INVENTORY MANAGEMENT AT HOSPITALS TO MINIMIZE PLATELET WASTAGE

A Thesis in
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by
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ABSTRACT

This research proposes inventory policies for the management of platelets at hospitals. It has been shown that a significant amount of platelets is wasted in hospitals due to its short expiration time after collection. Since the demand of the platelets is highly uncertain, the safety stock of platelets is kept extremely high to mitigate the risk of shortage. Hence, the objective of this research is to minimize the platelet wastage at the same time maintaining a specified service level. Finite and infinite time horizon inventory models are developed to determine the order quantity and the time to order platelet such that wastage and shortage are reduced.

The robustness of the solutions is tested by performing a sensitivity analysis. The lead time and review periods are varied in both inventory models. In addition, in the finite time horizon model, the effect of different cost scenarios on the four criteria is studied using simulation. In the infinite time model, the service levels are varied to analyze their effect on the criteria. For the sensitivity analysis, four criteria are considered; Wastage as Percentage of Procurement (WAPP), Holding as Percentage of Procurement (HAPP), Shortage as Percentage of Demand (SADP) and Total Cost (TC). The results of the finite time horizon model indicate that when more priority is given to reduce shortage, SAPD decreases while WAPP, HAPP and TC increase. The results of the infinite time horizon model indicate that when the service level increases, SAPD decreases and WAPP, HAPP and TC increase.

Keywords: Platelets, wastage, inventory management, Wastage as Percentage of Procurement (WAPP), Holding as Percentage of Procurement (HAPP), Shortage as Percentage of Demand (SADP), Total Cost (TC), forecasting, finite time horizon model, infinite time horizon model.
# TABLE OF CONTENTS

LIST OF FIGURES .......................................................................................................... vi

LIST OF TABLES ............................................................................................................. vii

ACKNOWLEDGEMENTS ............................................................................................... viii

Chapter 1 Introduction ................................................................................................. 1

1.1 Supply Chain for Perishable Items ........................................................................ 1

1.2 Blood Supply Chain .............................................................................................. 2

1.2.1 A Brief Overview of Blood Collection and Distribution Process .................. 2

1.2.2 Apheresis Platelet Supply Chain .................................................................... 5

1.3 Forecasting Demand of Blood at BSC .................................................................. 6

1.3.1 Demand Forecasting of Perishable Items ....................................................... 6

1.3.2 Necessity for Forecasting Demand for Blood Products .................................. 6

1.4 Motivation for this Research ................................................................................ 7

1.5 Research Plan ........................................................................................................ 9

1.6 Outline of the Thesis ........................................................................................... 10

Chapter 2 Literature Review ....................................................................................... 11

2.1 Inventory Policy for Perishable Items ................................................................... 11

2.2 Blood Products Supply Chain .............................................................................. 12

2.2.1 Taxonomy of Supply Chain Management of Blood Products ...................... 13

2.2.2 Blood Product Management: Hierarchy of Levels and Related Issues at Strategic, Tactical and Operational Levels ......................................................... 14

2.2.3 Multi-objective Blood Inventory Management .............................................. 16

2.2.4 Solution Techniques for Blood Product Inventory Management ............... 16

2.3 Review of Literature on Forecasting .................................................................... 20

2.4 Shortcomings of Previous Research on Blood Inventory Management ............... 21

Chapter 3 Research Methodology ............................................................................. 22

3.1 Finite Time Horizon Model ................................................................................. 23

3.1.1 Forecasting Platelet Demand ......................................................................... 23

3.1.2 Finite Time Horizon Model Description ...................................................... 25

3.1.3 Finite Time Horizon Model Formulation ...................................................... 27

3.1.4 Illustrative Example ...................................................................................... 31

3.1.5 Model Summary ........................................................................................... 32

3.2 Infinite Time Horizon Model .............................................................................. 32

3.2.1 Periodic Review, Order-up-to Level Policy .................................................. 33

3.2.2 Periodic Review, Base Stock Policy ............................................................. 33

3.2.3 Computation of Order-up to Level $S$ ........................................................ 33
LIST OF FIGURES

Figure 1-1: Members of the Blood Supply Chain ................................................................. 2
Figure 1-2: Flow of Blood along Blood Supply Chain (Nagurney et al., 2011) ..................... 3
Figure 2-1: Shortage-outdating operating curve: an independent hospital (Jennings, 1973) ... 17
Figure 3-1: Overview of Research Methodology .................................................................. 22
Figure 3-2: Flowchart of the proposed finite time horizon model ........................................ 30
Figure 4-1: HAPP when review period is 2 days and varying lead time ............................... 43
Figure 4-2: SAPD when review period is 2 days and varying lead time ............................... 44
Figure 4-3: Total Cost when review period is 2 days and varying lead times ....................... 46
Figure 4-4: WAPP when review period is 2 days and varying lead time ............................. 51
Figure 4-5: HAPP when review period is 1 day and varying lead time ............................... 52
Figure 4-6: HAPP when review period is 2 days and varying lead time ............................. 52
Figure 4-7: Total Cost when review period is 1 day and varying lead time ......................... 54
Figure 4-8: Total Cost when review period is 2 days and varying lead time ....................... 55
LIST OF TABLES

Table 2-1: Summary of Blood Inventory Models ................................................................. 19
Table 4-1: Results of forecasting errors for varying value of \( \alpha \) .................................... 37
Table 4-2: Forecasted demand for 30 days ........................................................................ 38
Table 4-3: Cost Scenarios .................................................................................................. 40
Table 4-4: Combinations of lead time and review period (in days) .................................... 41
Table 4-5: Sensitivity Analysis - Effect of lead time and review period on HAP ............... 42
Table 4-6: Sensitivity Analysis - Effect of lead time and review period on SAPD ............. 43
Table 4-7: Sensitivity Analysis - Effect of lead time and review period on Total Cost (dollars) ............................................................................................................. 45
Table 4-8: Combination of lead time (in days), review period (in days), and service level (in %) .................................................................................................................. 48
Table 4-9: Parameter settings (Fixed) ................................................................................ 49
Table 4-10: Sensitivity Analysis - Effect of lead time and review period on WAP ............ 50
Table 4-11: Sensitivity Analysis - Effect of lead time and review period on HAP ............. 51
Table 4-12: Sensitivity Analysis - Effect of lead time and review period on SAPD .......... 53
Table 4-13: Sensitivity Analysis - Effect of lead time and review period on Total Cost ...... 54
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Chapter 1

Introduction

Supply chain is defined as a series of coordinated stages that are situated at various locations to ensure the procurement of raw materials, production of the semi-finished and finished goods and distribution of the products to customers. The different stages of the supply chain include supplier, manufacturer, distributor, retailer and customers who are physically distinct and geographically separated (Ravindran and Warsing, 2013). Some companies include fewer members of the supply chain and some companies include more. These entities are generally independent and operate under different constraints and objectives. An efficient supply chain will result in the delivery of the right quantity at the right time at the right place.

1.1 Supply Chain for Perishable Items

Supply chains delivering perishable products like blood, food, medicines, drugs and flowers, are unique with specific challenges in comparison to that of non-perishable items due to the finite product shelf life (Nargurney et al., 2011). The product’s shelf life is defined by Donselaar et al., (2006) as the “lifetime of the product that is measured in days, counting from the day it is produced until the product becomes unacceptable for consumption or obsolete”. Therefore perishable item supply chain will definitely result in higher wastage of products compared to that of non-perishable item supply chain. Donselaar et al., (2006) also suggested that items which have a shelf life of 30 days or less can be categorized as perishable items. For instance, perishable items such as blood, food, medicines, drugs and flowers have a short shelf life and thereby leading to a significant wastage if not utilized within that duration (Parfitt et al., 2010).
In particular, blood supply chain deals with the delivery of different components of blood namely Red Blood Cells (RBC) and platelets suspended in liquid substance called plasma from the donor to the hospitals and surgery centers for patient treatment as shown in Figure 1.

1.2 Blood Supply Chain

Each component of blood has its own function/purpose in humans and therefore is essential to maintain appropriate proportion of these at all times.

(a) The RBC carries oxygen from the lungs to all parts of the body and is needed during surgery when there is major blood loss.

(b) Platelets are mainly used for arresting bleeding when there are any wounds and are needed during surgery to ensure coagulation of blood. In addition, platelets are used for treating cancer patients and during organ transplant.

(c) The function of plasma is that it helps in the treatment of burns (Belien and Force, 2012).

![Figure 1-1: Members of the Blood Supply Chain](image)

1.2.1 A Brief Overview of Blood Collection and Distribution Process

There are multiple suppliers for blood products in the United States. The U.S. Food and Drug Administration (FDA) has developed regulations for the blood collection and distribution process.
The American Red Cross (ARC) is the largest supplier of blood products. It has several blood collection sites across the US which distributes about 50% of the blood supplies. The other 50% is collected and processed by community blood centers. Community blood centers are independent non-profits, and are typically members of America’s Blood Centers (ABC). The FDA regulates all the blood centers in the US. ARC divisions at particular regions organize blood donation programs and set up blood collection sites. A regionalized blood banking system for the ARC in the USA is shown in Figure 2 (Nagurney et al., 2011).

Figure 1-2: Flow of Blood along Blood Supply Chain (Nagurney et al., 2011)

The flow of blood along the supply chain takes place as follows.

- The whole blood is collected at several collection sites from various donors and is then sent to blood centers. Blood that is drawn from the donor is usually undivided and in
whole form (Belien and Force, 2012). Every donor has to satisfy the FDA requirements. Each unit of blood that is collected from the donor is kept track (including the donor information).

- The blood at the blood center is separated into three major blood components: RBC, plasma and platelets. The average unit of donated whole blood is 450 to 500 milliliters which is used to provide one unit of RBC and 1 units of plasma. Platelets that are usually collected from five donors are required for one patient and hence five units of platelets are pooled together.

- From the blood centers, the blood is sent to the component labs for testing for any infection such as HIV, Hepatitis A, Hepatitis B, Hepatitis C, West Nile Virus, etc (American Red Cross, 2013). As of 2013, ARC has 5 testing labs across the US. There are 36 blood regions that share the testing labs. The small sample that is tested at the lab is discarded irrespective of the results of the test. From the sample testing if the blood is observed to be contaminated, the corresponding blood unit is discarded at the storage facility. The testing procedure however incurs an operational cost (Nagurney et al., 2011).

- The blood bank places orders to the blood center and thereafter blood at the storage facility is delivered to the requesting blood bank in validated, temperature controlled carriers.

- Several hospitals and surgery centers which are the demand points place order to the blood bank for various blood components depending upon their needs to serve their patients. Hospitals have contract only with a single blood center and cannot procure blood products from different suppliers. For example, Penn State Hershey Medical Center and Geisinger Medical Centers have their own collection centers and do not procure blood from any other blood centers. However, all collection centers are operated under the ARC or an ABC community blood center.

Blood center assumes that all the units of blood that are obtained by the hospitals are used by them. In other words, donor center does not keep track of whether a blood unit
procured by the hospitals is being utilized or not. It is the responsibility of the hospitals to have the record of the transfused and unutilized units.

