UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SOCIAL SCIENCES
DEPARTMENT OF MANAGEMENT

Doctor of Philosophy

ANALYSING THE SUPPLY CHAIN OF BLOOD IN THE U.K. USING SIMULATION

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This PhD thesis is concerned with analysing the supply chain of blood products within the UK National Health Service. The objective of the study is to improve procedures and outcomes by modelling a vertical part of the chain from donor to recipient. The supply chain of blood products is broken down into material flows, information flows and cost analysis. Discrete event simulation is used to determine ordering and inventory policies leading to reductions in shortages and wastage, increased service levels, improved safety procedures and reduced costs, by employing better system-wide coordination.

In this study the system is examined, the construction of the model and its inputs are described and evaluated, the performance criteria are determined and results are presented from several simulation experiments. Representative small, medium and big size hospitals (in terms of blood consumption) are individually examined in separate models with one blood centre and one hospital. The best combination of policies for all the different size hospitals is determined from the set of tested scenarios. The model is then expanded to incorporate all the three characteristic hospitals, and to observe the relationships as the hospitals compete for resources from the blood centre in a more realistic environment. Transportation, redistribution and transhipment policies are tested in the expanded model to check the impact of these practices on the key criteria. The model execution time problems which arise with the expansion of the model are resolved through the use of distributed simulation; a new, advanced simulation technique whose scope and potential is shown through a feasibility study which was carried out for the purposes of this thesis.

The model can be used by both the National Blood Service and by hospital managers as a decision support tool to investigate different procedures and policies.

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ABBREVIATIONS

BSMS = Blood Stock Management Scheme

CBB = Centre's Blood Bank

HBB = Hospital Blood Bank

Irrad. = Irradiated

ISI = Issuable Stock Index.

MSBOS = Maximum Surgical Blood Ordering Schedule

NBS = National Blood Centre

Neg = Negative

PLT = Platelet

Pos = Positive

PTI = Process, Testing, Issuing

RBC = Red Blood Cell

= Number

MEDICAL GLOSSARY

Apheresis: A procedure where whole blood is removed from the body and a desired component is retained, while the remainder of the blood is returned to the donor.
URL: www.nybloodcenter.org/glossary.htm (accessed 13/7/2006)

Cryoprecipitate: Component of blood obtained by freezing and thawing plasma. Useful in replacing some clotting factors in patients missing them congenitally or because of operation or trauma. URL: bloodcenter.stanford.edu/about_blood/glossary.html (accessed 13/7/2006)

Leucodepletion: The removal of white cells from the plasma
http://www.ibms.org/ (accessed 13/7/2006)

CHAPTER 1: INTRODUCTION

1.1 General Importance

It is widely known that Operational Research emerged during the time of World War II through its application to military operations. From that time on, Operational Research found applications in many peacetime operating systems such as agriculture, retailing, and transportation. Miser in his review on Operations Research and Systems Analysis (1980) refers to the blood distribution and utilisation problem as a notable example which typifies much of the work that has been done in this discipline. Blood inventory management has been proved to be a very fruitful application area of Operations Research (Prastacos, 1984).

Moreover, blood inventory management matches many of the typical health care management problems (Prastacos, 1981). Kendall (1980a) identified some of them, such as instant availability of the product to the client (blood to the patients), utilisation of the production mechanisms (blood resources), quality of the product (age of blood when given to patients), etc.

In addition, supply chain integration and management has been successfully applied in recent years to manufacturing firms and for-profit business and can equally be utilised in the public sector and specifically in health operations. The term supply chain is used here as a system of suppliers, manufacturers, distributors, retailers, and customers where materials flow downstream from suppliers to customers, and information flows in both directions [Houlihan (1985), Stevens (1989), Lee and Billington (1993), and Lamming (1996)].

An urgent need emerges in the health sector for integrating requirements and processes in order to achieve the required benefits. However, as Beier (1995) notes, health care supply chain management may be considered more complex than typical industrial applications since its product is more vital and there is a perceived need to provide very high levels of service. In the case, when dealing with a critical resource as blood, this is most certainly true. Blood is not only critical for medical treatment but it usually also involves matters of life and death to the patient (Spens, 1998). One way of utilising this scarce resource effectively without compromising the medical, ethical and legal aspects is through open cooperation between the members of this supply network, namely the National Blood Service (NBS) and the hospitals.

Furthermore, most of today's supply chains, including that of blood, are hugely complex and like all systems can benefit from Operational Research techniques. Among the quantitative methods, simulation is undoubtedly one of the most powerful techniques to apply, as a decision support system, within a stochastic supply chain environment (Terzi and Cavalieri 2004). It is a tool which can provide multi-decisional support in the context of "what-if" analysis and evaluation of quantitative benefits.

The system under examination can clearly be characterised as a distinctive stochastic system since both supply (deriving from volunteer donors) and demand (rising according to patients) for blood is variable. Furthermore, it comprises all the typical operations of a supply chain: from manufacturing (collection and processing) to distribution and consumption (transfusion) and moreover, controversial supply-chain issues arise since different parts of the chain are controlled by different organisations; NBS manages the supply side but the hospitals manage the demand side.

Therefore, blood inventory management, which has been thoroughly but not exhaustively studied by Operational Researchers in the past, needs to be examined nowadays together with many other functions, as part of a wider system which seeks an integrated approach to effectively manage flows of products rather than operations in "silo" .

1.2 The Problem and the Approach

The demand for blood in the UK National Health Service is immense. Blood transfusions are frequently required for trauma victims, many types of surgery, organ transplants, in childbirth, and for patients receiving treatment for diseases such as cancer, leukaemia, and anaemia. With an aging population and advances in medical treatments, requiring blood transfusions, the demand for blood continues to increase, despite some research evidence of shorter survival rates in transfused populations (Vamvakas, 2003; Wallis et al, 2004). Forecasts show an increase of 5% in the UK by 2008 (Wells at al, 2002), increasing within 20 years by 20% relative to supply (Currie at al, 2004). On the other hand, the introduction of precautionary measures to counteract the threat of new infections, such as CJD (Creutzfeldt-Jakob Disease), seriously restricts the pool of blood donors by ruling out existing or potential donors. These measures, together with the introduction of more sophisticated technologies for collecting blood, are constantly increasing costs within the blood supply system.

Currently only 6% of the UK population give blood, although 60% are eligible to donate (NHS Direct, 2006). The figures are even worse in the USA (5%) (Jones, 2003) and Canada (3.7%) (Canadian Blood Services, 2005). Nationally, in the UK the demand for blood is closely balanced by the overall supply and occasionally exceeds it. However, poor coordination can result in a shortage in one area while units are wasted in another area. Since blood is so vital, a shortage can put life at risk, for example if an operation has to be postponed. Moreover, from a purely financial perspective, blood is a very costly product and its wastage is highly undesirable.

The overall aim of this study is a detailed analysis of a complete vertical section of the blood supply chain, to identify the factors involved in decision-making by the NBS centre and the hospitals which it supplies. This detailed, holistic perspective has not been taken in previous research in this area. By taking this view, a better understanding of the system is sought, and therefore the ability to manage it for the benefit of both parts of the supply chain. This should lead to improved service levels and reduced shortage and wastage to meet increasing demand and/or reduced supply in the future.

Flows of material and information are included in the system as essential parts of the supply chain. Information flows are represented by placing orders and updating the status of delivery and record-keeping. Costs and quality of service represent the performance measurements of the system for comparing different strategies. The problem is tackled using discrete event simulation. Simulation models are produced in a standalone, traditional mode as well as in a distributed mode when more demand points, i.e. hospitals, are added in the supply chain. Results are presented for typical medium, large and small volume hospitals supplied by an NBS centre and best policies are recommended for adoption.

This research is geared toward developing effective performance analysis of an integrated supply chain of blood products. Overall, the following objectives are pursued:

1) To provide a modelling framework for supply chain simulation in which the interdependencies between model components are captured.

2) To develop an inventory-queue model for performance analysis of a blood supply network with inventory control at all sites.
3) To evaluate the impacts of different inventory reorder policies and service requirements for multi-echelon distribution systems.
4) To compare the performance of the proposed policies with traditional policies for the blood centre and different size hospitals separately, and then together, in an integrated supply chain.
5) To extend the previous work developed for blood banks and blood supply chains by incorporating the complexities of the blood supply chain system not covered by previous research, such as a) the inclusion of multiple products with different shelf lives in a single model, b) the adoption of product substitution policies, c) the distinction between assigned and unassigned inventory stages of products and d) the incorporation of detailed representations of more than one hospital blood bank into the model.

In view of the above, the following research questions are addressed:

A) Compared with previous studies on the topic, how far can we extend this research and make more realistic models with the tools available today?
B) Is it possible to use simulation to thoroughly explore the supply chain of blood?
C) Can a simulation model answer crucial questions about the management of a supply chain of a perishable product?
D) Are such models useful to real life users?
E) Can we apply the method used for blood products to the supply chain of other perishable products?

1.3 Organisation of the Thesis

The thesis is structured in the following way:
Chapter 1 describes the general importance of the issue discussed in this thesis and briefly explains the problem and the approached used to tackle it.

Chapter 2 presents an overview of the British Transfusion Service (BTS) and the National Blood Service (NBS) in particular. It then analyses the conceptual model of the blood supply chain and presents issues related to planning of donations and collections, donors' characteristics, processing, testing and storage, issuing and delivery, hospital inventory management and demand. It concludes with the financial planning of the whole chain and the associated costs.

Chapter 3 contains the literature review of the topic. It is formed in four parts. The first part deals with the general perishable inventory problem. The second part is structured in three sections. Section A considers research which has examined blood banks and related problems from an individual, local perspective. Section AB acts as an intermediate stage, presenting papers which are related to the development of information systems and technology relevant to blood banking for both blood centres and hospitals. Finally, section B deals with research concerning the coordination of the blood supply from a wider perspective, at the regional level. The third part focuses on Operational Research articles concentrating on platelets, and the fourth part presents the conclusions of the review, together with the contribution of this thesis to the already existing literature.

Chapter 4 justifies the selection of the particular Operational Research technique used to tackle the problem, and analyses some features crucial to the construction and execution of the simulation model. Moreover, it outlines the steps followed in performing the research with the use of this technique.

Chapter 5 describes the collection and analysis of data. It is separated into five main categories. These are: a) introduction, b) data collection methods and data description, c) analysis of data relevant to the blood centre and the NBS, such as collection teams, processing and testing, storage, issuing and distribution, d) analysis of data relevant to hospitals, such as physicians' ordering and inventory management and finally e) wastage figures and associated loss for both the NBS and hospitals.

Chapter 6 provides a full description of the simulation model, the assumptions made in the development of the tool and the chosen output results. It also imparts knowledge about model verification and validation.

Chapter 7 presents all the experiments for one NBS centre and a medium volume hospital, one NBS centre and a small hospital and one NBS centre and a high volume hospital. Several policies are tested and their impact on the main performance measurements is monitored and analysed. The best scenarios are indicated in each case.

Chapter 8 expands the one-centre-one-hospital model by including more hospitals in the model through the use of distributed simulation. Together with the methodology of distributed simulation, it also presents the experiments and conclusions of the combined scenarios. Moreover, the NBS transport utilisation is analysed and further experiments including redistribution policies are carried out.

Chapter 9 summarises the main outcomes of this study and suggests potential future research deriving from this work.

The Appendices are organised in four sections: A, B, C and D. Section A incorporates relevant material used during the data collection and analysis process of this study. Section B includes the pseudo-code for explaining in simple terms the Simul8 Visual Logic, the Visual Basic for Applications and the Excel spreadsheets which are connected to the simulation software allowing the model to implement its rules and procedures correctly. Section C entails tables with distribution inputs and conditions of the simulation models for each experiment. Finally, Section D displays a snapshot of the interface of the analytic simulation model.

CHAPTER 2: THE SUPPLY CHAIN OF BLOOD IN THE U.K.

2.1 The U.K Blood Transfusion Service

The UK Blood transfusion service is currently organised into four regional services for the collection and distribution of blood. These are the National Blood Service for England and North Wales (NBS), the Welsh Blood Service (WBS), the Scottish (SNBTS) and the Northern Ireland National Blood Transfusion (NIBTS). All the regional services serve around 413 hospitals across the UK. (Serious Hazards of Transfusion Committee, 2002).

During 2000/2001, the four national blood transfusion services together collected 2.82 million whole-blood donations and approximately 70,000 apheresis donations. The total annual cost incurred by the four blood transfusion services in collecting, testing, processing and issuing blood products was £284.1 million during 2000/2001. Of this, the NBS accounted for 80%, the WBS for 4%, the SNBTS for 13% and the NIBTS for 3%. When these costs are stratified by product, the production and issue of red blood cells (RBCs) accounted for 76% of the annual cost incurred by the blood transfusion services during that period. Fresh frozen plasma accounted for 12%, platelets for 7%, cryoprecipitate for 3% and paediatric products for 2% (Varmey et al, 2003). These statistics are presented in Table 2.1.

Table 2.1 Total percentage of amount and costs of blood transfusions to the National Health Service (NHS) in 2000/2001.

2000/2001 NHS	Red blood cells	Fresh frozen plasma	Platelets	Cryo-precipitate	Paediatric products	Total number
% of transfusions	76.3%	11.7%	7.1%	2.5%	2.3%	2,910,104 transfusions
% of Total NHS cost	69.0%	6.0%	9.00%	1.0%	14.0%	£898m cost
*Based on an average of 2.7 units, 2.8 units, 1 dose and 9.6 units per transfusion for red blood cell, fresh frozen plasma, platelet and cryoprecipitate transfusions, respectively.						

Source: (Varmey et al, 2003).

2.2 The National Blood Service

This study was carried out in collaboration with the National Blood Service for England and North Wales (NBS) alone, but the functions of each of the four organisations do not differ greatly.

The NBS is run by the National Blood Authority (NBA), recently expanded (1.10.2005) and renamed NHS Blood and Transplant (NHSBT) (Hospital communications, 2005), which is a special health authority of the NHS (National Health Service).

The NBS was set up in 1993 and took over the services previously run by individual regional health authorities. Since then, it has been reorganised to effect the change from a regional to a national service. The National Blood Service completed its transition to a national organisation in April 2000 (National Audit Office, 2000).

