in Figure 2.3. An inventory model is presented for a blood platelet bank with daily dual supply sources, one artificial and the other natural that serve a single hospital's demands. The supply of eight natural blood types has a six-days shelf-life with a one-day lead time, while the artificial blood platelet has O- properties (Reid & Kim 2006, Lasky et al. 2010) and is assumed to have a one-day shelf-life. The model also considers the fact that patients have the right to refuse transfusion using artificial blood platelets. As far as the author is aware, the problem of a blood bank inventory with dual supply sources (natural and artificial) where patients may accept or refuse artificial blood platelets has not been addressed before.

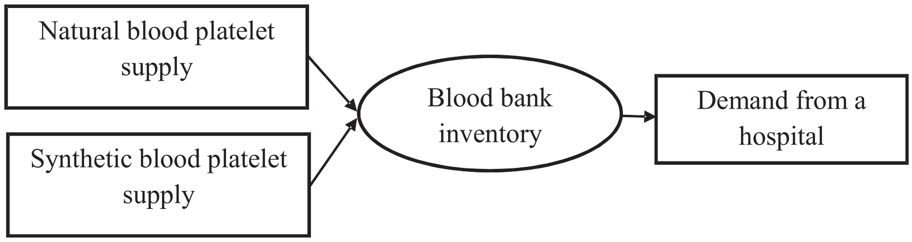

Figure 2.3: Phase III

2.17.4 Developing a Network of One Regional Blood Bank and Different Hospitals

The regional blood bank collects platelets and then distributes them to different blood centers and hospitals. Platelets are delivered on the day following that on which they are ordered; the components of a bag of platelets collected on a Thursday, for example, are ready to be delivered on a Friday. Blood products are ordered from hospitals from the CBS all around Canada on a daily basis (except Quebec). Ontario's CBS used to have four distribution centers: Ottawa, Toronto, Hamilton, and London. It collects platelets from its registered donors in Ontario and provides them to its customers. Ontario is divided into four regions: central; northern and eastern; south-west; and north-west.

The objective is to analyze a regional blood bank inventory system that serves a network of four demand stations within Ontario: Ottawa, Toronto, Hamilton, and London. The bank has dual-supply sources: natural and artificial blood platelets, as in Figures 2.4. The natural blood platelet order quantity is placed at the beginning of the day with a lead time of a single day. The artificial blood platelet order quantity is sent at the beginning of that day and received at the same day. The model also examines the result of patients' acceptance fluctuations on the blood bank and the synthetic platelets. Using actual data, an illustration (numerical) and examination of sensitivity are provided for the purpose of examining the dynamics of management of platelet stock. The hospitals' demand is served either by starting with the largest demand station or by starting randomly. The algorithm in objective III is modified to suit this model. The circular issuance policy proposed in objective II is enhanced to serve the incoming probabilistic demand. The major strategic challenges summarized by Harris (2012) are considered. The artificial blood percentage within the total inventory will be varied from zero up to half of the total inventory, as recommended by Lamme et al. (2010) and Katsaliaki et al. (2014).

Finally, each developed model is evaluated based on the research objective. The developed models were run using a Core i7 computer with 4096 MB of memory running Windows 7. The programming language used to code the model was Matlab 2011.

The dissertation's objectives have been addressed through a structured process consisting of a literature review followed by analysis, modeling, and testing models.

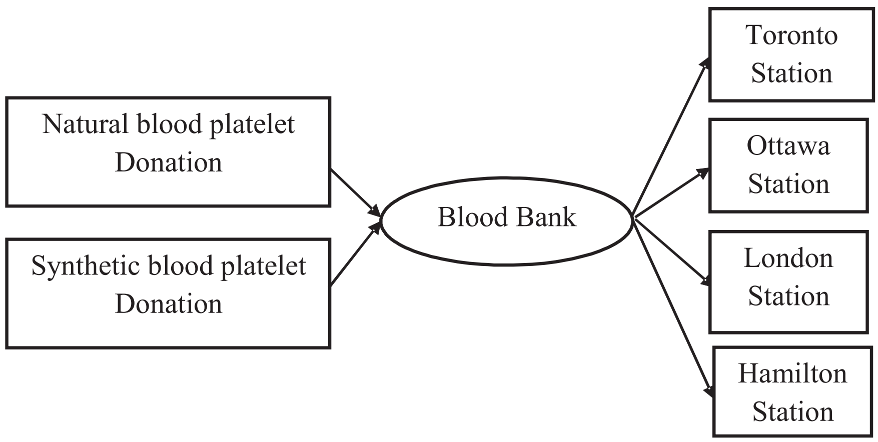

Figure 2.4: Phase IV

Chapter 3

DATA ANALYSIS

In this chapter an analysis of the raw data is presented. The analysis has incorporated several blood bank themes. These include blood types, blood platelets issued, and blood platelets expired. This chapter provides most of the tables that are used in this dissertation.

Blood platelet data was received from the Canadian Blood Services (CBS) for the period (1/4/2009-30/3/2010) for all of Ontario, Canada. Table 3.1 shows a sample of raw daily total blood platelets issued to different blood banks, in addition to expired blood platelets per blood type. The table also shows the source of platelets which is either by the apheresis method or from whole blood. The plan in Canada is to extract 100% of platelets by the apheresis method by 2015 (Canadian Blood Services 2012). The CBS data was used to calculate the demand distribution by day and by station. The data was analyzed and summarized to draw useful summaries. It was grouped by season to discover different parameters that will be used during the research. EasyFit statistical software was used to analyze the data. The following factors were analyzed in the data analysis: (1) blood type percentage; (2) blood bank issued, and expired data; (3) station data distribution; and (4) daily data distribution. Figure 3.1 shows the weekly fitting. It is clear that the data has a repeatable weekly pattern. Therefore , the demand data parameters are calculated per day of the week. The data is also sorted by season. Seasons are best defined in the following manner: the winter season started on December 22nd, the spring season started on March 22nd, the summer season started on June 22nd, and the fall season started on September 22nd. The data from each season are plotted in Figures 3.2, 3.3, 3.4, and 3.5. It can be seen that demand varies from season to season. This is due to variations in temperature, land-based activities, and holidays.

Table 3.1: Sample raw CBS data for 2009-2010

Date	Season	Day of Week	Center Name	Blood RH	Component	Issued	Expiry
01/04/2009	Spring	4	TORONTO	B POS	Aph Plts	3	2
01/04/2009	Spring	4	TORONTO	B NEG	Aph Plt	1	0
01/04/2009	Spring	4	TORONTO	A POS	Aph Plt	15	0
01/04/2009	Spring	4	TORONTO	O POS	Aph Plt	2	0
01/04/2009	Spring	4	TORONTO	A NEG	Aph Plt	5	0
01/04/2009	Spring	4	TORONTO	O NEG	Aph Plt	6	1
01/04/2009	Spring	4	TORONTO	AB NEG	Aph Plt	0	1
01/04/2009	Spring	4	TORONTO	A POS	Plt	29	0
01/04/2009	Spring	4	TORONTO	O NEG	Plt	6	0
01/04/2009	Spring	4	TORONTO	O POS	Plt	23	0
01/04/2009	Spring	4	TORONTO	B POS	Plt	6	0
01/04/2009	Spring	4	TORONTO	A NEG	Plt	3	0
01/04/2009	Spring	4	TORONTO	AB POS	Plt	1	0

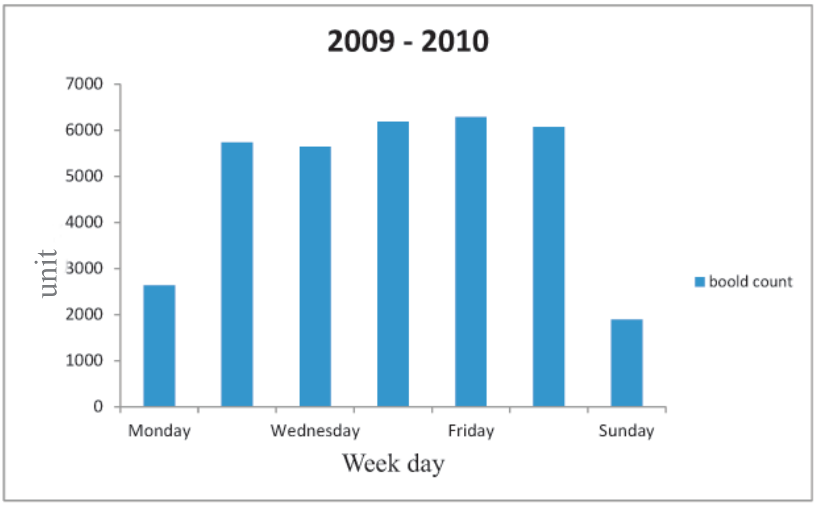

Figure 3.1: Blood platelet data, 2009-2010

3.1 Data Summary

The raw data test of fit was accomplished by means of the Kolmogorov-Smirnov goodness-of-fit test. The purpose of this particular analysis was to discover the data distribution. Most often, it is used to analyze normality. Normality tests are important because a multitude of procedures regarding statistics require them or work best with an assumption of normality. Consequently, one should determine if normality is fulfilled.

The focus of the data analysis is to study it and to find the data behavior. Then the raw data is analyzed to determine whether it in fact fits any known discrete distribution. The raw data fitting is summarized in Table 3.2, which shows the Kolmogorov test for single hospital blood platelet bank data. It presents the five best fitting distributions for each day. The first option is selected

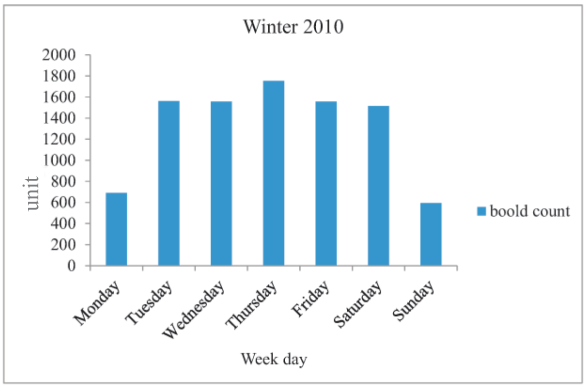

Figure 3.2: Blood platelet data, winter

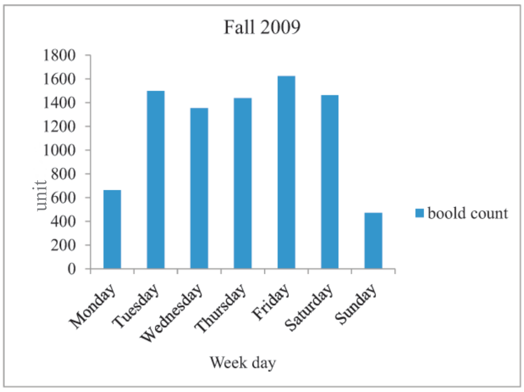

Figure 3.3: Blood platelet data, fall

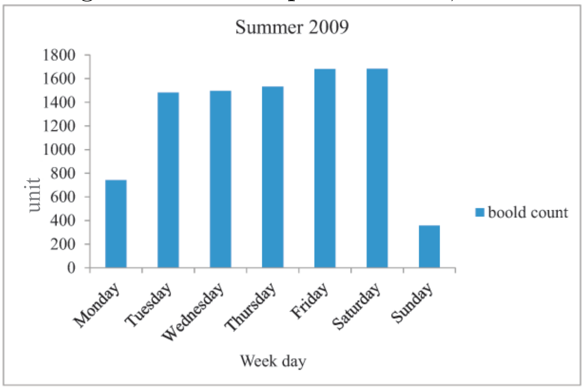

Figure 3.4: Blood platelet data, summer

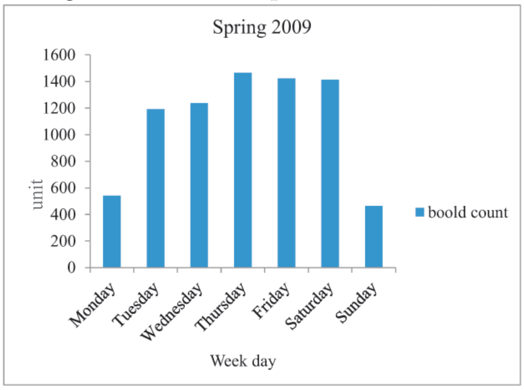

Figure 3.5: Blood platelet data, spring

because it fits the most. Table 3.3 shows the seven days demand. It is used in Chapters 4 and 5 to test the initial ADP model. Table 3.4, which is used in Chapter 6, summarizes the raw data fitting distribution.

Table 3.2: Kolmogorov test of the blood platelet bank data

Day	Sat.		Sun.		Mon.		Tue.		Wed.		Thu.		Fri.		Sat. Sun.	
Distribution	Stat.	Rank	Stat.	Rank	Stat.	Rank	Stat.	Rank	Stat.	Rank	Stat.	Rank	Stat.	Rank	Stat.	Rank
Uniform	0.285	2	0.222	2	0.307	2	0.240	2	0.230	2	0.230	2	0.222	2	0.095	1
Geometric	0.334	1	0.194	3	0.335	3	0.208	1	0.203	1	0.197	1	0.193	1	0.235	3
Logarithmic	0.368	4	0.309	4	0.369	4	0.310	4	0.287	4	0.312	4	0.319	4	0.470	5
N. Binomial	0.521	3	0.261	5	0.526	5	0.286	3	0.279	3	0.281	3	0.273	3	0.203	2
Poisson	0.250	5	0.373	1	0.249	1	0.358	5	0.358	5	0.359	5	0.373	5	0.298	4

3.2 Demand Stations Summary

The raw data in Table 3.1 is summarized by local blood bank locations as in Table 3.5, which shows a sample daily data issued and sorted by date and location. Furthermore, the data in Table 3.5 is again summarized by city and by day of week, as in Table 3.6. It demonstrates the total platelets issued per day of week for demand stations (Toronto, London, Ottawa, and Hamilton). The blood

Table 3.3: Weekly demand data summary and fitting distribution

Type	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.
Demand	Poisson	Geometric	Geometric	Geometric	Geometric	Geometric	Poisson
Parameters	4.41	0.1100	0.1077	0.1015	0.1017	0.1026	3.37

bank's daily issued data fitting by day of the week is summarized in Table 3.7, which is used in Chapter 7. In addition, the blood type percentage demands are summarized in Table 3.8. This table is used in Chapters 4, 5, 6, and 7. It shows that the blood types of the issued quantity do not match the demand quantity, as in Table 4.1.

Table 3.4: Weekly demand data summary and fitting distribution for every station

	Sun.	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.
Distribution	Poisson	Poisson	Uniform	Uniform	Uniform	Poisson	Poisson
Parameters	3.37	56.115	[57, 78]	[49, 68]	[47, 80]	62.462	27.385

Table 3.5: Sample blood platelet data issued, ordered by date and city

Date	Center Name				
Date	TORONTO	LONDON	HAMILTON	OTTAWA	Total
01/04/2009	38	4	7	15	64
02/04/2009	37	4	16	14	71
03/04/2009	37	4	9	15	65
04/04/2009	0	6	6	15	27
05/04/2009	0	0	0	0	0
06/04/2009	31	3	4	7	45
07/04/2009	33	3	15	10	61
08/04/2009	34	8	8	11	61
09/04/2009	36	5	17	14	72
10/04/2009	36	0	0	15	51
11/04/2009	39	4	4	15	62
12/04/2009	0	0	0	0	0
13/04/2009	0	4	2	15	21
14/04/2009	33	4	19	14	70
15/04/2009	30	7	9	11	57
16/04/2009	34	5	18	17	74
17/04/2009	33	4	11	15	63
18/04/2009	0	4	8	9	21
19/04/2009	0	0	0	0	0
20/04/2009	32	5	5	11	53
21/04/2009	34	6	20	16	76
22/04/2009	29	7	8	13	57
23/04/2009	32	3	19	10	64
24/04/2009	40	4	7	16	67

Table 3.6: Blood platelet data issued, ordered by city and by day of week

Center Name	Day of week	Subtotal
TORONTO	1	0
	2	1661
	3	1634
	4	1662
	5	1730
	6	1722
	7	94
TORONTO Subtotal		8503
LONDON	1	0
	2	194
	3	304
	4	303
	5	246
	6	255
	7	224
LONDON Subtotal		1526
HAMILTON	1	0
	2	383
	3	861
	4	499
	5	623
	6	569
	7	490
HAMILTON Subtotal		3425
OTTAWA	1	0
	2	680
	3	709
	4	632
	5	694
	6	702
	7	616
OTTAWA Subtotal		4033
Total		17487

Table 3.7: Blood bank shipment distribution in Ontario

City	Day	Sun.	Mon.	Tue.	We	Thu.	Fri.	Sat.
Toronto	Distribution	Uniform	Uniform	Neg. Binomial	Poisson	Neg. Binomial	Neg. Binomial	Uniform
Toronto	Parameters	[28, 73]	[52, 110]	$n = 49$ $p = 0.3837$	90.6420	$n = 154$ $p = 0.6275$	$n = 39$ $p = 0.3101$	[15, 54]
London	Distribution	Uniform	Uniform	Neg. Binomial	Neg. Binomial	Uniform	Poisson	Uniform
London	Parameters	[8, 30]	[52, 110]	$n = 23$ $p = 0.5531$	$n = 17$ $p = 0.4724$	[12, 29]	19.4420	[4, 19]
Hamilton	Distribution	Uniform	Poisson	Neg. Binomial	Neg. Binomial	Uniform	Poisson	Uniform
Hamilton	Parameters	[3, 23]	34.3650	$n = 18$ $p = 0.3112$	$n = 14$ $p = 0.3119$	[22, 51]	38.0770	[0, 23]
Ottawa	Distribution	Neg. Binomial	Uniform	Uniform	Neg. Binomial	Poisson	Uniform	Neg. Binomial
Ottawa	Parameters	$n = 4$ $p = 0.3036$	[25, 50]	[21, 44]	$n = 40$ $p = 0.5278$	39.3080	[24, 52]	$n = 11$ $p = 0.4437$
Total	Distribution	Neg. Binomial	Neg. Binomial	Neg. Binomial	Neg. Binomial	Neg. Binomial	Neg. Binomial	Uniform
Total	Parameters	$n = 35$ $p = 0.3045$	$n = 42$ $p = 0.1980$	$n = 103$ $p = 0.3736$	$n = 100$ $p = 0.3599$	$n = 295$ $p = 0.6116$	$n = 34$ $p = 0.1575$	[47, 96]

Table 3.8: Blood type issue distribution percentages in Ontario

Blood type	Total	Percent
AB POS	2832	5.2484
AB NEG	655	1.2019
A POS	18556	34.0380
A NEG	4010	7.3561
B POS	5925	10.8743
B NEG	1221	2.2406
O POS	16224	29.7612
O NEG	5135	9.4384

Chapter 4

APPROXIMATE DYNAMIC PROGRAMMING MODELING FOR A TYPICAL BLOOD PLATELET BANK

This chapter provides an analysis and a summary of the results obtained for Objective I: build an inventory model of a typical blood bank.

4.1 Introduction

The blood platelet challenge is an actual perishable inventory issue of considerable human interest. Three primary elements complicate platelet production challenges: differential groups of blood; fluctuating demand; and the blood platelets' short shelf-life. Hence, these factors should be carefully planned with blood bank costs.

The focus of this chapter is to develop an ADP model as suggested by Powell (2007). Moreover, the developed multi-period, multi-product model addresses some of the previously listed gaps and overcomes the curse of dimensionality issue. It considers several factors. First is the eight blood types with stochastic demand and deterministic lead times. Second is the use of a combination of a newsvendor model and current inventory to limit the order quantity variation; to understand the demand uncertainty and distribution; and to use special distribution to generate demand on a daily basis. The third factor is the use of linear programing to optimally solve the phase-one inventory model while looking for an effective policy to serve different demand types. Examples include the same blood type or substitution with suitable blood types. The fourth factor is how to solve the complete model without any downsizing. Lastly, the fifth factor is the study of a suitable O- percentage within the total inventory because it is a universal blood type. In addition, a piecewise linear function is utilized to approximate value functions. The value function will be used to optimize the phase-two model and to suggest the best inventory cell to use to serve incoming demand. The effectiveness of the system's performance is evaluated in regards to four measures: shortage of blood platelets, expiry, inventory level, and reward gained. The Canadian Blood Service's (CBS) data was processed and analyzed to determine the different parameters and statistical distributions that were needed during the research.

The rest of Chapter 4 is organized in the following manner: Section 4.2 briefly summarizes and explains the problem and the proposed ADP model, including both single and multi-period models; Section 4.3 presents algorithm fine tuning and policy controls; Section 4.4 discusses outcomes given by the model; and finally, Section 4.5 summarizes the conclusions.