The process of moving the blood components down the supply chain involves several costs (Ghandforoush and Sen, 2010):

- Cost of testing platelets for any infection
- Outdating cost
- Transportation cost
- Cost of separation of platelet rich plasma from RBC
- Shortage cost
- Blood components carrying cost

1.2.2 Apheresis Platelet Supply Chain

Platelets in particular, can be collected from the donor through a process called platelet apheresis by which blood is withdrawn and only platelets are extracted from the donor’s blood and the remaining blood components are injected back into the donor’s body. Though this method is expensive, the frequency of platelet donation is increased to once in every 2 weeks (i.e., 24 times a year) from once in every 56 days which is approximately 6 times a year (American Red Cross, 2013). From the donor site, apheresis platelets are sent to the blood center for testing and then shipped to blood bank and hospitals as in regular blood supply chain. A return feedback is provided from the hospital floor (transfusion tag), for example, a feedback mentioning that there is no hole in the bag, unit procured is transfused, etc. European countries have adopted a patented production process for platelets which utilizes a platelet additive solution instead of plasma for platelet storage whereas the US FDA has not licensed this production process.
1.3 Forecasting Demand of Blood at BSC

1.3.1 Demand Forecasting of Perishable Items

Forecasting of demand for perishable item is more difficult due to its limited life, but it is essential for hospitals, drug companies and supermarkets to avoid outdating of the products. In the paper by Donselaar et al., (2006), it was mentioned that general forecasting of the demand for perishable items in supermarket is done using individual judgment considering weather conditions, time of the year (particularly for seasonal products), promotions and price of the item. The paper also suggested that this approach is incorrect since individuals’ perspective varies and the approach becomes even more inaccurate when it is done for large number of items highlighting the necessity for using forecasting techniques. Also the paper suggests that weekly demand pattern of the product must be considered as an important input for forecasting the future demand.

In particular, forecasting demand for blood components at the blood supply chain is very essential because advanced information can increase blood collection efforts during the lead time if more blood is required and blood collection can be limited if less units are projected (Frankurter et al., 1974). In the research paper by Boyle et al., (2008), it was said that “forecasting is an important aid in many areas of hospital management, including elective surgery scheduling, bed management, and staff resourcing”. Therefore, adequate forecasting is required for planning future blood collection efforts to avoid outdating as well as stock-outs of blood units (Pereira, 2004).

1.3.2 Necessity for Forecasting Demand for Blood Products

a) Holmstrom et al., (2002) provided the fact that retailers generally do not pay much attention to forecasting perishable items if the service level of their suppliers is extremely high. However, the main challenge involved in blood supply chain is the shortage of blood products due to limited donor population resulting in low service level
from the blood centers and blood banks. Therefore, hospitals need to accurately forecast the patient demand and place their orders well in advance to the blood bank to reduce shortage.

b) In the paper by Frankfurter et al., (1974), the authors mentioned that during midsummer and end of year holiday season, donors do not prefer to donate and due to the short shelf life of blood, shortages occur. Therefore, it is necessary to forecast in advance the demand of blood during those periods and plan accordingly to collect blood.

c) During Easter and Christmas (which is referred to as “production breaks”), blood centers do not operate and hence supply of blood from the blood center is affected. Ordering policies of platelets for those special periods was studied in detail by Haijema et al., (2009). Hence, hospitals and blood bank forecast demand and order to the upstream member well in advance to reduce the risk of shortage.

1.4 Motivation for this Research

The study of blood collection and distribution process is very essential because

- There is a significant wastage of blood along the blood supply chain (i.e., from the time of collection of blood from the donor to the time of providing blood to the patient). Along the supply chain that is discussed above, it has been reported (Nagurney et al., 2011) that in 2006, “the national estimate for the number of units of whole blood and all components outdated by blood centers and hospitals was 1,276,000 out of 15,688,000 units”. In other words, approximately 8% of the total units collected are wasted.

- Components of blood are used for saving human lives.

There is more wastage of blood due to high inventory levels maintained at the hospitals and at the blood banks.
The reasons behind maintaining high inventory level are as follows.

a) Blood components have a very short shelf life. Moreover, blood after being collected is first being tested for any infection and only the uncontaminated blood is available for patient use. The process of testing takes about 2 days. RBC’s have a shelf life of 30-35 days. Platelets have a shelf life of 5-7 days and plasma has a shelf life of a year (American Red Cross, 2013). Among these components, platelets have the least shelf life. Moreover, after being tested at the labs (culture/ bacterial testing), they have a remaining shelf life of only 3-5 days. Due to the very short shelf lives of platelets, hospitals maintain high inventory to compensate for the outdated platelets.

b) The supply and demand of blood products are stochastic. Therefore, blood centers collect more blood than required to compensate for the extreme demand scenarios thereby resulting in outdating.

c) Critical patients may need numerous blood transfusions prior to recovery. However, the number of units of the specific blood component needed for each treatment cannot be determined. For example, platelets are mainly used for cancer patients during chemotherapy. During chemotherapy, platelet count decreases and if the count drops below $10^7$ platelets/L of blood, platelets are injected into the patient. However, it is not possible to determine whether a patient will be requiring platelets during each chemotherapy treatment. Therefore, the supply of blood components must be continuously maintained depending upon the treatment type (BJC Healthcare, 1997).

It is necessary to minimize platelets wastage at hospitals for the following reasons.

a) Over the past 10 years, demand of blood has increased but the supply of blood is not increasing enough to meet the demand (Landers, 2001). Moreover, increased strict regulation of FDA reduces the chances of eligible donors.

b) Blood products are perishable and hence donated blood cannot be stored and used for future demand.

c) Shortage of blood can even lead to the death of a person.
(d) Outdating of blood is also not acceptable because less than 38% of the population is eligible for donating blood and 5% of the eligible blood donors actually donate blood (American Red Cross, 2013; LifeStream, 2009). Also, depending upon the type of donation, time between donations is also required. Therefore, very frequent donation by the same person is not possible.

(e) It is observed from the literature that hospitals experience a surgical delay of 50 days due to shortage of blood. Sometimes even a delay of 120 days has been observed due to shortage of blood. Therefore, reduction of wastage can minimize the delay in performing the surgery (Frankfurter et al., 1974).

(f) Cost of procurement and testing is quite high. In 2011, mean cost of purchasing one unit of RBC by hospitals from its suppliers was $210.74 (Schrijvers, 2011).

In particular, platelets have the least shelf life and hence highest wastage (15% to 20% of the total units collected are outdated). Blood platelet demands are uncertain. Platelet transfusions are given to patients undergoing chemotherapy for leukemia, multiple myeloma, those with aplastic anemia, AIDS, hypersplenism, sepsis, and those in need of bone marrow transplant, radiation treatment, organ transplant, etc. (American Association of Blood Banks, 2005; Zhou et al., 2011).

Among the members of the entire blood supply chain, hospitals exhibit the maximum demand variability and hence the highest platelet wastage (Cachon, 1999).

1.5 Research Plan

This thesis aims to determine the following:

a. Forecast the platelet demand for a given planning horizon at the hospitals. Several forecasting methods will be tested to determine their suitability.

b. Determine how many units of platelets to order from the blood center and when to order them. Ordering policies for both finite time horizon and infinite time horizon
will be developed for platelets procurement at minimal cost. The different order policies will be compared using simulation.

1.6 Outline of the Thesis

The remainder of the thesis is organized as follows. The literature review of the proposed research is presented in Section 2. The proposed forecasting model and inventory models are discussed in Section 3. Analyses of the effectiveness of the various inventory policies are provided in Section 4. Conclusions and suggestions for future work are presented in Section 5.
Chapter 2
Literature Review

2.1 Inventory Policy for Perishable Items

Fries (1975) determined optimal inventory policy for the perishable items depending upon the shelf life of the product. Two cases were analyzed. In the first case, the shelf life of the product is considered one day (i.e., no inventory is carried from one time period to the next) with no backordering, then the inventory at each period is independent of the other and therefore, the problem becomes a “newsboy problem”. In the second case, where the shelf life is more than a day and no backordering, dynamic programming was developed to determine the optimal inventory ordering policy. The results were obtained for both finite and infinite horizon problem. Nahmias (1976a) also adopted a dynamic programming approach to develop an inventory model to reduce wastage and shortage of perishable items.

In the work by Nahmias (1975b), a heuristic was proposed for determining ordering policy instead of dynamic programming approach. The author also suggested that if the shelf life of the product is greater than 1 day, the dynamic programming problem becomes computationally difficult as well as the implementation of the policy becomes tedious. The results of heuristic approach were compared to that of the optimal policy developed by Nahmias (1975a).

Goyal and Giri (2001) provided the literature review of perishable items. The authors classified the research work done in perishable item since 1990 into the following three categories: (1) Inventory models with fixed lifetime (see Schmidt and Nahmias 1985; Nandakumar and Morton, 1993; Liu and Lian, 1999; Perry, 1997), (2) Inventory models with random lifetime (see Kalpakam and Sapna, 1994; Kalpakam and Sapna, 1995; Kalpakam and Sapna, 1996; Liu and Shi, 1999), (3) Inventory models in which items decay depending upon the utility function. For fixed life time, Schmidt and Nahmias (1985) assumed fixed lead time and developed a continuous review policy. Later, Berk and Gürler
(2008) developed $(s, Q)$ policy assuming fixed lead time and constant life time. Kalpakam and Shanthi (2001) analyzed the scenario in which life time is exponential. Goyal and Giri (2001) also suggested that demand plays an extremely important role in developing the perishable inventory model and classified the research done in the past based on the type of demand such as deterministic demand (see Haringa, 1995; Haringa, 1996; Xu and Wang 1992; Yan and Cheng, 1998) and stochastic demand (see Dave, 1991; Kim, 1995; Kalpakam and Sapna, 1996). Deterministic demand was further classified as uniform demand, time varying demand, stock and price dependent demand. Stochastic demand was classified as known and arbitrary probability distributions.

The research paper by Broekmeulen and van Donselaar (2009) took into account the age distribution of the inventory and developed a replenishment policy with stochastic demand and fixed lifetime. The results were compared to the base policy adopted from Tekin et al., (2001) and concluded that considering age distribution of the inventory reduced the wastage of perishable items to 8.2% for FIFO withdrawal and 11.0% for LIFO withdrawal.

### 2.2 Blood Products Supply Chain

In recent years, minimizing wastage and shortage of blood products have gained a lot of attention. For example, various inventory models were developed and tested with the major focus on regional blood banks (Haijema, 2007; Haijema, 2009; van Dijk, 2009). The management of blood and blood products is a challenging task in any hospital due to FDA regulations. Blood is drawn from donors and not many persons from the eligible donor population actually donate blood; in addition, the issue of infections and contaminations among donors limits the eligible donor population. The problem of supply side of blood assumes greater dimension given that hospitals need to rely on the neighborhood population, transport facilities in case of blood or blood products obtained from blood banks located elsewhere and the short response time to get blood in case of emergencies (Blake et al., 2010). The authors have suggested that minimization of the shortage and
outdating cost is not necessarily the correct objective function especially for platelets ordering and inventory management.

There are different costs associated with the blood inventory system such as purchasing cost, holding cost, shortage cost, outdating cost, etc. Outdating costs are associated with the blood or blood products that have to be discarded because they have expired. Shortage costs are encountered when an alternate source of supply is to be found resulting in an increased cost of procurement; for example, an emergency supply from another hospital or a different blood bank is sought in case of shortage of on-hand blood or blood products. Since the former cost is rather difficult to quantify, it is a normal practice to treat the ratio of shortage cost to the outdating cost as some value, say, five (see van Dijk et al., 2009). All these aspects make the operational issues such as the collection of blood at hospitals and blood banks, blood allocation to hospitals from blood centers and blood banks, blood delivery to hospitals and determination of optimal order policy for blood products at blood banks and hospitals rather challenging and quite complex to analyze, especially given the fact that the entire blood management system need to be examined as a whole supply chain system and not just as a system of isolated sub-systems (Pierskalla, 2004; Belien and Force, 2012).