The NBS consists of 15 blood Centres, of which 10 are fully functional Process, Testing and Issuing (PTI) Centres and 5 are smaller, partially functional Centres. The non-fully functional Centres are usually responsible for some of a blood Centre's activities. For example, they might organise collections but send the collected units to other, bigger Centres for processing and testing. Typically, these units are sent back to the small Centres for storage and issuing to hospitals the following day. It is believed that this arrangement facilitates the coverage of emergencies supplies to local hospitals geographically near to the small Centres, despite the extra transportation costs involved in the process. The opposite case is also possible, in which centres lack a marketing and collections department and such processes are carried out by other Centres on their behalf. Both these situations are common within the NBS.

Figure 2.1 illustrates the location of the 15 NBS Centres. Together they supplied around 286 hospitals across England and North Wales in 2005. Hence, each Centre serves around 20 hospitals, geographically nearest to it. The number of hospitals in these regions has slowly declined from 316 to 286 over a period of 5 years (BSMS Annual Reports, 2001-2005). Each of these hospitals should have a blood transfusion committee, composed of consultants, blood bank managers, theatre nurses, nurse managers and various other clinicians, to ensure appropriate blood product use and auditing and to educate clinicians on transfusions (Haynes et al, 2004).

Figure 2.1 National Blood Service sites

During 2000/2001, 97.5% (2.35m) of all blood donations were whole blood donations and only 2.5% (0.061m) were apheresis donations. In the NBS, currently apheresis donations are only used for the collection of platelets, in contrast to whole blood donations from which all products are produced. For the same financial year, the NBS supplied about 2.22m red cell units to 310 hospitals. Of those units 68% were delivered to district general hospitals, 29% to teaching hospitals and 3% to private hospitals (Chapman et al, 2002).

The NBS has a high service level target for supply. It aims to meet 99.51% of hospital demand for blood and blood components. Figure 2.2 depicts hospitals' satisfaction with the services provided by the NBS, on a scale of 1-10 (x-axis) with 1 being least satisfied and 10 being most satisfied. According to the survey, the areas of greatest satisfaction for that year were product quality, product safety and service provided by NBS drivers. The areas of least satisfaction were age of products, reporting and service from courier drivers.

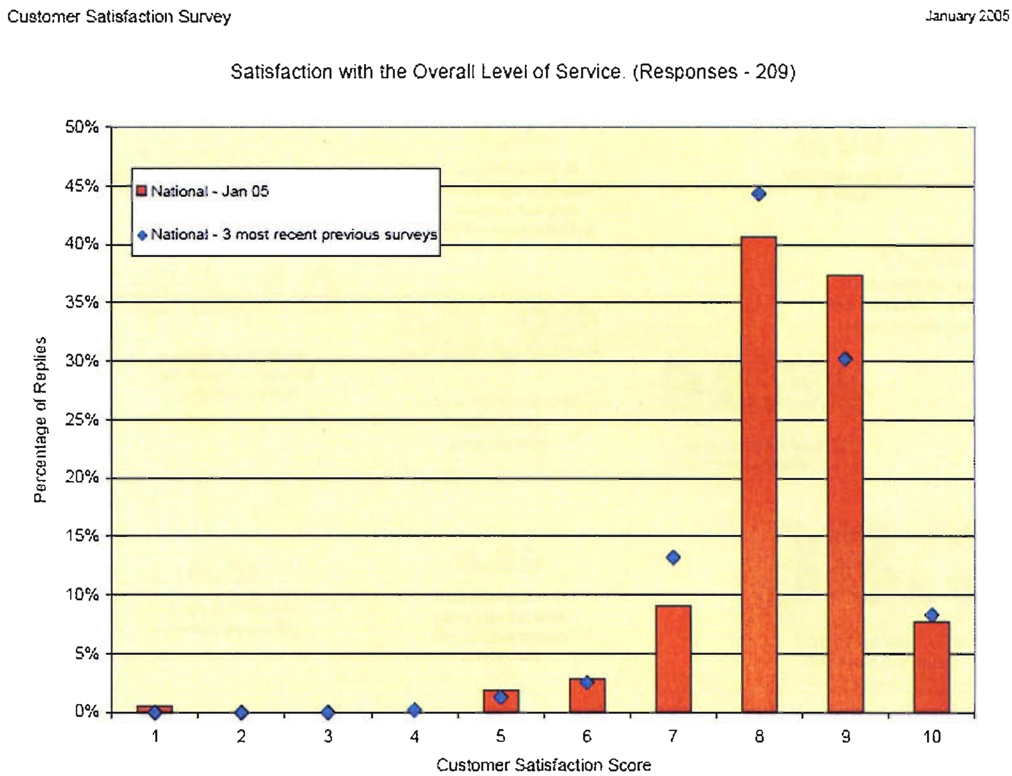

Figure 2.2 NBS Hospital Satisfaction Survey 2005
Source: http://www.blood.co.uk/hospitals/communications/Surveys/0501/survey_01_05.pdf

Over the past three years, trends in the relationship between supply of and demand for blood suggest that seasonal tendencies, to collect more blood at certain times of the year and less at others, are becoming more marked. However, the emerging long-term trend showed demand growing more quickly than collection. This trend was made worse by the 2% process loss arising from leucodepletion in 2000. Some cases of shortages were observed during that summer (National Audit Office, 2000). On the other hand, some cases of over-supply were observed during 2004 (Garwood, 2005).

As products are distributed to hospitals for transfusion, there are losses due to inventory management, transfusion practices, and outdating. Each of these steps has some potential for improvement and increase of overall yield if understood and managed in a more comprehensive manner (Jones, 2003). Figure 2.3 (National Audit Office, 2002) gives an idea of the percentages of blood unit losses which occur at different stages from collection to transfusion. Thus, for the year in question, 4.88% of units were lost through normal processing, for instance if a microbiology result was unfavourable. 1.84% was lost at sessions, e.g. if less than 450ml was collected or the donation was not suitable for use. 0.2% was used for quality control tests, reagents and other non-clinical use. Moreover, 0.52% of units time-expired while stored in NBS Centres, and 4.25% of units time-expired or otherwise become unavailable for use at hospitals. Therefore, only 88.31% of collected units of red cells were actually transfused to patients.

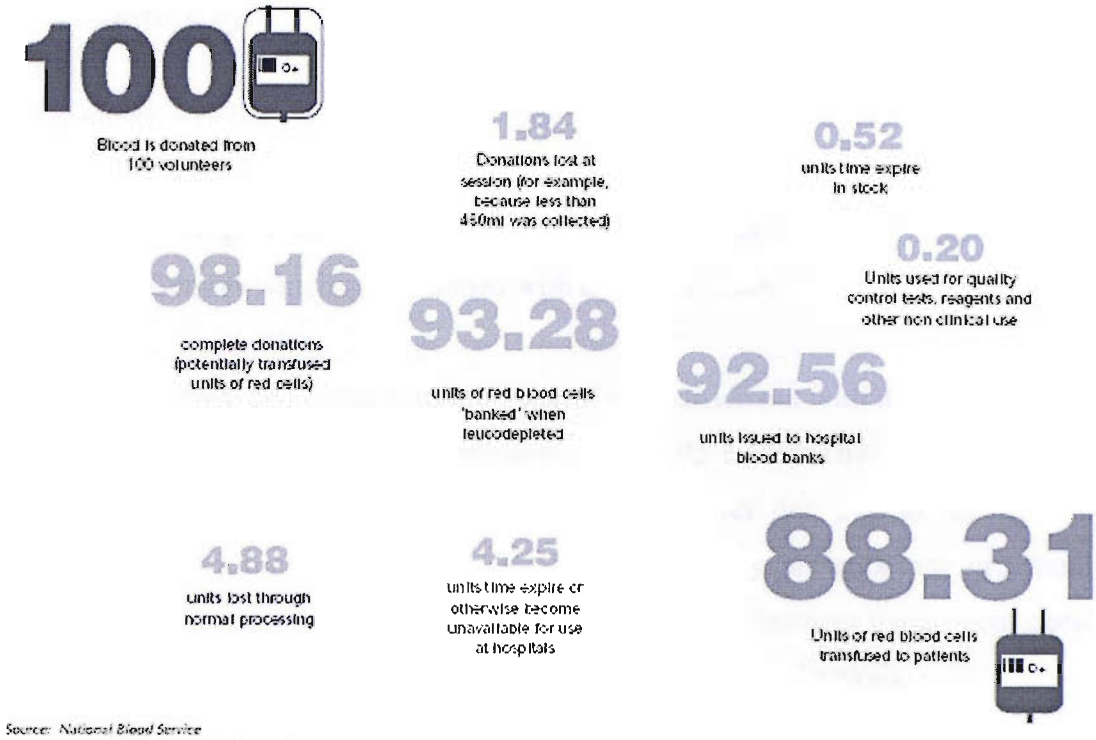

Figure 2.3 Process losses from collection to transfusion
Source: National Audit Office, 2000, p.10

Figure 2.4 illustrates the processes of the blood supply chain. The dotted arrows demonstrate information flow and the solid arrows represent the flow of blood units. The diagram will progressively be explained in detail in the following sections.

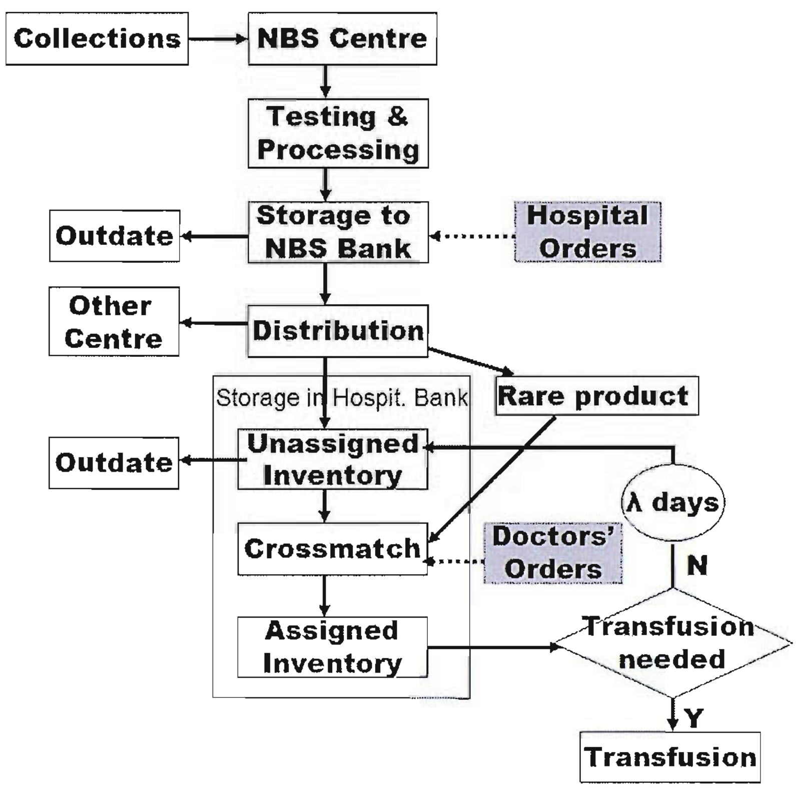

Figure 2.4 Flow Chart of the blood supply chain

2.3 Planning of Donations and Collections

Most blood is collected by NBS teams in "Bloodmobiles" – specially adapted vans and buses – in public and industrial venues. The blood is then transported to the Centres for processing during or after the scheduled sessions. Some collections also take place in those NBS Centres which are equipped with donor facilities.

Donor recruitment and collections are planned and carried out with the involvement of the Marketing and the Collections departments of the NBS centre. The tasks of the Marketing department are to recruit enough new donors to cover demand, to arrange donation sessions all over the region and to motivate donors by presentations in schools and companies, advertisements on the TV and radio. The Collections department decides on the timetable and the collection team which carries out the collections.

Collections are categorised by type. Actually less than 5% of collections are carried out inside the Centres. Most collections are either industrial or public or take place in bloodmobiles. Industrial collections are performed in companies and other organisations and can represent up to 33% of all donations. In fact, companies with high awareness of their social profile or due to employees' requests arrange donor sessions in their sites. People from the Marketing department visit the company and give presentations to its employees about the importance and timely process of a donation. The purpose of this visit is to appraise the amount of interest shown by the workforce. If the number of potential donors is believed to be sufficient and also the minimum requirements for a collection session are met by the company's premises, they liaise with the Collections department to include the session into the collections program. A collection team is assigned and the time and date are arranged.

Public collections take place in churches and other venues, where people have open access, in the afternoons and evenings. Bloodmobiles park in convenient locations where frequent donors live, in order to make it easier for them to participate. Bloodmobiles are also placed in densely populated areas, to attract people to donate while walking past the vehicle. These are typically the busiest sessions, as many people turn up to donate after finishing work.

The areas and venues of the donations are normally decided and arranged as much as a year or two ahead of the event. The lead time is regularly long, especially for the public places which are difficult to book. The collection points are almost the same from year to year with small changes. The public sessions are usually advertised by posters or on the local radio and local newspapers. There are also national advertisements on the TV from time to time to trigger awareness and enhance blood supply.

The collection team is sent to the venue to carry out the session. The team usually consists of 10-15 members; a team manager from the Marketing department, donor carers and health care staff. The role of the marketing staff in the sessions is purely administrative, e.g. collecting data about the number of attendees, the number of sessions, and donor comments. These data are analysed back in the Marketing department. Comparisons of the particular event with last year's similar sessions and with other historical data are performed. The aim is to assess the impact of marketing campaigns and also to measure whether the estimated collection targets were achieved, what was the deviation from them, and whether the lost numbers could be recovered in other sessions. The target number of donors in each session is roughly calculated by considering the active hours of the session (usually 5 hours), the number of medical staff and the number of donors that can be treated in this time. Each carer can usually take up as many as 9 donors in a 5 hour session. Industrial sessions are usually carried out from 09.00 to 16.00.

The donated units are collected in mid-session pick ups and at the end of the sessions. Mid-day pick ups are sometimes necessary, especially for platelets, since some evening sessions might not finish until 21.00, which would mean that units would not reach the Centre until after 23.00, by which time the processing department would be closed. In this case the collected units would have to wait for 1.5 days until they are processed and tests are released. The same vehicles collect the donated blood and also deliver blood to hospitals at several destinations. On their way back from the hospitals, they stop at the places where the sessions are run, to pick up the donations. These mid-way pick ups often depend on the pressure of demand on the day. Notice from the collections department to the teams is sent when they urgently need units for PTI.