4.2 Model Description

When each day of week commences, all outdated platelets (D_{ij}) are removed from the inventory. Then a decision is made on the platelet ordering quantity (p_{ij}). This decision is based on the newsvendor model, the weekday, and the current available inventory (z_{ij}). The inventory state (z_{ij}) (i × j) is a matrix where: $i = 1, 2, \ldots, 8$, blood types, $j = 1, 2, \ldots, 6$, blood age and 6 is the maximum shelf-life in days. The demand (y_i) occurs seven-days a week, while order quantity (p_{ij}) occurs six-days a week from Monday to Saturday. The demand distributions are day dependent, as in Table 3.3. Another decision regarding the issuing policy is made to serve the incoming demand. Any unserved demand (u_t) is to be counted as a shortage with a high cost and served from any other blood bank. Issuing the oldest items first reduces outdating and minimizes cost; this is done by introducing a penalty cost for using the new blood. In addition, holding cost, shortage cost, and outdate cost are considered. Shortage cost is five times more than outdate cost. The demand is satisfied with the same or suitable substitutable blood types, as in Table 1.2. The model is a discrete event, multi-product, multi-period model for a single blood bank that serves a single hospital. The algorithm runs for one year, which is $t = 1, 2, ..., T$, and repeated for n steps. Real data from the CBS is used to calculate the blood type percentage and to find the suitable distribution[1]. The newsvendor model, in addition to the existing inventory, is used to calculate the optimal order quantity that can mirror the demand behavior. Moreover, the ABO match is preferred while the RH is not a requirement for all patients (National Blood Centers 2004). It is assumed that the inventory has a limited capacity for each blood type, that there are no PLTs mishandled, and that

[1] Actual Data is received from CBS in Ottawa for Apr 2009: http://www.bloodservices.ca

Table 4.1: Blood type percentages

Type	AB+	AB-	A+	A-	B+	B-	O+	O-
Percentage	5.2	1.2	34	7.3	10.9	2.2	29.8	9.4

any unsatisfied demand is considered shortage, served by ordering blood from other neighborhood blood banks. Phase one is solved by Linear programming and Phase two is solved by ADP.

A demand can be fulfilled in one of the following ways: with new platelets of any age, with no substitution; with possible substitutions; and through substitution with O-, which will give the least reward to keep O- as the final general reserve or universal blood type. Two recommendation elements are to be found. The first recommendation is about the daily platelet order size for each blood type. The second recommendation is regarding the issuance policy used to fulfill the incoming demand. In the first recommendation, the newsvendor model is used to determine the daily optimal inventory level. This quantity is then used with the current inventory and the expected demand to calculate the daily order quantity. For example, Monday's data follows a Poisson distribution with $\lambda = 4.41$, shortage penalty = 100, and outdate penalty = 20. Thus, the critical ratio = $(100/(100+20)) = 0.833$, and the optimal inventory = 6. After calculating optimal daily inventory, the amount ordered is the minimum of (optimal daily inventory - current stock with age 6, yesterday's demand). In addition, the order quantity must not exceed the maximum inventory capacity. Moreover, the CBS demand data is analyzed to find the demand distribution per day. Thus, demand is generated using the demand distribution. The last step is to multiply both supply and demand with the blood type percentage, as in Table 4.1, to calculate the demand and supply per blood type. Table 4.1 shows the blood type percentages in Canada (Canadian Blood Services 2012).

The second recommendation point is the issuance policy. They suggest which policies are to be deployed, such as First In, First Out (FIFO) or Last In, First Out (LIFO). Therefore, the identification of a good inventory policy that balances outdating, shortage, inventory, and rewards is a key concern for decision makers.

4.2.1 Linear Programming Model

The problem is formulated as a multi-period model in which decisions are made sequentially. Eight blood platelet types exist, with six possible ages and a set of 27 predefined substitution rules. Thus the network is composed of 162 (27×6) supply nodes, eight demand nodes, and 48 inventory nodes. The model is represented by the networks in Figure 2.2. The process starts with the addition of the newly arrived platelets and the removal of outdated units, followed by serving the incoming demand. At the day's conclusion, all inventory is updated with the actual demand and supply. Next, the order-up-to level inventory decision is taken. Moreover, all inventory at the beginning of day $t+1$ are aged by one more day. Then, any blood platelet that is more than six-days old is removed from the inventory (outdated). In addition, at day $t+1$, the newly received blood platelets with an age of one-day will be added to the inventory. All the blood platelets used from the supply nodes to fulfill the demand will leave the inventory system. For example, the decision taken to transfuse a unit of O+ blood platelets which are three days old, for a demand for blood platelet type A+ is represented by the flow of a unit of blood platelet first from inventory cell of blood type O+ with age 3 days to the suitable supply node, then to the A+ demand node, then from the A+ demand node to out of the system. Unused blood platelets that have reached maximum age must be totally discarded from the system.

Next, the newsvendor model, as noted by Blake et al. (2010), is used to determine the next day's order quantity. Moreover, the blood platelet shortage cost is C_u and the outdate cost is C_g. Therefore, the newsvendor critical ratio is $C_u/(C_u + C_g)$. The optimal inventory of the newsvendor model is:

$$Q_t = F^{-1}\left[C_u/(C_u + C_g)\right]. \tag{4.1}$$

Where F^{-1} is the inverse function. The manager places the next day order quantity p_{t+1} based on the previous day's demand y_{t-1}. The newsvendor model is used to calculate the order-up-to inventory level Q_t. Thus, the daily order quantity p_{t+1} is the minimum of the order-up-to inventory level minus total blood units with age 6 days or the previous day's demand as follow:

$$p_{t+1} = Min\left((Q_t - \sum_{i=1}^{8} z_{i6,t}), y_{t-1}\right). \tag{4.2}$$

Then, the blood bank begins to serve demand based on blood platelet substitution relationships, as in Table 1.2. Let M_k be the set that consists of substitutable blood platelet types as follows:

$$M_1 = (AB+, AB-, A+, A-, B+, B-, O+, O-), \tag{4.3}$$

$$M_2 = (AB-, A-, B-, O-), \tag{4.4}$$

$$M_3 = (A+, A-, O+, O-), \tag{4.5}$$

$$M_4 = (A-, O-), \tag{4.6}$$

$$M_5 = (B+, B-, O+, O-), \tag{4.7}$$

$$M_6 = (B-, O-), \tag{4.8}$$

$$M_7 = (O+, O-), \tag{4.9}$$

$$M_8 = (O-), \tag{4.10}$$

For example, M_1 means that demand of blood type 1 or AB+ is served by all blood types, while M_8 means that demand of blood type 8 or O- is served only by blood type O- In addition, I_t is the start of the day's inventory. At the post-decision state variables (i.e., at end of day t); the variable is updated with the new information that arrives during day. So the starting inventory I_t at the start of the day will be:

$$I_{ijt} = z_{i,j-1,t-1} \;\; \forall \;\; i = 1, 2, ..., 8 : \; j = 2, 3, ..., 6 : \; t = 1, 2, ..., T, \tag{4.11}$$

$$I_{i1t} = p_{i1t} \;\; \forall \;\; i = 1, 2, ..., 9 : \; t = 1, 2, ..., T, \tag{4.12}$$

and the outdated D_{i6t} equation is:

$$D_{i6t} = z_{i6,t-1} \;\; \forall \;\;\; i = 1, 2, ..., 8 : \;\;\; t = 2, 3, ..., T. \tag{4.13}$$

and the demand y_t equation is:

$$\sum_i y_{it} = y_t. \tag{4.14}$$

The total shortage is the same as the difference between total demand y_t and total blood removed from inventory to serve each demand k:

$$\sum_i \sum_j x_{ijt} + \; u_t = y_t \;\; \forall \, t = 1, 2, ..., T, \tag{4.15}$$

$$\sum_{i \in M_k} \sum_{j=1}^{6} x_{ijt} \;\; \leq \;\; y_{kt} \; \forall \; k = 1, 2, ..., 8 : \;\; t = 1, 2, ..., T, \tag{4.16}$$

$$\sum_j z_{ijt} \leq N_{it} \;\; \forall \; i, \tag{4.17}$$

Finally, all variables should be non-negative:

$$x_{ijt} \geq 0, \;\; z_{ijt} \geq 0, \;\; u_t \geq 0, \;\; D_{i6t} \geq 0. \tag{4.18}$$

Constraints (4.3 to 4.10) describe the substitution relationship between demand and supply. Constraints (4.11) shows the starting inventory at time t. Constraint (4.12) shows that the order quantity, p_{i1t}, received at day t will enter the inventory with age 1 day. Constraint (4.13) calculates the amount of outdated units. Constraint (4.14) ensures that total demand equals the summation of all blood types demand. Constraint (4.15) insures that the summation of all served demand plus shortage equal total demand. Constraint (4.16) specifies that the total amount of blood platelets assigned to satisfy a type of demand cannot exceed that demand. Constraint (4.17) shows that each blood type has a maximum capacity that cannot be exceeded. Finally, constraint (4.18) specifies that all flow must be non-negative.

Table 4.2: Set of rewards for different demand types

Description	Value
Fulfill demand with the same blood type	50
Fulfill demand with a suitable blood type	45
Fulfill demand with new blood	0.5 ×age
Holding cost	0.2
Outdate cost	20
Shortage cost	100

4.2.2 Reward Function

This model's goal is to decrease both blood platelet shortage and outage as much as possible while maximizing the total rewards, simultaneously keeping the inventory level to a minimum by satisfying the different demand types using a suitable policy. As a result, a reward parameter is assigned to every arc in the network. The reward can be zero, positive, or negative. There are 162 possible methods or arcs that can be used to serve incoming demand from the current inventory. Same blood type arcs have the same reward value. The substitution arcs (except O-) have a lower reward value and the O- substitution arcs have the lowest reward value (to encourage keeping O- as a final choice). Forty-eight arcs are used to represent all possible movement from the current day's inventory to the next day's inventory and result in a penalty holding cost. In addition, lower penalty is assigned to the newest platelets, while a higher penalty is assigned to the oldest platelets to encourage their use. The set of reward parameters is described in Table 4.2. Notice that the shortage penalty is five times the outdate penalty, as suggested by Blake et al. (2003). Indeed, there are penalties connected with the gathering, analysis, labeling, and shipping of the donated product, but they are not considered in the developed model. The reward function is

$$\begin{aligned} \max\ C_t(I_t) \quad &= C_d\ \textstyle\sum_{k=1}^{8}(y_{kt} - \sum_{i\in M_k\ and\ i=k}\sum_{j=1}^{6} x_{ijt}) + C_r\ \sum_{k=1}^{8}(y_{kt} \\ &- \textstyle\sum_{i\in M_k\ and\ i\neq k}\sum_{j=1}^{6} x_{ijt}) - C_u u_t - C_g D_{i6t} -\ 0.5\sum_j\ (j\sum_i x_{ijt})\,. \end{aligned} \tag{4.19}$$

The basic parameters are defined as the reward for the use of blood platelets that are six-days old. In the case using of blood platelets that are less than six-days old, the reward value is lower by a pre-set penalty of 0.5 for each day to encourage using older platelets. Finally, if blood platelets with an age of six-days are not used on that day (since they will no longer be usable and will be discarded), a penalty of 10 is assigned as an outdate penalty. However, for any unsatisfied demand a penalty of 100 is assigned and the unsatisfied demand is lost. For example, the use of AB+ blood platelets that are two days old to satisfy an A+ demand will have an award of 45 (substitution) – 2 (two days old) = 43. Similarly, the holding of four day old B+ blood platelets will give a penalty of 0.2 per day.

4.2.3 Approximate Dynamic Programming Model

The simplest policy to solve this optimization problem is to disregard the impact of decisions on the future and only focus on the total contribution in the same period that the decision is made. This is called a myopic policy. Myopic policies only focus on the present. The effect of the current decision on future contributions is captured using ADP. The decision function for a myopic policy is given by:

$$V_t^n = arg\ max(C_t(I_t^n, x_t)). \tag{4.20}$$

Because of the "curse of dimensionality", ADP is used to solve the finite-horizon problem and to capture the effect of the current decision on future contributions. The ADP framework starts from the Bellman's equations:

$$V_t(I_t) = max(C_t(I_t, x_t) + \gamma\ E\ [V_{t+1}(I_{t+1}(I_t, x_t, W_{t+1}))]). \tag{4.21}$$

x_t needs to be solved as follows:

$$x_t = arg\ max(C_t(I_t, x_t) + \gamma\ E\ [V_{t+1}(I_{t+1}(I_t, x_t, W_{t+1}))]), \tag{4.22}$$

where W_{t+1} is best described as the expected next-day demand. V_{t+1} is approximated by $\bar{V}_{t+1}$. Some exogenous information is not available until day t, but the value function can be approximated using a simulation. After n iterations, the model steps advance in time using the value function approximation obtained from the previous step $n-1$, i.e., $\bar{V}_t^{n-1}(I_t)$. There are different methods available to approximate a value function. In this study, a piecewise linear functions is used. These can be easily estimated, and allow us to solve the model using linear programming. The relevant value function $\bar{V}_t^{n-1}$ can be calculated as:

$$\bar{V}_t^{n-1}(I_t) = \sum v_t^n x_{ijt}. \tag{4.23}$$

The inventory is composed of 48 cells. The function v_t^n is represented by a series of 480 parallel arcs (each inventory cell, z_{ijt}, is divided into 10 intervals). Each arc in a series corresponds to an interval of the value function approximation $\bar{V}_t^{n-1}(I_t)$, and each parallel arc has a reward. Every arc has an upper flow limit, and the blood platelets from the holding node flow through the first arc until they attain their upper flow limit. They then continue to flow to the second arc and the process is repeated. This model is a finite horizon model, using a discrete formulation of the value function so that there is no need to loop over all states. When a distinct state is visited, the value's slope in that particular state is updated. Not all states are visited at the time of every iteration; therefore the value function is initialized to reflect concave properties. This model applies a pure exploitation strategy, meaning that decisions are made so that the maximum possible reward is obtained with the given information. The decision vector x_t can be determined by:

$$x_t^n = arg\ max(C_t(I_t^n, x_t) + \gamma\ \bar{V}_t^{n-1}(I_t^x)), \tag{4.24}$$

where γ is the discount factor used to discount the future reward. The optimization problem is solved using linear programing.

In addition, the current day's order quantity, p_{t+1}, is ordered, and the previous day's order quantity, p_t, is received; the actual demand y_{kt} is known by the end of day t. After solving the linear programming model, the inventory is updated with the actual data at the end of day t (post-decision variables received from the linear programming):

$$I_t^x = \sum_i \sum_j (I_{ijt} - x_{ijt})\ \ \forall\, i,\ j, \tag{4.25}$$

where x_{ijt} represents the actual platelet doses removed from inventory to serve the demand y_{kt}.

The ADP solution is then used to determine the next day's inventory for the linear programming model

$$I_{t+1} = \ I_t^x + \sum_i \sum_j p_{ij,t+1}\ , \tag{4.26}$$

where p_{i1t+1} is the donation during day t+1. This will be the next day inventory for single period model.

Updating the Value Function Approximation

The values assigned to the parallel arcs refer to the slopes of the value function approximation and the value function is updated using derivatives with respect to the inventory state (Powell 2007). Solving a suggested optimization problem with a linear program yields a dual variable v_t^n. This dual variable is an estimate of $\frac{(\partial \bar{V}_t(I_t))}{(\partial I_t)}$ at the point $I_t = v_t^n$. In addition, the dual variable v_t^n can be used to estimate the derivative of $\bar{V}_t(I_t)$:

$$\frac{(\partial \bar{V}_t(I_t))}{(\partial I_{t-1})} = v_t^n. \tag{4.27}$$

Dual variables give a vector of derivatives of the piecewise linear approximations. These duals are stochastic gradients of $\bar{V}_t(I_t)$. There are two different slopes, one on each side:

$$Left\ slope : v_t^- = \bar{V}_t(I_t) - \bar{V}_t(I_t - 1). \tag{4.28}$$

$$Right\ slope : v_t^+ = \bar{V}_t(I_t + 1) - \bar{V}_t(I_t). \tag{4.29}$$

The dual variable v_t^n is in the range $v_t^{-,n} \le v_t^n \le v_t^{+,n}$. Once v_t^n has been computed, the value function approximation $\bar{V}_t^n$ is updated.

CAVE Algorithm

In amending value function approximation, one must ensure that it is concave. This is done using the concave adaptive value estimation (CAVE algorithm) (Godfrey & Powell 2002). CAVE uses stochastic samples of left and right gradients to build a piecewise linear concave value function approximation. The slope is updated at arc $a = I_{t-1}$, where a is the set of intervals affected in the last step. This results in either $v_t^n(a) > v_t^n(a-1)$ or $v_t^n(a) < v_t^n(a+1)$, and may affect the concavity of the value function.

CAVE looks at both sides of the parallel arc (the interval) being updated, and determines whether the concavity condition has been violated. The CAVE algorithm for inventory I_t works as follows:

$$\bar{V}^n_{t-1,a-1}(I_{t-1}) = \begin{cases} (1-\alpha_{n-1})\bar{V}^{n-1}_{t-1,a-1}(I_{t-1}) + \alpha_{n-1}v_t^n, & \\ & \bar{V}_{t-1,a}(I_{t-1}) > \bar{V}_{t-1,a-1}(I_{t-1}) \; . \\ \bar{V}^{n-1}_{t-1,a-1}(I_{t-1}), & \text{otherwise.} \end{cases}$$

$$\bar{V}^n_{t-1,a+1}(I_{t-1}) = \begin{cases} (1-\alpha_{n-1})\bar{V}^{n-1}_{t-1,a+1}(I_{t-1}) + \alpha_{n-1}v_t^n, & \\ & \bar{V}_{t-1,a+1}(I_{t-1}) > \bar{V}_{t-1,a+2}(I_{t-1}). \\ \bar{V}^{n-1}_{t-1,a+1}(I_{t-1}), & \text{otherwise,} \end{cases}$$

where α is the step-size smoothing factor, and $t-1, a-1$ are the set of affected intervals or inventory cells. This will be illustrated with an example. Assume one has 75 units of blood type A+ with age 3 days on day t-1, and uses 55 units but holds 20 units. A day later (i.e., day t), one receives a supply of 25 units of blood type A+ with age 0. This means one has a total of 45 units of A+ on day t. The dual value obtained for 45 units of A+ on day t should be used to update the slope of the value function corresponding to having 20 units of blood type A+ with age 3 days on day t-1 - not the value function for blood type A+ with age 0 days on day t-1.

4.3 Algorithm Fine-tuning

The following algorithm is a single-pass version of ADP. The algorithm runs for one year, where $t = 1, 2, \ldots, 365$, and is repeated for n steps, where n = 1, 2, …, 200.

Step 0: Initialization

Step 0a: Initialize $\bar{V}_t^1, \quad \forall\, t \in T$

Step 0b: Set $n = 1$ and $t = 1$

Step 0c: Initialize I_t^1

Step 0d: Decide on a sample path w and generate random demand and supply

Step 1: Do for $n = 1, 2, \ldots, N$:.

Step 2: Do for $t = 1, 2, \ldots, T$:.

Step 2a: Find the solution for the optimization problem and let x_{ijt}^n be the value that finds the model's solution.

Step 2b: save the dual variable v_t^n.

Step 2c: Update $\bar{V}_{t-1}^{n-1}$ around the value of the $t > 0$ policy using v_t^n and the step-size.

Step 2d: Update the current state.

Step 2e: Compute the next state space I_{t+1}^2 using the generated demand and supply.

Step 3: Increment t by one. if $t \leq T$ go to Step 2

Step 4: Increment n by one. if $n \leq N$ go to Step 1

Step 5: Return

An effective model requires a lot of fine-tuning. There are many parameters in the model that can be adjusted to improve it.

4.3.1 Step-size

It is important to select a suitable step-size which will affect value function convergence as well as value function smoothing. Constant step-sizes are not used because an extremely large number of iterations is needed to see convergence. This is a stochastic model, so the step-size must have the following properties (George & Powell 2006):

$$\alpha_n \geq 0 \tag{4.30}$$

$$\sum_{n=1}^{\infty} \alpha_n = \infty \tag{4.31}$$

$$\sum_{n=1}^{\infty} \alpha_n^2 < \infty \tag{4.32}$$

The first constraint shows that the step-sizes must be non-negative. The second constraint shows that the endless sum of step-sizes must be infinite. In the event that this condition does not stay, the algorithm may stall too early. The third constraint shows that the infinite sum of the squares of the step-sizes has an end. This condition, in use, necessitates that the step-size successive arrangement converges hurriedly. This model will implement step-size with the following format:

$$\alpha_n = \frac{b}{(b+n-1)}, \tag{4.33}$$

where α is the step-size smoothing factor and b is a suggested divider. This step-size rule satisfies Equations (4.31), (4.32), and (4.30) which are required for convergence. It has behavior similar to a *1/n* step-size, but as b increases, the rate at which the step-size declines with respect to iterations slows. Different values assigned to b (b: 1, 2, 4, 8, and 12) were tried to check how fast the solution is approached. The number of iterations for the myopic policy was 17 iterations, while the number of iterations for the suggested policies varied between 80 and 84. A step-size with $b =$ 8 is an ideal step-size for monitoring convergence and smoothing. This step-size was used to assess convergence of the reward function, since it approaches zero much more slowly than when $b = 1$, but shrinks fast enough to achieve convergence within a few iterations. The step-size successfully inhibits convergence occurring too early while allowing speedy convergence to an optimum solution.