2.2.1 Taxonomy of Supply Chain Management of Blood Products

Belien and Force (2012) presented taxonomy of supply chain management of blood products in terms of the following:

i. Type of blood product (e.g. whole blood, plasma, frozen blood and blood platelets)

ii. Solution method (simulation, queuing model, mathematical programming techniques such as linear, integer and stochastic dynamic programming (SDP), heuristics and statistical analyses such as exponential smoothing for forecasting and regression analysis to determine which factors would affect outdating of blood products)
iii. Hierarchical level (namely, individual hospital level, blood center or bank level, and supply chain level involving location, transportation logistics and order issue policies)

iv. Type of problem (inbound problems pertaining to inventory allocation to centralized blood banks and hospitals, and outbound problems in terms of delivery to hospitals)

v. Types of approach (stochastic and deterministic settings)

vi. Exact and heuristic methods; performance measures (involving service level, and costs of transportation, shortage and outdating)

vii. Implementation issues in real-life including participation and coordination of different hospitals in the blood inventory management

2.2.2 Blood Product Management: Hierarchy of Levels and Related Issues at Strategic, Tactical and Operational Levels

It is possible that the blood products supply could be managed at different levels: at an individual hospital level; at a regional level with a blood bank serving a host of hospitals; and at a State level or inter-regional level with a set of regional blood banks or blood center. According to Prastacos (1984), operational level decision issues are related to scheduling and coordinating in terms of ordering, collections, processing and issuing; tactical issues related to the determination of inventory levels, collection levels, issuing policies and processing policies; and strategic issues related to design of blood bank and hospital network, location of the blood bank and hospitals, and policies related to sourcing of blood and blood products. Prastacos also observed: “since the demand and usage of blood are stochastic, a fundamental part of every hospital’s effort for improved blood inventory management is understanding the statistical pattern of demand and usage of blood (through statistical analysis of collected data) in order to forecast these patterns
better. These patterns are determined by the behavior of three random variables for each blood type: the number of daily requisitions arriving at the hospital blood bank; the size of a requisition and the actual usage (number of units) of a requisition”. Once these patterns are analyzed, hospitals place orders and the ordering policy of a hospital answers the following questions: when to place an order and how much to order.

Analytical approaches make some assumptions such as the complete usage of all demanded items (i.e., both demand and usage are identical random variables) and most analytical research assume the demand to follow Poisson distribution and hence with such assumptions, closed form results are obtained. However, these assumptions limit the applicability of analytical techniques and in such cases, simulation and heuristics are used. For example, Cohen and Pierskalla (1979) assumed unit costs to shortages and outdates, and used search techniques and simulation to derive inventory levels as functions of all hospital parameters that affect shortages and outdating. An important aspect in blood inventory system is the cross matching policy. This policy is a testing procedure according to which units of blood are selected from inventory, and then allotted to patients. Note that blood products are perishable and not all units are eventually transfused. Assuming all crossmatched units are consumed, Pierskalla and Roach (1981) showed that issuing the oldest units first (FIFO) minimizes the average units short and outdated.

Brodheim and Pierskalla (1980) noted that there could be differences between the demand and usage of blood products, and they developed an algorithm for selecting units in a decreasing age from inventory (FIFO) and assigning each unit sequentially to the request that maximized the likelihood of using it. They found that the rule minimized the shortage and outdated units. As for issues related to regional blood banks (blood centers), an important problem is related to the collection of blood that comes from sources such as the following: visits to organizations or places where donors have already agreed to donate; random walk-in donors; and invited or sought donors who respond to emergency cases. This aspect of regional banks deals with setting targets for collection; a forecasting system to predict collection from different sources; and scheduling either visits to organizations or getting donors. Another problem at the regional blood bank level is to allocate blood or blood products to different hospitals with the consideration of costs such as transportation
costs, outdate costs and shortage costs. There are centralized systems that help a regional blood center to allocate the resources across hospitals with the overall objective of minimizing the costs (such as the transport costs from the center to the hospitals, emergency deliveries from the center to the hospitals and outdate costs at hospitals), with hospitals usually not storing blood or blood products. There are also decentralized systems, where the problem is to determine the inventory levels for the regional center with provisions for allocation of blood from the regional center to hospitals and for re-allocation of excess blood from the center to hospitals with storage of blood being allowed in hospitals.

2.2.3 Multi-objective Blood Inventory Management

Most real-life problems deal with multiple objectives that are conflicting in nature; for example, typically conflicting goals that are considered involve keeping a certain level of inventory for a high service level, minimize outdating, shortage and collection costs. Goal programming approach is commonly used by setting goals for such objectives (Kendall and Lee, 1980; Prastacos, 1984). In the paper by Kendall and Lee (1980), goal constraints were related to blood availability, blood outdating, average age of inventory and total cost. The model was applied to American National Red Cross in the Midwest. The results indicated that the total unused blood was reduced from 14.9% to 9.2% without increasing the shortage.

2.2.4 Solution Techniques for Blood Product Inventory Management

As for the blood and blood products, the term ‘whole blood’ associated with blood types such as A, B, AB and O, and Rhesus factor (positive or negative) is quite commonly used. Not many papers deal with the plasma product. However, frozen blood (or frozen red blood cells) can be kept in cold storage for years and Hesse (2004) reported the advantages and disadvantages of using such frozen blood products. According to the paper, the
problem with blood platelets is that they have a very short shelf life (generally 3 days) compared to other blood products, and hence the analysis of platelet inventory system is extremely complex.

Jennings (1973) discussed in detail the inventory management problem at the hospital as well at the regional level. It was mentioned in the paper that the inventory control of blood was very difficult due to the stochastic nature of the demand and supply and due to the process of “crossmatching”. The author observed that for a single hospital, as the inventory level was increased, the shortage decreased and outdating increased as shown in Figure 2.1, where $S$ represented the order-up-to level. For example, when $S = 22$ units, the shortage was less than 4% but the outdating was more than 12%; whereas, when $S = 10$ units, the shortage was more than 24% but the outdating was less than 8%. Therefore, it would be necessary to tradeoff between shortage and outdating.

Figure 2-1: Shortage-outdating operating curve: an independent hospital (Jennings, 1973)

Jennings (1973) also analyzed the effect of hospitals collaborating with each other and sharing RBC. He developed an inventory model investigating the potential costs and benefits of improved control of inventories of whole blood. He concluded that both shortage and outdating decreased as the number of hospitals in the multi-collaboration network increased.
As for blood platelet inventory management, techniques such as simulation, mathematical programming and dynamic programming are widely used. Most commonly considered problem is related to order policy determination and its parameters. The research on perishable inventory management has been done for more than five decades, and the early overview research articles are due to Nahmias (1982) and Prastacos (1984). Dynamic programming formulations were developed by Pierskalla and Roach (1972) and Haijema et al., (2007). Pierskalla and Roach (1972) concluded that FIFO policy is optimal for blood due to its short shelf life whereas Haijema et al., (2007) considered both FIFO and LIFO issuing policy.

In Haijema et al., (2007), it was assumed that order-up-to policies evaluated by simulation or by a Markov chain analysis had zero lead time. The author came up with a combined Markov dynamic programming and simulation approach, and applied it to a real-life regional blood bank problem. A double-level order-up-to rule, called, 2D rule, was proposed, with one level corresponding to relatively new or young platelets and another related to the total inventory.

A five-step approach was proposed by van Dijk et al., (2009), where Markov dynamic programming (MDP) was combined with computer simulation. It included the formulation of a MDP, followed by the downsizing of the problem to reduce the complexity of dynamic programming formulation. After that, a description of the process simulation and an assessment of the most frequent order-up-to levels were discussed. Order up-to rules reduced the outdating of platelet units from 15% - 20% to just 1%. While the work by van Dijk et al. (2009) used a multi-step procedure, combining dynamic programming and simulation, by selecting the order-up-to rule for each day, Blake (2009) noted that the work by van Dijk et al. (2009) ignored the age distribution of stock, and hence the work was rather restrictive. As an extension to that research, a SDP-Simulation approach was modeled, including special periods (Haijema et al., 2009). Special periods included irregular production breaks during Christmas and Easter since there was no collection of blood from the donors during Christmas, New Year and Easter. This model was applied to a Dutch Blood Bank. Then, it was observed that the average annual shortage was virtually nonexistent (reduced to .04%), and outdating was reduced from 15% - 20% to 0.11%.
A recent work by Haijema (2013) dealt with a new class of stock-level dependent order policy, called \((s, S, q, Q)\) policy, which was basically a periodic review \((s, S)\) policy restricted by a minimum \((q)\) and maximum \((Q)\). In other words, the policy followed a periodic ordering strategy per weekday with the inclusion of upper and lower level order quantities. Optimal parameter values were determined by dynamic programming and simulation. The results were compared to that of an \((s,S)\) policy and it was illustrated that the total cost reduced by 7.2%.

A summary of the blood inventory models discussed in the literature is given in Table 2.1.

<table>
<thead>
<tr>
<th>Article</th>
<th>Type of Blood Product</th>
<th>Solution Method</th>
<th>Hierarchical Level</th>
<th>Performance Measure</th>
<th>Planning Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jennings (1973)</td>
<td>RBC</td>
<td>Simulation</td>
<td>Regional Blood Centers and Hospital</td>
<td>Shortage, Outdating</td>
<td>Finite</td>
</tr>
<tr>
<td>Kendall and Lee (1980)</td>
<td>RBC</td>
<td>Goal Programming</td>
<td>Hospital</td>
<td>Fresh blood availability, average age of inventory, outdating, shortage</td>
<td>Finite</td>
</tr>
<tr>
<td>Hesse (2004)</td>
<td>Platelets</td>
<td>Simulation</td>
<td>Blood Center</td>
<td>Outdated units Order placed</td>
<td>Infinite</td>
</tr>
<tr>
<td>Haijema et al. (2005)</td>
<td>Platelets</td>
<td>SDP</td>
<td>Blood Center</td>
<td>Shortage, outdating</td>
<td>Finite</td>
</tr>
</tbody>
</table>
2.3 Review of Literature on Forecasting

Forecasting of blood components is essential since the demand is increasing and the supply is not increasing enough to meet the demand. Forecasting of perishable items is difficult because of the limited shelf life. Forecasting techniques are seldom applied in the supermarkets to forecast perishable commodities (Donselaar et al., 2006). However, in their paper, it was also mentioned that proper forecasting techniques should be used and the approach based on individual perspective was incorrect.

In particular, forecasting demand for blood components in the blood supply chain is very essential because advanced information can increase blood collection efforts if more blood is required and blood collection can be limited if less units are needed (Frankurter et al., 1974). In their paper, regression technique was used to forecast demand of red blood cells for two weeks considering the number of units collected and units expired. The results of the paper indicated that the forecasting of the short term demand had a significant impact on controlling the inventory levels at the blood centers. In the paper by Pereira (2004),
three forecasting techniques - autoregressive integrated moving average (ARIMA), the Holt-Winter’s exponential smoothing method and neural-network based method, were applied to forecast demand of blood at a hospital in Spain. Ten years of data were used to develop the three models. The models were validated using three years of data and the results indicated that the Holt-Winter’s exponential smoothing model performed the best.