Moreover, the Marketing department provides after donation services which involve donor rewards, such as NBS cards and presents.

The fact that the arrangements for the donation venues and sessions are made 1 or 2 years in advance means that demand should also be estimated a year ahead so that balance between supply and demand will be achieved both locally and seasonally. The Marketing department predicts demand by looking the historical data, and taking into account other criteria which might have an effect on future demand, such as trends, bank and summer holidays, other big events, etc. The Collections department works closely with the Marketing department, especially in cases of low donor turnover, when new plans are needed for fitting into the existing schedule new sessions, to make up for the loss.

The NBS make product and group type estimations according to historical data, kept in their electronic information system (PULSE), by examining relevant information on a daily basis. Hospitals are also obliged to send the NBS Centres their predictions about the following year's demand by product and blood group, to help the planning of supply. Nevertheless, patterns about product demand are not always predictable. Demand for red cells was quite steady in the past, but recently has started falling with no indication about how long this trend will last. Moreover, demand for platelets is continuously increasing, but by a different amount from year to year. The prediction of blood groups seems difficult because hospitals cannot identify their future patients, but nevertheless this can be estimated by using the distribution of blood groups in the population. This is shown in table 2.2 for the U.K. population.

Table 2.2 Frequency of ABO and Rh(D) grouping among the UK population

ABO Group	Rh (D) Pos	Rh (D) Neg	Total
A:	35%	7%,	42%.
AB:	3%	1%,	4%.
B:	8%	2%,	10%.
O:	37%	7%,	44%.
Total Rh (D)	83%	17%	100%

Source: National Blood Service, URL: http://www.blood.co.uk/pages/all_about.html (accessed 13/7/2006)

2.4 Donor Characteristics

In the UK donors are volunteers. The NBS relies on the charitable contribution of whole-blood and apheresis donors in order to obtain different blood components. Any healthy adult between the ages of 17 and 60 can donate blood, and regular donors can donate until the age of 70. Whole-blood donors can donate up to three times a year, whereas apheresis donors can donate up to every 2 weeks. (Varmey et al, 2003).

It has been estimated that 60% of the UK population are eligible to give blood, yet only 6% does (NHS Direct, 2006). The eligibility of the UK population for blood donations is constantly declining, due to increased scanned diseases. In 2004, the UK government announced that people who have received a blood transfusion in the UK since 1980 will no longer be able to give blood, as a precaution against the transmission of variant CJD (mad cow disease) (The Donor, spring 2004). Other countries have restricted from their donor pool all people who have lived in the UK for a period of time (FDA, 2001). As a result, it has been suggested in some countries that it might be time to consider paying donors to solve some of the critical type-specific needs for whole blood and platelets (Simon, 2003). However, this has not yet been adopted in the UK.

Each donor has his/her own identification number, the donor number. According to the new European implementations the donor number will be the National Insurance Number (DIRECTIVE 2002/98/E). Each bag of collected blood is labelled with a donation number. This is unique to each bag and is different from the donor number. The existence of two separate numbers is essential, as a donor is recalled with the same number but the same person may donate blood lots of times.

2.5 Processing

Blood is processed into several components:

- Red blood cells (RBCs), the most commonly used component. This can be stored for a maximum of 35 days in the UK, or 42 days in the U.S and Canada. A very small amount is frozen for up to 10 years, but this process is ineffectively costly (http://www.bloodbook.com/facts.html). Red cells carry oxygen and are used to treat anaemia.
- Platelets, which may be kept for a maximum of five days only. These are important in the control of bleeding and are generally used in patients with leukaemia and other forms of cancer.
- Fresh frozen plasma, which is kept in a frozen state for up to a year, and is used to control bleeding.
- Cryoprecipitate, which can be stored in freezing temperatures for a year, and helps blood clotting.
- 115 other products, basically deriving from the main blood components after extra tests or processing, which modify the shelf life of each product. This secondary process takes place only at the request of a client. For example, irradiated red cells are produced from red cells that have been in the blood bank no more than 14 days. The new component of irradiated red cells has a life expectancy of 14 days. The process of

irradiation takes just a few minutes. Washed red cells derive from fresh red cells, up to 5 days old, and have a life span of 24 hours. They are also only produced on demand. They are used for inter-immune and exchange transfusions.

A list of the 35 most commonly used products and their corresponding NBS codes can be found in Appendix A.1.

Blood is processed only during the daytime. Normally the time between collection and processing is about 3 hours, and processing itself takes 2 to 3 hours. The new blood components have the same donation number on their bags as the whole blood from which they are derived. The official life span of the blood component starts from the day following collection. Therefore, the day of collection is day zero and from the midnight of that day the shelf life of the component begins to count.

There are two processing systems for whole blood. The BAT (Bottom-And-Top) is the longer and in addition to plasma and red cells, also produces platelets. The other method, the whole system, only produces plasma and red cells. In addition, the apheresis method is used in the UK for the production of platelets alone. 25-30% of donations, usually the morning ones, are manufactured with the BAT system which, in addition to 2-3 hours normal processing time for the production of plasma and red cells, takes a further 4 hours for the processing of platelets. After this, 14 hours are needed for the Buffy coats (the fraction of a blood sample that contains most of the white blood cells) to settle down. The production method used in the BAT system is different from the whole system, even for the production of red cells and plasma. Of all the platelets produced in the UK, half are manufactured by apheresis and the other half by whole blood processing. Platelets are labelled differently, depending on the production method.

The following table shows a comparison of units between collection and component production:

Table 2.3 Comparison between collected units and processed units

1 unit of whole blood (450ml) = 1 unit of red cells (220 -340ml)
1 unit of whole blood (450ml) = 1 unit of fresh frozen plasma (250-300ml)
4 units of whole blood (450ml) = 1 unit of platelets (220-280ml)
1 unit from the apheresis method = 1 unit of platelets

Source: Bryan Lees, Scientific & Technical Training Courses Organiser, Southampton NBS Centre

It can be seen that the number of derived units is not fixed, but can fluctuate within a certain range.

Platelets derived through whole blood processing are produced only from regular donors. Since four units of whole blood are required to produce one unit of platelets, the group of whole blood units has to be known in advance. Usually, testing for group identification takes place after processing and therefore in the case of platelets only the units from returning donors are used, because their blood group can be recognised before testing. Subsequently, it is possible to increase the production of platelets on request, by firstly testing the group of whole blood units coming from all donors and then manufacturing platelets. Platelets produced in this way are double tested to ensure correct grouping. AB group platelets are not produced, because this group is infrequent among the population. If such a patient's need occurs, compatible groups are provided instead.

Some units are discarded during processing due to manufacturing problems, underweight or overweight collection or component, label error, handling damage, split bags or visual abnormality.

2.6 Testing and Storage

After blood has been drawn, samples of the components are tested for ABO group and Rh type (positive or negative), as well as for any unexpected red blood cell antibodies that may cause problems in a recipient. Screening tests are also performed for evidence of donor infection. The most important of these are hepatitis B, hepatitis C and HIV/AIDS. Two samples are collected from each donated blood unit. The one is for these tests which are carried out on the site and the other is sent out for NAT (Nucleic Acid Amplification technology) testing at one of the four Centres across UK specialising in this.

The samples are sent for testing early the following morning after collection and the results are released the afternoon of the same day. Any donated blood that fails these tests is discarded. The rest are stored in the Centre blood bank after the label with all the required specifications has been placed on the blood component's bag. So, irrespective of the time of collection, the blood will be available for storage the following afternoon at the earliest. Some units may be on a pending status due to complications emerging during the testing process. These units will temporarily stay in a fridge and will be checked twice per week for completion of testing. If the tests are satisfactory they will be stored in the blood bank. Nevertheless, if there is an excessive waiting time the items will be eventually discarded.

Since 1998, all components have been leucodepleted as a precaution against the transmission of variant CJD (NHS Executive, 1998). Research from the NHS shows that continual enhancement of safety criteria could lead to an insufficient supply of blood products to meet current levels of hospital demand. The researchers suggest that it will become necessary to reassess the safety - sufficiency trade-off. Moreover, the introduction of further testing of donors will increase the cost of blood transfusions above current estimates (Reynolds et al, 2001).

Autologous transfusion is a technique that can reduce the need for donors. The method can be utilised in situations of elective surgery, in which a patient can donate their own blood to be used in the operation. However, this technique is not widely exploited in the UK (Torella et al, 2001). Some studies have found autologous transfusions to be cost effective (Etchason et al, 1995) but others dispute this assertion (Brecher et al, 2002).

The NBS target of holding stock is around 5 days (averaged across all groups), which ensures that fresh blood is issued but also that peaks and troughs in demand during the year can be met. In difficult periods, the NBS tries to hold higher stocks, to ensure availability for supporting any unusual requests. Nevertheless, there are situations in which actual demand is less than the forecast demand. This has a negative effect on the NBS stocks of ageing units. During the years 2002 to 2004 this was a hot issue for the NBS, since demand for red cells was falling year-on-year. In 2003 demand fell by 1.5%. As a result NBS supplies were increased to 9 days, which led to strong complaints from the hospitals about the age of blood at issue (Letter to hospitals, May 2003). The opposite situation also arises. In 2005 NBS red cell stocks were around 38,000 units, 8,500 units below the target figure of 46,500 (Letter to hospitals, December 2005). Also, a national platelets shortage occurred in October 2005 which had an impact on several hospitals. The contributing factors were identified as low donations whilst demand remained stable (Letter to hospitals, November 2005).

As with processing, losses also occur during testing and storage due to identification of viruses, contaminated bags and complications on testing. Nevertheless, most discards occur because of time expiration. This percentage fluctuates from 2.5% to above 4% of the products in stock. The NBS is not allowed to issue red cells over the age of 23 days to hospitals. Therefore, the units which reach this age and have not been issued are discarded, even though their actual expiration day is 12 days later. This measure has been applied to avoid old units being issued to hospitals, since hospitals are charged for these units but their lifetime is not enough for them to be transfused. Exceptions are made for any hospitals that want to accept the over-aged units. All the discarded units go through the PULSE system.

Group AB units are the most prone to ageing, since they are rarely requested by hospitals. These blood group products are mainly given only to patients that are on long term transfusions. In particular, AB positive is the blood group component (red cell or platelet) with the highest wastage rate, because it is not commonly used and it cannot be mismatched as it is incompatible with all the other blood groups. Incompatible blood groups are those in which some components of one group act against components of the other group. Serious reactions can occur if a person is exposed to blood of an incompatible blood type. Therefore, this blood type (together with AB negative) is not included in the government indicators of expired and wasted items. Most AB units are collected solely for the production of AB plasma. On the other hand, great effort is put into the collection of group O negative, as this group is compatible with all the other blood groups.

2.7 Issuing and Delivery

2.7.1 The PULSE System and Issuing

The NBS stocks are issued to hospitals in response to orders from hospital blood banks.

In 2002 the NBS took the initiative to upgrade its existing electronic system, which had operated since 1996, with the PULSE computer system; an endeavour which cost £375,000. PULSE is a database management system containing more than 1 billion records. It is growing at a rate of 8 million per week, and operates on a 24/7 basis. The NBS PULSE system has a community of more than 3,500 active users today, all of whom can access it over the internet (Mimer, 2003).

The PULSE system enables electronic procedures which minimise the risk of human error during the donation, testing/processing, storage and issuing process. Donations and test samples are identified electronically by scanning a unique barcode into the PULSE system. PULSE can then automatically track and control data associated with each donation. Once test results have been produced, they are automatically transferred to the PULSE system. The system then performs checks to ensure that all relevant information is present to allow a component to be labelled and issued for clinical use. Once this check is completed, a label unique to the produced blood component is printed, identifying the blood group and expiry information. At the time of issue the system checks the information again to confirm that the component has the expected group, and to check any additional medical information required.

Historical data show that the risk of issuing an incorrectly grouped labelled unit has been reduced to 1 in 100 million (Blood Matters, January 2002). PULSE has greatly improved the logistics of the NBS and has achieved major advances in tracking stock and eliminating human error from its processes.

Hospitals fax their orders and/or call and then the orders are dispatched from the NBS blood bank. Issuing is carried out in a "first-in, first-out" (FIFO) basis which means the oldest blood is issued first. This approach is recently under review by the Blood Stocks Management Scheme (BSMS) and the NBS.

The units ready for issuing to hospitals are scanned electronically to confirm suitability for use and to update the Centre's stock. They are packed in the correct coloured box which keeps them safe and at the right temperature during delivery. Red boxes store red cells and they can carry around 15-20 units. Blue boxes carry platelets of only 1 or 2 bags. Plasma and cryoprecipitate are packed in yellow boxes and can fit up to 5 bags. Each box is labelled with details of the cargo it carries. The label, which is produced by PULSE, details all the required information, such as the number of units in the box, the component name, group identification and time of expiry, time of issuing, delivery type and the name of the NBS employee responsible for this issue.

The details of every transaction are also kept in the PULSE system with no need for manual entry. However, there are still some items that are lost through the chain due to human error. A recent suggestion proposes the use of metallic detectors located by the doors of the Centre's issuing department, similar to the system implemented in many libraries. This suggestion is still under consideration.

An order dispatched to a hospital very rarely returns to the NBS Centre. Even if the Centre makes an error in filling an order, it is expected that the delivery would be accepted by the hospital and not returned to the NBS Centre. There is currently a debate about whether hospitals should be charged for these incorrect deliveries. The NBS is reluctant to accept items back once they have been removed from their blood banks, because of the loss of control over the items: all the required safety measures may not have been followed strictly. Moreover, as well as the prohibition of returns to the NBS, rotation of blood between hospitals is not desirable. There are only atypical cases in which a big hospital might serve a private, small one. In other countries blood rotation is used to minimise wastage, by rotating old blood from low usage to high usage hospitals.

2.7.2 Deliveries

The National Blood Service makes around 200,000 deliveries of blood a year, half routine and half in response to specific requests (National Audit Office, 2000).