4.3.2 Flow Limits of the Parallel Arcs

Inventory is modeled as a series of 48 cells. Each cell is divided into ten parallel arcs. Each arc corresponds to part of the separable, piecewise linear function over an interval of z_{ijt} which is determined by the flow limits specified for that arc and the previous arcs. For example, if the first arc has a flow limit of $a_1 = 5$, and the second arc has a flow limit of $a_2 = 9$, then the second arc will represent the value function approximation over the interval of $5 < z_{ijt} < 14$. For convenience, the same flow limit is applied on all arcs except the last one, which is unbounded. The parallel arc system is controlled by two parameters - the total number of arcs (in each series), A, and a multiplier m. The multiplier m determines the flow limits of parallel arcs as:

$$L_{ba} = \begin{cases} \lceil U_s m/A \rceil, & \text{if } (a \neq A). \\ \infty, & \text{if } a = A. \end{cases} \tag{4.34}$$

Where $\lceil X \rceil$ is the smallest integer greater than or equal to X, and U_s is a parameter in the developed model that sets the upper bound for the demand. The parameter A should be set according to the range of z_{ijt}. Moreover, most hospitals and blood centers typically maintain a blood platelet inventory level of three days' worth of supply (Blood Book 2011). To be as realistic as possible, $m =$ 0.5 and $A = 10$ were chosen so that the last arc will be updated when z_{ijt} is equal to approximately three to four days of supply.

4.3.3 Optimal Policy Analysis

This section assesses and compares how well different blood platelet allocation policies perform in different scenarios. The assessment criteria are as follows:

I. Total Contribution Function Value: The total reward function value is a convenient way to compare alternative policies. A policy that gives a higher total reward function value is not necessarily *better* than one that gives a lower reward. This is because blood Shortage is more important.

II. Shortage Percentage: To obtain a meaningful analysis, a second assessment criterion will be needed. The main objective is to satisfy all demands. Thus, it has been decided to measure the success of an allocation policy through the percentage of unsatisfied demand (i.e. shortage). Specifically, we measure (i) the percentage of unsatisfied demand in an average day and (ii) total shortages over the entire period. As aforementioned, it is obvious that an allocation policy is better than another if it results in fewer shortages.

III. Outdate Percentage: In addition to shortage, a third assessment criterion will be needed. One of the objectives is to reduce the blood platelet outdates. If a policy gives a higher contribution, a low shortage but a high outdate is not an acceptable policy.

IV. Average Inventory Level: Moreover, a fourth assessment criterion will be needed. An average inventory level criterion is important. The average inventory level should be between 1 to 4 days of need. The best policy should give a minimum shortage, a minimum outdate, and a high contribution with a low average inventory level.

V. Myopic Model: Further assessment criterion is to consider the developed model in comparison with a myopic one. A myopic model disregards the impact of the future and focuses only on the total reward in the same period in which the decision is made. To see how well the ADP model solves the blood platelet problem, its performance is compared with a myopic policy. The myopic policy is essentially the same as proposed model, except that the value function is always zero and will never be updated. In other words, the myopic policy only focuses on maximizing the contribution function value in the current time period, and does not consider the effect on the future when making allocation decisions.

The proposed models solve the problem in two steps. Linear programming is used in the morning with the expected available information to solve the Phase one. At the end of the day where all actual information is known, the inventory is updated and ADP is utilized to formulate a solution for the step two model and estimate the next day's inventory, and it then optimizes the complete model again. In the myopic model, linear programming is used with the expected available information to solve the step one model and suggest the final solution.

All criteria are important, and the most important one is that of shortage, because it puts human lives at risk. Outdate is the second most important criterion because the platelets are a unique expensive limited resource. When inventory level is low with a high reward, it will support the policy with the lowest shortages and outdates.

4.3.4 Model Calibration

To examine how well the Approximate Dynamic Programming model solves the blood allocation problem, the following factors need to be considered.

Random Sample Realization

Each day has its own unique distribution. The distribution parameters vary; they depend upon the week day. The created need and donation are multiplied by the blood type percentage to find the daily demand and donation for each blood type.

Calibration of Parameters

Before running the ADP model, one must evaluate and calibrate the following parameters:

1. Select a favourable initial value function that suits the model's behavior.
2. The value function approximation should capture the problem structure.
3. Select a favourable stepsize because the wrong stepsize formula can ruin an ADP algorithm.
4. Select a reasonable and favourable discount factor.

Training of the Value Function

Before the model can be tested, it is essential to sufficiently train it so that the value function is adequately updated based upon a specific supply and demand distribution. When the value function smoothing no longer produces large modifications, the training phase is complete, or the convergence of the averaged contribution function value across iterations is used to check if the value function is adequately trained.

Assessing Convergence

The optimality equation is solved in each iteration, to determine the optimal solution given to the set of contribution parameters and value function slopes. The decision vector that is returned from the Linear Programming solver is the optimal set of decisions based on the one-period contribution plus the discounted future value of any blood platelets held to the next-period. The purpose of including the value function (or more specifically the slopes arising from it) is to increase the solution's quality. To measure convergence, however, contribution function is examined. Therefore, plotting the contribution function over all iterations provides a reasonable reflection of convergence.

In addition, the variance can be calculated as follows:

$$\sigma^n = ((1 - \alpha_n)\sigma^{n-1} + \alpha_n(V_{t-1}^n) - \bar{V}_{t-1}^n)^2 \tag{4.35}$$

The step-size given in Equation (4.33) with $b = 8$ is used for the variance smoothing. This variance is initialized at zero and is updated throughout all iterations. The reason for updating the variance estimate is that it allows for a 95% confidence interval to be calculated by the following equation:

$$95\%CI : [\bar{V}^n - 1.96(\sqrt{\sigma^n}/n), \bar{V}^n + 1.96(\sqrt{\sigma^n}/n)] \tag{4.36}$$

This confidence interval gives an indication of the accuracy of the reward functions as well as an indication of convergence as the interval shrinks.

4.4 Results and Discussion

ADP methodology is used to solve the developed model and to overcome the curse of dimensionality. Then three different supply policies - FIFO, LIFO, and Circular - are used to serve different incoming demands. In circular policy, the selection process is based on the reward function as given in Table 4.3. In circular policy the oldest platelets are used first, starting with the same blood type. For example, in Table 4.3, the demand for AB+ is served, starting with the same blood type (AB+) with an ages of six days. If there is not enough AB+, then demand is served using a suitable blood type (O-, O+, B-, B+, A-, A+, AB-) with an ages of six days. If an age of six days inventory is not enough to satisfy the AB+ demand, then units with an age of five days are used starting with AB+ units. This continues down to the last choice of O-. This sequence starts with the highest profit of \$50, then \$49.5, \$49,.etc. This policy gives an equal chance to all blood types. The suggested

Table 4.3: Circular policy reward function for blood type AB+

Age \Type	O-	O+	B–	B+	A–	A+	AB–	AB+
1	47	47	47	47	47	47	47	47
2	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5
3	48	48	48	48	48	48	48	48
4	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5
5	49	49	49	49	49	49	49	49
6	49.5	49.5	49.5	49.5	49.5	49.5	49.5	50
7	-10	-10	-10	-10	-10	-10	-10	-10

policies are compared with a myopic policy that does not consider the inventory changes during the day.

The inventory was initialized as 0, 1, 2, 3, and 4 days needs to select the optimal initial inventory, as in Figure 4.1. The figure shows that as the initial inventory increases, the shortage percentage approaches zero and the outdate increases. The minimum inventory level will not be less than two

Table 4.4: Comparison of the three policies

Policy	Outdated	Shortage	Total Inv.	Reward	Myopic Outdated	Myopic Shortage	Myopic Total Inv.	Myopic Reward
FIFO	4.6	3.9	58	4.5×10^5	9.6	6.4	62	2.1×10^4
Circular	5.0	4.8	59	3.5×10^5	9.5	5.5	63	2.2×10^4
LIFO	5.8	7.3	62	1.5×10^5	9.8	8.1	69	2.0×10^4

days' worth of supply, with shortages of 3.9% and outdated units at 4.6%. The results regarding shortages, outdated units, inventories, and rewards are summarized in Table 4.4.

The model is run daily for 365 days and repeated for 200 times. Tables and figures are done based on 95% confidence interval as in equation 4.36. Table 4.4 shows that the shortages for all policies range from 3.9% to 7.3%, while the outdated units vary between 4.6% and 5.8%. FIFO shows the lowest inventory level when compared to the other policies. It is clear from Table 4.4 that FIFO shows the best results that satisfy multiple research goals (i.e., to minimize shortages, minimize outdated units, minimize average inventories, and to maximize rewards).

The inventory level is an important factor in any blood bank. Based on a 95% confidence interval, demand percentage and supply percentage vary between 90% and 110%, as shown in Figures 4.2 and 4.3. In a FIFO policy, the average inventory level varies between 0 and 16 units per day, as in Figure 4.2, while in the Circular policy in Figure 4.3 the average inventory level varies between 0 and 11 units per day, with blood types A+ and O+ having the largest inventory.

Figures 4.4, 4.5, and 4.6 demonstrate the result of demand percentage variation on the model. Notice the FIFO policy in Figure 4.4 gives the lowest shortage of approximately 0.7% and the lowest outdated units of 0.3%. FIFO and Circular policies have a large variation between them (0.3% to 14%, respectively), as shown in Figures 4.4 and 4.6. LIFO has a low variation between 2% and 13%, as shown in Figure 4.5.

Accordingly, Figures 4.7, 4.8, and 4.9 demonstrate the result of donation percentage variation on the model. Notice that donation is very sensitive; as the donation decreases, the shortage percentage increases even more quickly and reaches up to 18%, as illustrated in Figure 4.7. As with demand variation, FIFO is the most efficient policy, with the lowest shortages and outdated units (around 1% and 0.5%, respectively). A significant note should be made that the Circular policy has low variation. In addition, Table 4.5 shows how each policy affects the inventory of each blood type. One should notice that in Table 4.5 FIFO has the lowest inventory, and there may be a shortage in AB+, AB-, A+, and B+, while the Circular policy has a reasonable inventory level. LIFO has a higher inventory level, which may cause more outdated units. The most expected stock out occurs with AB+, AB-, A+, and B+. This can be covered by the substitution of extra O- or

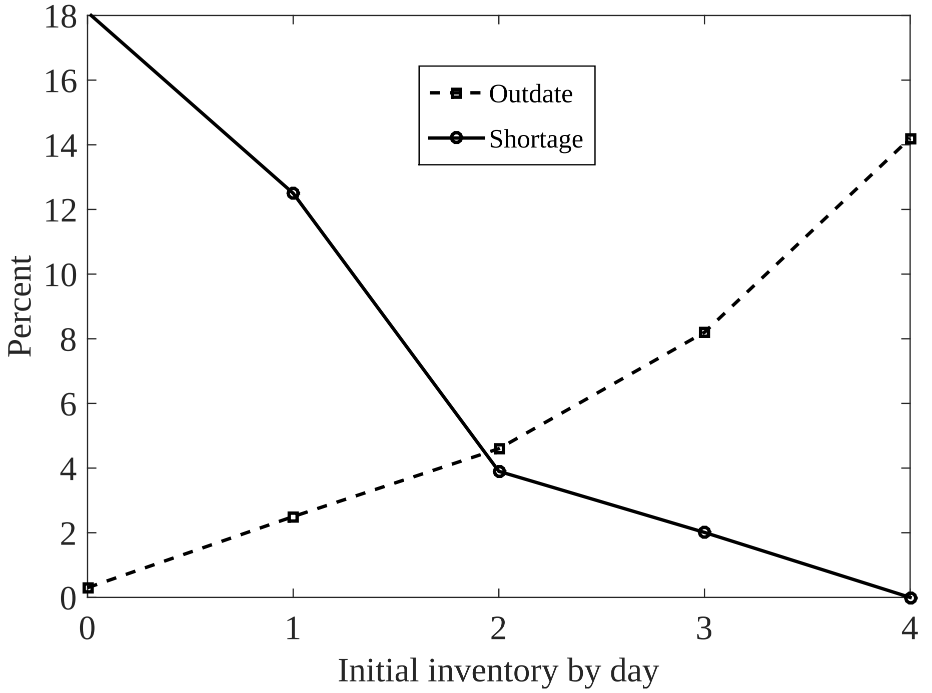

Figure 4.1: Initial inventory level variations of FIFO policy

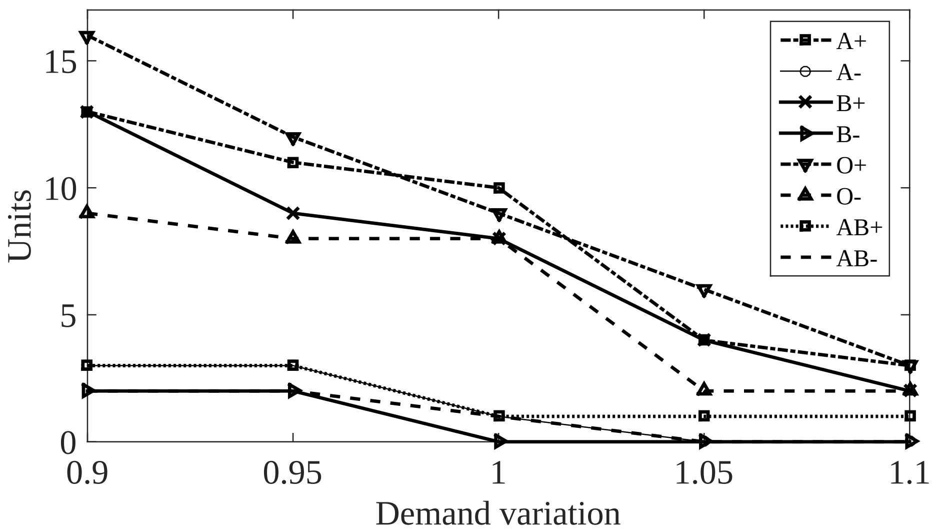

Figure 4.2: Demand variations and blood types of FIFO policy

any other suitable blood type.

Moreover, the process is modified so that the daily order quantity is calculated using the newsvendor model. It is then assumed that the blood bank receives half's the order quantity on an early morning and starts serving the demand. Consequently, based on the morning activities and the current available inventory, the second half's quantity may be canceled or changed. If a shortage is faced, some non-critical demands can be delayed to the afternoon until the second

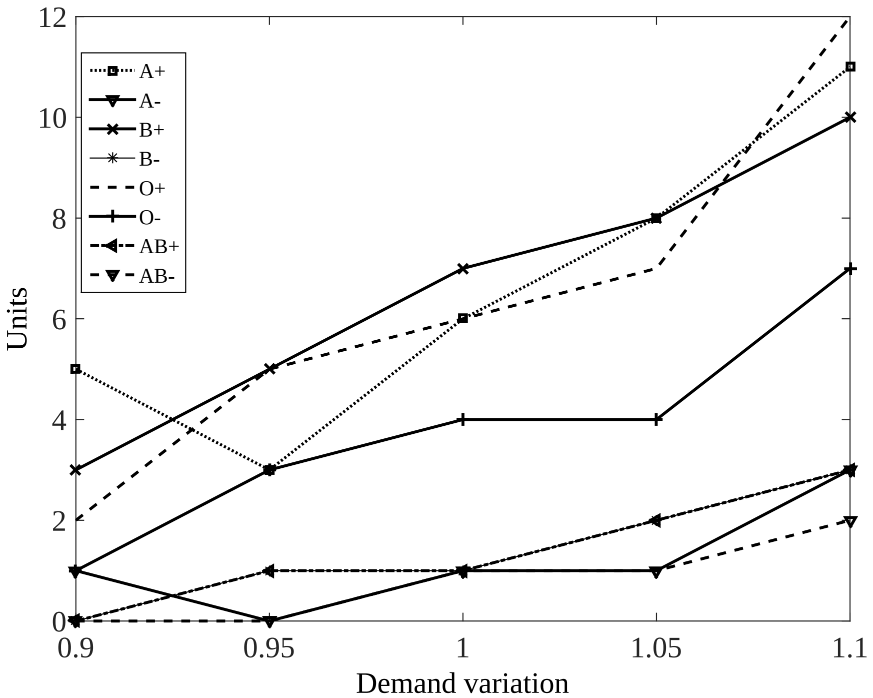

Figure 4.3: Donation variations and blood types of circular policy

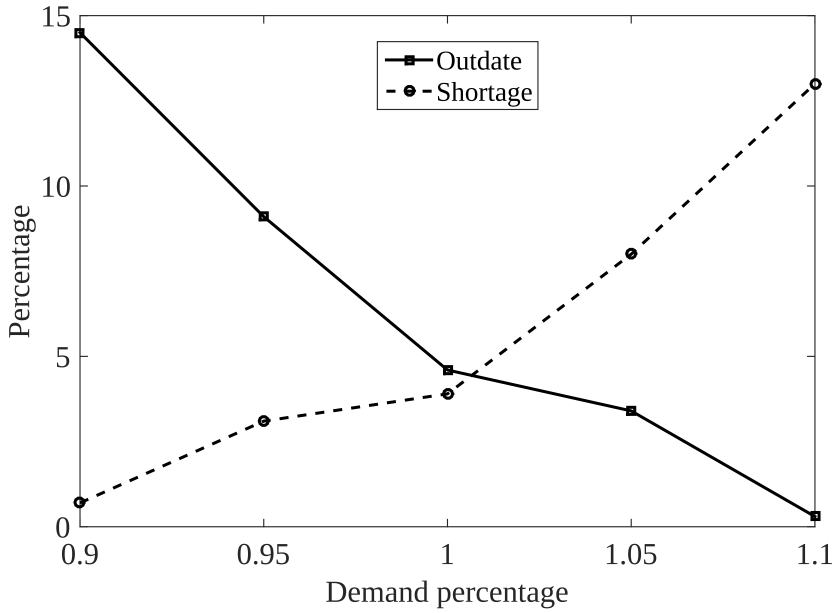

Figure 4.4: FIFO policy and demand variations

half's quantity has arrived. The result was very effective - the outdated units dropped to 2.1% and the shortages dropped to 1.8%. However, CBS has a limited budget as it is required to pay for collections and shipments twice a day. The organization may either refuse or agree to only apply this proposal to large hospitals.

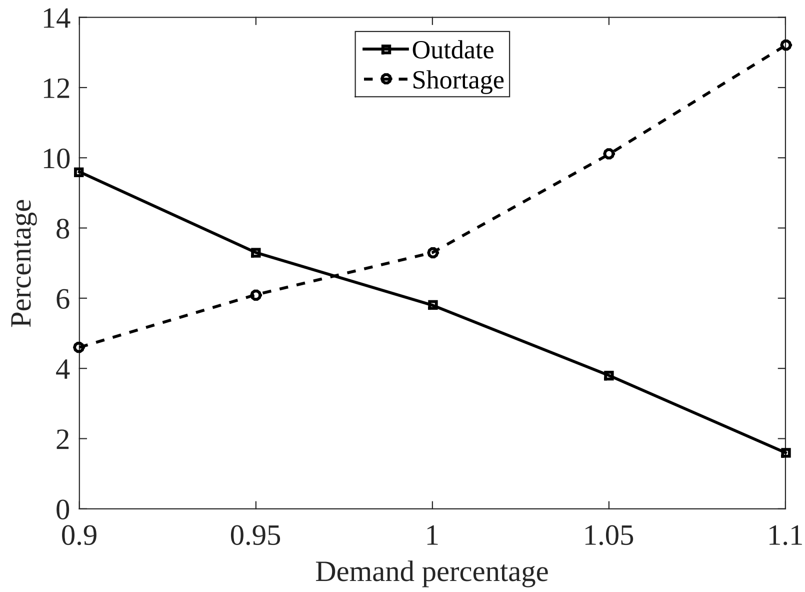

Figure 4.5: LIFO policy and demand variations

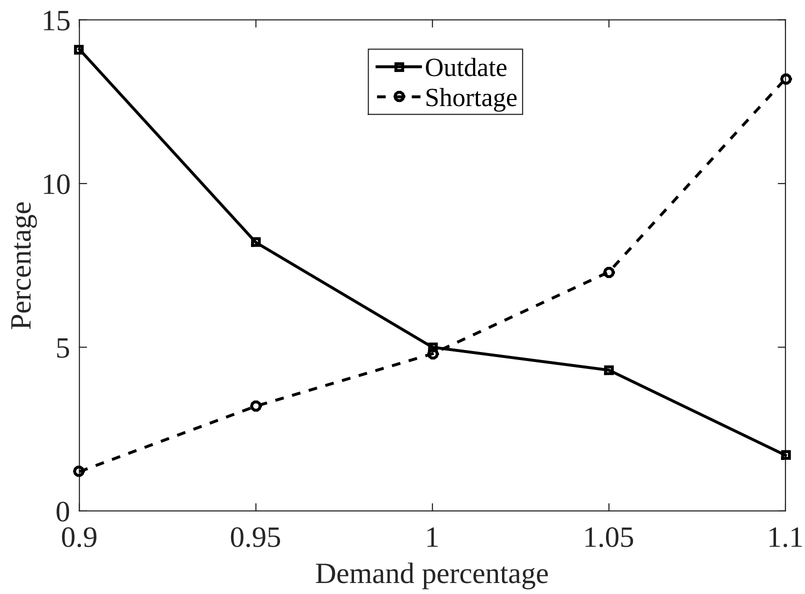

Figure 4.6: Circular policy and demand variations

The effect of generating eight daily demands and donation instead of only one aggregated demand and donation was studied. To simplify the process, the model was tested for one year and repeated 200 times. It was assumed that all week-day mean blood type inventory level is = (1 1 2 1 1 1 2 1), with respect to the blood type percentages in Table 4.1. The model was run for each blood type and the output was much more favourable. Outdated units were 3.84%, the shortage rate was 2.85%, average inventory level was 31 units, which is (2 0 15 0 4 0 9 1). The average processing time was 19,043 seconds. In contradistinction, the same model was run while generating