2.4 Shortcomings of Previous Research on Blood Inventory Management

In the research work on inventory management of perishable items and blood in specific done thus far, reducing platelet wastage is seldom considered due to the extremely short shelf life of platelets. Most of the papers that are dealing with platelet inventory control assume the shortage cost is five times the outdated cost. However, shortage cost cannot be quantified in reality. Moreover, better inventory models can be developed if conflicting criteria such as outdated and shortage, holding cost and ordering cost are included. Therefore, this thesis aims to develop finite and infinite time horizon inventory models capturing the above mentioned criteria specifically focusing on hospitals since hospitals experience the highest wastage of blood along the supply chain.
Chapter 3

Research Methodology

The research methodology includes both finite time horizon and infinite time horizon models to determine the order quantity and when to order platelets such that wastage and outdating are reduced. In the first section, the finite time horizon model is discussed. Platelet demand is forecasted for the planning horizon based on the historical data and is used as an input to the finite time horizon model. In the next section, infinite time horizon model is developed. The historical data is fitted using ExpertFit® and the distribution for platelet demand is determined and is used as an input to the infinite time horizon model.

Figure 3-1: Overview of Research Methodology
3.1 Finite Time Horizon Model

3.1.1 Forecasting Platelet Demand (Ravindran and Warsing, 2013):

Forecasting demand for blood components in the blood supply chain is very essential because advanced information can increase blood collection efforts if more blood is required and blood collection can be limited if less units are needed (Frankurter et al., 1974). Therefore, adequately forecasting the platelet usage can reduce outdating as well as stock-outs of blood units.

3.1.1.1 Steps in Forecasting Platelet Demand

*Step 1:* Calculation of Seasonality index

Seasonality index for day $i = \frac{\text{average demand during day } i}{\text{overall average of demand for all periods}}$

*Step 2:* Computation of Deseasonalized Demand Data

Deseasonalized demand is obtained by dividing the actual demand data by the respective seasonality index.

*Step 3:* Forecasting Demand using Exponential Smoothing Method

Exponential smoothing method is the most popular forecasting method in practice and it is basically a weighted averaging method with weights decreasing exponentially on older demands. The forecast for period $(n + 1)$ is given by

$$F_{n+1} = \alpha D_n + (1 - \alpha)F_n$$

where $D_n$ is the actual demand for period $n$

$F_n$ is the forecasted demand for period $n$

$\alpha$ is called the smoothing constant

$\alpha$ is generally chosen between 0.1 and 0.4. We plan to vary $\alpha$ from 0.1 to 0.4 in increments of 0.1 to determine the forecast for the planning horizon. Then the models will
be validated using the three techniques mentioned in Section 3.1.1.2 and the best value of \( \alpha \) that reduces the errors will be used to forecast the future demand.

**Step 4: Converting the Deseasonalized Forecast to Seasonalized Forecast**

The actual forecast is computed by multiplying the deseasonalized forecast with the respective seasonality index.

### 3.1.1.2 Validation of the Techniques using the Actual Data (Ravindran and Warsing, 2013):

Three different measures of forecast errors, MAD, MSE and BIAS, are used for forecast validation.

1. **Mean Absolute Deviation (MAD)**
   \[
   \text{MAD} = \frac{1}{n} \sum_{t=1}^{n} |e_t|
   \]

2. **Mean Squared Error (MSE)**
   \[
   \text{MSE} = \frac{1}{n} \sum_{t=1}^{n} e_t^2
   \]

3. **BIAS**
   \[
   \text{BIAS} = \sum_{t=1}^{n} e_t
   \]

These forecast errors are used to obtain the best value of parameter \( \alpha \). If a specific \( \alpha \) value yields the best result for all the three measures, then the corresponding value of \( \alpha \) is used to forecast the platelet demand. Otherwise an average of the two best \( \alpha \) values will be used for forecasting.

Using the forecasted platelet demand, finite time horizon integer linear programming platelet inventory model is built to determine how much to order and when to order.
3.1.2 Finite Time Horizon Model Description

Assumptions

1. Lead time for order processing is assumed to be negligible
2. All platelets that arrive at hospital from the blood center are fresh and have a remaining shelf life of 3 days
3. Model is for a single blood type
4. FIFO issuing policy is practiced at the hospital, namely, the platelets with the shortest shelf life is used first. That is, demand is first fulfilled with platelets with remaining shelf life of 1 day, followed by platelets with remaining shelf life of 2 days, followed by platelets with remaining shelf life of 3 day.

Notations, Data and Decision Variables

The notations used in the finite time horizon model are as follows:

---

Parameters (known data):

- \( C^F \): Fixed cost of procuring platelets
- \( C^P \): Platelet purchasing cost per unit
- \( C^H \): Daily inventory cost of holding platelets per unit (based on beginning inventory)
- \( C^E \): Cost of expired platelet per unit
- \( C^S \): Cost of shortage per unit
- \( D_t \): Platelet demand at the beginning of day \( t \)
- \( L \): Constant lead time (\( L \leq 2 \) days)
- \( RP \): Review period in days
- \( S^1 \): Initial inventory with shelf life of 1 day (\( I_{1,1} \))
- \( S^2 \): Initial inventory with shelf life of 2 days (\( I_{1,2} \))
- \( T \): Time horizon in days (i.e., \( t=1, 2, 3, \ldots, T \))
**Decision variables (unknown):**

\[ D^1_t \] Remaining demand for day \( t \) after using platelets with shelf life of 1 day

\[ D^2_t \] Remaining demand for day \( t \) after using platelets up to shelf life of 2 days

\[ D^3_t \] Remaining demand for day \( t \) after using platelets up to shelf life of 3 days

\[ I_{t,1} \] On-hand inventory at the beginning of day \( t \) with residual shelf life of 1 day

\[ I_{t,2} \] On-hand inventory at the beginning of day \( t \) with residual shelf life of 2 days

\[ I'_{t,1} \] Remaining platelet units after satisfying \( D_t \) with shelf life of 1 day

\[ I'_{t,2} \] Remaining platelet units after satisfying \( D^1_t \) with shelf life of 2 days

\[ I'_{t,3} \] Remaining platelet units after satisfying \( D^2_t \) with shelf life of 3 days

\[ Q_t \] Quantity of platelet units ordered at the end of day \( t \)

\[ S_t \] Number of platelet units short on day \( t \)

\[ x_t \] Platelet units received from blood center at the beginning of day \( t \) with shelf life of 3 days

\[ \delta_t \] \[
\begin{cases} 
1 & \text{if platelet units are ordered by hospital on day } t \\
0 & \text{otherwise}
\end{cases}
\]

\( t = 1, 2, \ldots, T \)

**Sequence of Events**

1. Hospital receives platelet units, \( x_t \), from the blood center
2. Hospital receives platelet demand, \( D_t \)
3. If the demand at the hospital is greater than the on-hand inventory (i.e., if \( D_t \geq (I_{t,1} + I'_{t,2} + x_t) \)), the demand is partially fulfilled with the available on-hand inventory and the on-hand inventory is updated to 0. The unfulfilled demand units incur shortage cost.
4. If the demand at the hospital is less than the on-hand inventory (i.e., $D_t < (I_{t,1} + I_{t,2} + x_t)$), then there are 3 possible cases:
   - Case (i): If $D_t < I_{t,1}$, then the unutilized platelet units with remaining shelf life of 1 day ($I_{t,1} - D_t$) are thrown away at the end of the day and incur outdating cost. The remaining platelets (after discarding the outdated units) are carried over to the next day and the on-hand inventory is updated.
   - Case (ii): If $I_{t,1} \leq D_t < I_{t,1} + I_{t,2}$, then there are no unutilized platelet units with remaining shelf life of 1 day and hence no outdating cost is incurred. The remaining platelets are carried over to the next day and the on-hand inventory is updated.
   - Case (iii): If $I_{t,1} + I_{t,2} \leq D_t < I_{t,1} + I_{t,2} + x_t$, then there are no unutilized platelet units with remaining shelf life of 1 day and 2 days, and hence no outdating cost is incurred. The remaining platelets are carried over to the next day and the on-hand inventory is updated.

5. Hospital determines platelet order quantity ($Q_t$) at the end of day $t$

### 3.1.3 Finite Time Horizon Model Formulation

**Model Objective**

Equation (3.1) represents the objective function, which is to minimize the total cost comprising of fixed cost of procurement, variable purchasing cost, holding cost, shortage cost and outdating cost.

Minimize $TC = \sum_{t=1}^{T} [\delta_t * C^F + Q_t * C^P + (I_{t,1} + I_{t,2}) * C^H + S_t * C^S + E_t * C^E]$  \hspace{1cm} (3.1)

Note: Inventory cost are charged based on beginning inventory.

**Model Constraints:**

(1) **Platelet Units Ordered**

Equation (3.2) ensures that $\delta_t$ takes the value 1 if platelet units are ordered from the blood center by the hospital on day $t$ and 0 otherwise. Platelets must be ordered only
during the review periods and not during the other days which is taken care by Equation (3.3).

\[ \begin{align*}
Q_t & \leq M \delta_t & & \text{for } t = 1, 1+RP, 1+2RP, +\ldots \\
Q_t & = 0 & & \text{for all other } t
\end{align*} \]  

Equations (3.2) and (3.3) guarantee that \( Q_t \) is defined only for those time period \( t \) when platelets can be ordered. For example, if the review period \( RP = 2 \) days, then platelets can only be ordered on day 1, 3, 5, 7,…

(2) Platelet Units Received

Equations (3.4) and (3.5) are used to calculate the total units received by hospital at the beginning of day \( t \) \((x_t)\), which must be equal to the order quantity placed before the lead time \((Q_{t-L})\).

\[ \begin{align*}
x_t & = Q_{t-L} & & \forall t > L \\
x_t & = 0 \text{ or known constants} & & \forall t \leq L
\end{align*} \]  

(3) Demand Constraints

If the demand, \( D_t \), is greater than platelet units with shelf life of 1 day, \( I_{t,1} \), then the left-over demand upon consumption of \( I_{t,1} \) is \( D^1_t \) and is given by \( D^1_t = D_t - I_{t,1} \). Also, \( I'_{t,1} = 0 \). On the other hand if the demand, \( D_t \), is less than platelet units with shelf life of 1 day, \( I_{t,1} \), then the left-over demand, \( D^1_t \) is 0 and the remaining platelet units after satisfying the demand is given by \( I'_{t,1} = I_{t,1} - D_t \). Equation (3.6) is used to calculate \( D^1_t \) and \( I'_{t,1} \). Note that both \( D^1_t \) and \( I'_{t,1} \) cannot be positive simultaneously.

\[ D_t - I_{t,1} = D^1_t - I'_{t,1} \]  

If the left-over demand, \( D^1_t \), is positive, then it is completely or partially fulfilled by platelet units with shelf life of 2 days, \( I_{t,2} \). If \( D^1_t \) is greater than \( I_{t,2} \), then the left-over demand, \( D^2_t \), is given by \( D^2_t = D^1_t - I_{t,2} \). If \( D^1_t \) is less than \( I_{t,2} \), then the left-over demand, \( D^2_t \), is 0 and the remaining platelet units after satisfying \( D^1_t \) is given by \( I'_{t,2} = I_{t,2} - D^1_t \). Equation (3.7) is used to calculate \( D^2_t \) and \( I'_{t,2} \). Note that both \( D^2_t \) and \( I'_{t,2} \) cannot be positive simultaneously.
\[ D_t^1 - I_{t,2} = D_t^2 - I'_{t,2} \quad (3.7) \]