There are three types of delivery. Routine scheduled deliveries are made on a daily basis for the big hospitals, usually once per day excluding Sundays, and more infrequently for smaller hospitals. These are free of charge to the hospital. In the near future a small cost will be charged. Typically, the NBS transport fulfils routine orders to several hospitals in one round trip at the same time of day. The NBS also makes additional deliveries in response to specific requests. These are:

- Emergency or "blue light" deliveries, which are prioritised on receipt for immediate dispatch and transportation within two hours.
- Ad-hoc deliveries, which are additional to routine deliveries and are made to an individual hospital if it places an order. The fulfilment of the order will be as soon as possible by the next available NBS transport (Service Agreements – Section 3, 2006).

There is a single national charge of £15 for emergency and ad-hoc deliveries, regardless of distance or frequency. This rather low price, which does not cover the actual cost of these deliveries, arguably allows hospitals to misuse the service, allowing them to avoid developing a better ordering policy. Consequently, NBS employs more drivers and staff than strictly necessary to deal with these orders.

A Trust may provide its own collection and delivery service, such as courier or taxi, on agreement with the NBS. In these cases, there are no reductions in the unit price and no additional delivery charges. The guarantee of delivery within two hours in the case of emergency deliveries does not also apply.

The NBS collects blood and banks it locally. The majority is also used locally, but the NBS also moves blood between Centres and zones to iron out surpluses and shortfalls as part of a national stock management process. Donors give blood as a resource for the benefit of fellow citizens wherever it might be needed. Consequently, blood is treated as a national resource. Centres with excessive stock send middle-aged RBC units to Centres with deficient stock once a week, if necessary.

The role of the national stock manager is to ensure that the NBS keeps an appropriate amount of stock of blood and blood components and that the stock is held at the appropriate NBS sites. To ensure optimal distribution, many variables are considered, including local demand, local supply, storage capabilities, processing capabilities, availability of transport, and contingency plans. Basically there is an attempt to hold stock split by demand, so if for example a certain NBS Centre has 5% of total issues (demand) then according to the national stock scheme this site should also hold 5% of national stock.

The NBS has a stock model in place to guarantee the success of this endeavour. The national stock is examined on a weekly basis and is reallocated on the basis of likely demand profile and age. Some geographical areas collect more than they use, so they are net exporters, while other areas collect less than demand, so are net importers. This leads to imbalances in the age of stock, i.e. some Centres end up with older stock than others. So, there is a routine movement of aged stock from some sites to others to ensure that the age of stock is more balanced. This is to make sure that no customer is "penalised" by receiving consistently older stock than other customers, in other parts of the country. Age of stock is important to customers as the younger/fresher it is, the more opportunities the hospitals have to use it, and the less likely it is to be wasted, bearing also in mind that a blood unit costs around £130 to £220. The relocated stock is not fresh but is not too old either. Usually, it is during the second or third week of its life span, if it is for a red cell unit.

However, there are two main problems in the attempt to move stock around the country, namely variable demand and variable supply. Demand is extremely variable on a local basis, to the point of being practically unpredictable. Supply is also highly variable, although slightly more predictable. These two factors mean that it is impossible to have standing orders between NBS Centres to routinely reallocate stock, and thus the stock distribution is reviewed each week. The stock model generated for this job is a fairly simple spreadsheet model. The NBS developed a more sophisticated model which examined all Centres and all blood groups at all ages, and redistributed stock on the basis of predicted demand and supply. Unfortunately, this proved too expensive, as it would have entailed thousands of movements per week. Therefore the simple version of the system currently in use is more manageable, but not perfect.

The reallocation suggestions produced by the stock model, are sent to all the NBS Centres once a week (typically on a Monday), and the Centres should take the required action. However, the instructions of the model are not always followed to the letter. In practice, the Issues Managers of the sites proposed for stock reallocation contact each other to confirm space availability for accommodating the products and also the amount and status of "work in-progress", i.e. the units currently being processed or planned to be collected from each site. Putting all these together they decide how many units will be eventually moved from the one site to the other. The refrigerated site van is used for the transfer of these items.

In contrast to red cells, which are managed both centrally and locally, platelets are managed only locally due to their short shelf life. These local procedures do not follow set standards, but all Centres tend to use similar processes.

Apart from the reallocation of stock, there are also movements of blood units between NBS Centres and also movements of supplies to hospitals from NBS sites, other than the geographically closest, for the provision of special products (e.g. rare blood types) which are not available at the normal supplying NBS Centre. Therefore, theoretically any NBS Centre can supply to any UK hospital, if demand dictates.

Since 2000 a national contingency plan has been drawn up, based on identified threats that could lead to local interruptions to supply, and how these can be overcome. Moreover, local plans have been prepared and tested for coping with major incidents requiring blood components (National Audit Office, 2000).

2.8 Hospital Inventory Management and Demand

Most hospitals keep a stock of red cells units in their blood bank for immediate use. Platelets on the other hand are rarely kept in stock due to their short shelf life, but they are usually ordered promptly under physician requests. However, there are a few exceptions of high-volume hospitals which keep a stock of platelets too.

Hospital blood bank managers are typically responsible for placing orders. Orders are classified as routine scheduled orders, emergency and ad-hoc exactly as the delivery types. Hospitals should place orders requiring routine scheduled delivery within the time specified in the ordering and delivery schedule of the service agreement, unless otherwise specified by the Trust at the time of ordering. Components will be delivered on the next scheduled routine delivery service (Service Agreements, Section 3 – 2006). Hence, for a small NBS Centre, the agreement could be that hospitals must place a routine order before 07.00 on a week day, in order for this order to be satisfied in the scheduled delivery setting off at 10.00 on the same day. If an order arrives later than 07.00 then the order will be dispatched with the following day's scheduled delivery. In other, busier, sites this time-lag might be wider, for example orders should arrive the day before the delivery day. This time gap is needed in order for NBS staff to check availability of the requested units, prepare units for dispatching, remove them from the NBS Centre's blood bank, scan them at the PULSE system and arrange all the paperwork including communications with the hospital in case of shortages or deals with special requirements. These tasks are time consuming, especially since up to 20 hospitals can simultaneously place orders.

Hospital blood banks determine the optimal stock levels of RBC according to their own estimates of potential demand. This is usually based solely on experience, or according to historical data from past orders placed with the NBS, including the seasonality effects (e.g. in December higher blood inventory is required). In practice at most hospitals the stock levels are not updated frequently enough to capture current trends in demand, but the laboratory staff have the right to order less or more than the suggested levels, according to their estimates of supply and demand in the given period.

The optimal stock levels are usually stated in terms of days. So, for example if the ideal stock represents 4 days of stock, this means that if no further blood units are supplied by the NBS the inventory in the hospital blood bank will cover blood transfusion requirements for 4 days.

The ideal stock levels clearly differ between hospitals, since each hospital performs a different combination and number of surgical operations. In reviewing the literature, many Operational Research techniques have been studied for estimating the optimal stock levels of a hospital blood bank. These are discussed in Chapter 3 of this thesis. Unfortunately, only few hospitals make use of them so far. A list (not exhaustive) of the parameters which are important for computing the ideal blood stock levels for a particular hospital is as follows:

1. Daily average estimation of
   a) the number and type of operations, both elective and emergency (α), and
   b) the quantity of units required for each type of surgery (β);
2. The crossmatched-to-transfused-units ratio (explained in detail later on) (γ);
3. Daily average estimation of
   a) the number of patients who are on a long-term transfusion plan (anaemic or patients treated for leukaemia) (δ) and
   b) the number of units in each of these transfusions (ε) and
4. The number of days for which a hospital reserves stock (ζ).

An illustrative example of how these parameters can be combined with each other to form an equation which indicates the optimal stock level is as follows:

$$OptimalStock = \zeta \sum \{\alpha\beta\gamma + \delta\varepsilon\}$$

The outcome of the equation can be split over the blood groups according to the population blood group percentages, with the assumption that patients and donors share the same group frequency.

An order is placed with the local NBS Centre when the inventory falls below a predetermined ordering point, or when rare products not held in stock are requested for particular patients. This predetermined re-ordering point may differ between routine and ad-hoc or emergency orders. Typically, this point for re-ordering stock is more sensitive (higher) for orders for routine deliveries which are free of charge, less sensitive (lower) for ad-hoc deliveries which cost extra, and even lower for emergencies.

However, even for routine deliveries, hospitals avoid sending orders for only a few units. Therefore they order every time the stock levels drop down by 20-25 %. The greater the distance between the blood Centre and the hospital, the more days of stock are usually kept.

Emergency or ad-hoc deliveries are placed, for instance, in cases when emergency surgeries are about to take place and the stock is not enough to cover the need in blood units. It can also be a special case of a patient who requires a particular blood type with antigen screening. In this situation the order is directly assigned to the particular patient and is kept in the reservation fridge in the blood bank. In other occasions ad-hoc or emergency orders are placed to recover very low or zero levels of stock because it has all been used. In this situation the order is normally stored in the blood bank.

Hospital doctors are responsible for the quantity of blood products required and consumed for each patient in the hospital. Following a doctor's request for blood for a particular patient, crossmatching takes place in the hospital blood bank, although very occasionally units need to be sent over to an NBS site for further antibody identification. Crossmatching is a test to determine blood compatibility by mixing blood samples from the donated blood and the recipient. Crossmatched units are termed "assigned inventory".

Based on past experience, guidelines known as the Maximum Surgical Blood Ordering Schedule (MSBOS) have been drawn up to indicate the appropriate number of units required for each type of surgery (British Committee in Haematology et al, 1990; BCSH, 1996). The aim is to prevent excessive ordering and crossmatching of RBCs prior to a surgical procedure. To order more blood than is mandated by an MSBOS, the physician needs to have a valid rationale. Consultant haematologists are the experts in the area of the number of units required for a particular transfusion, but the physician has authority to make the final decision on the amount of blood needed. Nevertheless, this is still an issue as some doctors prefer to err on the side of caution and over-order.

Factors, suggested by experience, that affect the number of requested units and returning units are:

- The experience of the doctor or nurse demanding blood. Junior doctors, especially in University hospitals, tend to ask for excessive units to ensure patient safety, being also vigilant for complications in the patient's condition (i.e. secondary medical problems) which might occur (Gupta, et al, 2003).
- Procedure performed and technique used.
- Heavy bleeding patients needing a lot of blood, who die during the procedure and subsequently only part of the blood gets used.

- The “weekend is coming” syndrome, during which fewer staff are occupied in the blood bank and in the hospital in general and scheduled deliveries are not available.
- Urgency of blood. Higher urgency often results in over-ordering “just in case”.

Every hospital has its own Maximum Surgical Blood Ordering Schedule, even though one might think that the same recommendations for a certain type of surgery should apply to all hospitals. In reality each Trust develops a unique MSBOS according to a historical review of its own blood usage patterns. There are types of surgeries for which the historical review indicates that blood was seldom required. In such cases the MSBOS would recommend that no units should be crossmatched. Instead group and save (G&S) is all that should be done. The G&S is limited to an ABO, Rh(D) type and antibody screen for unexpected antibodies in the patient. Providing that the antibody screen is negative, donor blood is not crossmatched and not reserved for the patient. If blood is unexpectedly required during surgery, it can be quickly crossmatched because the blood bank is aware of the patient’s blood needs. There are obvious advantages of the Group & Save technique, as blood is not tied up in assigned inventory and needlessly held for patients who will probably not use it. Moreover, blood bank personnel are not occupied by pointlessly crossmatching units or by removing tags from unused products, but are available for more useful purposes (Medical Laboratory, 2006).

A typical MSBOS consists of a list of types of surgery and the corresponding recommended maximum number of units that a physician should order for crossmatching. The MSBOS is developed by the hospital transfusion committee, which consists of professionals such as staff surgeons, anaesthetists, and the medical director of the transfusion service. An MSBOS form is presented in Appendix A.2. The MSBOS should be often updated to keep up with hospital needs and current practices. A BSMS survey examining 76 hospitals (BSMS, 2001a) revealed that only 33% of hospitals update their MSBOS at least once per year.

A physician can request blood as early as a week ahead of the transfusion, but normally the request is made only a couple of days to a couple of hours in advance. The crossmatching takes place as soon as possible after the request. However, not all crossmatched units are transfused, because of over-ordering or postponed operations and in practice, only around half of all crossmatched units are actually transfused (Jennings, 1973a; Gupta et al, 2003). Several types of patients regularly need transfusion, not only patients undergoing surgery. For example, people with cancer and chronic anaemia regularly require transfusions. For such patients it is more likely that all the crossmatched units will be transfused. In Gupta, et al (2003) data can be found on the crossmatching to transfusion ratios per surgical and medical cases.

Any untransfused crossmatched blood remains assigned to that patient for a certain time in case complications arise, but it is eventually returned to the hospital blood bank as released inventory. The elapsed time between assigning blood to a named patient and returning any unused units to the unassigned inventory is called the crossmatch release period or reservation period, usually symbolised by λ in the literature. The duration of this period is determined by the hospital, but normally is about 2 days. The longer this period, the less chance a unit has of being transfused, because of outdating. Typically, a unit could be crossmatched around 3 to 4 times in its lifetime, until it is finally transfused or expires. The unused units stay locally in the ward fridges after the operation and return, all together, to the main blood bank fridge at a certain time, normally in the mornings. In some hospitals these units return after that day's routine orders have been placed by the hospital blood bank manager, with the consequence that they are not considered when computing the order.

Multiple crossmatching, as described by Deuermeyer et al (1977), is a way of decreasing this constant rotation of units in the bank. In this case a unit is crossmatched to several different operations, which require the same blood group and do not all take place at the same time. There is a high chance that if the unit is not used in the first operation, it will be used in one of the others. Nevertheless, in order to avoid the risk of running out of assigned units only half of the units under the same request are multi-crossmatched. However, this policy failed to gain strong support, as hospital blood managers tend to follow a pessimistic approach for the worst case to occur where all patients, successively, will need all the crossmatched units. The method has been implemented only in a few American hospitals but not in the U.K., even though the chances of the worst case scenario occurring are very small, at least for hospitals that have a high crossmatch-to-transfusion ratio.