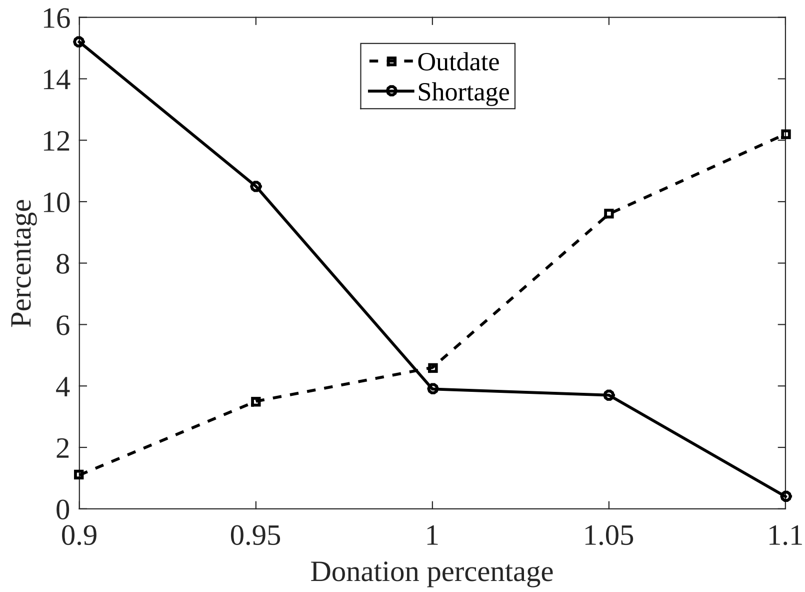

Figure 4.7: FIFO policy and donation variations

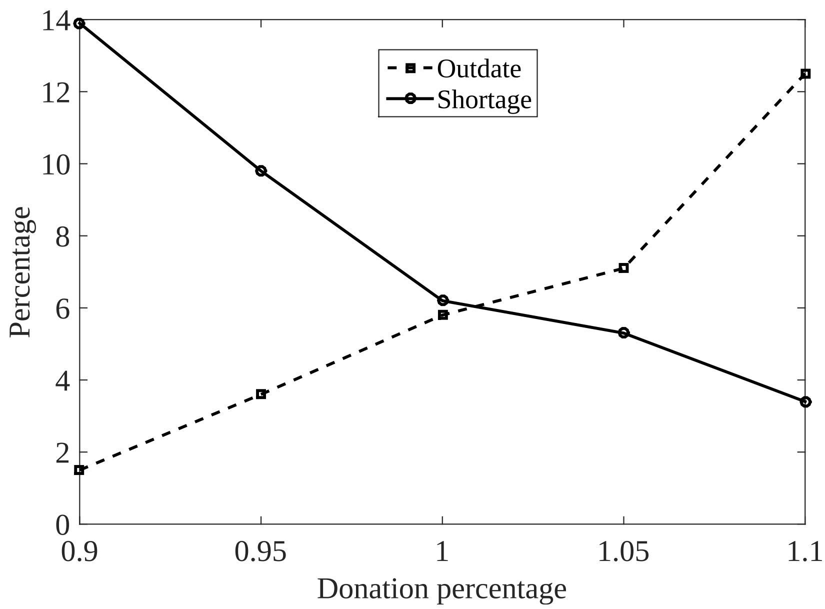

Figure 4.8: LIFO policy and donation variations

only one aggregated demand. The outdated units were 4.92%, the shortage rate was 4.14%, the average inventory level was 40, which is (2 0 16 1 5 1 12 3). The average processing time was 10,357 seconds. Thus, generating eight daily demands resulted in the reduction of outdated units from 4.92% to 3.84%, and the shortage rate made a large drop from 4.14% to 2.85% with a lower average inventory level. The processing time was almost doubled.

Furthermore, O- is considered a universal blood type that can be used to satisfy any blood type demand. Figures 4.10, 4.11, and 4.12 show the behavior of shortages and outdated units when

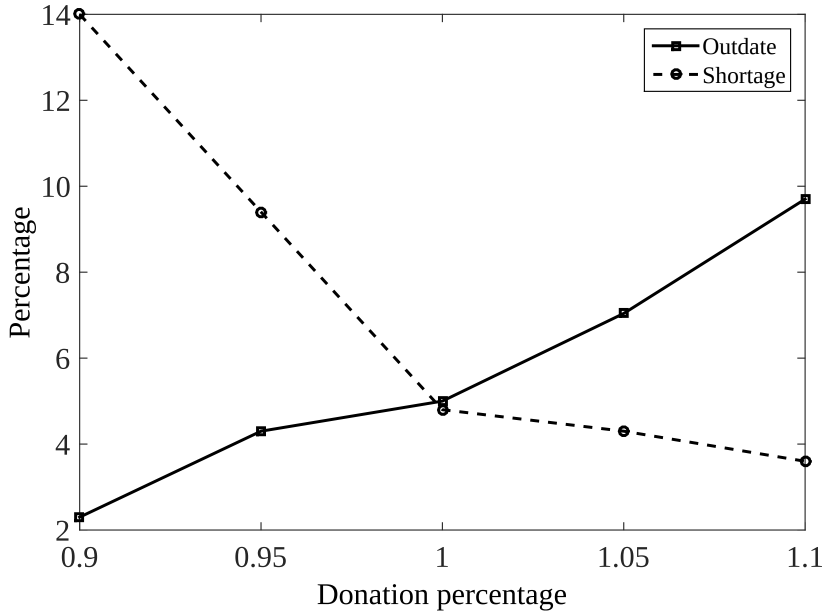

Figure 4.9: Circular policy and donation variations

Table 4.5: Blood type inventories and policies

Type	Demand									
Donor	AB+	AB-	A+	A-	B+	B-	O+	O-	Outdated	Shortage
FIFO	1	1	10	1	8	0	9	8	4.6	3.9
Circ.	3	1	10	1	8	2	14	6	5.0	4.8
LIFO	4	2	11	2	9	2	20	12	5.8	7.3

O- varies for all policies. Shortages and outdated units consistently decrease as the O- percentage increases, until the O- percentage reaches 40%. The shortage percentage went down from 17.7% to 1.5%, while the outdated unit percentage went down from 16.5% to 1.83%. Circular policy, as in Figure 4.12, performed very well within the O- variation. Its shortage percentage was reduced from 17.7% to 1.83%, while its outdate percentage lowered to 3.2% from 15.5%. In the analysis of the other policies, (detailed in Figures 4.10 and 4.11), outdated units and shortages dropped down most in the Circular policy. It is clear that all policies benefit from O- percentage increases, but the Circular policy performed the most efficiently. On the other hand, the variation has a minor positive effect with LIFO, while both Circular and FIFO respond more positively to the variation and go down to the minimum when O- percentage is 40%. Thus, the recommended O- percentage with the inventory should be around 40%.

Nonetheless, blood platelet banks with large demands have a greater need for additional units and immediately implement substitution behaviors. However, they consequently do not free up units of blood types as they are filling what would otherwise be shortages. As the quantity of

O- increases, the linear program finds solutions that allocate other blood types optimally, given the growing donation of O-. The ability of the substitute to free up units of blood to fill non-substitutable demands greatly moderates shortages and can also build up stored inventory without a corresponding increase in donation. The availability and long shelf-life of a blood substitute would therefore greatly reduce shortages and would relieve the mismatch of blood types in supply and demand. Unlike many other substitutable resources, blood platelets are a resource that have an unpredictable demand. When demand is not met, lives may be at risk. Thus, maintaining adequate inventory to fulfill demand is of critical importance. In conclusion, the findings can

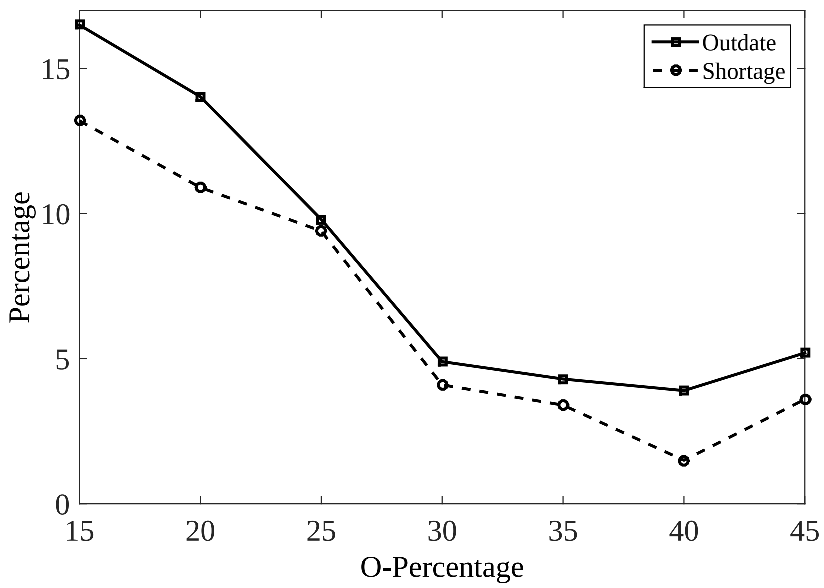

Figure 4.10: FIFO policy and O- variations

be summarized. To begin, whenever possible the blood platelet bank should be operated close to the optimal inventory level in order to maximize its effectiveness. Secondly, the lowest number of outdated units and shortage rates are achieved when the O- percentage is 40%. If the daily order quantity is delivered twice a day, the outdated units and shortage will be around 2%. Finally, the best policies in order of overall efficiency were FIFO, Circular, and LIFO. The simple ordering policy commonly used by blood platelet bank managers (FIFO) seems the best in terms of shortage, outdated units, and inventory level. It also has the benefit of requiring less computation and implementation times.

4.5 Summary

The need for blood platelets will never cease. Understanding how to manage this vital resource is of utmost importance as it is likely that many people will need blood platelets at some point. A com-

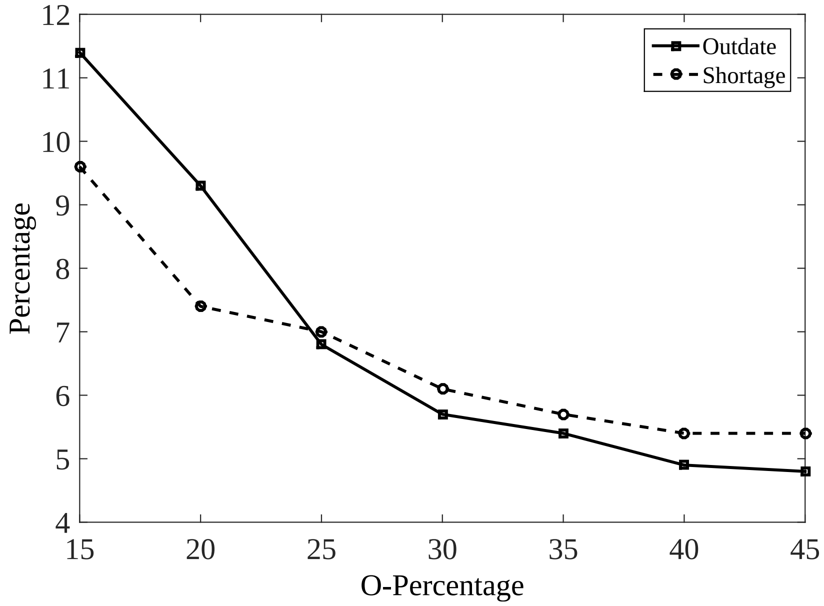

Figure 4.11: LIFO policy and O- variations

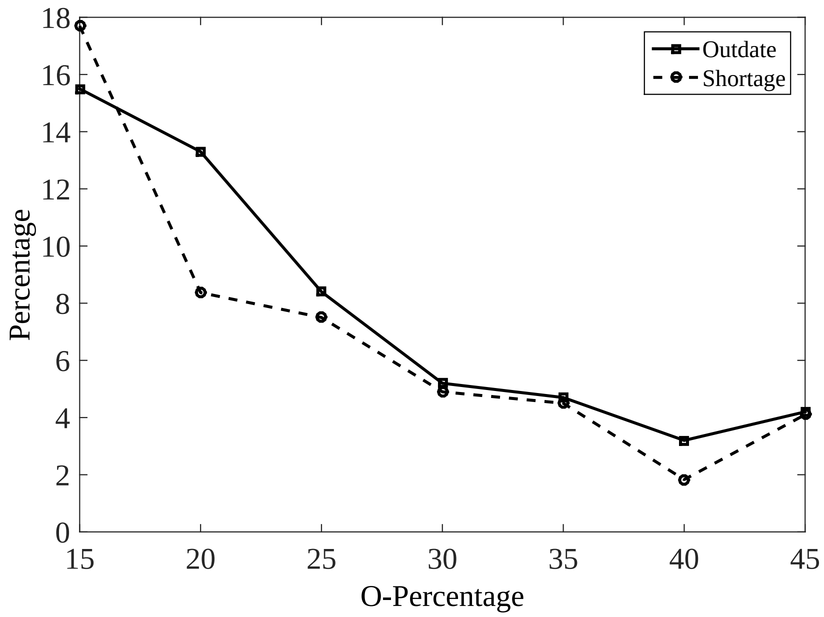

Figure 4.12: Circular policy and O- variations

bined newsvendor model, Linear Programming, and ADP approach are used to develop the blood platelet inventory model. A strategy of solution and a tractable algorithm that is computational are proposed to address this challenge. Moreover, it has been shown that the algorithm provides reasonable shortage and outdate rates when applied theoretically using three policies. Test results showed a significant reduction in shortage and outdate percentages. The demand uncertainty is reduced by using the daily demand distribution to generate demand. The donation is determined by using both the newsvendor model and the existing inventory to select the optimal order quantity. The model includes factors that affect order quantity such as daily demand distribution, each blood type demand, inventory level for each blood type, and their ages. All of these succeed in reducing outdated units, shortages, and the inventory level. Furthermore, the model succeeds in overcoming the "curse of dimensionality" and solving the developed model without any downsizing. This includes the eight blood types, platelet ages, and stochastic demand. FIFO and Circular policies reduce the outdating to 4.6% of the annual production. Shortages are reduced to 3.9% of the total annual demand, even with all of the above mentioned complications. In addition, this resulted in cost reduction and low inventory levels. Moreover, both FIFO and Circular policies are simple and can be easily applied. When the order quantity is received twice a day, the outdated units drop to 2.1% and the shortage drops to 1.8%. Finally, when the percentage of O- within the inventory was also studied, the shortage dropped down to 1.8% and the outdated units dropped to 1.5% when the O- percentage was 40% of the total inventory.

Chapter 5

HOSPITAL BLOOD PLATELET INVENTORY CONTROL POLICIES

This chapter provides an analysis and a summary of the results obtained for Objective II: look for the best policy for different incoming blood platelet demands.

5.1 Introduction

This chapter addresses the difficult platelet inventory management issue and reduces both outdate and shortage rates from a supply chain perspective. Blood banks need a new issuing policy to serve hospital demands. The focus of this chapter is to develop a blood bank issuing policy based on the model developed by Abdulwahab & Wahab (2014). New issuing policies will reduce both outdate and shortage percentages while keeping inventory levels and costs at a minimum. Four policies were developed: FIFO (First In First Out), LIFO (Last In First Out), Circular policy, and a mix of FIFO and Circular policy. Prastacos (1984a), Blake et al. (2010), and Karaesmen et al. (2010) studied and suggested different issuance policies.

The model developed in Chapter 4 is used to study policies that can handle different types of demands and incoming donations. The success of the system's performance is evaluated in regards to four effectiveness measures: lack of platelet availability, expiry, inventory level, and reward gained. The CBS data is processed and analyzed to determine the different parameters and statistical distributions that are needed during the research.

The outline of Chapter 5 is as described: Section 5.2 describes the proposed model. Section 5.3 discusses the policies used, as well as their assessment criteria. Section 5.4 examines the implementation methodology. Section 5.5 presents a comparison between the four policies and shows different results, and lastly, Section 5.6 presents the conclusion.

5.2 Proposed Model

The proposed model includes the steps that follow. At the beginning, blood bank inventory is counted and checked. Any outdate platelets are removed from the inventory. The order quantity is calculated and ordered using a newsvendor model. The previous day's order quantity arrives and is added to the inventory. This model is solved using linear programming. At the end of each day, the actual demand is known and the inventory is updated accordingly. After that, the next day's inventory is calculated using ADP. Finally, the developed model is tested and optimized using different policies. The demand is generated randomly based on the data in Table 3.3 for Ontario region. Demand can be served either by a same or a suitable blood type. The relationship between the supply and demand of the eight blood types is shown in Table 1.2. This is a multi-product, multi-period problem with uncertain demand over multiple time periods. It is assumed that there is no mishandling or damaging of blood platelets, and that any unsatisfied demand is replaceable by any other hospital - but with a high penalty cost.

5.3 Implementation

Each policy has its own reward value based on Tables 5.1, 5.2, 5.3, 5.4, and 5.5. The reward values are organized in a way that they serve demand with the inventory units that maximize profit. This is explained in Table 5.5. For example, if a six-day old platelet is used to serve demand, the profit is \$49.5; if a five-day old platelet is used, the profit is \$49; and if a new platelet is used, the profit is \$48.5. This will encourage the model to use older platelets first to maximize profit.

Although each criterion has relevance, the most important concern is shortage; it puts human lives at risk. Outdated units are the second most important criterion because platelets are a unique, expensive, and limited resource. When inventory levels are low but give a high reward, the ideal model is to be the one which supports the policy with the least shortages and outdated units. In addition, all policies are compared with a myopic policy. The myopic model is a simple model that contains all the characteristics of the proposed model, except that no inventory updates are applied during the day. Moreover, the proposed policies can be easily implemented. The staff only needs to feed the correct data into the program and it will give them the recommendation.

5.4 Issuance Policies Description

The proposed policies are similar to the "2D rule" presented by Haijema et al. (2007) and Duan & Warren (2014) in principle, but they differ in implementation. These policies try to improve the performance by discriminating between old and new inventories. The "2D rule" corresponds to an order-up-to rule that is double-leveled, with only one level dealing with "young" stock and only one level dealing with the total inventory. Four policies were developed. Each one has its own reward value based on how the policy serves the incoming demand and policy priorities. Notice that the new blood platelets' mean age is from 1 to 3 days, while the old blood's age ranges from 4 to 6 days. The four implemented policies are discussed in detail:

1. Circular policy and FIFO (CRF): The selection movement is based on the reward function with a priority given to the same blood type and keeping O- as the last choice. Service rule: The oldest platelets are used first, starting with same blood type. Thus, in Table 5.1, the demand for AB+ is served, starting with the same blood type with ages of 6 days, 5 days, and 4 days, respectively; this sequence gives the highest profit of $50, $49.5, and $49, respectively. If there is not enough AB+, then demand is served using a suitable blood type of ages 6, 5, and 4 days, which will give less profit: $49, $48.5, and $48, respectively. This continues down to the last choice of O–. This policy gives priority to serving the same blood type, keeping O- as a last supply choice.

Table 5.1: CRF policy reward function for blood type AB+

Age \Type	O-	O+	B–	B+	A–	A+	AB–	AB+
1	44.3	46.5	46.5	46.5	46.5	46.5	46.5	47.5
2	44.8	47	47	47	47	47	47	48
3	45.3	47.5	47.5	47.5	47.5	47.5	47.5	48.5
4	45.8	48	48	48	48	48	48	49
5	46.3	48.5	48.5	48.5	48.5	48.5	48.5	49.5
6	46.8	49	49	49	49	49	49	50
7	-10	-10	-10	-10	-10	-10	-10	-10

2. Circular policy and FIFO with a different blood order (CRFR): The policy starts by serving demand for blood types that have the lowest substitution options, as follows: O-, O+, B-, A-, B+, A+, AB-, AB+. One may see, for instance, that the blood type labeled O- can only be served by O-; O+ can only be served by O+ and O-, as shown in Tables 5.2 and 5.3. Table 5.2 represents how the model serves demand for O-. The O- demand is served by the O- blood type, starting with six-day old platelets because they give the highest reward. Then, if platelets with an age of six-days are not enough, the program looks for five-day old blood platelets and so on until it reaches one-day old platelets. Since O- demand can only be served with O-, the O+ column cannot be used to serve O- demand. The O+ demand, as in Table 5.3, is served by the O+ blood type, starting with platelets with aged 6 to 2 days because they give the highest reward. Then, if there are not enough platelets, the blood type O- is used to serve O+ demand, starting with six-day old platelets. Thus, in this policy the serving demand process starts in this order: O-, O+, B-, A-, B+, A+, AB-, AB+, respectively.