If \( D_t^2 \) is positive, then it is completely or partially fulfilled by platelet units with shelf life of 3 days, \( x_t \). If \( D_t^2 \) is greater than \( x_t \), then the left-over demand, \( D_t^3 \), is given by \( D_t^3 = D_t^2 - x_t \). \( D_t^3 \) is the platelet shortage at end of day \( t \). If \( D_t^2 \) is less than \( x_t \), then no shortage is incurred and remaining platelet units after satisfying \( D_t^2 \) is given by \( I'_{t,3} = x_t - D_t^2 \). Equation (3.8) is used to calculate \( D_t^3 \) and \( I'_{t,3} \). Note that both \( D_t^3 \) and \( I'_{t,3} \) cannot be positive simultaneously.

\[ D_t^2 - x_t = D_t^3 - I'_{t,3} \quad (3.8) \]

(4) Inventory Updates

At the end of the day \( t \), the inventory is updated for the next day using Equations (3.9) and (3.10).

\[ I_{t+1,1} = I'_{t,2} \quad (3.9) \]
\[ I_{t+1,2} = I'_{t,3} \quad (3.10) \]

(5) Expired Platelets

Unutilized platelet units with remaining shelf life of 1 day, \( I'_{t,1} \), are discarded at the end of the day and given using Equation (3.11).

\[ E_t = I'_{t,1} \quad (3.11) \]

(6) Platelet Shortages

The unfulfilled demand units, \( D_t^3 \), is considered as shortage in day \( t \) and is calculated using Equation (3.12).

\[ S_t = D_t^3 \quad (3.12) \]

(7) Initial Inventory of Platelets

Equations (3.13) and (3.14) gives the initial conditions at time \( t = 1 \).

\[ I_{1,1} = S^1 \quad (3.13) \]
\[ I_{1,2} = S^2 \quad (3.14) \]

(8) Non-negativity

Constraints (3.15 – 3.16) force non-negativity and binary restrictions in the model.
Figure 3.2 illustrates the possible outcomes (Eqns 3.6 – 3.12) between platelet demand and availability at time $t$.

\[
D^1_t, D^2_t, D^3_t, E_t, I^{'\prime}_{t,1}, I^{'\prime}_{t,2}, I^{'\prime}_{t,3}, I_{t,1}, I_{t,2}, Q_t, S_t, S^1, S^2, x_t \geq 0 \quad \forall t = 1,2,3,...,T \quad (3.15)
\]
\[
\delta_t \in (0,1) \quad \forall t = 1,2,3,...,T \quad (3.16)
\]
3.1.4 Illustrative Example

For a given $t$, let the platelet inventory be as follows.

$I_{t,1} = 16$
$I_{t,2} = 9$
$x_t = 20$

Thus, the on-hand inventory on day $t$ is $16 + 9 + 20 = 45$.

**Case 1**: $0 < D_t \leq I_{t,1}$

Let $D_t = 15$

From Equation (3.6),

$15 - 16 = D_1^t - I_{t,1}'$

Therefore, $I_{t,1}' = 1$ and $D_1^t = 0$

From Equation (3.7),

$0 - 9 = D_2^t - I_{t,2}'$

Therefore, $I_{t,2}' = 9$ and $D_2^t = 0$

From Equation (3.8),

$0 - 20 = D_3^t - I_{t,3}'$

Therefore, $I_{t,3}' = 20$ and $D_3^t = 0$

Total expired units is $E_t = 1$ (Eq. 3.11)

Total units shortage is $S_t = 0$ (Eq. 3.12)

**Case 2**: $I_{t,1} < D_t \leq I_{t,1} + I_{t,2}$

Let $D_t = 20$, then, $D_1^t = 4, D_2^t = 0, D_3^t = 0, I_{t,1}' = 0, I_{t,2}' = 5, I_{t,3}' = 20, E_t = 0$ and $S_t = 0$

**Case 3**: $I_{t,1} + I_{t,2} < D_t \leq I_{t,1} + I_{t,2} + x_t$

Let $D_t = 35$, then, $D_1^t = 19, D_2^t = 10, D_3^t = 0, I_{t,1}' = 0, I_{t,2}' = 0, I_{t,3}' = 10, E_t = 0$ and $S_t = 0$

**Case 4**: $D_t > I_{t,1} + I_{t,2} + x_t$ (i.e., $D_t >$ on-hand inventory)

Let $D_t = 55$, then, $D_1^t = 39, D_2^t = 30, D_3^t = 10, I_{t,1}' = 0, I_{t,2}' = 0, I_{t,3}' = 0, E_t = 0$ and $S_t = 10$

31
3.1.5 Model Summary

Minimize $TC = \sum_{t=1}^{T} [\delta_t \cdot CF + Q_t \cdot CP + (l_{t,1} + l_{t,2}) \cdot CH + S_t \cdot CS + E_t \cdot CE]$

$Q_t \leq M \delta_t$ for $t = 1, 1+RP, 1+2RP, +...$

$Q_t = 0$ for all other $t$

$x_t = Q_{t-L}$ $\forall t > L$

$x_t = 0$ or known constants $\forall t \leq L$

$D_t - I_{t,1} = D^1_t - I'_{t,1}$

$D^1_t - I_{t,2} = D^2_t - I'_{t,2}$

$D^2_t - x_t = D^3_t - I'_{t,3}$

$I_{t+1,1} = I'_{t,2}$

$I_{t+1,2} = I'_{t,3}$

$E_t = I'_{t,1}$

$S_t = D^3_t$

$I_{1,1} = S^1$

$I_{1,2} = S^2$

$D^1_t, D^2_t, D^3_t, E_t, I'_{1,1}, I'_{1,2}, I'_{1,3}, I_{1,1}, I_{1,2}, Q_t, S_t, S^1, S^2, x_t \geq 0$ $\forall t = 1,2,3,...,T$

$\delta_t \in (0,1)$ $\forall t = 1,2,3,...,T$

The optimization model is a mixed integer linear programming model. An optimal solution will provide the best ordering policy to minimize cost over the planning horizon.

3.2 Infinite Time Horizon Model

The periodic review policy is considered for developing an infinite time horizon model. In periodic review policy, time between orders is a constant and order quantities vary at each time period (Ravindran and Warsing, 2013).
3.2.1 Periodic Review, Order-up-to Level Policy

In the order-up-to level policy, inventory position is reviewed every $RP$ periods and an order is placed to bring the level to $S$, i.e., the inventory position is raised to constant value, $S$, by placing an order, $Q = S - IP$ where $IP$ is the current inventory position. The inventory position is reviewed at the beginning of every $RP$ days considering the platelets units that are outdated and discarded at the end of the previous day.

3.2.2 Periodic Review, Base Stock Policy

In the base stock policy, the inventory position is reviewed every day (i.e., $RP = 1$) and order an amount such that the inventory position is raised to $S$. In the base stock policy, the ordering cost is assumed to be negligible.

3.2.3 Computation of Order-up to Level $S$

The optimal value of the parameter $S$ is calculated based on the demand distribution over lead time and review period. The value of parameter $S$ is determined such a specified service level is being met during the $RP + L$ periods. In other words, when determining $S$, it is necessary to consider the in-stock probability level that is to be achieved. Service level represents the percent of time demand is met from inventory.

Assuming that the daily demand follows a normal distribution with mean $\mu_D$ and standard deviation $\sigma_D$,

- Mean demand during lead time plus review period $= \mu_{DLTR} = (L + RP)\mu_D$
- Standard deviation of the demand during lead time plus review period $= \sigma_{DLTR} = \sigma_D\sqrt{L + RP}$
Assuming that the demand during the lead time plus review period is stationary and follows a normal distribution, the order-up-to level $S$ for the given service level is given as follows:

- $S = \mu_{DLTR} + z_{SL} \sigma_{DLTR}$
- Safety stock, $SS = z_{SL} \sigma_{DLTR}$

where $z_{SL} = \phi^{-1}(SL)$, where $SL$ is the service level or expected in-stock probability in each replenishment cycle and $\phi$ is the standard normal cumulative distribution function.

In general, at the hospitals, the review period, $RP$, is 1 day and lead time, $L$, is 0 day. The impacts of varying $RP$ and $L$, as well as the service level, will be discussed in detail in Chapter 4.

As in the finite horizon model, total cost comprises of fixed cost of procurement, variable purchasing cost, holding cost, shortage cost and outdating cost.
Chapter 4

Case Study

This chapter is organized into three sections. In the first section, details of forecasting platelet demand are discussed. In the second section, the results and analyses of finite time horizon inventory model are discussed. In the last section, the results of the infinite time horizon inventory model are presented.

To illustrate the performance of the proposed finite and infinite time horizon models, four performance measures are used: Wastage as A Percentage of Procurement (WAPP), Holding as A Percentage of Procurement (HAPP), Shortage as A Percentage of Demand (SAPD), and Total Cost (TC).

- Wastage as A Percentage of Procurement (WAPP) = \( \frac{\text{Units outdated}}{\text{Units procured}} \times 100 \)
- Holding as A Percentage of Procurement (HAPP) = \( \frac{\text{Units in inventory}}{\text{Units procured}} \times 100 \)
- Shortage as A Percentage of Demand (SAPD) = \( \frac{\text{Shortage Units}}{\text{Total demand}} \times 100 \)
- Total Cost (TC) = fixed cost of procurement + variable purchasing cost + holding cost + shortage cost + expiration cost

4.1 Results of Finite Time Horizon Model

4.1.1 Forecasting Platelet Demand

The platelet demand data is obtained from Tetteh (2008) in which the daily demand data of platelets at a hospital in New York for 122 days are available (see Appendix A for the platelets demand data). From the time series demand data, it is observed that there exist daily variations in the demand pattern. Hence seasonality is incorporated in the constant level forecasting method by calculating the seasonality indices for each day of the week.
4.1.1.1 Steps in Forecasting Platelet Demand

Step 1: Calculation of Seasonality Index

Seasonality index for day $i = \frac{\text{average demand during day } i}{\text{overall average of demand for all periods}}$

For example: day 1 average = 193.6923 and overall average = 184.8352

Seasonality index for day 1 = $\frac{193.6923}{184.8352} = 1.047919$

Step 2: Computation of Deseasonalized Demand Data

Deseasonalized demand is obtained by dividing the actual demand data by the respective seasonality index.

For example: actual demand on day 1 is 174 units and seasonality index is 1.047919

Deseasonalized demand for day 1 = $\frac{174}{1.047919} = 166.0433451 \approx 166$ units

Step 3: Forecasting Demand using Exponential Smoothing Method

Exponential smoothing method is the most popular forecasting method in practice and hence it is used in this research to forecast the platelet demand. The forecast for period $(n+1)$ is given by

$$F_{n+1} = \alpha D_n + (1 - \alpha)F_n$$

Where $D_n$ is the deseasonalized demand for period $n$

$F_n$ is the forecasted demand for period $n$

$\alpha$ is the smoothing constant

Initial condition: $F_1$ is assumed to be equal to $D_1$

For example, Let $D_n = 166$ units, $F_n=173$ units and $\alpha = 0.1$, then

$F_{n+1} = 0.1 \cdot 166 + (0.9) \cdot 173 \approx 172$ units

Step 4: Converting the Deseasonalized Forecast to Actual Forecast

The actual forecast is computed by multiplying the deseasonalized forecast by the respective seasonality index.