Hospital blood banks try to issue blood units according to their age by giving the oldest blood first in a FIFO order. In practice, unfortunately, true FIFO issuing policies are difficult to implement. There are cases such as open-heart surgery where a large amount of fresh blood of less than 5 days old is required. Additionally, there is a belief among some physicians on the beneficial properties of fresh blood for other types of operations, even though this is not medically proved. So, no matter how willing some blood bank managers are to follow FIFO policies, old preconceptions are difficult to change and undeniably physicians should make the final decision. A typical practice is to crossmatch 1 or 2 old units and use fresher units for the rest of the request size. Nevertheless, this might lead to over-ordering by some physicians. (Kendall and Lee, 1980b)

Another interesting issue in the transfusion process is mismatching. Blood Transfusion Task Force guidelines (BCSH, 1996) state that "red cell components of the same ABO and Rh(D) group as the patient must be selected whenever possible". So, ideally, a patient should be transfused with the same blood group as his/her own, but this is not always possible. When a patient's blood group at the time of request is unavailable, a compatible blood group must be provided. For example, patients with group A positive blood can receive blood from group A negative, O negative or O positive. Table 2.4 shows all the possible combinations. For clinical reasons, some compatible blood types are preferable to others. Nevertheless, in practice the reason for providing a particular compatible group in such cases is mainly based on expiry time. However, in general, mismatching is undesirable because it increases the risk to the patient (Canals et al, 2004).

Table 2.4 Mismatching donor against patient group

		Patient							
Donor	**UK**	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg
Apos	35%			√					
Aneg	7%	√		√	√				
ABpos	3%								
ABneg	1%			√					
Bpos	8%			√					
Bneg	2%			√	√	√			
Opos	37%	√		√		√			
Oneg	7%	√	√	√	√	√	√	√	

The "tick" symbols show which group may receive blood from which other groups.

Negotiations between hospitals and NBS Centres for cases outside the routine guidelines take place in the presence of the Hospital Liaison Manager, who acts as a facilitator between the NBS Centres and hospitals. Such cases might be the provision of a special product to the hospital from another centre because of unavailability of this product from the regular NBS Centre supplier.

Most hospitals use an electronic database system for tracing blood units internally. They keep information about, for example, the status of the unit (assigned or unassigned), the number of times a unit has been crossmatched, the patients' names that it was crossmatched against and the time it was transfused. These records are called audit trails. Unfortunately, in contrast with the PULSE system which is a shared database among all the NBS sites and employees, every hospital uses different software for their audit trails. Subsequently, although keeping similar information, data appear in a different format which does not allow easy comparisons. Fortunately, most hospitals have switched to electronic management rather than keeping data in paper form only. However, it seems that very busy or less organised hospital banks do not update their databases frequently. Only 44%, of a sample of 76 examined hospitals, review the stock levels annually (BSMS, 2001a).

The National Blood Stocks Management Scheme (BSMS), established in January 1998, is an initiative concerned with hospitals' use of blood. The project was set up by the National Blood Service and involves work with many participating hospitals. It aims to improve the management of blood stocks through greater collaboration between the Blood Service and hospitals. The Blood Stock Management Scheme employs 4 members of staff and uses software called VANESA. The enrolled hospitals enter data electronically on a monthly basis in VANESA about their red cells stock, their transfusion figures, their wastages and other relevant information. Following analysis of these data, VANESA produces graphs and comparison tables. BSMS staff compiles six-monthly and annual reports for all the NBS centres and hospitals jointly and also separately for each blood Centre. The reports are distributed to the NBS managers and the Haematology managers of the hospitals. The software is self-sufficient and provides all the necessary information to those who have access without the need for programming analysts. The scheme also runs other projects and surveys useful for the understanding of blood usage. So, overall, the scheme provides the software and reports investigating wastage rates, usage and mismatches. The majority of NBS hospitals are registered with the scheme. However, this does not necessarily mean that all hospitals are scrupulous about data entry.

2.9 Financial Planning and Costs

Blood products are expensive, even though the base material of whole blood is obtained through voluntary donation. There is a single national price for each blood product, with extra charges for additional testing as shown in Table 2.5. Hospitals, which have a set budget to spend on buying blood components, pay monthly invoices to the NBS for their purchases. Savings within this budget are realisable within the Trust.

Generally, this money generates funding to enable the NBS to extend its product range and enhance its research and development. In more detail, every year hospitals announce how many units they will require the following year. The NHS Trust supplies the following information to the National Blood Service: annual forecast of usage of blood components, monthly information about usage, stock, and wastage of blood components through voluntary participation in the Blood Stocks Management Scheme and information about usage of blood components by major specialities, twice yearly, through voluntary participation in clinical audit and the Regional/National Transfusion Committees.

According to these forecasts the NBS Executive Director, in agreement with the Marketing department, decides on the collection targets and calculates how many collection sessions will need, how much advertisement will require for recruiting these donors and what the cost will be for processing the amount of units for all the supplied hospitals.

Every department in each NBS Centre calculates its costs in line with these figures and composes a budget. The sum of all budgets is divided by the number of units required in total and the price for each unit is given. The National Commissioning Group is responsible for this process. However, the money for the purchased blood products is only paid monthly by hospital Trusts to the NBS Centres. This means that if the hospitals eventually purchase fewer units over the year than their initial estimations, the NBS would make a loss, as most of its budget has already been spent in organising the donations, preparing the blood units and all the required processes. On the other hand, if the hospitals purchase more than they originally estimated and these extra units are available, the NBS makes a profit. Small differences in supply and demand can easily be handled by arranging extra collection sessions but big differences can be a problem.

Overall, the NBS supplies the following information to the hospital Trust: components issued, services provided and charges made monthly and cumulative, and satisfaction monitoring information as required (Service Agreements Section 3, 2006).

Since 1999, when the national charges were established, prices have been increasing by more than 10% per annum, due to the introduction of new safety tests, more advanced processing methods, and so on. Further information about price lists over recent years can be obtained from http://www.blood.co.uk/hospitals/index.htm.

Blood group AB is rare, and therefore the NBS does not charge hospitals for AB units which have time expired. Nevertheless, there are charges for the group AB units which have been transfused. Charges for purchase of blood components to private hospitals are the same as to any NHS hospital.

Trusts which have serious financial problems and fail to pay for their blood purchases may cease to be clients of a particular NBS Centre, if the latter decides to end the collaboration. In these rare cases the particular Trust can seek another supplier which might be another NBS Centre or, in the case of a small Trust, a big hospital.

Table 2.5 National Blood Service, Price List 2005/06

Components	Price per pack	Added Value Services
Whole Blood	£132.07	
Red Cells RBC	£131.80	+ £240
Platelets PLT	£216.87	+ £75
Plasma FFP	£34.67	+£92 US import
Cryoprecipitate	£39.55	

Source: www.blood.co.uk/hospitals/communications/hl/

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

In this chapter we explore relevant research in the field under examination and analyse topics related to this thesis.

Research on the regional and local management aspects of the blood supply essentially started in the 1960s, peaked in the late 1970s and early 1980s, and then dropped off to the present day. Most studies took place in the U.S. and often address issues which are applicable only to that country. Nevertheless, all countries can learn from research carried out in other areas of the world and adjust their policies and legislation for adopting successful, tested systems.

This literature review starts by discussing some initial Operational Research studies in the wider field of perishable products, and then concentrates on papers dealing specifically with blood inventory systems and the blood supply chain. However, during the latter there are further references to research on perishable products considered to be relevant and interrelated with advances in this particular study.

The topic is approached by adopting two perspectives. One lies within the local level, in which Operational Researchers aim at examining blood banks and the problems related with them individually. In this stage we also attempt to follow some of the steps which were used to describe the blood supply chain in the previous chapter, where possible. The other perspective concerns the regional level, in which researchers take a wider perspective and investigate the coordination of the blood supply, in terms of structure, inventory allocation problems and distribution options. As a link, between the two viewpoints, papers are presented which are related to the development of information systems and technology relevant to blood banking for both blood centres and hospitals.

Furthermore, studies related exclusively with the supply chain of platelets are discussed separately. Platelets have attracted the attention of researchers due to their very short shelf life.

Finally, the advances of the current thesis are briefly mentioned.

3.2 Perishable Inventory

Researchers have extensively discussed the perishable product inventory problem thirty-five years ago. The excellent review by Nahmias (1982) on perishable inventory theory involving ordering policies examines the research which was undertaken at that time in this field. The focus of this research had been on inventory models of periodic systems with fixed or variable product lifetime, with either deterministic or stochastic demand, and FIFO or LIFO order or allocation policies. From that point on, several more studies took place, focusing on different aspects of this problem, trying to make more realistic assumptions and take forward specific sub-problems.

Some of the basic obstacles in developing optimal inventory policies for perishable goods had been the computational complexities involved in storing a large state vector describing the age of stock at each decision point. Therefore, it is apparent, while scanning the literature, the initial attempt of formulating the problems by adopting exact methods but subsequently resorting to the use of heuristics and approximations, such as simulation, in order to overcome the difficult computations and finally present results. Only studies pertinent to perishable products with fixed shelf life and stochastic demand will be considered here, as these better approximate the object of interest, blood.

An initial insight was the case of a product with a shelf life of exactly one period and of orders which occur at cycles of multiple periods, which are independent. This problem is similar to the newsboy problem and can be easily solved. However, when the life span of the product exceeds the ordering cycle then this similarity ceases to exist.

Nahmias and Pierskalla (1973) worked on this problem and calculated the optimal ordering policies for a product with stochastic demand and a fixed shelf life of two periods. Replenishment takes place in each period, thus the product shelf life is longer than the ordering cycle. The one-period cost function including shortage and wastage was formulated as a dynamic program. The optimal ordering policy is dependent on the age distribution of the inventory, and thus is non-stationary. They proved the convex shape of the corresponding cost functions and presented bounds to certain results.

Nahmias (1975a, 1977) and Fries (1975) took this study forward to consider inventories of several (m) periods of fixed shelf life, with a maximum of m ordering cycles and hence more frequent ordering cycles over the product shelf life. They used dynamic programming functional equations to define the optimal ordering policy under the above circumstances. They tried to derive a formula which, by knowing the inventory on hand of a given age, could calculate the fresh quantity to be ordered, which minimizes the total n-period cost. Using this formula they proved that if the inventory increases by one unit, the order size decreases, but by less than one unit and the decrease in order size is bigger when a fresher than an older unit is added to the stock. However, since the optimal ordering policy is still dependent on the age distribution of the inventory, the large dimensionality and complexity made their formula extremely difficult to be solved even for 3 shelf life periods. Hence, such a model could not be used for blood products which have a shelf life of at least 35 periods under the hypothesis that ordering takes place at maximum one time per day.

As a result, attention was given (Nahmias, 1975b) not only to determining but also to evaluating policies for the optimal order size according to their simplicity and proximity to the best solution. For this purpose, Nahmias compared the effectiveness of different policies by means of Monte Carlo simulation. Basic variables for determining the equations of these policies were: the total inventory on hand and the ordering-up-to quantity variables that most researchers included in their attempt to tackle this problem, irrespective of their methodological approach. The method which was closest to the optimal policy and also easiest to implement was the policy characterised by the order-up-to quantity, the so-called optimal critical number policy. Consequently, all subsequent research in this area followed this method.

Cohen (1976) considered this perishable inventory problem as well. He applied the method of the stationary distribution of final inventory levels for subsequently defining the optimal size that minimizes cost, and thus he avoided the age distribution for the disposition process. He also considered backordering of excess demand. Like other researchers, he concluded that even with this method it is very difficult to solve the problem for more that 2 shelf life periods.

Nahmias (1976) also tried a heuristic approach for approximating the order size of a critical number order policy, which is not fixed like the optimal number policy, and therefore responds better to fluctuations in demand. This method uses the one-period expected cost function to approximate the final inventory by replacing it with its expectation. He showed, for a range of tested cases, that this heuristic performs well in comparison with the optimal order size.

Furthermore, Chazan and Gal (1977) approached the same problem by using a Markov Chain and modelling the starting inventory levels as a discrete state. They proved that the expected outdating per period is a convex function of the order-up-to quantity. They also verified that FIFO policies minimize the expected outdating. Furthermore, they developed an approximate algorithm for the case of Poisson demand, which calculates outdating per period and average age of a unit when used.

An attempt to circumvent the difficulty of solving the previously mentioned models with more than 2 or 3 shelf life periods of the inventory state was also made by Brodheim et al (1975) by eliminating this dimensionality. They assumed a system, such as blood banking, which receives n fresh units every period. Each unit has a shelf life of m periods and a FIFO issuing policy is used. In this case, the state of this system can be completely characterised by the total inventory on hand. The authors used Markov Chain analysis with the objective of deriving operating characteristics of the system rather than cost minimisation.

3.3 Blood System Modelling

A very interesting point is that research on the perishable inventory problem initially thrived directly from the need to address the problems relevant to blood bank management (Nahmias, 1982), and not the other way round as one would have thought. It is not accidental that one comes across the same authors' names when examining studies on blood supply problems and perishable inventory problems for the same chronological periods. However, even though perishable inventory theory started from addressing basic and slowly more complex and realistic situations with apparent similarities to the blood management problem, later on, it took a broader view and dealt with other, less similar, applications.

Nevertheless, perishable inventory theory bypasses some of the genuine, complex problems related specifically to blood bank inventory management. However, its contribution to the understanding of many relevant problems to blood ordering and stocking is undoubtedly significant, and will be mentioned together with the examination of more focused studies of blood supply problems. Another point that has become obvious so far and that will be, even more, strengthened as studies related to the blood system modelling are described is the following: the failure of exact analytical techniques to address the multi-period perishable inventory problems, such as the blood banking problem, eventually led to the adoption of simulation techniques by the majority of researchers.

This section will cover studies which used Operational Research (OR) and Management Science (MS) approaches to study blood supply management from the 1960s until the early 80s, including also the very few studies that have been appeared from that point until today. Most of the work carried out at that time was related to the development of blood banking information systems to support decisions about inventory levels, ordering policies, components usage evaluation, donor screening and compatibility tests. The last two concerns are beyond the scope of this study since they concern medical issues.

There are three hierarchy levels of decision making in blood inventory management or generally in the blood system as described by Prastacos (1984). These are: the hospital blood bank, the regional blood centre and the inter-regional blood program. Most researchers initially focused on the hospital level, but when a level of complexity was reached which could not be easily overcome with the existing tools, this focus shifted to the regional blood centre. The inter-regional blood program was rarely considered by Operational Researchers, possibly for the reason that it involved more "soft" managerial skills and politics than modelling. This section of the literature review attempts to disclose studies related with hospital blood banking problems and also with the regional blood centre's decisions on inventory allocation and distribution and improvements in several specific parts of the supply chain of blood.