3. Circular policy with a mix of all demands (no substitution, substitution is allowed, give O-

Table 5.2: CRFR policy reward function for blood type O–

Age \Type	O+	O–
1	0	44.3
2	0	44.8
3	0	45.3
4	0	45.8
5	0	46.3
6	0	46.8
7	0	-10

Table 5.3: CRFR policy reward function for blood type O+

Age \Type	O+	O–
1	46.5	44.3
2	47	44.8
3	47.5	45.3
4	48.	45.8
5	48.5	46.3
6	49	46.8
7	-10	-10

low priority) (CRN): Priority is given to new platelets starting with the same blood, with platelets with ages of 3, 2, and 1 days, respectively. The demand for AB+, for example, is served starting with new units from AB+ cell 24 (give a reward of $48.3) down to cell 1 (give a reward of $47.3). If there is not enough of the relevant new inventory between ages 3 to 1 days, the demand is served with older platelets, starting with units of age 4, then 5, and then 6 respectively, as shown in Table 5.4. This policy is important for patients who need new blood, such as pregnant mothers.

Table 5.4: CRN policy reward function for blood type AB+

Age \Type	O-	O+	B–	B+	A–	A+	AB–	AB+
1	47.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3
2	47.8	47.8	47.8	47.8	47.8	47.8	47.8	47.8
3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3
4	46.8	46.8	46.8	46.8	46.8	46.8	46.8	46.8
5	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3
6	45.8	45.8	45.8	45.8	45.8	45.8	45.8	45.8
7	-10	-10	-10	-10	-10	-10	-10	-10

4. FIFO policy: It is a common practice that is widely used in most hospitals. The selection movement is based on the reward function with a priority given to the same blood type and age. Service rule: The oldest platelets are used first, starting with same blood type. For example, the demand for AB+ is served, starting with same blood type platelets aged 6 days; if there is not enough AB+ with age 6, then demand is served using a suitable blood type aged 6 days. This continues down to the last choice of O- with an age of one-day, as shown in Table 5.5.

Table 5.5: FIFO policy reward function for blood type O–

Age \Type	O-	O+	B–	B+	A–	A+	AB–	AB+
1	47	47	47	47	47	47	47	47
2	47.5	47.5	47.5	47.5	47.5	47.5	47.5	47.5
3	48	48	48	48	48	48	48	48
4	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5
5	49	49	49	49	49	49	49	49
6	49.5	49.5	49.5	49.5	49.5	49.5	49.5	50
7	-10	-10	-10	-10	-10	-10	-10	-10

5.5 Results and Discussion

Four different supply policies were used to serve different incoming demand types. FIFO is the current practice of the hospital. The three policies are compared with the FIFO policy and the myopic policy. A Matlab package was used to code the model on a Windows 7 PC with 4 GB RAM as well as an Intel Core i7 processor. The solution time for each run was between 4 and 5 minutes for a period of 52 weeks and was replicated 200 times.

The start-up inventory was initialized with 0, 1, 2, 3, and 4 days' demand to select the optimal initial inventory, as in Figure 5.1. Inventory and outdated units have an inverse relationship, and inventory and shortage units have a direct relationship, so when the initial inventory increases the shortage percentage approaches zero. If three days' initial inventory or more is used, shortage is almost zero, while outdated units at an initial inventory of one-day or less decrease to zero. Thus, two days' supply of each blood type is considered suitable for the initial inventory level to balance between outdate and shortage. The minimum inventory level will not be less than two days' demand. The results regarding shortage percentage, outdate percentage, average inventory level, and reward gained for the four policies are summarized in Table 5.6. The shortage ranged between 1.9% and 4.4% for all policies, and the outdate percentage ranged from 1.8% to 4.1%. All policies outperform the myopic policy because the proposed approach considers daily changes in the inventory. The CRFR policy, which serves demand starting with O- blood types first, appears to be the most efficient with an outdate percentage of around 1.8% and a shortage percentage of around 1.9%. CRN appears to be the least efficient, with shortage and outdate percentages of 4.4% and 4.1%, respectively. The CRF policy appears to be the second most efficient policy, with shortage and outdate percentages of 2.4% and 2.3%, respectively. The FIFO Policy gives better results than the CRN policy.

The Demand variations is an important factor in any blood bank. Demand percentage varied between 90% and 110%, as shown in Figures 5.2 and 5.3. In a CRN policy, the outdate percentage varies between 1 and 14, as in Figure 5.2, while in the CRFR and CRF policies approach zero as demand increased. Vice versa, as demand increases, shortage percentage increase as in Figure 5.3.

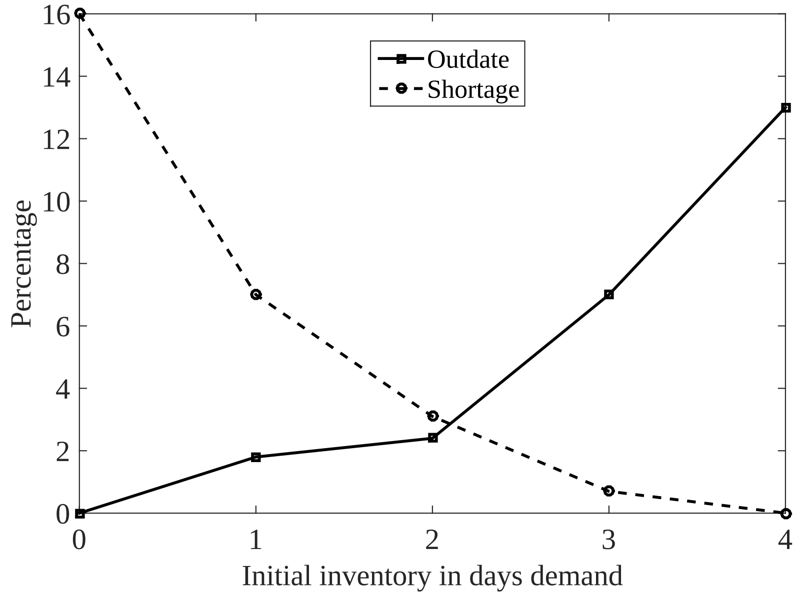

Figure 5.1: Initial inventory levels

The CRFR and CRF policies shortage showed the least increase compared to the other policies.

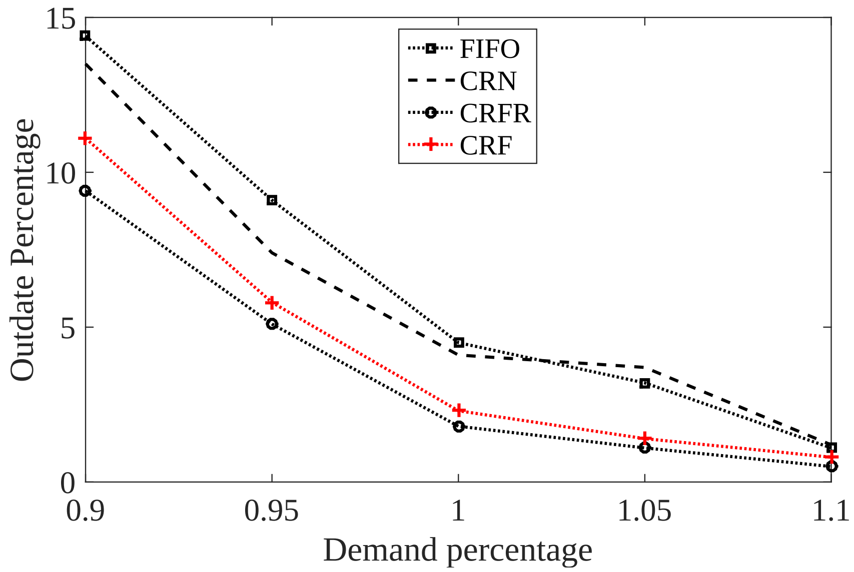

Figure 5.2: Demand variations and outdate percentages

Additionally, the minimum inventory levels were with the CRFR and CRF policies, and the best rewards, in ascending order, are the CRFR, CRF, FIFO, and CRN policies. Moreover, all policies have a reasonable inventory level however the CRFR Policy has the minimum inventory level. The table clearly shows that the best policies are CRFR, CRF, FIFO, and CRN, respectively.

Since the CRFR policy gives the best results, a sensitivity analysis is employed starting by analyzing the inventory age. Table 5.7 shows the last inventory at the end of the simulation run.

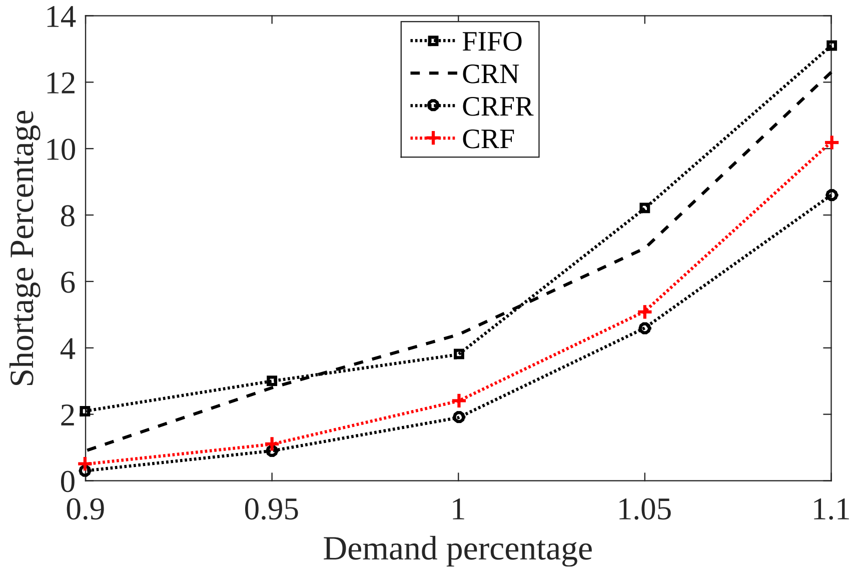

Figure 5.3: Demand variations and shortage percentages

Table 5.6: Comparison between the four policies

Policy Name	Outdate %	Shortage %	Inv.	Reward	Myopic Outdate %	Myopic Shortage %	Myopic Inv.	Myopic Reward
CRF	2.3	2.4	55	5.2 $\times 10^5$	6.8	7.1	62	9.0$\times 10^4$
CRFR	1.8	1.9	49	5.4$\times 10^5$	6.7	6.3	56	11.5$\times 10^4$
CRN	4.1	4.4	61	3.9 $\times 10^5$	11.3	12.3	64	4.0$\times 10^4$
FIFO	4.5	3.8	60	4.5 $\times 10^5$	5.3	4.8	63	12.$\times 10^4$

The average age for the CRFR policy is 2.6 days, while in Duan & Warren (2014) the average age was 4.2 days. It is clear that A– has the lowest average age, and may cause more shortages because there is only one unit left in the inventory. In contrast, B-, O+, and O– are a possible source of outdating. Hence, if the supply mirrors the demand, the results will be improved. If donation of A- is increased and donation of B-, O+, and O– is decreased, both shortages and outdates will be decreased. Table 5.8 shows the inventory left when A- donation is increased and B- and O+ is decreased. It is clear that the distribution of blood platelets with the inventory is better for AB+, O+, and A–. In addition, the O– inventory is still high, but will not affect the outdate percentage because it can be given to any blood type demand. In addition, the blood platelet average age is reduced from 2.6 to 2.19 days. The survey done by Whitaker (2012) showed that the average age of platelets was 3.96 days at transfusion, while in the proposed policy the average age was 2.19 days at transfusion. The total inventory is reduced from 59 to 49 units; this can be achieved if the donation follows the demand behavior. Notice that CRFR and CRF policies resemble each other except that the CRFR policy serves incoming demand starting with O- (which can be served only

Table 5.7: Inventory levels median for CRFR policy

Age \Type	AB+	AB–	A+	B+	A–	B–	O+	O–	Total
1	1	1	1	1	1	1	1	1	8
2	0	1	1	1	0	1	1	1	6
3	2	8	1	4	0	8	2	2	27
4	0	3	0	0	0	6	2	2	13
5	0	1	0	0	0	0	2	2	5
6	0	0	0	0	0	0	0	0	0
Average	2.33	3.14	2.00	2.50	1.00	3.18	3.38	3.38	2.61

Table 5.8: Inventory levels median for CRFR policy (revised)

Age \Type	AB+	AB–	A+	B+	A–	B–	O+	O–	Total
1	1	2	1	2	1	1	1	1	10
2	1	3	2	1	1	3	3	2	16
3	0	5	0	2	0	5	1	1	14
4	0	1	0	0	0	2	2	3	8
5	0	0	0	0	0	0	0	1	1
6	0	0	0	0	0	0	0	0	0
Average	1.50	2.45	1.67	2.00	1.50	2.73	2.57	3.12	2.19

by O-) and ending with AB+ (which can be served by any of the eight blood types). Similarly, the FIFO policy gives reasonable results and can be easily implemented. The CRN policy gives the worst result, but every blood bank needs it to serve the special blood requests that every hospital has. The overall best policies, in ascending order, are the CRFR, CRF, FIFO, and CRN Policies.

Next, the percentage of O- within the inventory varied from 5% to 35%. Figure 5.4 shows the effect of O- variations on all four policies. It is apparent that as the O- percentage increases, both the shortage and outdate percentages decrease. The lowest shortage occurs when the O- percentage is between 30% and 35% where shortage dropped to below 1%. The O- substitution has a positive marginal benefit, even after donation surpasses the total demand. This is because of the blood-type substitution effects. Therefore, a blood center would be able to conclude that maintaining a suitable O- inventory should allow all demand to be satisfied. An obvious expectation is that a higher demand level will benefit more from extra O- since more units of demand can be satisfied. This means that increases in O- supply produce the same marginal benefit, regardless of the demand level at each step. The key finding here is that all demand levels still show the same behavior; even after total donation meets total demand, there is a benefit in adding additional units of O- blood. This conclusion is valuable in that blood banks with varied average supplies and demands will respond to additional units of O- differently. Blood banks in which average donation is close to average demand do not have a strong requirement for additional units of O-, but many substitution possibilities exist nonetheless. Making donations follows demand behavior, and the availability of O- in any large demand hospital blood bank will greatly help serve any type of demand. Moreover,

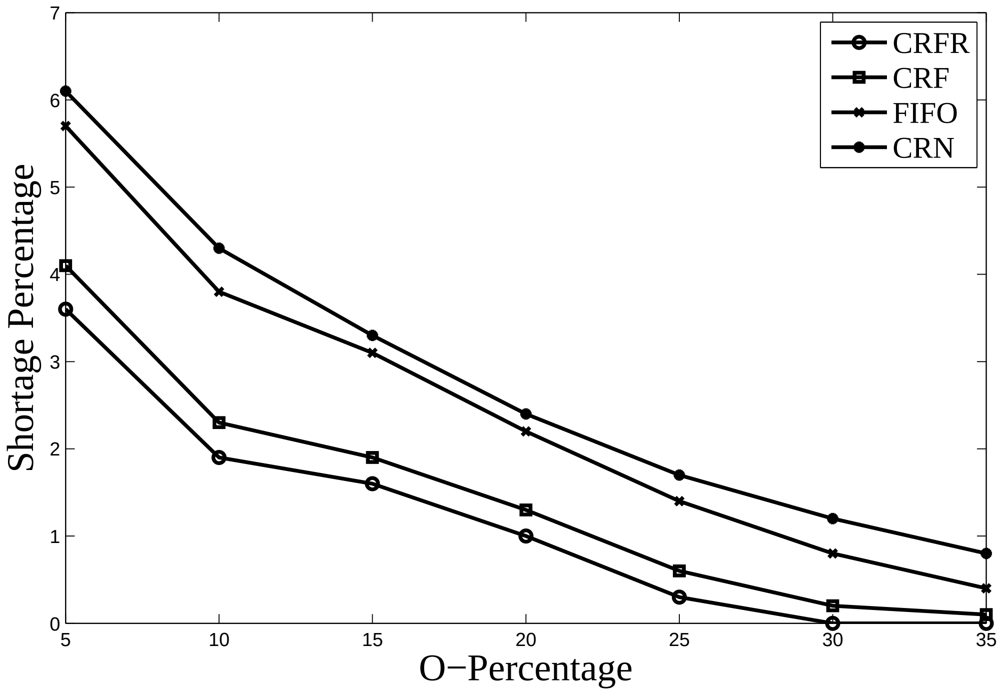

Figure 5.4: O– variations and shortage percentages

serving demand in order of blood scarcity will improve the process. In addition, if the ordered blood type is not found, the bank can substitute with extra O- inventory. As the quantity of O- blood increases, the linear program finds solutions that allocate other blood types optimally, given the growing donation of O- which will be used to fill more demands and reduce shortages, and can also build-up stored inventory without a corresponding increase in donation.

Finally, the findings can be best described as follows: (a) the newsvendor model tracks the optimal inventory level to maximize the effectiveness of blood platelet banks; (b) the linear programing method gives the daily optimal inventory at a point in time; (c) the ADP monitors daily changes, and then optimizes and updates the model parameters; (d) the developed model enables managers to better understand the blood platelet bank process and to replicate model behavior by trying different policies to satisfy different demand types; (e) the combination of an adequate inventory level and the actual ordering decisions, along with a suitable policy, should allow blood banks to decrease the number of shortages and expired units as much as possible through a better understanding of optimal inventory levels.

5.6 Summary

The blood platelet bank model is a large-scale model with large state, action, and outcome spaces. The multi-period model developed in this study addresses some of the previously listed gaps in the literature, and overcomes the curse of dimensionality. It also considered eight blood types with probabilistic demand and supply and deterministic lead times. The effects on overall performance when applying this model, considered against several other alternative inventory control policies, were analyzed.

The system's success was evaluated in regards to four previously listed effectiveness measures: outdating, inventory level, blood platelet shortage, and reward gained. The results showed that the employment of ADP, in conjunction with a suitable supply policy, provides more reward, less shortage, fewer outdated units, and lower inventory levels when compared to a myopic policy.

Chapter 6

DUAL SUPPLY SOURCE BLOOD PLATELET BANK INVENTORY MODEL

This chapter provides an analysis and a summary of the results obtained for Objective III: Analyze the effect of having an extra, new, artificial, universal blood type alongside the existing eight blood types.

6.1 Introduction

In this chapter, an inventory model is presented for a blood platelet bank with daily dual supply sources, one artificial and the other natural. The supply of eight natural blood types has a short shelf-life of six-days and a one-day lead-time, while the artificial blood platelet has O- properties (Reid & Kim 2006, Lasky et al. 2010) and is presumed to have a one-day shelf-life. As far as the author is aware, no one has addressed the challenge of a blood bank inventory containing dual supply sources (natural source and artificial source) where patients may accept or reject artificial blood platelets.

The arrangement of this chapter is as follows: introduction, Section 6.2, provides a detailed description of the problem; Section 6.3 discusses the developed model; and Section 6.4 discusses the findings, followed by the conclusion.

6.2 Problem Definition

Demand is generated daily, dependent upon the distribution of the week day as in Table 3.3. The generated daily aggregated demands are multiplied by the standard blood type percentage as in

Table 4.1, which is derived from actual Ontario, Canada data. Moreover, since the patient's demand is fulfilled by a mixture of same and substitutable natural blood types (American Blood Centers 2011b), it is assumed that he or she will be given a mixture of natural and artificial blood platelets using predefined substitution policies as in Table 6.1.

As discussed in the literature review, patients have different reasons for refusing artificial platelets (Berend & Levi 2009, Bingham 2012, Rajtar 2013). When a patient refuses artificial blood platelets, the hospital will provide him or her with a suitable natural blood platelet type only if the patient brings donors on the same day to replace the given blood. The donated blood platelets will be processed and added to the next day's inventory.

The patient's acceptance percentage and the artificial platelet percentage within the total inventory will be varied, as discussed in review of relevant literature (Blake et al. 2010, Lamme et al. 2010, Katsaliaki et al. 2014, Rijpkemaa et al. 2014). However, donation for the eight blood types takes place six-days a week from Monday to Saturday (the donation center does not operate on Sunday). Artificial blood platelets are also available six-days a week from Monday to Saturday. When platelets become outdated or a shortage occurs, a penalty will be charged, while a reward will be earned when the demand is satisfied.

Table 6.1: Blood platelet substitution relationships (American Blood Organization 2013)

Type	Demand							
Donor	AB+	AB-	A+	A-	B+	B-	O+	O-
AB+	1							
AB-	1	1						
A+	1	0	1					
A-	1	1	1	1				
B+	1	0	0	0	1			
B-	1	1	0	0	1	1		
O+	1	0	1	0	1	0	1	
O-	1	1	1	1	1	1	1	1
θ	1	1	1	1	1	1	1	1

The solution process starts by using the newsvendor model to determine the order quantity from the daily optimal inventory for the eight blood types. The artificial platelet order quantity is estimated as a proportion of the ordered quantity (the patient's acceptance percentage). Next, linear programming will be used to solve the first phase using the expected demand and donation. At day's end, actual demand is known and the inventory is updated accordingly. Then ADP will be utilized for the purpose of solving the second phase based on actual available inventory. The new inventory calculated by ADP will be the input inventory for the next day's linear programming model.