Actual forecast for day 1 = $172 \cdot 1.047919 \approx 180$ units

Appendix B contains the seasonality indices and the forecasted demand data.
### 4.1.1.2 Validation of the Forecasting Model

The value of $\alpha$ is varied from 0.1 to 0.4 in increments of 0.1 to determine the forecast for the planning horizon. Next, the models are validated using the techniques discussed in Section 3.1.1.2. Among the 122 platelets demand data that were obtained from the literature, 92 data points are used to forecast and the remaining 30 data points are used for the purpose of validation. The results of the forecasting errors (i.e., the values of MAD, MSE and BIAS) are shown in Table 4.1.

**Table 4-1: Results of forecasting errors for varying value of $\alpha$**

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>BIAS</th>
<th>MAD</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-233.84</td>
<td>22.160245</td>
<td>790.7485</td>
</tr>
<tr>
<td>0.2</td>
<td>-139.057</td>
<td>22.4249616</td>
<td>829.9781</td>
</tr>
<tr>
<td>0.3</td>
<td>-99.0658</td>
<td>22.8479006</td>
<td>882.5821</td>
</tr>
<tr>
<td>0.4</td>
<td>-77.4491</td>
<td>23.6224505</td>
<td>942.5586</td>
</tr>
</tbody>
</table>

### 4.1.1.3 Selection of the Best Method for Forecasting Demand

From Table 4.1, observing the forecasting error measures obtained from different $\alpha$ values, the exponential smoothing method for $\alpha = 0.1$ yields the least MAD and MSE. For $\alpha = 0.4$, the least BIAS is achieved for the provided demand data. Therefore, the average of forecasted values of $\alpha = 0.1$ and $\alpha = 0.4$ is used as the platelet demand for the next 30 days. The forecasted demand for the next 30 days is shown in Table 4.2.

The forecasted demands for different values of $\alpha$ are attached in Appendix B.
Table 4-2: Forecasted demand for 30 days

<table>
<thead>
<tr>
<th></th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>198</td>
<td>198</td>
<td>198</td>
<td>198</td>
<td>198</td>
</tr>
<tr>
<td>Day 2</td>
<td>216</td>
<td>216</td>
<td>216</td>
<td>216</td>
<td>216</td>
</tr>
<tr>
<td>Day 3</td>
<td>202</td>
<td>202</td>
<td>202</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Day 4</td>
<td>187</td>
<td>187</td>
<td>187</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>Day 5</td>
<td>186</td>
<td>186</td>
<td>186</td>
<td>186</td>
<td></td>
</tr>
<tr>
<td>Day 6</td>
<td>169</td>
<td>169</td>
<td>169</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>Day 7</td>
<td>161</td>
<td>161</td>
<td>161</td>
<td>161</td>
<td></td>
</tr>
</tbody>
</table>

4.1.2 Numerical Example to Show Performance Measures Calculation in Finite Time Horizon Model

For the purpose of illustration, the following are the values of the known and unknown data that are considered:

- Time horizon ($T$): 30
- Lead time ($L$): 0
- Review period ($RP$): 1
- Total number of times shipments were made from the blood center to hospital ($\sum_{t=1}^{T} \delta_t$): 30
- Total number of units expired ($\sum_{t=1}^{T} E_t$): 20
- Total number of units shortage ($\sum_{t=1}^{T} S_t$): 10
- Total number of units in inventory ($\sum_{t=1}^{T} (I_{t,1} + I_{t,2})$): 100
- Total number of units purchased ($\sum_{t=1}^{T} Q_t$): 1000
- Total demand ($\sum_{t=1}^{T} D_t$): 1100
- Fixed cost of procuring platelets ($C^F$): $1
- Variable platelet purchasing cost ($C^P$): $1/unit
• Inventory cost of holding platelets \( (C^H) \): $1/unit
• Cost of expired platelet \( (C^E) \): $1/unit
• Cost of shortage \( (C^S) \): $1/unit

Then,

• Wastage as A Percentage of Procurement (WAPP) = \( \frac{20}{1000} \times 100 = 2\% \)
• Holding as A Percentage of Procurement (HAPP) = \( \frac{100}{1000} \times 100 = 10\% \)
• Shortage as A Percentage of Demand (SAPD) = \( \frac{10}{1100} \times 100 = 0.909\% \)
• Total Cost (TC) = \( \sum_{t=1}^{T} [\delta_t \times C^F + Q_t \times C^P + (I_{t,1} + I_{t,2}) \times C^H + S_t \times C^S + E_t \times C^E] \)

Therefore, TC = 30 + 1000 + 100 + 10 + 20 = $1160

For the above data set,

• Total number of decision variables: 36 (out of which 3 are binary variables)
• Total number of constraints: 45
• The mathematical model discussed in Chapter 3 is programmed using C++ and solved using IBM CPLEX® 12.4.0.0 optimizer
• Solution time is 23 seconds

In this example since all cost components are given equal importance, in order to reduce wastage and inventory cost due to holding platelets, no units are held in inventory. At the end of each day, platelet units are ordered depending upon the next day’s demand. Therefore, there exist no shortage and outdating cost. Except for the cost incurred for holding the initial inventory (i.e., 198 units), no other holding cost is incurred in the model. For this example, the optimal solution is given below:

Total units procured: 5492
Total units held in inventory: 198
Total units shortage: 0
Total units wasted: 0
4.1.3 Sensitivity Analysis for Finite Time Horizon

The ratio of each of the cost component to the holding cost is varied and the different cost scenarios that are considered for the sensitivity analysis are given in Table 4.3. The cost ratios are varied and the change in the performance measures is analyzed.

<table>
<thead>
<tr>
<th>Cost scenario</th>
<th>Fixed Cost</th>
<th>Variable Cost</th>
<th>Holding Cost</th>
<th>Expiration Cost</th>
<th>Shortage Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

In cost scenario 1, ratio of each cost component to the holding cost is 1. Whereas in cost scenario 2, shortage cost is five times the holding cost and all the other cost components are same as in cost scenario 1. Therefore, it is expected that under scenario 2, the total units shortage will be less compared to cost scenario 1. In cost scenario 3, shortage is five times the holding cost and also fixed cost is set four times the holding cost. It is expected that the total units shortage will be less and also frequency of placing orders will be less compared to cost scenario 1.

For each cost scenario, the lead time and review period are varied and the changes in WAPP, HAPP, SAPD and TC are analyzed. The summary of the possible combinations of lead time and review period is given in Table 4.4.
Table 4-4: Combinations of lead time and review period (in days)

<table>
<thead>
<tr>
<th>Lead time ($L$)</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review Period ($RP$)</td>
<td>1,2</td>
<td>1,2</td>
<td>2</td>
</tr>
</tbody>
</table>

4.1.3.1 Effect of Varying Lead Time and Review Period on WAPP

Recall WAPP is defined as follows:

\[
\text{Wastage as A Percentage of Procurement (WAPP)} = \frac{\text{Units outdated}}{\text{Units procured}} \times 100
\]

It is observed that WAPP is 0 for all different combinations of lead time and review period for all the cost scenarios. This is so because, when the review period is 1 day, platelets can be frequently ordered and hence resulting in reduced number of units being held in inventory. When the review period is 2 days and lead time is 0 day or 1 day, platelet units held in inventory are exactly equal to the demand during the lead time plus review period. However, when the review period is 2 days and lead time is 2 days, it is not possible to reduce shortage during the lead time plus review period ($L+RP = 4$ days) because of the very short shelf life of new platelets of 1 day. Therefore, demand during the lead time plus review period cannot be satisfied and hence platelet units are not held in inventory which results in no wastage.

4.1.3.2 Effect of Varying Lead Time and Review Period on HAPP

Recall HAPP is defined as follows:

\[
\text{Holding as A Percentage of Procurement (HAPP)} = \frac{\text{Units in inventory}}{\text{Units procured}} \times 100
\]
Table 4-5: Sensitivity Analysis - Effect of lead time and review period on HAPPP

<table>
<thead>
<tr>
<th></th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost scenario 1</td>
<td>3.6052</td>
<td>3.6052</td>
<td>29.8097</td>
<td>7.5057</td>
<td>7.5057</td>
</tr>
<tr>
<td>Cost scenario 2</td>
<td>3.6052</td>
<td>3.6052</td>
<td>51.6387</td>
<td>61.9409</td>
<td>7.5057</td>
</tr>
<tr>
<td>Cost scenario 3</td>
<td>3.6052</td>
<td>3.6052</td>
<td>51.6387</td>
<td>61.9409</td>
<td>7.5057</td>
</tr>
</tbody>
</table>

Table 4.5 illustrates the change in the HAPPP when the lead time and review period are varied for different cost scenarios. When the review period is 1 day and lead time is 0 day and 1 day, it is observed that HAPPP is the same for all the three cost scenarios because orders can be placed frequently. Therefore there exist only initial inventory carrying cost and hence reduced HAPPP. However, when the review period is 2 days and lead time is 0 day, 1 day and 2 days, HAPPP varies across the cost scenarios as shown in Figure 4.1. It is observed that when the review period is 2 days and lead time is 0 day or 1 day, HAPPP is greater for cost scenarios 2 and 3. For cost scenarios 2 and 3, priority is given for reducing shortage and hence, as the lead time increases, in order to avoid shortage of platelets during the lead time plus review period, there are more platelet units held in inventory and thereby leading to increase in inventory. For cost scenario 1, when the review period is 2 days, in order to satisfy the demand during lead time plus review period, there should be excess units held in inventory. But cost scenario 1 gives equal importance to all cost components and hence a tradeoff is made between shortage and holding platelets. When the review period is 2 days and lead time is 2 days, HAPPP remains the same across the three cost scenarios. The reason behind this is that when lead time is 2 days, the platelets that are arriving at the hospital have a remaining shelf life of 1 day only. Therefore, platelets arriving at hospital on day \( t \) can only satisfy the demand at hospital occurring till the end of day \( t \) and hence shortage of platelets cannot be avoided during the lead time plus review period. Therefore, even though cost scenarios 2 and 3 give priority to reduce shortage, it is
not possible to reduce shortage during the lead time plus review period (L+RP = 4 days) because of the very short shelf life of new platelets of 1 day.

4.1.3.3 Effect of Varying Lead Time and Review Period on SAPD

Recall SAPD is defined as follows:

\[
\text{Shortage as A Percentage of Demand (SAPD)} = \frac{\text{Shortage Units}}{\text{Total demand}} \times 100
\]

**Table 4-6**: Sensitivity Analysis - Effect of lead time and review period on SAPD

<table>
<thead>
<tr>
<th></th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost scenario 1</td>
<td>0.0000</td>
<td>0.0000</td>
<td>30.0176</td>
<td>50.1582</td>
<td>50.1582</td>
</tr>
<tr>
<td>Cost scenario 2</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>50.1582</td>
</tr>
<tr>
<td>Cost scenario 3</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>50.1582</td>
</tr>
</tbody>
</table>

Table 4.6 shows the changes in the SAPD when the lead time and review period are varied for different cost scenarios. When the review period is 1 day and lead time is 0
day and 1 day, it is observed that SAPD is 0 for all the three cost scenarios because order can be placed frequently, thereby reducing shortage cost. However, when the review period is 2 days and lead time is 0 day, 1 day and 2 days, SAPD varies across the cost scenarios as shown in Figure 4.2.