SECTION A

3.3.1 Ordering Policies and Inventory Levels

A big issue in blood inventory management which triggered much research in the past is the setting of optimal ordering policies and inventory levels. The first is related to the frequency of ordering and the size of the order, and the latter to the optimal number of units in stock for each product by period. Several approaches were tried to solve this task, nonetheless, many of them had serious limitations and were unable to overcome the computational problems. The objective of most of these studies is the reduction of shortages and outdating.

As early as the 1960s, preliminary attempts to deal with blood bank inventory models for individual hospitals resulted in simple statistical analysis or simulation of simplified and approximate models. Millard and Sonnedecker in 1960 were the first to identify that inventory models could be used to tackle the difficult area of stock control. Hulburt and Jones (1964) used statistical analysis to determine the size and maintenance of acceptable, individually tailored, inventories according to supply, demand and usage patterns for balancing shortages and outdates. They plotted graphs to illustrate favourable and unfavourable inventory management according to the age distribution of the units in inventory. Silver and Silver (1964) also proposed an empirical method for balancing shortage and outdating costs by setting minimum and maximum inventory levels on the basis of historical occurrences of unusually low and high usages.

The first pencil and paper simulation application to such a problem was developed by Rockwell et al (1962). This was followed by an analytic model which demonstrates how changes in various ordering parameters affect blood lab performances, such as inventory levels and shortages. Their model was far more advanced than the preceding ones; however, they neglected to study outdating for various inventory levels, which is also a significant performance measure.

The first computer simulation models were developed by Elston and Pickrel (1963, 1965) to measure and evaluate the results in shortage and outdating by altering the volume of the supplied blood and also by applying FIFO or LIFO issuing policies. They assigned a somewhat arbitrary cost to shortages associated with the cost of outdates with a ratio of 25$:4$ respectively in the first study. Then, elaborating on this, they set a more complicated loss function in the second study. Additionally, they assumed two sources of supplies; one controllable source being the arrival of aged units from the centre's blood bank (CBB) after ordering, and the second, the random arrivals of donors to donate at the hospital. The blood units obtained from the second source are fresher than the former. They made an empirical study by using real demand and usage data from a North Carolina hospital. They obtained target inventory levels according to the specific supply and demand of the hospital by using a warm-up period in the simulation run and then employing linear interpolation for different levels of inputs and usage. Some of their results were validated by applying the loss function of Silver and Silver (1964) in their data. They showed that FIFO policies are always optimal except in the case where a large percentage of wastage is bound to occur anyway; then, LIFO issuing may be considered. They also demonstrated that better results for every blood type are obtained when the random input from donors is unchanged rather than when it is doubled or even completely eliminated. These improved simulation models still make the unrealistic assumption that blood enters the blood bank with a fixed age of two days if the blood comes from a random donor or six days if it is ordered from the centre, a fact that may distort outdating rates. Furthermore, the results are partially dependent on the arbitrary costs assigned to them and hence might not be very accurate.

Pagels and Jelmert (1970) used the absorbing Markov chain methodology with hypothetical probabilities to model a hospital blood bank for comparing different issuing policies on the grounds of average inventory levels, average shortage and age of blood transfusions. However, the validity of this model has repeatedly been criticised. Kolesar (1973) objected to the use of Markov Chain theory, arguing that since the probability of transition of a blood unit from one state to the other is not independent of the inventory on hand this method was unsuitable. Also Jennings (1973b) questioned the practicality and realism of the model itself. He argued that on the one hand the authors assume that the probabilities of a unit being transfused are specified by blood bank managers as a function of their chosen policy, but on the other hand the aim of the model is to determine adequate policies as a function of these probabilities. Thus, they are trapped in a vicious circle.

An excellent review of all these studies can be found in Elston (1970). A common weakness of the above models is their inability to distinguish between assigned and unassigned inventory, and this is also the reason why perishable inventory theory cannot be genuinely applied to blood bank problems.

This shortcoming brings four types of distortion. Firstly, shortages are underestimated since such models consider a blood bank to be short only when usage has depleted the total blood supply, rather than being short in an earlier stage when blood has been exhausted in the unassigned form regardless of how much blood is in the assigned inventory. Secondly, outdating is also underestimated because these models do not take into account the ageing of blood while in the assigned inventory stage. Thirdly, the ordering policies are biased since the order quantity is based on the total inventory and not on the unassigned inventory alone. Finally, the rotation of unused blood between these stages alters the inventory levels, a fact that was previously ignored.

Jennings (1968, 1973b) was the first to realize the effects on stock levels by differentiating between assigned and unassigned inventory in a hospital blood bank. He used simulation to model a hospital blood bank, populated the model by collecting empirical data from a large hospital in Boston, and studied several of the related issues. He claimed that the complexity of blood inventories defeats analytical approaches to tackle the issues under examination and thus the use of an accurate computer simulation is a way to overcome these limitations.

He followed the order up-to level concept and was the first to derive trade-off curves of outdating versus shortages as functions of different blood inventory levels. He also examined the positive effects of fresher blood entering the hospital bank or of extending the shelf life of whole blood and the consequences of the establishment of a minimum, buffer inventory level or a re-ordering point. Furthermore, the model showed that a reduction in the variability of shipments from the blood centre to the hospitals would only slightly reduce outdating; however, it might be beneficial for balancing the workload of personnel. He also showed the gains in shortages and outdating of the placement of a second order per day from the hospitals.

His studies were among the most significant for tackling the blood bank inventory problem at that time. However, the assumptions that all ordered blood arrives at the hospital bank with the same age and also that the condition of a unit being transfused or returned back to free inventory is described by a fixed ratio of 55%/45% (transfusion to rotation), limited the demonstration of the real effects of these policies. He also incorrectly assumed that the eight major blood types can be treated independently. Thus, he failed to see the consequences of mismatching on the inventory levels of different blood groups.

Brodheim et al (1976) used empirical demand data from 21 hospital blood banks, treating each blood group separately. They examined the relations between mean daily demand and inventory blood levels for different shortage rates and developed curves to demonstrate the effects of these related parameters by using statistical regression analysis. They determined the inventory needed to meet daily demand at all times and showed that stock depends on mean daily demand. They compared their predicted results by the statistical model results with real data obtained from the hospitals. The comparison showed approximately 90% accuracy for all sizes of hospital. Thus, they provided blood bank managers with a function with which they can select inventory levels and shortage rates based on their demand.

Cohen and Pierskalla (1975, 1979) extended this analysis. They attached costs to shortages and outdates and identified hospital parameters which affect them. Then, by running extensive simulation experiments and using regression techniques they derived a formula to calculate optimal blood inventories by taking into account three of the most significant parameters. These are 1) the aggregated mean daily demand (with no daily differentiation), 2) the crossmatched to transfusion ratio (calculated annually) and 3) the crossmatch release period (λ). This was the first time the latter appears in the literature as a factor that influences inventory levels. Cohen and Pierskalla illustrated by simulation experiments conducted for a large hospital in Philadelphia, that the increase of the crossmatch release period consecutively from 1 to 4 days severely increased outdating for several shortage rates. They also showed that for low values of λ, FIFO yields smaller values of expected outdates than LIFO does. As λ increases to more than 6 days, LIFO becomes better and FIFO gets worse. Their optimal decision rule is a single formula with explicit functional relationships between the above factors and the target inventory level, which minimizes excepted total cost. Nowadays this method is still in use, with some adaptation, by several hospitals seeking to determine optimal inventory levels.

More recently (Pink, 1994) a regression analysis technique was used to determine the factors that correlated significantly with increased outdating in public hospital blood banks in Sydney. These were found to be: a) the absence of an effective hospital transfusion committee, b) a high ratio of inventory levels compared with transfusion levels, c) less than 3 routine deliveries per day from the CBB, d) delay in deliveries of urgent requests, e) less than half of the crossmatched units are transfused, f) premature performance of the crossmatch and g) lengthy crossmatch-release period.

All of these parameters but the first are tested in this study. Experiments are carried out by altering the values of the parameters to find satisfactory combination of policies.

3.3.2 Planning of Collections

The planning of collections has also been studied in the past. No matter how well collections are scheduled in advance, the actual number of donors who finally give blood is unknown. Additionally, because there is a lag between a) the planning of collections (i.e. booking venues and allocating blood teams to areas), b) the actual collections and c) the occurrence of demand, a balanced system is very difficult to achieve. Another concern which resembles the problem of setting optimal ordering policies for a hospital is the setting of collection targets. The exact solution of this problem is very difficult to obtain and compute.

However, Prastacos (1980) developed a simple heuristic approach to deal with it. He made the assumption that daily collections equal daily demand plus outdates, but ignored the important time lag between collections and usage. His algorithm gave satisfactory results for a hospital which was planning its own collections and thus this time lag was much smaller than in a system where collections are made by a blood centre.

Frankfurter et al (1974) used exponential smoothing forecasting techniques to estimate as accurately as possible the demand from different hospitals by using real data from a New York regional system. Their forecast system attempts to change blood centre management to the short-term inventory level of blood supplies, so that corrective action can be taken to adapt collection levels accordingly.

Cumming et al (1976) developed a collection planning model for regional blood suppliers by scheduling and rescheduling the operations of bloodmobiles. A valuable contribution of the planning model is to forecast the number of blood units in inventory on any given day, according to the initial scheduled distribution of bloodmobiles to existing sponsors and the expected turnover of donors. Subsequently, the shortage below or the surplus above the adequate inventory level to meet demand can be identified and thus collections can be rescheduled or sponsors persuaded to run more collections to smooth the seasonal inventory imbalances. They created an interactive computer-based system, easily used by a non-programmer blood planner, which generates graphs of scheduled collections covering a planning period of several months to one year. The system manipulates estimated collections, annual blood demand and usage, outdating and age of blood, on a 21-day shelf life basis, by using a slightly modified Markovian population model to project total inventory. It runs a daily schedule by using probabilities and weights to accurately spread the aggregated information over the time horizon. It was validated for two regions to perform with an only ±5 percent error in estimating inventory and also to perform reasonably well for other performance measures. It is a medium-range planning model which, if kept up-to-date with actual inventories inputs and revised forecasts, can also take care of short-term interventions. A long-term planning multiple objective model was also introduced by Kendall et al (1980a) to determine annual collection and regional inventory levels.

3.3.3 Crossmatching Methods and Issuing Order

Problems considering best issuing policies have also been examined in detail in the literature. Pagels and Jelmert (1971) showed that an efficient policy for crossmatching blood is to assign old blood to those patients with the highest probability of transfusion and fresher blood to those with a lower probability. These probabilities need to be evaluated by the blood bank managers according to their chosen policy. However, this limitation restricts the usefulness of the model as it falls in a circle of assumptions.

Pierskalla and Roach (1981) showed that for a perishable product, assuming that all the demanded units are used, the policy that minimizes shortages and outdates is that of giving the oldest unit first (FIFO). However, in the case of blood the assumption of using all the demanded units does not apply most of the time, because of the assigned inventory and the rotation of the unused blood as explained above.

Brodheim and Prastacos (1980) took this distinctive phenomenon into account. They considered two queues while describing the process; one for the selection of units in the inventory waiting to be crossmatched and one for the requests waiting to be fulfilled. They developed an algorithm which showed that a) an assignment of a request to the most likely to-be-used units and b) a FIFO order for the selection of units minimizes shortages and outdates. The algorithm also indicated that the unit assigned to a request of size one cannot be older than the first unit assigned to an order of bigger size. They conducted simulation runs for a variety of hospital parameters. The results illustrated a 5-10% improvement with a FIFO assignment-FIFO selection policy and 8-13% improvement over the FIFO assignment- random selection policy.

More recently Jagannathan and Sen (1991) focused on the problem of crossmatching and setting desirable unassigned blood inventory levels with the prior determination of shortages and outdates. They developed a decision support system which allows the blood bank manager to conduct sensitivity analyses by changing parameters such as the proportion of crossmatched to transfused units, the length of the crossmatch release period and the life of blood. Their mathematical model allows multiple optimisation criteria to be used to determine optimal inventory levels and also to compute unlimited combinations of parameter values, in contrast with previously applied statistical and simulation techniques based on limited data sets. However, their model also has limitations like any other quantitative model. The main restriction is that the authors assume a fixed crossmatch-transfusion ratio and crossmatch release period, though in practice these may be variable, especially the former. Moreover, they did not consider emergency demand above the regular crossmatch demand. The relaxation of these assumptions may significantly alter the number of shortages and outdates.

Another consideration towards maximising the likelihood of a blood unit being used is double-crossmatching, assuming that the probability of both patients using the same unit is low, which is explained in detail in the work of Deuermeyer et al (1977) and Dumas and Rabinowitz (1977). This policy performs well since it increases the probability of a crossmatched unit being used. Empirical results of double-crossmatching from a New York hospital showed that outdating was reduced by around 10% over the sole FIFO crossmatching (Rabinowitz and Valinsky, 1970).

Together with this strategy, Dumas and Rabinowitz (1977) discussed another policy which underlines the use of Rh-negative blood for Rh-positive patients (mismatching) under certain blood–age conditions, when it is medically feasible. Using this policy, they proved that the wastage of Rh-negative blood types, which have a low usage, can be significantly reduced without altering wastage of Rh-positive types. The combination of both policies brings a substantial decline in outdates of all blood types.

3.3.4 Frozen Blood and Expansion of Blood Shelf-life

Another advanced concept for alleviating shortages and outdates in blood banks is the use of frozen blood, which largely eradicates the perishability of the product. Extensive simulation runs were conducted (Cumming et al, 1977, Kahn et al, 1977) to show the effects that such a policy of converting to frozen blood would have on the hospital inventory. The results showed it was possible to maintain of a stable operation of the blood bank without much alteration in the outdate rates. Nevertheless, blood bank administrators have been reluctant to adopt the use of frozen blood as the high cost of freezing and thawing blood prohibits it.

There are also studies focusing on the effects of extending the shelf life of blood. Pagels (1978) researched the outcomes of varying blood life span from 14 to 28 days, using simulation. He demonstrated that a shelf life of 14 days offers a better quality of transfused blood since blood is fresher, but results in shortages if collections are not increased and in outdates if they are. A 28-day shelf life would reduce outdating to nearly zero but would not affect the variation in inventory levels. A prolonged life with reduced collections, according to Pagels, would be the best policy. So, an extension from 21 to 28 days blood shelf life could reduce national (U.S.) collections by 5%.