It is a multi-product, multi-period inventory model for a blood platelet bank with two sources of supply (eight blood types and artificial blood). The model is tested using actual data provided by CBS and will be run for 52 weeks and repeated 200 times

6.3 Model

The most important successful factor in blood bank model is blood type. The inventory contains eight natural blood types that have a shelf-life between one and six days. As per Table 6.1, there are 27 natural supply rules and 8 artificial supply rules to serve the demand. There are 162 (27 $\times$6 possible ages) blood type supply options in addition to eight artificial supply options (artificial blood platelets can serve demand for all eight blood types). Thus, a total of 170 options are used to represent all possible inventory issuance policies to satisfy the demand. The inventory has one artificial blood type, and eight natural blood types, each with six possible ages. Thus, the inventory has forty-eight natural inventory options and one artificial option. The forty-eight natural options or arcs are used to represent all possible movements from today's inventory to the next-day's inventory, and results in a negative reward for the holding cost. Any blood platelet age is more than six-days old must be discarded; this results in a negative reward for the outdate cost.

6.3.1 Linear Programming Model

The process starts in the morning, when all previous day's inventory is aged by one-day. Any blood platelets that are more than six-days old are removed from the inventory because they are outdated. In addition, the previous day's order quantity of age one-day is received and added to the inventory.

Next, the newsvendor model, as recommended by Blake et al. (2010), is used to determine the next day's order quantity. Moreover, the blood platelet shortage cost is C_u and the outdate cost is C_g. Therefore, the newsvendor critical ratio is $C_u/(C_u + C_g)$, and Equation 4.1 is used to calculate the optimal inventory of the newsvendor model Q_t. Then, an order quantity is calculated as follows:

$$p_{t+1} = Min\left[(Q_t - \sum_{i=1}^{8} z_{i6t}), y_{t-1}\right], \tag{6.1}$$

where p_{t+1} is the order quantity, p_{i1t} is the received quantity, Q_t is the order-up-to level, z_{i6t} is the total inventory with an age of six-days. Since λ represents the patient's acceptance percentage for the artificial platelet, the artificial order quantity will be λp_t and the natural order quantity will be $(1-\lambda)p_t$ percent of the total ordered amount. The natural amount ordered is multiplied by the percentage of each blood type, as in Table 4.1, to get p_{i1t}. The order quantity will be received and added to the inventory in the next-day's morning.

Table 6.2: Sample reward set for different types of decisions

Description	Symbol	Value
Fulfill demand with the same blood type	C_r	50
Fulfill demand with a suitable natural blood type	C_d	45
Fulfill demand with the artificial θ	C_θ	40
Holding cost	C_h	0.5
Outdate cost	C_g	10
Shortage cost	C_u	50

After the order quantity is placed, the linear programing model is solved to serve the incoming demand so that the reward is maximized. The set of reward parameters for the linear programming objective function are described in Table 6.2. Notice that the shortage expense is presumed to be five times the outdate cost (e.g., Blake et al. 2003). Related costs such as blood platelet collection, testing, labeling, and shipping are not considered in this model.

The complete reward for day t is given by: total reward = fulfill demand with substitution + fulfill demand with no substitution - shortage cost - outdate penalty - holding cost + use of θ for substitution - θ outdate cost. The reward function is:

$$\max\ C_t(I_t) = C_d \sum_{k=1}^{8}(y_{kt} - \sum_{i\in M_k\ and\ i=k}\ \sum_{j=1}^{6} x_{ijt}) + C_r \sum_{k=1}^{8}(y_{kt} - \sum_{i\in M_k\ and\ i\neq k}\ \sum_{j=1}^{6} x_{ijt})$$
$$- C_u u_t - C_g D_{i6t} - C_h \sum_{i=1}^{8}\sum_{j=1}^{6} z_{ijt} + C_\theta x_{91t} - C_g\ (p_{91t} - x_{91t}). \tag{6.2}$$

At the beginning of day t the inventory I_{ijt} will be:

$$I_{ijt} = z_{i,j-1,t-1}\ \forall\ i = 1,2,...,8:\ j = 2,3,...,6:\ t = 1,2,...,T, \tag{6.3}$$

$$I_{i1t} = p_{i1t}\ \forall\ i = 1,2,...,9:\ t = 1,2,...,T, \tag{6.4}$$

plus all of yesterday's natural inventory older than six days will be counted as outdated doses.

$$D_{i6t} = z_{i6,t-1}\ \forall\ \ i = 1,2,...,8:\ \ t = 2,3,...,T. \tag{6.5}$$

Artificial platelets' proportion of the total order quantity is equal to the patient's acceptance percentage (λ). At the day's conclusion all unused artificial platelets are considered expired.

$$D_{92t} = p_{91t} - x_{91t}, \tag{6.6}$$

$$\sum_i \sum_j x_{ijt} + x_{91t} + u_t = y_t\ \ \forall\, t = 1,2,...,T, \tag{6.7}$$

$$\sum_{i\in M_k} \sum_{j=1}^{6} x_{ijt}\ \leq\ y_{kt}\ \forall\ k = 1,2,...,8:\ t = 1,2,...,T, \tag{6.8}$$

At the conclusion of day t the unused stock cannot exceed the maximum capacity:

$$\sum_{j} z_{ijt} \leq N_{it} \ \ \forall\, i, \tag{6.9}$$

$$x_{ijt} \geq 0, \ \ u_t \geq 0, \ D_{i6t} \geq 0, \ \ z_{ijt} \geq 0. \tag{6.10}$$

Constraint (6.3) shows that the ending inventory for $t-1$ will be the starting inventory for day t except the outdated units. Constraint (6.4) shows that the order quantity, p_{i1t}, received at day t will enter the inventory with age 1 day. Constraint (6.5) calculates the amount of natural blood outdated. Constraint (6.6) calculates the outdated artificial blood platelet doses. Constraint (6.7) shows the sum of the doses, x_{ijt}, moved from the inventory to fulfill demand, the artificial blood, x_{91t}, and shortages, u_t, are equal to the demand. Constraint (6.8) ensures each blood type demand is served with a suitable blood type and can not exceed that demand. Constraint (6.9) shows that each blood type has a maximum capacity that cannot be exceeded. Constraint (6.10) specifies that all flows must be non-negative.

6.3.2 ADP Model

The multi-period objective function is:

$$V_t^n(I_t) = arg\ max\ [\ C_t(I_t^n, x_t) + \gamma\ V_{t+1}^{n-1}(I_t^x)], \tag{6.11}$$

where I_t^n is the stock's state at time t, replication n, I_t^x is the inventory state at the end of time t after all expected information is known, and V_{t+1}^{n-1} is the value function expectation of the post-decision state at replication $n-1$. To reduce the outcome space, V_{t+1}^{n-1} is replaced with value function approximation $\bar{V}_{t+1}^{n-1}$. This is computed in replication n-1 and evaluated after the actual information is received at the end of time t. Various methods to approximate a value function exist. A piecewise linear function is used to approximate V_{t+1}^{n-1} because it gives adequate estimations and allows the use of linear programming to solve the problem. The ADP model is the same as the model listed from Equation 4.21 to Equation 4.29 in Chapter 4.

6.3.3 Issuance Policy

The circular policy CRFR used in Chapter 5 will be used her. It is a mixture of First In, First Out policy and Last In, First Out policy. The policy starts by serving demand for blood types that have the lowest substitution option as in Table 6.1, in the following order: O-, O+, B-, A-, B+, A+, AB-, and AB+. For example, type O- can only be served by O- and θ; O+ may be served by O-, O+, and θ, as in Tables 6.3 and 6.4. Notice that the O- reward is less than O+ and all other natural blood types. This will make the O- inventory as the last choice. Table 6.3 represents how the model serves demand for O-. The O- demand is served by O- blood type, starting with supply that is six days old, because it gives the highest reward. If platelets aged six days are not enough to fulfill demand, platelets of a lower age are used next, starting with five day old platelets, until the model reaches platelets with an age of one-day. If there is not enough O- inventory to serve O- demand, θ is used to serve it. However, the O+ demand, as in Table 6.4, is served by the O+ blood type, starting with platelets of age six to age two because they give the highest reward. Then, if there are not enough platelets from the O+ inventory, blood type O- (starting with age six) is used to serve O+ demand. If there is not enough O- inventory to serve O+ demand, θ is used to serve it.

Table 6.3: O- Circular policy reward function

	Type	
Age	O–	θ
1	44.3	1
2	44.8	0
3	45.3	0
4	45.8	0
5	46.3	0
6	46.8	0
7	-10	-1

Table 6.4: O+ Circular policy reward function

	Type		
Age	O+	O–	θ
1	46.5	44.3	1
2	47	44.8	0
3	47.5	45.3	0
4	48.	45.8	0
5	48.5	46.3	0
6	49	46.8	0
7	-10	-10	-1

6.3.4 Implementation

The process starts by using newsvendor to calculate the platelet order quantity. For example, the newsvendor critical ratio is $= 50/(50 + 10) = 0.833$; it is based on the expenses of shortage, which are five times (50) the expiry cost (10). For example, Tuesday's data follows a uniform distribution. Using Matlab, $uniinv(.833) = 65$ doses are found; this is the optimal inventory level on Tuesday. The blood demand, y_{kt}, is generated using the daily data distribution as in Table 3.3. The linear programming model will use the generated quantity from the newsvendor model to solve the single-period model. This will give the optimum solution of the current problem and the dual variables associated with the solution. Thus, the models serve the incoming demand based on the linear programming recommendation. If there is a demand for A+, it will be served from blood types A+, A-, O+, O-, and θ, respectively. At the day's end, the actual information is known and the inventory is updated accordingly. ADP will use the updated inventory I_t, the linear programming solution x_{ijt}, and the dual variable v_t, to build the value function approximation. ADP will then optimize the inventory to find the optimum solution for the second phase model. ADP then suggests the next day's inventory, I_{t+1}, which will be the input to the $t+1$ linear programming model.

6.4 Results and Discussion

The performance of the ADP model will be assessed based on the following factors: to maintain a minimal inventory level, to maintain a minimal shortages percentage, and to maintain a minimal outdate percentage with the maximum reward. In an effort to further illustrate the above model, the Matlab program runs for 52 weeks and is repeated 200 times. A plethora of different scenarios and tests are suggested as follows:

6.4.1 Single or Dual Source

The model is run with a supply of two different types of blood platelets: natural and artificial. Rossi et al. (2012) studied the effect dual sourcing has on food supply chain networks. They varied quality at consumption, age at consumption, and waste rate, and found that the product age was affected by the product wastage. In this model, the inventory percentages are assumed as follows: $(1-\lambda)\%$ natural blood platelets and (λ) artificial blood platelets. The patient will accept $\lambda\%$ of the assigned artificial blood platelets and will refuse $(1-\lambda)\%$. This is because some patients refuse blood transfusion for different religious and ethical reasons or other personal reasons, as stated by Berend & Levi (2009) and Rajtar (2013). Table 6.5 shows a comparison between single- and dual-supply source inventories. It shows their success in regards to shortages and expiry as a fraction of the yearly demand, inventory levels, and rewards. It shows that dual supply (nine blood types) is better than a single supply (eight blood types), where both shortage and outdate rates are around 1%. The inventory level is also lower by 3 units. The reward is higher than the single supply source because the outdate and shortage percentages are less. Furthermore, the cost of natural blood platelets in 2011 was $365 CAD (Canadian Blood Services 2012), which was very high compared to the cost of artificial blood platelets. The reduction of outdate percentage (from 2.6% to 1.2%) will reduce blood bank costs.

Table 6.5: Comparison between single- and dual-supply sources

Supply sources	Shortage %	Outdate %	Inventory level	Reward
Single	1.9	1.8	49	5.4×10^5
Dual	1.1	1.2	46	8.3×10^5

6.4.2 Artificial Blood Platelet Percentage Variations

The artificial platelet substitution has a positive marginal benefit because it has the same character as the O- group and can be used as a universal artificial blood type substitution. Thus, the percentage of artificial platelets within the inventory varies between 0% and 50% of the total inventory; such as Lamme et al. (2010) and Katsaliaki et al. (2014). Lamme et al. (2010) in their blood dual-supply chain model, and Katsaliaki et al. (2014) in their UK blood supply chain game, fluctuate supply, order quantities, and inventory between 0% and 30% to understand and improve the blood supply chain process. In our model, different critical variables are varied to study their effect on the proposed model. Table 6.6 shows the effect of the artificial platelet percentage variation on shortage and outdate percentages. It should be noted that when the percentage is 0, a single supply source is used. When the artificial platelet percentage increases, the natural outdate percentage approaches zero and the artificial outdate percentage increases to 40% of the total inventory, due to the patient's refusal percentage. In contrast, the total shortage percentage decreases to zero. As 80% of the artificial blood platelets are always outdated, the outdate rate increases as the percentage of the artificial blood platelets increases.

Table 6.6: Artificial platelet percentage variations within the total inventory

Artificial Blood %	Shortage %	Natural Outdate %	Artificial Outdate %	Inventory level	Reward
0	1.9	1.8	2.6	49	5.4×10^5
10	1.3	1.5	9.0	53	5.3×10^5
20	0.9	1.1	16	49	5.8×10^5
30	0.5	0.7	24	46	5.4×10^5
40	0.2	0.5	32	43	5.1×10^5
50	0.0	0.2	40	40	5.7×10^5

In contradistinction, the acceptance percentage of the patient of the artificial blood platelet also varied from the total inventory, from 0% to 50%. The artificial blood platelet is kept to 20% of the average total inventory, as suggested by Rijpkemaa et al. (2014). Rijpkemaa et al. (2014) distinguished two consumer groups: 40% of consumers select LIFO (Last In, First Out) products, whereas the remaining 60% select FIFO (First In, First Out) products. In the developed model, it is noted that when 40% accept the artificial blood platelets, the outdate and shortage rates approached zero. The patient's acceptance percentage variation is reported in Table 6.7. As the percentage of acceptance increases, shortage and outdate rates approach zero, while reward increases. As the artificial supply percentage increases and patient acceptance rate increases, the shortage problem will disappear. Thus, if the patient's acceptance percentage and the inventory's artificial platelet percentage are more than 30%, both shortage and outdate rates are below 1.0%.

Table 6.7: Artificial blood platelet acceptance percentage variations

Patient Acceptance Percent	Shortage %	Natural Outdate %	Artificial Outdate %	Reward
0	2.7	2.6	20	1.9×10^5
10	1.2	1.4	18	2.1×10^5
20	0.8	1.1	16	2.2×10^5
30	0.4	0.6	14	4.5×10^5
40	0.1	0.3	12	5.8×10^5
50	0.0	0.1	10	7.1×10^5

Notice that the reward in Table 6.7 is higher than that of Table 6.6. This is because the patient's acceptance rate increases, which leads to a reduction in artificial outdate rates.

To clarify, the patient's acceptance percentage and the artificial blood percentage within the inventory varies together. In Figures 6.1, 6.2, 6.3, and 6.4, the patient's acceptance percentage varies between 0% and 50%, and the percentage of artificial blood platelets within the total inventory varies between 0% and 25%. Figures 6.1 and 6.2 show that both shortage and outdate percentages approach zero as the acceptance percentage approaches 50% and the artificial inventory percentage approaches 25%. As a result, the inventory levels in Figure 6.3 are also decreased, which results in the reward reaching its maximum, as in Figure 6.4. It can be seen that the improvement in expiry rates is more significant because of the fact that the artificial platelet can be used to serve any demand. In addition, shortages are again best described as events where blood platelets are ordered from additional blood banks and approach zero as the percentage of artificial blood acceptance increases.

Figures 6.1, 6.2, 6.3, and 6.4 show a significant decrease in outdate and shortage percentages. The figures also show an already visible significant improvement in all successful factors, including outdate and shortage percentages. They illustrate a need to teach the public about the benefit of artificial platelets, as well as about their similarity to the O- blood type, to increase their acceptance percentages and hence eliminate the problem of blood platelet shortages. If the blood bank maintains a percentage of artificial platelets higher than 30% of the total inventory with more than 40% acceptance percentage, all demand should be satisfied. Moreover, the highest demand level will benefit from maintaining artificial platelets in addition to O-, as additionally demanded doses can be satisfied. As noted by Duan & Warren (2014), the O- percentage in Canada and America is below 9%; thus, O- is reserved to serve O- demand. As a result, the increase in artificial platelet supply reduces the shortage rate, regardless of the demand level. It should be noted that all demand levels show the same behavior. Even in the event that total donation meets the total demand, adding additional doses of artificial platelets is beneficial. As the artificial blood

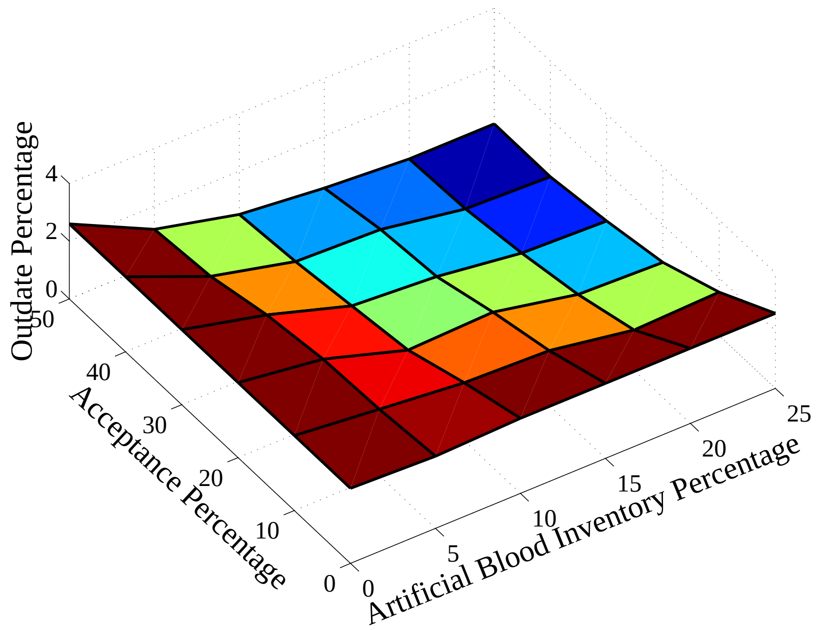

Figure 6.1: The effect of artificial platelets and acceptance percentages on outdate rates

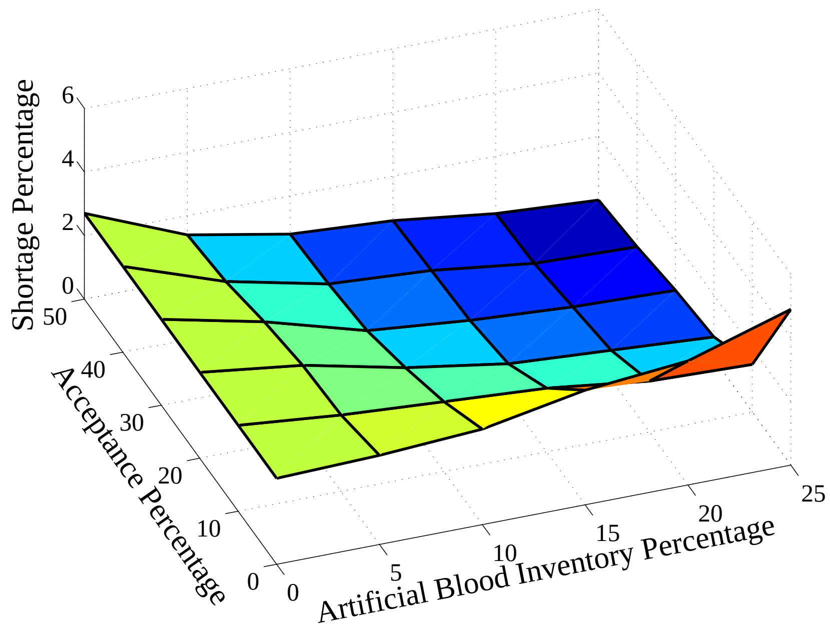

Figure 6.2: The effect of artificial platelets and acceptance percentages on shortage rates

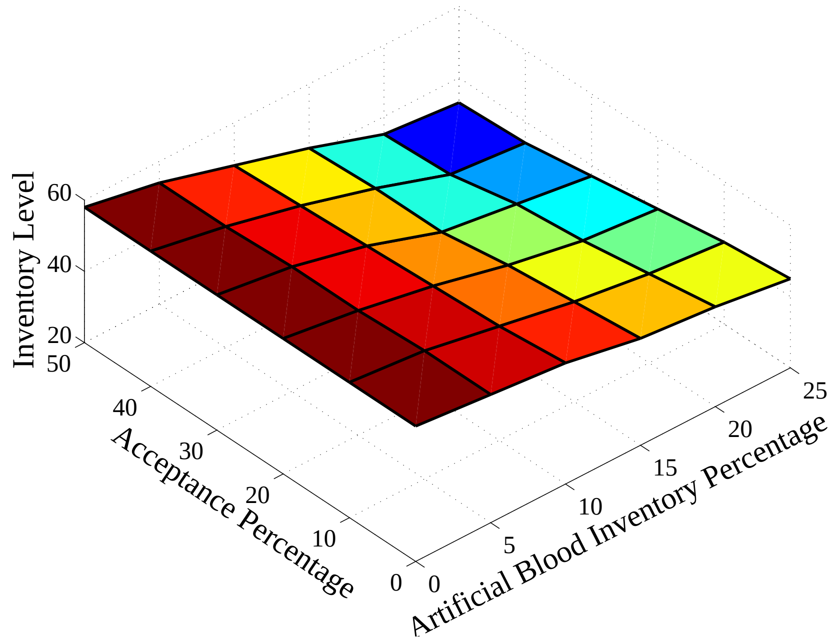

Figure 6.3: The effect of artificial platelets and acceptance percentages on inventory levels

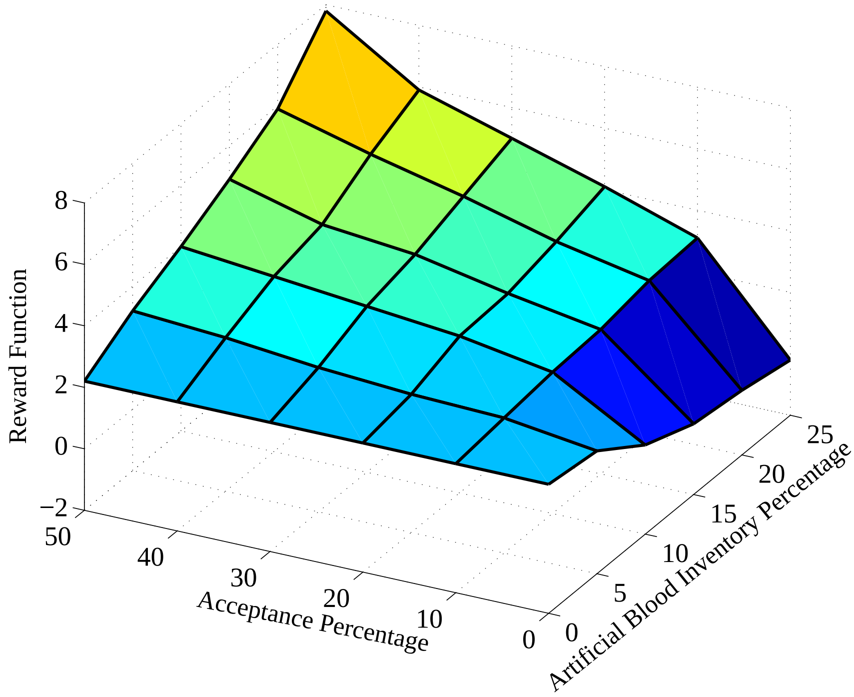

Figure 6.4: The effect of artificial platelets and acceptance percentages on reward functions

platelet percentage increases from the available inventory, all blood types are affected. The patients who refuse the artificial platelets will take natural platelets; consequently, the inventory level of the natural platelets will be reduced, as will the average age. This has a significant impact on the demand fill rate. Within the model that is proposed, demand fill rate percentage is more than 99% compared to the actual fill rate percentages in Canada, listed in Table 6.8 (Canadian Blood Services 2012). In Table 6.6, both outdate and shortage rates are below 1% when patient acceptance percentage is more than 20%. In Table 6.8 the shortage rate varies between 2.3% and 2.7%. Table 6.7 shows that if the platelet acceptance percentage is more than 20%, and more than 20% of the inventory is from the artificial blood platelet, shortage and outdate rates are below 1%. This will also overcome the loyal donor variation, as discussed by Grant (2013) who notes that keeping loyal blood bank donors is difficult.