It is observed that when the review period is 2 days and lead time is 0 day or 1 day, SAPD is 0 for cost scenarios 2 and 3, because in those scenarios, priority is given for reducing shortage and hence SAPD is 0. However, SAPD is not 0 for cost scenario 1. This is so because, when the review period is 2 days, in order to satisfy the demand during lead time plus review period, there should be excess units held in inventory incurring holding cost. But cost scenario 1 gives equal importance to all cost components and hence a tradeoff is made between shortage and holding platelets. When the review period is 2 days and lead time is 2 days, SAPD remains the same across the three cost scenarios because when lead time is 2 days, the platelets that are arriving at the hospital have a remaining shelf life of 1 day only. Therefore, it is not possible to reduce shortage during the lead time plus review period (L+RP = 4 days) because of the very short shelf life of new platelets of 1 day.

![Figure 4-2: SAPD when review period is 2 days and varying lead time](image-url)
4.1.3.4 Effect of Varying Lead Time and Review Period on Total Cost (TC)

Assuming that the holding cost is $1/unit, the total cost is given as follows.

Total Cost (TC) = fixed cost of procurement + variable purchasing cost + holding cost + shortage cost + expiration cost

Table 4-7: Sensitivity Analysis - Effect of lead time and review period on Total Cost (dollars)

<table>
<thead>
<tr>
<th></th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost scenario 1</td>
<td>191</td>
<td>191</td>
<td>278</td>
<td>285</td>
<td>285</td>
</tr>
<tr>
<td>Cost scenario 2</td>
<td>191</td>
<td>191</td>
<td>278</td>
<td>28</td>
<td>571</td>
</tr>
<tr>
<td>Cost scenario 3</td>
<td>194</td>
<td>195</td>
<td>280</td>
<td>287</td>
<td>572</td>
</tr>
</tbody>
</table>

Table 4.7 shows the changes in Total cost when the lead time and review period are varied for different cost scenarios. When the review period is 1 day and lead time is 0 day or 1 day, the total cost is highest for cost scenario 3. In cost scenario 3, fixed cost of procurement is higher compared to cost scenarios 1 and 2. Therefore, even though the same number of units are purchased as in the previous two cases, cost scenario 3 incurs higher fixed cost and hence TC increases. It is observed that when the review period is 2 days and lead time is 0 day or 1 day, the total cost is almost the same for all the three cost scenarios as shown in Figure 4.3. However, when review period is 2 days and lead time is 2 days, the total cost is less for cost scenario 1, compared to cost scenarios 2 or 3, because in the latter scenarios, there is priority given for shortage. When L+RP = 4 days and the shelf life of platelets arriving at hospital is only 1 day, shortages are occurring and thereby incurring more shortage cost higher total cost.
4.1.4 Implementing Rolling Horizon Approach

In practice, the same order policy may not be used for all the 30 days of the planning horizon. Instead a rolling horizon approach may be followed to implement the optimal solution. For example, even though the IP model gives optimal order policy for 30 days, only the first week of the optimal solution may be implemented. The IP model will then be rerun for the next 30 days, after updating inventory and demand forecast. Since long term forecasts may not be as good as short term forecasts, a rolling horizon policy helps to update forecasts weekly and determine the best solution based on the revised forecasts.

4.1.5 Summary and Observations of Finite Time Horizon Model (Managerial Implications)

- For a fixed lead time and review period,
  - When equal priority is given to all cost components, shortage is high and outdated is less
  - When priority is given to reduce shortage cost, holding cost increases
  - When priority is given to reduce shortage cost, total cost increases
4.2 Infinite Time Horizon Model

In the infinite time horizon model, demand is assumed to be stationary and uncertain. Therefore, the daily demand data obtained from Tetteh (2008) was fitted to a probability distribution using ExpertFit® and for each day, demand is generated from that distribution.

The data follows normal distribution with the parameters given below.
- Daily mean demand = 185
- Variance of the daily demand = 1026
- Standard deviation of daily demand ≈ 32

Result from the ExpertFit software is attached in Appendix C.

4.2.1 Numerical Example to Show Safety Stock Calculations in Infinite Time Horizon Model

For the purpose of illustration, following are the known parameters that are assumed:
- Service level (SL): 98%
- Lead time (L) = 0 day
- Review period (RP) = 1 day
- Mean demand (μ_D) = 185 units per day
- Standard Deviation (σ_D) = 32 units

We then calculate the following quantities:
- Mean demand during lead time plus review period = μ_{DLTR} = (L + RP)μ_D = (0+1)∙185 = 185
- Standard deviation of the demand during lead time plus review period = σ_{DLTR} = σ_D√(L + RP) = 32·√0 + 1 = 32
- For SL= 98%, z_{SL} = 2.06
- S = μ_{DLTR} + z_{SL}σ_{DLTR} = 185 + 2.06 ∙ 32 ≈ 251 units
- Safety stock, SS = z_{SL}σ_{DLTR} ≈ 67 units
• HAPP is calculated from the formula given below:

\[
\int_{x=0}^{S} (S - x)p(x)dx \\
\int_{x=1}^{\infty} p(x)xdx
\]

where \(p(x)\) is the probability of occurrence of demand \(x\)

• SAPD is calculated from the formula given below:

\[
\int_{x=S+1}^{\infty} (x - S)p(x)dx \\
\int_{x=0}^{\infty} p(x)xdx
\]

Therefore, at the end of each day, the hospital personnel will look at the inventory system and if the inventory position (\(IP\)) is less than the \(S\) (which in this case is 251), then order is being placed for \(S - IP\).

4.2.2 Sensitivity Analysis for Infinite Time Horizon

In the infinite time horizon model, review period (\(RP\)), lead time (\(L\)) and service level (\(SL\)) are varied and the changes in WAPP, HAPP, SAPD and TC are calculated. Table 4.8 gives the possible combinations of review period, lead time and service levels considered in the analysis.

The system parameters are given in Table 4.9.

**Table 4-8:** Combination of lead time (in days), review period (in days), and service level (in %)

<table>
<thead>
<tr>
<th>Lead time ((L))</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review Period ((RP))</td>
<td>1,2</td>
<td>1,2</td>
<td>2</td>
</tr>
<tr>
<td>Service Level ((SL))</td>
<td>90,92.5,95,97.5,98,99</td>
<td>90,92.5,95,97.5,98,99</td>
<td>90,92.5,95,97.5,98,99</td>
</tr>
</tbody>
</table>
**Table 4-9: Parameter settings (Fixed)**

<table>
<thead>
<tr>
<th>Parameter (units)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily demand distribution of platelet</td>
<td>$N{\mu=185,\sigma=32}$</td>
</tr>
<tr>
<td>Fixed cost of purchasing ($)</td>
<td>$C^F = 1$</td>
</tr>
<tr>
<td>Cost of purchase of platelet ($/unit)</td>
<td>$C^P = 1$</td>
</tr>
<tr>
<td>Cost of holding platelets ($/unit)</td>
<td>$C^H = 1$</td>
</tr>
<tr>
<td>Cost of shortage of platelet ($/unit)</td>
<td>$C^S = 1$</td>
</tr>
<tr>
<td>Cost of platelet expiration ($/unit)</td>
<td>$C^E = 5$</td>
</tr>
<tr>
<td>Simulation time (in days)</td>
<td>500</td>
</tr>
<tr>
<td>Number of replication</td>
<td>100</td>
</tr>
</tbody>
</table>

Note that when the review period is 1, the (T,S) policy becomes base stock periodic review policy. The infinite time horizon model is modeled and the results are obtained for the above mentioned parameter settings using C++.

As mentioned earlier, daily demand is assumed to follow normal distribution with mean 185 and standard deviation 32. At the beginning of each time period $t$, demand is simulated from the above mentioned parameters. The demand is partially or completely fulfilled with the available on-hand inventory. The simulation is run for 500 days and is replicated 100 times.
4.2.2.1 Effect of Varying Lead Time and Review Period on WAPP

Table 4.10 shows the changes in WAPP (Wastage As a Percentage of Procurement) when the lead time and review period are varied for different cost scenarios.

<table>
<thead>
<tr>
<th>SL</th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL = 90%</td>
<td>0.0000</td>
<td>0.2661</td>
<td>0.0054</td>
<td>0.1109</td>
<td>8.6825</td>
</tr>
<tr>
<td>SL = 92.5%</td>
<td>0.0000</td>
<td>0.2896</td>
<td>0.0089</td>
<td>0.1329</td>
<td>9.0058</td>
</tr>
<tr>
<td>SL = 95%</td>
<td>0.0000</td>
<td>0.3396</td>
<td>0.0221</td>
<td>0.1884</td>
<td>9.9046</td>
</tr>
<tr>
<td>SL = 97.5%</td>
<td>0.0000</td>
<td>0.4017</td>
<td>0.0925</td>
<td>0.3776</td>
<td>11.2888</td>
</tr>
<tr>
<td>SL = 98%</td>
<td>0.0000</td>
<td>0.4210</td>
<td>0.1381</td>
<td>0.4707</td>
<td>11.9783</td>
</tr>
<tr>
<td>SL = 99%</td>
<td>0.0000</td>
<td>0.4789</td>
<td>0.3655</td>
<td>0.8590</td>
<td>12.9549</td>
</tr>
</tbody>
</table>

From Table 4.10, it is observed that when review period is 1 day and lead time is 0 day, WAPP (Wastage as A Percentage of Procurement) is 0 because platelets received from blood banks are fresh and have shelf life of 3 days and frequency of placing order is higher. However, if the review period is 1 day and lead time is 1 day, then WAPP increases as SL increases. This happens because as the SL increases, more platelet units are held in inventory to avoid shortage, which results in higher wastage to satisfy the demand during lead time plus review period. When the review period is 2 days and lead time is 0 day, 1 day and 2 days, it is observed that WAPP increases as SL increases as shown in Figure 4.4. This happens because as SL increases, more platelet units are held in inventory to avoid shortage, resulting in higher wastage.
4.2.2.2 Effect of Varying Lead Time and Review Period on HAPPC

**Table 4-11**: Sensitivity Analysis - Effect of lead time and review period on HAPP

<table>
<thead>
<tr>
<th></th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL = 90%</td>
<td>24.0787</td>
<td>84.1104</td>
<td>77.4367</td>
<td>76.7352</td>
<td>91.5122</td>
</tr>
<tr>
<td>SL = 92.5%</td>
<td>26.0490</td>
<td>86.1374</td>
<td>80.3311</td>
<td>79.9686</td>
<td>93.0622</td>
</tr>
<tr>
<td>SL = 95%</td>
<td>29.5955</td>
<td>89.5197</td>
<td>85.1998</td>
<td>84.9202</td>
<td>94.8252</td>
</tr>
<tr>
<td>SL = 97.5%</td>
<td>34.8217</td>
<td>94.2508</td>
<td>92.0049</td>
<td>91.9601</td>
<td>97.1161</td>
</tr>
<tr>
<td>SL = 98%</td>
<td>36.4147</td>
<td>95.6081</td>
<td>93.9147</td>
<td>94.0027</td>
<td>97.7744</td>
</tr>
<tr>
<td>SL = 99%</td>
<td>41.2389</td>
<td>99.9960</td>
<td>97.3308</td>
<td>99.9990</td>
<td>99.9987</td>
</tr>
</tbody>
</table>
Table 4.11 shows the changes in HAPP (Holding as A Percentage of Procurement) when the lead time and review period are varied for different SL values. When review period is 1 day and lead time is 0 day or 1 day, HAPP increases as SL increases. This happens because as SL increases, more platelet units are held in inventory to avoid shortage and hence results in higher holding cost as shown in Figure 4.5. The same trend is observed when the review period is 2 days and lead time is 0 day, 1 day and 2 days as shown in Figure 4.6.