Cohen et al (1983) also showed with the use of simulation that by increasing the shelf life of blood from 21 to 35 days, due to the adding of adenine at that time, outdates and shortages could be reduced by 80% and 43% respectively and thus collections can be downsized by 8-10%. However, this advantage could be eliminated if the tightness of other inventory management controls is to be relaxed.

These studies are still relevant as the UK is considering extending the RBC shelf life from 35 to 42 days, as in US and Canada, as well as increasing the lifespan of platelets from 5 to 7 days.

3.3.5 The Management of Blood Types

In the literature there has been particular concern about stocking different blood types since they do not all behave in the same way. Their behaviour depends on the frequency of occurrence among the population, which determines not only demand from patients but also collections from donors of that particular group. Rare blood types such as AB or Rhesus negative groups have a smaller usage rate. However there is an agreeable tendency to prefer excessive wastage to excessive shortage to avoid risking patient lives. Thus, the ratio of stored to used units of rare types is much higher than for more popular types. Therefore, it can be noticed that for the same shortage rate, rare blood types indicate a higher outdate rate (Graf et al, 1972; Prastacos, 1980; Lau et al, 1984). Graf et al proposed some alternative strategies to deal with the problem such as: a) centralised storage of rare blood type units only in blood centres and big hospitals and rapid distribution to hospitals blood banks when demand arises; b) interchange of unusual types between hospitals; c) avoidance of excess donor recruitment of these blood types. The first and second strategies are also tested in our study.

3.3.6 Mismatching - Substitution

We have only been able to find two studies in the whole literature of blood systems modelling that consider the phenomenon of mismatching.

Abbott et al, (1977, 1978) developed a simulation model that captures in great detail the processes of a hospital blood bank, including the activity of mismatching. In this study substitution of blood groups takes place when the same group is unavailable. Also, substitution between whole blood and RBC is allowed. Hence, there are numerous alternatives between products and compatible blood types of these products. The algorithm developed for mismatching performs very well, accounting for the oldest compatible group to substitute the demanded blood group with the only inconsistency of allowing for a changeover between the products too. For example, whole blood could be given instead of red blood cells. Nowadays, this practice is out-of-date as, first of all, whole blood is rarely kept in this form and secondly this switchover would no longer be acceptable for the patient's health.

The second study which considers substitution is a very recent one. Kopach et al (2003, 2004) built pilot simulation models for RBC and platelets separately in order to predict blood product shortages. The models account for substitutions according to ranked preferences of the compatible types of a single product. Each model is a basic representation of a blood centre serving one hospital and it uses empirical, averaged, data to represent donor inputs in the centre and unit inputs in the hospital, segregated by trauma condition and gender. These pilot models utilize a reduction policy in the fulfilment of hospital requests based on the centre's inventory. This policy, together with the substitution preferences matrix and categorised medical consequences of shortages, quantifies the risk of a shortage and the resulting medical impact on the patient. However, no concerns are raised about how substitution affects stock levels and orders.

SECTION AB

3.3.6 Computerised Information Systems for Blood Management

In addition to modelling parts of the blood supply chain with the purpose of developing decision tools for several related topics, there are also excellent reviews focusing on the use of computerised information systems for the management of blood operations (Allen et al, 1978; Catassi et al, 1967; Hirsch et al, 1970; Hogmar et al, 1970, Brodheim, 1978). Most of these propose the administration of the following elements: 1) information about donors and collections, 2) inventory reporting of hospital or regional blood banks 3)records of compatibility tests performed 4) personal data of blood recipients 4) setting of performance measurements and control.

A computer-based inventory control system for controlling distribution between the blood centre and the client hospitals has been operating since 1964 in the U.S. Daily processed information by a centralised computer led to a 60% reduction in outdating and 30% in inventory keeping (Catassi et al, 1967).

Moreover, as early as 1970, Hirsch et al realised the significance of record keeping in a computer-based form for producing statistical summaries for various blood bank activities and identifying bottlenecks. They also foresaw the need for creating a compatible computer system to allow sharing of information between the hospital and the regional blood centre in the future. The same year Frankfurter et al published a detailed description of a regional computerised blood inventory information system in terms of system features, inputs, summary reports, system operation, set-up and operating costs and implementation steps. Masouderis et al (1970) also analysed the use of an automated blood inventory and information system to support all phases of the Milwaukee blood centre operations. He particularly focused on the cost aspect, in money and personnel needs, of implementing and running the system and defended the costs incurred by attaining an improved service with efficient operations.

Later, Allen et al (1978) described a computer-control system of donor blood processing and labelling. They proposed the substitution of the manual system of eye-read/hand written process with a bar-code/laser beam identification system, which would save time, reduce tedium and make the process error-free. Also, the sorting, segregation, aggregation and printing of the laboratory record sheets would eliminate hand transcription and visual comparisons, which further eradicate errors.

As early as in 1984 Prastacos identified that the future of blood management is the development of distributed computer networks that will provide real-time information on inventory and patients needs. Though this has not yet achieved there are many people looking towards this approach as the new transparent way of managing the blood supply and many other supply chains. Rapid advances in technology have given the opportunity to make these suggestions realisable. Thus, a real-time, web-based network with instant access to information from the cooperating locations is closer to reality than ever before. Only the obstacles of implementation costs and human resistance to adapt to new technologies delay what is going to happen probably in the next decade.

SECTION B

3.3.7 Blood Supply Network Structures

Researchers concerned with changes in policies of the blood system processes approached the issue from a broader perspective, focusing on the structure of the whole supply chain network (Pierskalla, 1980; Popp and Vollert, 1981). First of all they identified the existence of centralised and decentralised structures between the supplier (blood centre) and the demand points (hospital blood banks). The criterion for this differentiation is which of the two parts of the chain has control over the other. A centralised structure exists when the blood resources allocation, for instance hospital inventory levels and the quantity and age of blood distributed to them is decided by the centre. A decentralised system exists when each hospital works under its own rules and the centre tries to maximise the fulfilment of the received requests. Pop and Vollert (1981) demonstrated the effectiveness of a centralised system over a decentralised one in terms of shortages and outdates. The UK system examined in this thesis is a decentralised system.

Cohen et al (1981) broaden this analysis to cover these and also more complicated structures appropriate for supplying bigger areas or whole countries. They identified:

1) A single, autonomous, regional blood centre which collects and supplies all the hospitals in a two-echelon model.
2) Multiple independent centres, essentially a replication of the previous, two-echelon, network. Each centre serves the geographically nearest hospitals and supports all the necessary departments from collection to distribution. Thus, this structure is faced with excessive administration costs. There is a choice of the level in which the centres compete against or co-operate with each other. This

system enables the supplied hospitals to bargain for extra services or to be served by another centre in cases of product unavailability from the assigned centre.

3) Coordinated multiple centres which form a three-echelon set-up with the assignment of some costly functional areas such as information systems, donor services and testing to the higher level and the remainder to the second level (centres).

This research concentrated on decisions about allocation of services to the three echelons and the sizes of centres for which cost-effectiveness can be attained. Their findings, by manipulating data collected from the Chicago area, showed that:

a) Donor activities and coordination of inventory should be controlled by the third structural level.
b) Economies of scale exist for operations above 50,000 units in blood centres annually.
c) The single centre structure is the least costly.
d) There is a change in operating costs depending whether a centralised or de-centralised system exists.

Cohen et al also developed a transportation model to locate blood centres and hospitals in a region and a model which assigns donor areas to blood centres, both in a minimum cost manner.

3.3.8 Blood Allocation, Distribution and Redistribution

The issue of cost effective distribution of blood units from a blood centre to the hospitals and between hospitals has been addressed in the literature in much detail.

Yahnke et al (1972) for the Milwaukee region, and Graf et al (1972) for the Connecticut region, were among the first to focus on this problem. They indicated that centralised management should be established and showed empirically that scheduled deliveries from the centre to supplied hospitals can significantly cut down the number of total deliveries. They also demonstrated through statistical and operational analysis that scheduled redistribution, via the blood supplier's transport, of unused blood to other hospitals can considerably reduce outdating for the whole region.

Jennings (1973b) also looked at transhipments between collaborating hospital blood banks which form a system, although without the presence of a central blood bank with buffer inventory. Specifically, he illustrated that a larger number of hospitals performs better because it is easier to spread the daily fluctuations in demand between hospitals. However, the marginal benefit in reducing shortage and outdate via transhipments by adding a new hospital into the system was not significant after five hospitals were already in the system. Nevertheless, this study tends to exaggerate the number of transhipments because of the lack of a central blood bank. However, this study could be useful nowadays if we replace the hospitals with blood centres that exchange stock from time to time.

Yen (1975) was the first to develop a multi-echelon, perishable, de-centralised inventory model applicable to blood banking and food management where goods are produced in a facility and from there delivered to other facilities for satisfying client demand. He considered a two-echelon system which a central centre (CBB) supplies two other centres (HBB) according to a FIFO policy. He tried to find those ordering and allocation policies which minimize outdating and shortage. However, his examination is limited to a stationary order-up-to policy with the assumption that stock is allocated from the first centre to the two others following a percentage which was derived from past observed patterns of demand. His results showed that, under certain conditions, the total expected outdating of inventory in a certain period is a convex function of the critical number (order-up-to quantity) of the same period.

Cohen et al (1979) took this work forward and examined in addition a policy under which a fixed amount of available stock is allocated to the two centres of the second echelon. They compared the outcomes with Yen's results and concluded that the two allocation policies are equivalent under certain circumstances.

Some of the following studies attempt together with good allocation policies to apply redistribution methods of aged blood between hospitals, usually via the blood centre's transport. Redistribution policies are tried out in the experimentation part of this study, however, in UK hospitals returns to the blood centre are forbidden. Nonetheless, there are some excellent ideas for improvement of allocation policies which attract notice.

Brodheim and Prastacos' research (1979a, 1979b; Prastacos and Brodheim, 1979) involves some of these. They studied a distribution system implemented by the blood centre supplying 34 hospitals in Long Island, New York. In order to describe the system under examination they introduced the terms “rotation” and “retention” of blood. In their mathematical program they assumed that every 10 days blood units of the age of one day are distributed to the hospitals. The units which were not yet transfused after 10 days were returned to the centre and were immediately redistributed. Then, they were either transfused or outdated. Blood of the age between 1 to 10 days old was referred as “rotation” blood, since there is a chance of redistribution, and blood which was in the last 10 days of its life (21 days) was the “retention” blood. In order to simplify the problem, they considered only one redistribution point, but they also showed that adding more stages of returns would only slightly improve outcomes. Also they proved that their problem structure was not only optimal for the next period but was close to optimal for the long run. They applied a “fair” allocation rule. This was achieved by first allocating those units which were intended to outdate in the current planning period and thus, assigning equal probability to outdate among the hospitals, and secondly by allocating in a FIFO order all the remaining stock among the hospitals with the same probability of a shortage occuring in any of them. Conditions for optimality are treated as constraints and the algorithm is executed parametrically until a feasible solution for blood distribution has been reached. Under this allocation logic, in which the centre has more control over the total inventory distribution between the hospitals, outdates were reduced from 23% to 4% and shortages by 9%. These redistributions took place using approximately 3 non-scheduled, supplementary deliveries per hospital per month. Deliveries were made periodically with a variable frequency according to the size of the hospital. However, the one redistribution point of 10 days, nowadays would not care for the more specialised products with different, usually, shorter shelf lives such as platelets which need faster rotation if they are not to outdate.

A more frequent scheduled delivery system has been also examined in another study by Brodheim et al (1975) in a more theoretical approach. They modelled policies for scheduled deliveries by using a Markov chain with a controllable number of states. They obtained measures of average number of discards per time period, the probability of shortage and the average age of inventory from the Markov chain’s stationary distribution. They examined the behaviour of these measures as functions of demand by placing bounds on them. They also evaluated the class inventory policies under consideration but without examining optimal inventory policies, as in previously mentioned studies. This class of policies consisted of scheduled deliveries of fixed quantities of blood at regular intervals to replenish most of the blood that is used. In this way, they tried to schedule most deliveries in advance, minimize distribution costs and sustain an acceptable, predetermined outdate rate.

The same issue was approached by goal programming modelling (Kendall and Lee, 1980b). A series of goals were set and prioritised by a blood administrator, such as the reduction of outdating by maintaining at least the same shortage rate and cost levels by rotating blood with systematic redistribution to the hospitals. Goal constraints were related to inventory levels, availability of fresh blood, blood outdating, the age of blood and the cost of collecting it. The potential of the model was validated by applying it in a large blood region in the Midwest of the USA, Nebraska, which supplied 105 hospitals of mainly medium and small size. Due to the lack of large-volume hospitals the Long Island program was not expected to perform very well. The outcomes were: a reduction from 15% to 9% in outdates without increasing the frequency of shortages, no overstocking in hospital blood banks, sufficient fresh blood was available when needed for special surgery and a reduction in collections by 5% producing savings of $115,000 per year in 1978. The methodology is expected to perform better in regions with large-volume hospitals. Its great contribution lies in the fact that it is applicable to many blood regions because it allows for goal re-organisation tailored to the region's specific needs.

In reviewing all these policies Prastacos (1981) clarified the big difference between optimal ordering policies and optimal allocation policies. In the first situation there is a decision about how much inventory to bring into the system (HBB) by ordering. More inventory results in less shortage and more outdating and there is an obvious competition between these performance measures which the hospital tries to balance. Conversely, an allocation policy considers that the total quantity of products/stock in the system (CBB) is fixed and by allocating older units to hospitals with high demand, both shortages and outdates can be minimised. The latter case assumes that at the beginning of each allocation period the quantity of stock in each location (HBB) is known to the main centre (CBB). A web-based information system with real time information for each location would be ideal for this situation to support the system's transparency.