Table 6.8: Percentages of platelet orders filled by year

Date	Fill rates %	Shortage %
2006/2007	97.6	2.4
2007/2008	97.3	2.7
2008/2009	97.7	2.3
2009/2010	97.6	2.4
2010/2011	97.6	2.4

6.4.3 Average Inventory Level and Age

Another important factor in blood bank inventory is the blood's average age, which is extended from problems similar to those discussed by Katsaliaki & Brailsford (2009), Lamme et al. (2010), and Duan & Warren (2014). The inventory's average blood platelet age is a critical factor in the blood bank process. Table 6.9 gives the average inventory level per blood type, the mean age and the distribution of the age of the blood platelets that are issued. The overall average blood platelet age is 2.1 days, while in Whitaker (2012) the average age was 3.96 days; in Duan & Warren (2014) the average age was 4.2 days at transfusion. O- and O+ have the highest age (3.3 days), but will not cause any problems as they can serve demands for other blood types. AB- and B+ have a higher age; demand is less than donation. In the meantime, B- has a significantly lower age; demand is higher than donation. The B+ donation should be increased to reduce expected shortages. In addition, the last column in Table 6.9 shows the total inventory by age. Notice that more than 75% of inventory is aged 3 days or less. This will increase blood platelet bank efficiency.

The amount of days' worth of platelets available within the blood platelet inventory directly impacts the amount of wasted doses in both the blood bank and healthcare facilities. Hospital inventory is very stable between 2-5 days; any fluctuation is absorbed by the blood inventory, with the consequence of the aging of the stock profile. Platelet stock levels that are higher result in remaining blood platelets having a decreased shelf-life in hospitals. Consequently, doses do not have enough remaining days to be transfused, and they will eventually expire.

Table 6.9: Average inventory levels and ages by blood type

	Blood Type								
Age	AB+	AB-	A+	A-	B+	B-	O+	O-	Total
1	1	1	1	1	1	1	1	1	8
2	0	1	1	1	1	0	1	1	6
3	2	8	1	4	8	0	2	2	23
4	0	3	0	0	6	0	2	2	10
5	0	1	0	0	0	0	1	0	2
6	0	0	0	0	0	0	0	0	0
Average Age	2.3	3.1	2	2.5	3.2	1	3.3	3.3	-

6.5 Summary

A new ADP model for the dual-source blood platelet bank inventory problem is presented. The model strives to capture the dynamic and probabilistic characteristics of the environment in which real-world systems operate. This model is used to show that dual supply has a good potential, especially for short shelf-life products. The research concludes with several test scenarios that represent the effect of artificial blood platelets on the inventory model and blood types. It demonstrates that as the percentage of artificial blood platelets increases, the shortage percentage decreases. If the percentage of artificial platelets within the total inventory is 30% or more, and the patient acceptance percentage is 30% or more, both shortage and outdate rates are below 1%, improving system performance. Furthermore, the inventory performance is improved and the inventory level is decreased. The reduction in outdate and shortage rates and inventory levels results in an overall increased blood bank reward. Finally, the combination of an adequate inventory level and successful ordering decisions with a suitable policy and a suitable artificial platelet percentage should allow blood banks to minimize shortage and outdate rates.

Chapter 7

REGIONAL BLOOD BANK NETWORK MODEL WITH DUAL SUPPLY SOURCE

This chapter provides an analysis and a summary of the results obtained for Objective IV: implement the new model on the chain of supply of a single regional blood bank and different hospitals.

7.1 Introduction

This chapter addresses a platelet inventory network issue which can be best described as having a fixed shelf life, general uncertain demand, and sourcing that is dual-supplied. As far as the author is aware, no one has addressed the problem of a regional blood bank inventory with dual supply sources (natural and artificial) where patients may accept or refuse artificial blood platelets. The regional blood bank will serve a network of four large demand stations (Toronto, Ottawa, Hamilton, and London), as shown in Figure 2.4. We considered the major strategic challenges summarized by Harris (2012). He explained that the vital objective is to provide a high service and low cost network that is better than the competitors'. The artificial blood percentage within the total inventory will be studied and increased up to half of the total inventory, as recommended by Lamme et al. (2010) and Katsaliaki et al. (2014). A circular issuance policy will be used to serve the incoming uncertain demand. The circular policy is derived from Haijema et al. (2007) Abdulwahab & Wahab (2014). The model will be tested using actual data from CBS. The data shows the total blood platelet quantity shipped to four main demand stations: Toronto, Ottawa, Hamilton, and London.

The chapter will discuss the following subjects in the following order: The developed model is discussed in Section 3; Section 4 examines the findings; and both are followed by the conclusion.

7.2 Problem Description

The Canadian Blood Service (CBS) is responsible for all blood collection and production in Ontario region. The CBS in Ontario in 2012 had four distribution centers: Toronto, Ottawa, Hamilton, and London. It collects platelets from its registered donors in Ontario and provides them to its customers. The assumption has been made that products of blood such as platelets are collected, produced, and end labeled at the regional blood center in Ottawa and then delivered to the four demand stations via ground transportation to meet transfusion demand (Canadian Blood Services 2012, Whitaker 2012). Typical orders are sent to the blood center at day's end. They are fulfilled the next morning before exiting the system. One should note, however, that unexpected events out of the ordinary do occur. When those who make the decisions encounter a situation such as running out of stock; express couriers are often sent with great haste to gather platelets from the blood bank, if they are available. Alternatively, some other ways where this situation is approached include: searching for extra platelets from healthcare facilities within the same scheme of consignment; searching for extra platelets nearing outdate from small hospitals, to be used before their expiry; and canceling lower priority surgeries that require urgently needed supplies, such as elective surgeries (Fontaine et al. 2009).

Information on platelet deliveries from the CBS to its four demand stations in the year 2009-2010 is used to test the developed model. During this time, almost all platelets were shipped due to demand needed by hospitals, and 97.6% of demand was met (Canadian Blood Services 2012). In this sense it is assumed that the shipments represented the demands at the demand stations. On the basis of CBS data, Table 3.7 summarizes the four station shipment distributions per day. The daily demand per station is generated from the blood bank shipping data in Table 3.7. Table 7.1, which is derived from Table 3.7, summarizes the total blood bank shipment distributions per day in the Ontario region. Notice that there is no shipping on Sunday because CBS does not work on Sunday. The newsvendor model is used with Table 7.1 to calculate the replenishment order quantity. After that, the aggregated demand and supply are multiplied by the blood type percentage in Table 7.2 column 2 to get the order-up- to quantity per blood type. Table 7.2 summarizes the blood type percentage in Canada and the substitution relationships between blood types. We further assume an issuance policy as suggested by Abdulwahab & Wahab (2014), in which a circular issuance policy is used to serve incoming demand, starting with demand for the rarest blood type, as follows: O-, O+, B-, A-, B+, A+, AB-, AB+, respectively. Furthermore, the blood bank will compare two methods to serve the four demand stations. The first method is by serving the previous demand stations in order of largest demand: Toronto, Ottawa, Hamilton, and London. The second method is by serving the four hospitals randomly, as noted by Pierskalla (2004) and Katsaliaki et al. (2014).

Table 7.1: Total blood bank shipment distribution in Ontario region

Type	Sun.	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.
Distribution	Na	Neg. Binomial	Neg. Binomial	Neg. Binomial	Neg. Binomial	Neg. Binomial	Uniform
Parameters	Na	$n = 42$ $p = 0.1980$	$n = 103$ $p = 0.3736$	$n = 100$ $p = 0.3599$	$n = 295$ $p = 0.6116$	$n = 34$ $p = 0.1574$	[47, 96]

Table 7.2: Patient and donor compatibilities, based on blood types

Blood type	Canadians blood type %	Patient and donor red blood cells compatibilities
AB+	2.5	AB+, θ
AB-	0.5	AB-, AB+, θ
A+	36	A+, AB+, θ
A-	6	A-, A+, AB+, AB-, θ
B+	7.6	B+, AB+, θ
B-	1.4	B-, B+, AB-, AB+, θ
O+	39	O+, A+, B+, AB+, θ
O-	7	All blood types

Four performance indicators have been defined to assess the model performance. These are: the blood platelet shortage rate, the blood platelet outdate rate, the blood platelet average inventory level, and the total reward.

7.3 Model

This is a dual-supply source regional blood bank that serves a chain of four demand stations. The regional blood bank inventory has 48 natural options (8 blood types $\times$ 6 possible ages) and one artificial blood type inventory option. Table 7.2 shows the substitution supply rules between the blood types. This model will be solved in two steps: first, with a Linear Programming model, and second, with an ADP model.

7.3.1 Linear Programming Model

The newsvendor model is used to calculate the optimal inventory level Q_t. The replenishment natural order quantity, p_{t+1}, is calculated based on Q_t. Since λ represents the patient's acceptance percentage for artificial platelets, the artificial order proportion will be λp_t units, and the natural order proportion will be $(1-\lambda)p_t$ units of the total order quantity. The natural order quantity, p_t is multiplied by the percentage in Table 7.2 to get the order quantity from each blood type p_{i1t}. The order quantity will be received and added to the inventory on the morning of day t. After the order quantity is placed, the linear programming model is solved to serve the demand from the current inventory.

The reward function is:

$$\max\ C_t(I_t) = C_d \sum_{k=1}^{8}\sum_{l=1}^{4}(y_{klt} - \sum_{i\in M_k\ and\ i=k}\ \sum_{j=1}^{6} x_{ijklt}) + C_r \sum_{k=1}^{8}\sum_{l=1}^{4}(y_{klt} - \sum_{i\in M_k\ and\ i\neq k}\ \sum_{j=1}^{6} x_{ijklt})$$
$$- C_u(\sum_{l=1}^{4}\sum_{k=1}^{8} y_{klt} - \sum_{i=1}^{8}\sum_{j=1}^{6} x_{ijt} - x_{91t}) - C_g \sum_{i=1}^{8} z_{i6,t-1} - C_h \sum_{i=1}^{8}\ \sum_{j=1}^{6} z_{ijt}$$
$$+\ C_\theta x_{91t} - C_g\ (p_{91t} -\ x_{91t}). \tag{7.1}$$

The blood bank starts serving the four demand stations' demand based on blood platelet substitution relationships, such as in Table 7.2.

At the beginning of day t the inventory I_{ijt} will be:

$$I_{ijt} = z_{i,j-1,t-1}\ \ \forall\ \ i = 1, 2, ..., 8 :\ j = 2, 3, ..., 6 :\ t = 1, 2, ..., T, \tag{7.2}$$

$$I_{i1t} = p_{i1t}\ \ \forall\ \ i = 1, 2, ..., 9 :\ t = 1, 2, ..., T, \tag{7.3}$$

All previous day's natural inventory older than six-days will be counted as outdated doses.

$$D_{i6t} = z_{i6,t-1}\ \ \forall\ \ \ i = 1, 2, ..., 8 :\ \ t = 2, 3, ..., T. \tag{7.4}$$

$$D_{92t} = p_{91t} -\ x_{91t}, \tag{7.5}$$

$$\sum_{l=1}^{4}\ \sum_{k=1}^{8}\sum_{i=1}^{8}\sum_{j=1}^{6} x_{ijklt}\ + x_{91t} + \sum_{l=1}^{4} u_{lt} = \sum_{l=1}^{4}\ \sum_{k=1}^{8} y_{lkt}\ \ \forall\, t = 1, 2, ..., T, \tag{7.6}$$

$$\sum_{l=1}^{4}\ \sum_{k=1}^{8}\sum_{i=1}^{8}\sum_{j=1}^{6} x_{ijklt}\ \leq \sum_{l=1}^{4}\ \sum_{k=1}^{8} y_{lkt}\ \forall\, t = 1, 2, ..., T, \tag{7.7}$$

$$\sum_{j} z_{ijt} \leq N_{it}\ \ \forall\ i, \tag{7.8}$$

$$x_{ijt} \geq 0,\ \ u_{lt} \geq 0,\ D_{i6t} \geq 0,\ \ z_{ijt} \geq 0. \tag{7.9}$$

Constraint (7.2) shows that the ending inventory for $t-1$ will be the starting inventory for day t except the outdated units. Constraint (7.3) shows that the order quantity p_{i1t} received at day t will enter the inventory with age 1 day. Constraint (7.4) calculates the amount of natural outdated doses. Constraint (7.5) calculates the artificial blood platelet outdated doses, while constraint (7.6) shows the sum of the doses, x_{ijt}, moved from the inventory to fulfill demand, artificial platelet, x_{91t}, used to serve demand, and shortages, u_{lt}, which are equal to the total demand from the four demand stations. Constraint (7.7) ensures that each blood type demand from the four demand stations is served with a suitable blood type that does not exceed that demand. Constraint (7.8) shows that each blood type has a maximum capacity that cannot be exceeded. Constraint (7.9) specifies that all flows must be non-negative.

7.3.2 ADP Model

An algorithm example is as follow: let D_1 be the daily demand in the first period. Define p_1 to be the order quantity, I_0 to be the initial inventory, I_1^x to be the leftover inventory at the first period's conclusion, and I_2 the inventory when the second period starts. Any shortage faced will cost C_u per dose and any outdated dose will cost C_g per dose. Since this expediting cost consists of a purchasing cost (which is usually the market price of the blood platelet) and an emergency transportation cost, it is assumed that $C_u >> C_g$. The multi period model is defined in Equations 4.21 to 4.30. Hence, the sequence of events is as shown below:

1. Given initial inventory I_0.
2. In each order cycle the following events occur:
   - 2a. The four demand stations place their orders at night using the newsvendor model.
   - 2b. In the morning, the supplier removes any outdated doses from the inventory and arranges the inventory by age.
   - 2c. The supplier prepares young blood platelet doses as recommended by the newsvendor model, while considering the received orders from the four demand stations.
   - 2d. The supplier, based on the linear programming solution, ships doses to the demand stations.
   - 2e. At the first period's conclusion, the actual demand and supply is known and inventory I_1^x is updated accordingly.
   - 2f. The ADP model is solved using the updated inventory and the dual variables that resulted from solving the linear programming model.
   - 2g. Second-period expected demand y_2 is realized.
   - 2h. The second period inventory I_2 is determined.
3. In the next period, the stock is analyzed and each dose staying in the inventory age has a one-day increase.
4. Doses that have expired through their shelf-life ending are counted and considered waste (incurring a cost of C_g per dose).
5. In case of shortages, the demand station must expedite required doses from the external market, incurring a cost of C_u per dose.

7.4 Results and Discussion

Due to consideration that the process of platelet production includes critical and scarce resources being used, any large adjustments to operation (for example, a sudden increase in blood demand), will have a large impact on these resources' management. The model has dual blood platelet supply sources: natural and artificial. The order quantity percentages are as follows: $(1 - \lambda)$ natural blood platelets and (λ) artificial blood platelets. This is because there are some patients who refuse artificial blood transfusions, as stated by Berend & Levi (2009) and Rajtar (2013). CRFR policy developed in Chapter 5 is used to serve demand.

7.4.1 Serving Demand Stations

The average demand doses per demand station for one week are summarized in Table 7.3. The sequence of serving the demand station was either started with the largest demand or started by selecting station randomly, as suggested by Katsaliaki et al. (2014). In the first method, demand is served by starting with the largest demand stations and working towards the smallest demand stations. The order is as follows: Toronto, Ottawa, Hamilton, and London. At the run period's conclusion, the shortage doses occur at the last served demand station, which is the London station. Table 7.4 shows that London has a total shortage of 22 doses, and the probability of shortage occurrence is 0.015.

Accordingly, when the demand stations are served randomly, a significant number of shortages are in the last station, as in Table 7.5. The total stock-out is 27 doses, and and the probability of shortage occurrence is 0.02. This is higher than when serving the largest station first, but the shortage is distributed among the four stations. The days of the week during which the majority of blood shortages occurred were Monday and Thursday. However, the remaining days of the week had a lower number of shortages. Thus, it is better to serve the station randomly, because the shortage will be distributed among all stations - not only in London. In this case, the shortage can be easily handled in each station by either delaying some non-critical demand or by taking from the patient's relatives or an emergency shipment.

7.4.2 Average Inventory Level and Age

Average inventory level and average inventory age are evaluated to find their impact on platelet availability and outdate rate, as recommended by Lamme et al. (2010) and Rijpkemaa et al. (2014). When the run period concludes, Table 7.6 shows the average supply doses per week. It should be noted that more than 75% of the inventory age is 3 days or less. This means that average inventory levels with an age less than 3 days is high. This will result in reducing the outdate rate. It is clear

Table 7.3: Average demand doses per station

Day of week	Demand station Toronto	Ottawa	Hamilton	London
Monday	62	28	40	82
Tuesday	103	37	47	13
Wednesday	101	40	16	24
Thursday	92	41	31	20
Friday	87	39	37	24
Saturday	51	43	48	10
Sunday	58	28	26	16
Total	554	256	245	189

Table 7.4: Average shortage doses for ordered demand stations

Day of week	Demand station Toronto	Ottawa	Hamilton	London
Monday	0	6	0	10
Tuesday	0	0	0	0
Wednesday	0	0	0	0
Thursday	0	0	0	11
Friday	0	0	0	0
Saturday	0	0	0	1
Sunday	0	0	0	0
Shortage %	0	0	0	11.6

Table 7.5: Average shortage doses for random demand stations

Day of week	Demand station Toronto	Ottawa	Hamilton	London
Monday	0	6	0	0
Tuesday	0	0	0	4
Wednesday	0	0	0	0
Thursday	12	0	0	0
Friday	0	0	0	0
Saturday	0	0	5	0
Sunday	0	0	0	0
Shortage %	2.1	2.3	2.0	2.1

Table 7.6: Average inventory level per blood type per day

	Blood Type							
Age	AB+	AB-	A+	A-	B+	B-	O+	O-
1	2	1	28	4	5	1	31	5
2	1	0	21	3	4	1	23	4
3	0	1	14	2	3	0	15	3
4	0	0	17	2	3	0	18	3
5	0	0	2	3	4	0	4	4
6	0	0	1	0	2	0	3	1

Table 7.7: Average outdate and shortage percentages per type of blood

Type	AB+	AB-	A+	A-	B+	B-	O+	O-
Average outdate %	4.1	1.1	33.6	7.5	9.1	2.7	32.7	9.2
Average shortage %	3.5	1.3	35.4	6.3	11.2	1.9	28.1	12.2

that as the average inventory age decreases, the outdate rate also decreases.