**Figure 4-5**: HAPP when review period is 1 day and varying lead time

**Figure 4-6**: HAPP when review period is 2 days and varying lead time
4.2.2.3 Effect of Varying Lead Time and Review Period on SADP

Table 4-12: Sensitivity Analysis - Effect of lead time and review period on SAPD

<table>
<thead>
<tr>
<th>SL</th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>0.7393</td>
<td>1.4244</td>
<td>0.4967</td>
<td>0.5394</td>
<td>1.0019</td>
</tr>
<tr>
<td>92.5%</td>
<td>0.5590</td>
<td>1.4116</td>
<td>0.3673</td>
<td>0.4042</td>
<td>0.9722</td>
</tr>
<tr>
<td>95%</td>
<td>0.3323</td>
<td>1.4068</td>
<td>0.2149</td>
<td>0.2572</td>
<td>0.9615</td>
</tr>
<tr>
<td>97.5%</td>
<td>0.1475</td>
<td>1.3815</td>
<td>0.0924</td>
<td>0.1332</td>
<td>0.9038</td>
</tr>
<tr>
<td>98%</td>
<td>0.1132</td>
<td>1.3861</td>
<td>0.0709</td>
<td>0.1105</td>
<td>0.9041</td>
</tr>
<tr>
<td>99%</td>
<td>0.0468</td>
<td>1.3603</td>
<td>0.0298</td>
<td>0.0644</td>
<td>0.9034</td>
</tr>
</tbody>
</table>

Table 4.12 shows the changes in SAPD (Shortage as A Percentage of Demand) when the lead time and review period are varied for different SL values. It is observed that when review period is 1 day and lead time is 0 day or 1 day, SAPD decreases as SL increases to avoid shortage. Similarly when the review period is 2 days and lead time is 0 day, 1 day and 2 days, SAPD decreases as SL increases for the same reason.

4.2.2.4 Effect of Varying Lead Time and Review Period on Total Cost

Table 4.13 shows the changes in Total Cost (TC) when the lead time and review period are varied for different SL values. It is observed that when review period is 1 day and lead time is 0 day or 1 day, TC increases as SL increases as shown in Figure 4.7. This happens because as SL increases, more platelet units are held in inventory to avoid shortage, resulting in higher inventory and higher wastage. Hence total cost increases as
SL increases even though shortage cost decreases. Similar reasoning can be given when the review period is 2 days and lead time is 0 day, 1 day and 2 days as shown in Figure 4.8.

**Table 4-13**: Sensitivity Analysis - Effect of lead time and review period on Total Cost

<table>
<thead>
<tr>
<th>SL</th>
<th>RP=1, L=0</th>
<th>RP=1, L=1</th>
<th>RP=2, L=0</th>
<th>RP=2, L=1</th>
<th>RP=2, L=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>233.4216</td>
<td>441.6530</td>
<td>341.2060</td>
<td>357.6435</td>
<td>737.7738</td>
</tr>
<tr>
<td>92.5%</td>
<td>235.7662</td>
<td>447.5695</td>
<td>346.0187</td>
<td>363.9057</td>
<td>747.5558</td>
</tr>
<tr>
<td>95%</td>
<td>240.6844</td>
<td>457.6033</td>
<td>354.6202</td>
<td>374.0176</td>
<td>761.3780</td>
</tr>
<tr>
<td>97.5%</td>
<td>248.9877</td>
<td>471.4625</td>
<td>367.4972</td>
<td>389.4225</td>
<td>779.9955</td>
</tr>
<tr>
<td>98%</td>
<td>251.6730</td>
<td>475.5346</td>
<td>371.3011</td>
<td>394.1301</td>
<td>786.9331</td>
</tr>
<tr>
<td>99%</td>
<td>260.0632</td>
<td>488.3955</td>
<td>383.9252</td>
<td>408.5352</td>
<td>804.3358</td>
</tr>
</tbody>
</table>

**Figure 4-7**: Total Cost when review period is 1 day and varying lead time
Figure 4-8: Total Cost when review period is 2 days and varying lead time

4.2.3 Summary and Observations of Infinite Time Horizon Model (Managerial Implications)

- HAPP increases as the service level increases
- WAPP increases as the service level increases
- SAPD decreases as the service level increases
- Total cost increases as the service level increases
- Fixing the review period, WAPP increases when the lead time increases
- Fixing the review period, HAPP increases when the lead time increases
- Fixing the review period, SAPD increases when the lead time increases
- Fixing the review period, Total Cost increases when the lead time increases
- When the sum of lead time and review period is greater than shelf life of platelets arriving at hospitals (i.e., $L + RP > 3$), there is excessive wastage and shortage of platelets
4.3 Comparison of the Finite Time and the Infinite Time Horizon Model

We compare the two models under the following criteria.

1. Computational effort
2. Implementation
3. Ease of use
4. Effectiveness

1. Computational Effort in Developing the Optimal Order Policy

*Finite:* More effort is required. The forecasts have to be updated periodically and new integer programming models have to be solved each time.

*Infinite:* Less effort is required. The optimization model has to be solved only once to determine the order-up-to level. The formulae required for the optimal policy are simpler.

2. Implementation

*Finite:* Implementation is not easy since order policy may change week to week.

*Infinite:* Easy to implement since the hospital administrator needs only the order-up-to level \( S \). The value of \( S \) remains the same as long as the underlying demand distribution is the same.

3. Ease of Use

*Finite:* Required users to have a good knowledge of optimization models and skills to solve them. The optimal policy is also not very easy to explain to the hospital personnel.
Infinite: The optimization model is solved only once. It is easy to solve using a spreadsheet. The policy is also easy to explain to the hospital personnel.

4. Effectiveness of the Order Policy

Finite: Policy will be more responsive and will reflect the most current demand conditions. It is expected that the order policy will be better, leading to less wastages and shortages.

Infinite: Because of the stationarity assumption on the demand, the order policy will not be able to respond to the changes in demand due to seasonality and environmental conditions. Hence, the order policy may not reflect current conditions and will not be optimal. That would lead to more wastages and shortages.
Chapter 5
Conclusions and Future Work

5.1 Conclusion

In this research, inventory management of platelets at hospitals is considered. In the research work on inventory management of blood done in the past, reducing platelet wastage is seldom considered due to the extremely short shelf life of platelets. However, a significant amount of platelets is wasted along the supply chain and therefore it is necessary to control wastage of platelets. It has been reported that 15% to 20% of the total platelets collected from the donors are wasted due to the 5 day shelf life of platelets. Also, the inventory of platelets is kept high at the hospitals to reduce shortage. In this research, a finite time and infinite time horizon inventory models are developed to determine the order quantity and when to order platelets such that the inventory, wastage and outdating are reduced, considering the shortage cost, expiration cost, inventory holding cost, transportation cost and purchasing cost.

For the finite time horizon model, the platelet demand is forecasted for the planning horizon based on the historical data and is used as an input to the model. For the infinite time horizon model, the historical data is fitted using ExpertFit® and the distribution for platelet demand is determined and is used as an input to the model. To illustrate the performance of the proposed finite and infinite time horizon models, four performance measures are used: Wastage as A Percentage of Procurement (WAPP), Holding as A Percentage of Procurement (HAPP), Shortage as A Percentage of Demand (SAPD), and Total Cost (TC).

- Wastage as A Percentage of Procurement (WAPP) = \( \frac{\text{Units outdated}}{\text{Units procured}} \times 100 \)
- Holding as A Percentage of Procurement (HAPP) = \( \frac{\text{Units in inventory}}{\text{Units procured}} \times 100 \)
- Shortage as A Percentage of Demand (SAPD) = \( \frac{\text{Shortage Units}}{\text{Total demand}} \times 100 \)
Total Cost (TC) = fixed cost of procurement + variable purchasing cost + holding cost + shortage cost + expiration cost

Sensitivity analysis is performed to find the impact of the change in the four criteria when the cost settings are varied for the finite time model. In the infinite time horizon model, service level, lead time, and review period are varied to analyze their effect on the performance measures.

The results of the finite time horizon model indicate that when more priority is given to reduce shortage, SAPD decreases while WAPP, HAPP and TC increase. The results of the infinite time horizon model indicate that when the service level increases, SAPD decreases simultaneously increasing WAPP, HAPP and TC.

5.2 Future Scope

As a scope of future work, the following can be considered.

- Conflicting criteria such as wastage and shortage; inventory holding and ordering, can be evaluated using multi-criteria decision making (MCDM) techniques to develop optimal order policies.
- Varying the coefficient of variation (CV) of the demand and finding the effect on the four criteria on the CV (CV of the demand is defined as the ratio of standard deviation of the demand to the mean of the demand).
- Blood collection and distribution policies at blood centers can be studied in detail extending the work to the entire blood supply chain.
- The results of the finite and infinite time horizon models can be compared by using the same demand data and replicating the results through simulation.
## Appendix A
### Forecasting Data and Seasonality Index

<table>
<thead>
<tr>
<th>Day</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>193.6923</td>
</tr>
<tr>
<td>Day 2</td>
<td>211.6154</td>
</tr>
<tr>
<td>Day 3</td>
<td>198</td>
</tr>
<tr>
<td>Day 4</td>
<td>183.7692</td>
</tr>
<tr>
<td>Day 5</td>
<td>182.6923</td>
</tr>
<tr>
<td>Day 6</td>
<td>165.7692</td>
</tr>
<tr>
<td>Day 7</td>
<td>158.3077</td>
</tr>
<tr>
<td>Overall</td>
<td>184.8351</td>
</tr>
</tbody>
</table>

Seasonality index for day $i = \frac{\text{average demand during day } i}{\text{overall average of demand for all periods}}$

Seasonality index for day 1 = $\frac{193.6923}{184.8352} = 1.047919$

Seasonality index for day 2 = $\frac{211.6153846}{184.8352} = 1.144887$

Seasonality index for day 3 = $\frac{198}{184.8352} = 1.071225$

Seasonality index for day 4 = $\frac{183.7692308}{184.8352} = 0.994233$

Seasonality index for day 5 = $\frac{182.6923077}{184.8352} = 0.988407$

Seasonality index for day 6 = $\frac{165.7692308}{184.8352} = 0.896849$

Seasonality index for day 7 = $\frac{158.3076923}{184.8352} = 0.85648$
## Appendix B
### Expertfit Software Results

<table>
<thead>
<tr>
<th>Data Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source file</td>
<td>Book.dat</td>
</tr>
<tr>
<td>Observation type</td>
<td>Integer valued</td>
</tr>
<tr>
<td>Number of observations</td>
<td>91</td>
</tr>
<tr>
<td>Minimum observation</td>
<td>123</td>
</tr>
<tr>
<td>Maximum observation</td>
<td>266</td>
</tr>
<tr>
<td>Mean</td>
<td>184.83516</td>
</tr>
<tr>
<td>Median</td>
<td>179</td>
</tr>
<tr>
<td>Variance</td>
<td>1,026.01</td>
</tr>
<tr>
<td>Lexis ratio (var./mean)</td>
<td>5.55092</td>
</tr>
<tr>
<td>Skewness</td>
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</tr>
<tr>
<td>SD</td>
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</table>
Bibliography