Table 7.5 shows the average shortage from each station. the distribution of these shortages with respect to blood type is shown in Table 7.7. It shows the average outdate and shortage percentages per blood type. The behavior of the respective blood types in Table 7.7 is close to the percentage of blood types in Canada, as in Table 7.2. Both blood types A+ and O+ are the highest in terms of outdate and shortage rates. Notice that blood type AB+ can be served from all eight blood types while A-, B-, and O+ may be served from limited numbers of blood types. That is why AB+'s outdate is less than expected while the others have a higher outdate rate. The shortage rate among them is high. Thus, the proposed issuance policy will first serve blood types that can be served from a limited number of blood types.

In the event that the refusal percentage of the artificial platelet is 80%, the outdated rate 20%. If the artificial platelet dose cost is higher than \$365 (the cost of natural blood platelets is \$365), then the artificial platelet is used only in the event that it is difficult to get the natural blood. An example of an event in which this occurs is on the battlefield. Patients need more time to start accepting the artificial platelets, the blood bank costs will decrease and the platelet shortage problem will be greatly eliminated.

7.4.3 Artificial Blood Platelet Percentages Variation

An additional sensitivity analysis was conducted through the process of varying the percentages of the artificial blood platelets from the total inventory from 0% to 50% (Katsaliaki et al. 2014), while keeping the total inventory level fixed. Table 7.8 summarizes the artificial blood platelet percentage variations. Column 1 is the artificial platelet percentage from the total inventory; column

Table 7.8: Artificial platelet percentage variations within the total inventory

Artificial Platelet %	Shortage %	Natural Outdate %	Inv. level	Reward
0	2.1	2.2	253	2.5×10^7
10	1.8	1.9	231	3.1×10^7
20	1.4	1.6	228	3.6×10^7
30	0.8	0.8	224	4.3×10^7
40	0.4	0.4	220	4.4×10^7
50	0.0	0.1	213	5.2×10^7

Table 7.9: Patient' acceptance percentage variations for artificial platelets

Patient Acceptance %	Shortage %	Natural Outdate %	Inv. level	Reward
0	2.1	2.2	249	1.9×10^7
10	1.7	1.8	236	3.1×10^7
20	1.4	1.6	228	3.6×10^7
30	0.6	1.3	222	4.3×10^7
40	0.3	1.0	213	5.0×10^7
50	0.1	0.6	202	5.6×10^7

2 is the shortage percentage when the artificial platelet percentage within the total inventory is varied; column 3 is the outdate percentage from the natural platelets; column 4 is the average inventory level for the blood bank; and column 5 is the expected reward. It shows that as the percentage of acceptance increases, the shortage and outdate rates approach zero, and inventory level decreases. As a result, reward increases and system performance improves. Furthermore, the acceptance percentage of patient to the assigned artificial blood platelets was varied from 0% to 50%, respectively. Artificial blood platelets are kept to 20% of the total average inventory. The patient's acceptance percentages variations are reported in Table 7.9. Column 1 is the percentage of patient's acceptance to the assigned artificial platelet, column 2 is the shortage percentage when the percentage of patient' acceptance is varied, column 3 is the outdate percentage when the percentage of patient' acceptance is varied, column 4 is the average inventory level for the blood bank, and column 5 is the expected reward. As the percentage of acceptance increases, shortage and outdate rates approach zero and the inventory level decreases from 249 to 202 doses. As a result, the reward increases.

To clarify, the percentage of artificial blood acceptance and the artificial blood percentage within the inventory are varied together. The four successful blood bank factor test results are summarized in 4 figures. In Figures 7.1, 7.2, 7.3, and 7.4, the percentage of artificial blood acceptance is varied to 0%, 10%, 20%, 30%, 40%, and 50%, and the percentage of artificial blood platelets within the total inventory is varied to 0%, 10%, 20%, 30%, and 40%. Figures 7.1 and 7.2 show that both shortage and outdate percentages approach zero as the acceptance percentages approach 50% and

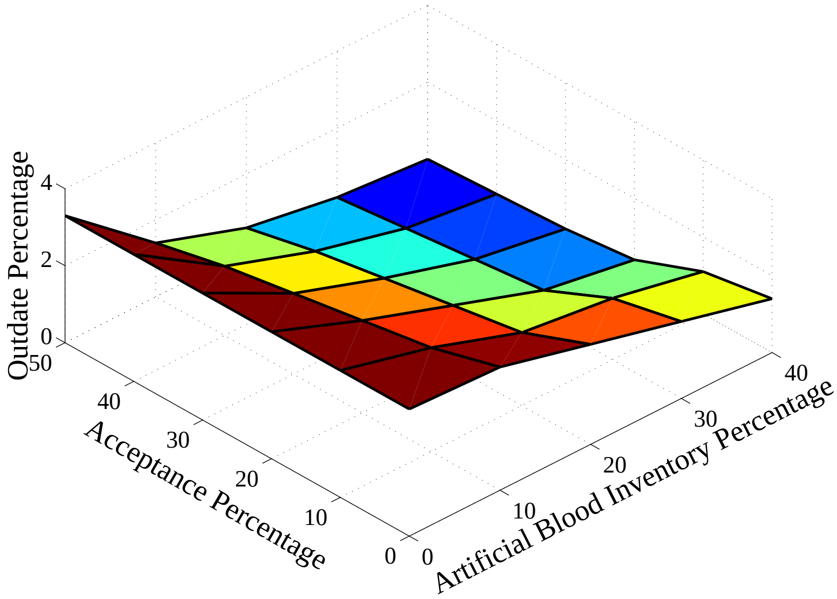

Figure 7.1: The effect of artificial platelets and acceptance percentages on outdate rates

the artificial inventory percentage approaches 40%. As a result, the inventory level in Figure 7.3 also decreased, which led to the reward reaching its maximum value, as shown in Figure 7.4. It is clear that the expiry's improvement is more significant because the artificial platelet can be used to serve any demand. Furthermore, shortages approaching zero as the percentage of artificial blood acceptance increases. As the acceptance percentage increases, shortage and outdate rates decrease. There is no benefit when increasing the artificial blood platelet percentages with the total inventory while patients refuse them. When both percentage factors increase, shortage and outdate rate will approach zero.

Occasionally, the situation of 0 rejection will occur. This situation will transpire when the patients are familiar with artificial blood. At that time, the outdate and shortage percentages are significantly close to zero. There is a need to teach the general public about the strengths of artificial blood platelets as well as how they are similar to the O- blood type; this will increase the artificial blood platelet acceptance percentage, and hence completely omit the challenge of blood platelet shortages.

7.5 Summary

Blood centers' blood platelet production gives a close attention to managing rare resources - for example, carefully managing collection, order quantity, and expenses connected with this process. Transfusions of platelets have demonstrated a continual growth. This occurs alongside an extremely

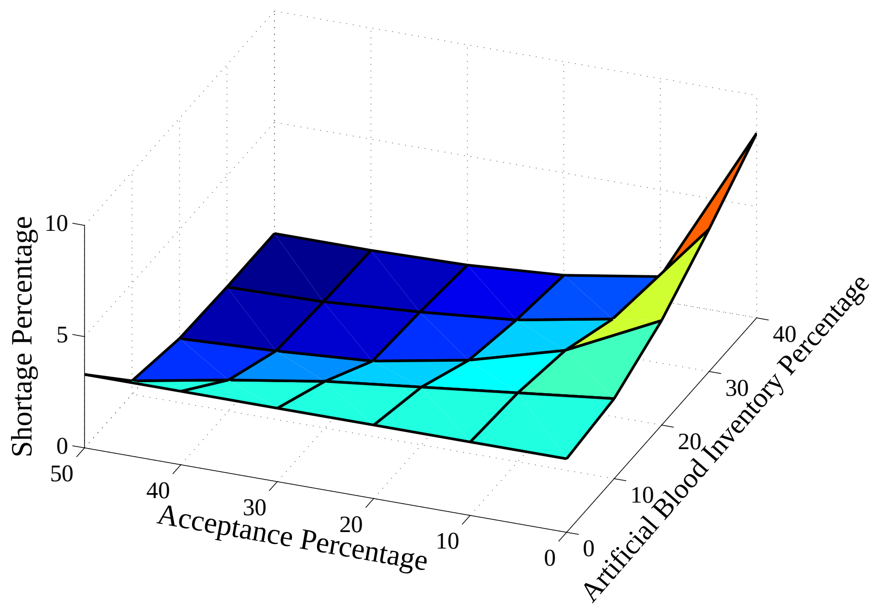

Figure 7.2: The effect of artificial platelets and acceptance percentages on shortage rates

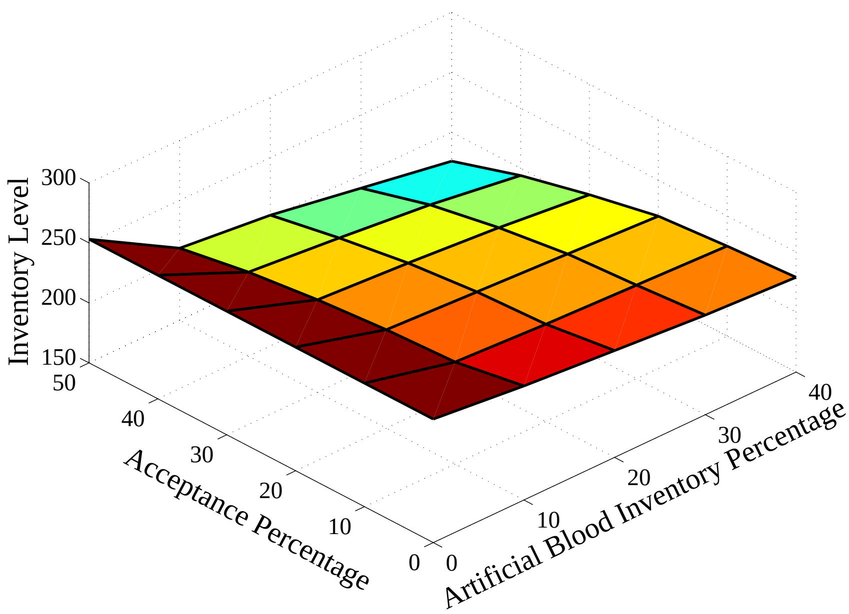

Figure 7.3: The effect of artificial platelets and acceptance percentages on inventory levels

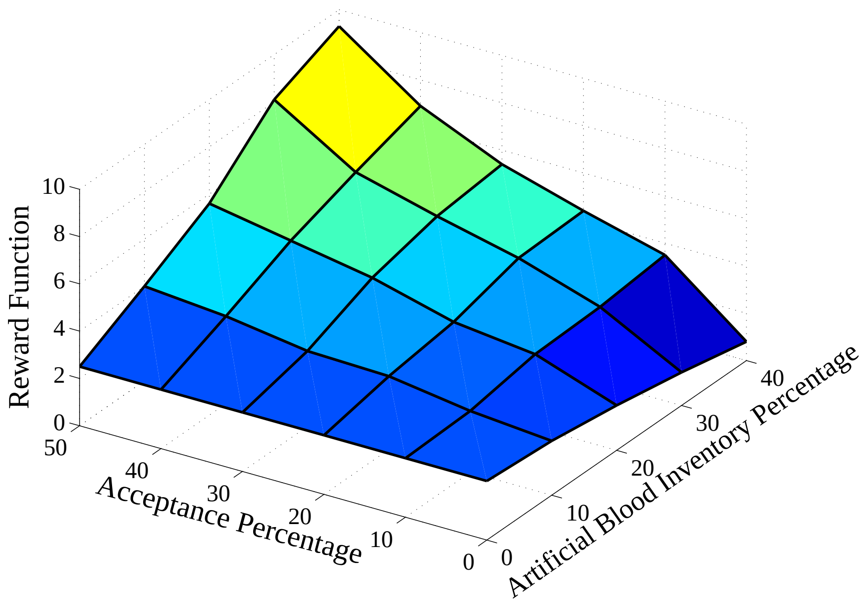

Figure 7.4: The effect of artificial platelets and acceptance percentages on rewards

limited platelet shelf-life; successfully controlling and organizing their supply in a favourable manner is extremely difficult. This chapter proposes an ADP model that supports a regional blood center that serves a network of hospitals' demands. The model has two supply sources: artificial and natural blood platelets. It serves a network of four demand stations. A solution for the optimization challenge was successfully discovered through the utilization of actual information gathered from the Canadian Blood Services. Primarily two factors affect the model: artificial blood platelet percentages within the total inventory, and patient's percentages of acceptance. Computational experiments with the proposed model and variation of the two factors result in the elimination of a portion of the outdate rate while meeting demand requirements; this benefits the blood center by reducing cost, inventory level issues, and shortage rates.

Chapter 8

CONCLUSION AND FUTURE RESEARCH

This chapter has four sections. Section 8.1 presents the conclusions of the dissertation; Section 8.2 provides findings and contributions; Section 8.3 considers the dissertation's implementation limitations; Section 8.4 considers the dissertation's limitations; and Section 8.5 lists future research and directions.

8.1 Conclusions

The need for blood platelets will never cease. Understanding how to manage this vital resource is of utmost importance as you or someone you know will most likely need blood platelets at some point in your lifetime. The blood platelet bank inventory model is a large-scale model with large state space, action space, and outcome space. Management of blood bank inventories grew due to an increased demand for blood products, especially platelets. Many research limitations exist within blood platelet inventory management. Given these limitations in the literature, there is a need to address these research gaps and to bring blood platelet bank modeling efforts closer to reality. Accordingly, in this dissertation several models were developed to address these limitations (in the context of inventory) through a series of contributions. The approach of this dissertation was multidisciplinary. The study addressed blood platelet inventory management, issuance policies, dual supply sources, and distribution. The blood bank inventory management system is a multi-period, multi-product inventory model with single or dual sources of supply (natural eight blood types, and the artificial blood platelet). The natural eight blood type supply has a one-day lead time and a short shelf-life of six-days. The artificial blood is received on the same ordered day and outdated by the end of the same day.

Moreover, the model proposed in Chapter 4 (Objective I) introduces a workable model that represents a blood bank inventory. The model considers a blood platelet bank with eight blood types, uncertain demand, and a deterministic lead-time. Approximate Dynamic Programming, linear programming, and the newsvendor model are combined, presented and applied to a blood platelet inventory model. Furthermore, several alternative issuance inventory policies are used to test the proposed model using Canadian Blood Services data.

In Chapter 5 (Objective II), the model proposed in Chapter 4 is used to study different issuance policies that can serve different blood platelet demands; it tries to give insight on possible beneficial parameters of order strategies. The policies start by serving demand for the blood types that have the lowest substitution option, as follows: O-, O+, B-, A-, B+, A+, AB-, AB+. A special interest lies in finding a practical issuance policy that can serve various demand types with minimum shortage and outdate percentages.

The model proposed in Chapter 6 (Objective III) presents an alternative solution that focuses on adding a second source of supply to the model proposed in Chapter 4 and to the policy proposed in Chapter 5. The model has two sources of supply: natural blood platelets (the eight natural blood types with deterministic lead-times) and artificial blood platelets (the one artificial blood type). The model also considers the fact that patients have the right to reject transfusion of artificial blood platelets.

The model proposed in Chapter 7 (Objective IV) analyzes a regional blood bank inventory that serves a network of hospitals and demand stations within Ontario. The bank also has dual-supply sources: natural and artificial blood platelets. Hospitals' demand are served either starting with the largest demand station or starting with a random station. Using actual data, a sensitivity test is provided alongside a numerical illustration for the purpose of examining blood platelet inventory management dynamics.

8.2 Contributions

In the blood platelet bank inventory literature, several factors that have significant effects on inventory optimization, were either ignored or forgotten. Examples of these factors include: the estimated quantity used per patient, the inventory model downsizing, the ignorance of the eight blood types and their ages, unit outdate costs compared to unit shortage costs, and the variation of blood platelet production rates due to uncertain demand effects. This study contributes by introducing an applicable methodology to improve blood platelet bank inventory management. It addresses some of the literature research gaps. The developed models succeed in reducing blood platelet shortages, blood platelet wastages and inventory levels which result in maximizing rewards.

This work contributes to the following research goals: (a) Develop a multi-period and multi-product model based on ADP, addressing some of the literature gaps and overcoming the curse of dimensionality. (b) Develop an ADP approach to model blood bank inventories, with the aim of including the eight blood types and their ages. The model is successfully applied without any downsizing, and overcomes the curse of dimensionality. (c) Develop policies that can handle different types of demands while keeping both shortages and outdates at a minimum. keeping a rotation policy for blood platelets can considerably decrease outdate rates. (d) Consider two supply sources: the artificial blood platelet with deterministic supply and lead-times, and the eight natural blood types with uncertain demand and deterministic lead- times. (e) Analyze a regional blood bank inventory system that serves a network of hospitals and demand stations within Ontario. The blood bank has dual-supply sources comprised of natural and artificial blood platelets. As aforementioned, the model considers the fact that patients have the right to refuse transfusion using artificial blood platelets. As far as the author is aware, no one has addressed models (for items (d) and (e), a blood bank inventory with dual supply sources (natural and artificial) where patients may accept or reject assigned artificial blood platelets.

8.3 Implementation

When the model was built, the process and the sequences were built based on an interview with CBS staff. The model considers the most important factor that affects the hospital blood bank. To implement the developed software, blood data, staff training, and top management commitments are needed. CBS provided demand data per day. This data was used to find the model parameters, blood types percentages, and data distributions. This parameters is the input for the model's developed program. The policy developed will be calibrated to give priority to low demand blood types and keep high demand blood types as much as possible, to serve more patients and avoid blood shortages. Based on this information, aggregated blood demand was generated using the daily data distribution. Supply data was created using a combination of a newsvendor model and the same demand distribution. The laboratory staff need a suitable training, in addition to a strong commitment from top management. The staff should start the day by removing any outdated units and receive the new donations. Then, they must update the computer program with the actual available inventory. They then receive the recommended order quantity from each blood type. Next, they start serving the incoming demand based on the program recommendation. At the conclusion of the day, the inventory is updated with the actual demand and supply. The software developed default is set to use the circular policy, but it can be changed to other policies. The process is repeated daily.

8.4 Limitations

Most literature models are based on assumptions and require defined inputs that have limitations and weaknesses. Thus, systems built on such models cannot be expected to perform as well as anticipated; imposing strict assumptions leads to distorted results (Smaros et al. 2003). One of the key limitations of using these models in practice is the availability of data and its accuracy. In the event that accurate data is not present, the computation of required input information as demand and supply will not represent actual model parameters. Furthermore, if the data is less than one year old the applied parameters may be different (less or more) than they should be. This will not give exact ethnic blood groups or show clear community characteristics. In addition, urgent shipments are not considered, although they happen quite often. This is because central blood banks do not usualy record all urgent shipments for a long period of time. Central blood banks need to expend additional efforts to record three to five years of data containing all urgent shipments so that the data can be studied in detail. Close collaboration between suppliers (blood establishments and blood banks) and users (hospitals) is of utmost importance.

Two of the key assumptions in this dissertation are the artificial blood platelet's shelf-life and production lead-time. No literature has been found regarding this. It is assumed that its shelf-life is one-day and its production lead-time is neglected. Other assumptions may also change over time or when the artificial blood platelets are produced in large quantity. For example, the character and quality of artificial blood platelets compared to the natural blood platelets may change.

8.5 Future Research

A significant number of problems in the blood platelet banks were studied. Nonetheless, a notably large percentage of open questions concerning research require attention. There is need for: (1) Research is needed on various inventory handling problems such as: unit mishandling, misplacing, or damaging which will affect blood inventory management. Leaving the blood units in uncontrolled temperatures will spoil the blood platelets. The use of electronic devices such as RFID may automate, control, speed up, and overcome some of blood bank inventory problems. (2) The effective usage of O- and the artificial blood platelet, because they are a universal blood type wherein total platelet need is larger than the willingness of people to donate. Optimizing and balancing their production and usage will sure reduce blood shortage and can also reduce public expenditure in this regard. (3) It would be particularly valuable to study the problem wherein inventory levels may be reviewed more frequently in a dynamic inventory setting. This will reduce both outdate and shortage percentage (as shown in Chapter 4) but will increase blood bank shipping and handling cost. (4) Different challenges between blood platelet banks and hospital blood platelet banks need to be studied. Some of these challenges include: when and who owns blood products - and in what way they can be priced to effectively achieve the most favourable donor and patient results, while maximizing overall social benefits. Business Process Management and Organizational structures for blood platelet banks can be used to study this problem. (5) Demand data integration with centers of transfusion, such as healthcare facilities; donor centers could supply data integration. It would be favourable as a goal as there is a limited amount of time between platelet collection, production, and transfusion. (6) Additional research should examine sources of information necessary for the implementation of these inventory models becoming accessible to staff, so that they may consider it and use it in their process of decision-making. The effect of asymmetric information on blood products (e.g., the demand forecast or the available amount of old doses) is another intriguing possibility for future research. (7) The effect of urgent shipment and emergency demands on long holidays such as new year holiday, needs to be studied. The proposed model (with some changes) can handle some of these research.

A number of additional areas of potential research can be listed, but those mentioned above present the reader with an effective sense of the significant need for more blood platelet bank knowledge. Some seemingly insignificant improvements can have a notable impact and can assist in decreasing national expenses. One can only hope that over time we will couple our modeling efforts with supporting empirical work to resolve these issues.

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