Furthermore, the work of Federguen et al (1985) points out the importance of transportation costs, in addition to the costs of shortages and wastages, in the situations under review and develops on a single integrated model of the centralised inventory allocation and the transportation planning problems. Thus, together with the allocation policy two types of scheduled deliveries are examined. The first considers that all demand points receive individual deliveries and the second assumes deliveries are combined in multi-stop routes covered by a fleet of vehicles to satisfy more demand points at once. In the first case delivery costs are linear; in the latter case transportation costs lead to the vehicle routing problem. So, the first integrated model is described by a simple convex allocation problem and the second adopts a similar logic with a repeated subroutine within a routing algorithm. These models are compared according to the produced inventory (shortage-wastage) and transportation costs and total aggregated costs for certain values of the parameters used, such as number of locations, rotation and retention units, outdate and shortage rates and vehicle capacity. The results obtained by the multi-stop routes approach are only slightly better in terms of total cost than the individual deliveries approach. However, this reflects the particular choice of the parameter levels, with inventory costs dominating travel costs.

In all these studies there are excellent reviews of blood rotation and scheduled deliveries, but nevertheless, they do not thoroughly examine the problem of numerous non-scheduled deliveries which increase delivery and personnel costs. The reason is that at that time blood components were limited in range and had a limited use in medical treatments. However nowadays the use of hundred different blood components with different shelf lives which are not always kept in stock gives rise to the problem of very frequent ad-hoc and emergency deliveries in order to meet demand instantly.

3.3.9 Emergency Deliveries

There are a few papers in the literature pertinent to emergency deliveries of perishable products but which are not tailored to the specific characteristics of blood. The key papers are mentioned below.

Barankin (1961) was the first to address the issue of emergency replenishments together with regular orders for a non-perishable product using a periodic review system. Tagaras and Vlachos (2001) extended this research of an order-up-to-level policy by including regular orders issued in every cycle consisting of several periods, and emergency orders in the case of forthcoming stock-outs. They developed a heuristic algorithm to calculate the unique minimum cost solution of the problem.

Schmidt and Nahmias (1985) adopted a continuous review rule of perishable inventory with fixed shelf life, stochastic demand considering also a fixed lead time and lost sales. They produced numerical results that reveal some appealing characteristics of the base stock level, which depends on different systems parameters. Liu and Lian (1999) showed results of a renewal demand process including backorders, but, with immediate replenishments.

This paper adopts a multi-stop route approach for routine deliveries and a star-like, individual delivery system for ad-hoc and emergency deliveries, initially without allowing for redistribution of blood but then incorporating this variable in the system as well.

3.4 Platelets

After the 80's interest shifted to the analysis of platelets, which have most of the characteristics of RBC but also have two main differences. Firstly, the shelf life of this component is only 5 days and secondly, a stock of platelets is not usually kept in the hospital blood banks, mainly because of the short shelf life. They usually follow an "order only as necessary" policy. However, high volume hospitals may do so and thus platelet inventory control studies can be found in the literature. Most of them use the same techniques as those which were applied to whole blood or RBC to tackle the problems. However, they are concentrated on the particularities of this blood component.

The first detailed study specifically about platelets was Deuermeyer (1976). The author considered the relationships between platelet inventory levels and average daily outdates and shortages in a medical centre. He used a computer simulation to generate graphs showing the relations between stock levels and mean daily demand. He concluded that acceptable levels of shortages and outdates are difficult to obtain by considering inventory policies determined alone by mean daily demand. However, the shelf life of platelets was only 3 days at that time, and Deuermeyer's conclusions were derived by looking only at one dataset.

Later, Sirelson and Brodheim (1991) showed that good inventory policies are possible by considering empirical data from 14 high-usage hospitals of New York and with a shelf life of 5 days. They stated the fact that "the prevailing practice of shipping platelets 'on demand' to hospitals often results in delivery frequencies to larger hospitals of two or more times per day". They used computer simulation and linear regression to derive a predictive model of shortage and outdates related to fixed base stock levels, using mean daily demand as the sole parameter. Their findings indicate that by applying a platelets stock replenishment policy with daily scheduled deliveries, the overall number of deliveries can be decreased to just over one per day. They assumed that shortages are filled immediately by extra supplementary shipments and also that the age of platelets when they arrive in the HBB is 1 day. They also showed that low shortages and outdates are easy to achieve at a regional level but are difficult within individual hospitals.

Their study reported similar results to those of Katz et al (1983), who used simulation to model a day-to-day production policy with a fixed inventory level determined also by mean usage and a multiple of the standard deviation. Katz et al used different stock levels for each day of the week and predicted 1% or lower rate of shortages and outdates.

Ledman and Groh (1984) considered the problem of choosing platelet production levels in a particular regional blood bank which supplied 60 hospitals. They set up a daily protocol with specialists for determining how many platelets to produce every day in order to sustain the centre's inventory level of mean demand plus 3 times the standard deviation, which leaves a probability of almost zero for shortages to occur. Using this method they managed to reduce outdates at the regional blood bank from over 20% to less than 3%.

Hesse et al (1997) developed periodic review inventory policies for a centralised blood bank and each of the 35 client hospitals which they tested in a simulation model. Due to the complexity of their dynamic programming approach, they aggregated hospitals into risk groups, and they used an enumerative process to form policies for each group.

Finally, Blake (2003) was one of the first who actually produced a usable dynamic programming model to optimize the platelets supply chain. He utilised data from Nova Scotia. The province included two collection/production centres which supplied 41 facilities. He developed a dynamic program for the producer and he implemented an approximate solution to the problem, without the need to adopt heuristics like other authors in the past ended up doing due to the complexity of the program. However, he downsized the problem by using batches of units, assuming that usually 5 units are requested for each patient (according to the data presented in Chapter 2, table 2.1, this figure is close to 1). Thus, the quality of the obtained solutions depends on the size of batches and also the length of the time horizon. Nevertheless, it was possible to generate results of target inventory levels, within a modest runtime, which decrease costs by 18%.

3.5 Conclusions

Nahmias (1982) identified the following limitations in all previous research of blood inventory management:

1) the problem is too complex to be handled by a single mathematical model;
2) studies did not separate the assigned and unassigned inventory;
3) studies did not consider the ageing of blood when into the loop of assign-unassigned inventory;
4) mismatching was not considered;
5) models did not take into account practical medical limitations of requests of fresh blood for some certain transfusions.

The model which will be presented in this thesis overcomes the first four limitations.

Also, Prastacos (1984), in his excellent overview on blood management, identified open research questions still to be examined, which concentrate on the following:

1) Optimal component processing policies.
2) Distribution scheduling with the development of heuristic algorithms for scheduling the distribution of multiple blood products from the centre to the hospitals.
3) Organisational structures of regional systems with optimal segregation of the regions in clusters and assignment of depots to reduce transportation cost and improve operating efficiency.
4) Inter-regional collaborations and pricing of blood products.

Unfortunately, there has been little research following the publication of these reviews as far as we can see. Management Science researchers have left this area of interest. To some extent this mass departure was caused by the collapse of federal funding for studies in the area and also because the remaining problems were increasingly difficult to tackle (Pierskalla, in Brandeau, 2004). The emphasis of research shifted towards blood supply safety and especially the introduction of new tests. However, in this study the second of Prastacos' questions is examined and also the third and fourth are briefly mentioned.

In general, this study considers a perishable inventory problem with a fixed shelf life and an order-up-to-level policy of a regular and frequent periodic review for replenishments. It entails a variable lead time of deliveries and takes into account emergency deliveries with an extra cost attached. It also considers stock-outs and backorders. There is a continuous review of the remaining shelf life of the product in certain stages of the model. Technically, it is a queuing model with impatience.

In conclusion, the model which will be presented in this thesis encapsulates the following advances from previous models:

1) it represents and mimics a detailed, vertical part of the supply chain, from donor to patient for both echelons of the chain;

2) it incorporates in a single model products with different shelf lives

3) it includes mismatching;

4) it includes the time a unit spends in the assigned inventory stage when calculating the remaining shelf life.

5) it expands by introducing more hospitals into the model.

6) it considers different sizes of hospitals and obtains satisfactory policies for each size separately and for all hospitals in the same supply chain together.

CHAPTER 4: METHODOLOGY

4.1 Introduction

This chapter starts by giving a rationale for the selection of the discrete event simulation technique to tackle the problem and describes this Operational Research tool. Furthermore, it briefly analyses some features crucial to the construction and execution of a simulation model in general, and of the model constructed with the COTS package (Simul8) used here in particular. Moreover, it outlines the steps followed in performing the research with the use of this technique.

4.2 Discrete Event Simulation

Discrete event simulation was chosen as the most appropriate method to model this complex system of the blood supply chain. This Operational Research technique was considered to be the only suitable approach, since, in this case study, both supply and demand are stochastic, the system is many sided, and the processes and outcomes, for example outdates, are time driven. Cohen et al stated (1979b) that this complex stochastic multi-product, multi-echelon perishable inventory problem is intractable by analytic techniques. Since then, there has been a tremendous amount of research in dynamic discrete event simulation of supply chain management (SCM) (Viswanadham et al, 2000). In particular, as described in the literature review, many authors in the past used this technique in order to produce meaningful results and to experiment with new ideas on blood stock holding and distribution systems.

The term "simulation" is normally used to describe the practice of mimicking some or all of the behaviours of a system with a different, usually simplified, system. Computer simulation is an approach to modelling using interconnected blocks to represent interaction between specific processes and is run on a computer using mathematical models. The latter are stochastic, that is they involve input generated according to probability distributions. A discrete model assumes that the state of the system changes only at specific times, often referred to as events, and that the state of the system is unchanged between these times. Thus, discrete event simulation involves the modelling of a system as it progresses through time and is particularly useful for modelling queuing systems (Robinson, 1994).

The process of building simulation models always involves some form of software. The software could either be a high level programming language or a data-driven software system in which the model is specified using user-defined and default data items. In this study a combination of these two is used. Simul8 is a Commercial Off-The-Shelf (COTS) simulation package, which is connected with Visual Basic, the programming language, to enhance the capabilities of the software. Inside the software or model are a number of important concepts, namely entities and logical relationships, which define the overall behaviour of the model.

Entities are the elements of the system that can be individually identified and processed, i.e. packs of blood units. They flow through the system requiring resources (i.e. vehicle to transfer these units from the collection point to the blood centre) in order to perform activities (i.e. processing, testing, crossmatching). Waiting lines (queues) (i.e. hospital blood bank) are where the entities wait for needed resources to become available or for events to take place (i.e. request for a blood unit). Logical relationships link the different entities together and make them behave in a certain way.

In Simul8 entities are called "work items" and represent the work that is done and is being simulated. In Simul8 there are default simulation objects such as work entry points, work centres, storage bins and resources, which are in some way connected to each other and form a simulation model. An object in Simul8 is something in the simulation which is drawn on the screen and which is normally involved in the work done (work item). Typically the work item in a system will be simulated by it going through a number of objects that are on the screen, and some types of object (e.g. resources) being "used" at other objects (e.g. at work centres) (Simul8, 1999).

A "work entry point" is a place where entities appear in the simulation for the first time. A simulation model can have more than one work entry point. Each can feed in work items using different statistical distributions if required. Statistical distributions provide a method of simulating the variations that occur in timing (and other numbers) in any process involving people or machines or anything in nature.

Individual work items, initiated by a "work entry point", flow through the "work centres" in a simulation. A "work centre" is a place where work takes place on work items. Work done at work centres usually takes up time, which is usually defined by a statistical distribution, and sometimes requires the availability of resources. "Resources" are items in the simulation that are required at work centres in order for the work centre to work on a work item. Work centres cannot start work until both a work item and the specified resources are available. At a work centre a work item may be transformed in some way (perhaps by changing one or more of its "labels"). After the work is done the work item may be sent on to another simulation object, depending on routing rules, which can be specified.

Entities have attributes that make possible to distinguish one entity from another. In Simul8 attributes are called "labels" and can be attached to any work item going through the simulation. Labels can determine the routing of the work item through the simulation objects or can be used to tell work centres which distributions to use for sampling work times. Labels can also be used to prioritize work items as they enter a queue. In Simul8 queues are called "storage bins", and are places where work items can wait until appropriate resources or work centres are available (Simul8, 1999).

The logical relationships (e.g. "start processing if blood units are waiting") are a key part of the simulation model; they define the overall behaviour of the model. All Simul8 objects have dialog boxes in which the logical relationships can be specified. Inside these boxes, logic statements can also be written with the use of Visual Logic, which is a simplified form of a programming language offered by Simul8. More complex logic statements can be enforced in the Simul8 model with the use of Visual Basic.

Another key part of any simulation system is the simulation clock, which keeps track of time. The clock will control the logical relationships between the entities and advance the time to the next scheduled event. This operation is central to providing the dynamic, time-based behaviour of the model.

Two other elements that are vital to any simulation system are the random number generators and the results collation and analysis (Ball, 2001). The random number generators are used to provide stochastic behaviour typical of the real world. Typically model experimentation is conducted by running the simulation model more than one time with the use of a different random number stream in each run. An experiment, or "trial" in Simul8, is a series of runs of the simulation that are performed with the same settings of all the parameters in the simulations except for the random numbers. As a simulation contains variability it is important to run a simulation more than once. A trial provides information about how variable the runs are and how accurate the performance measures (results) are expected to be. The results collation provides the user with a means of utilising the simulation tool to provide meaningful analysis of the new or proposed system after it has been simulated for a specified period. Important factors in simulation that are related to the latter are the "warm up period" and the length of run. The "warm-up period" is the time that the simulation will run before starting to collect results. This allows the queues (and other aspects in the simulation) to get into conditions that are typical of normal running conditions in the system being simulated. The run-length or runtime, called "results collection period" in Simul8, is how long the simulation should be run before automatically stopping while collecting results (Simul8, 1999).

4.3 Steps of the Simulation Study

Successful simulation of a complex system consists of two major aspects: accurate understanding of the system, and reasonable translation of the system concept into an appropriate simulation environment (Crosbie, 2002). Chapters 2 and 3 dealt with the first aspect by assisting in the development of a conceptual model that can adequately represent the behaviour of the system. Chapter 2 provided a thorough observation of the system and Chapter 3 gained more insights by revising previous studies on this topic, which have analysed the system and attempted to address some of its fundamental problems. This Chapter described the methodology for constructing such a simulation model and Chapter 5 gives a thorough description of the data collection and data analysis which was carried out in order to supply the model with data in the form of distributions, coefficients, system constants and initial conditions. This is often the most difficult aspect of producing a useful simulation.

The second aspect is attempted in chapter 6 by converting the conceptual model of the blood supply chain into a computer program that performs the simulation. This is done in conjunction with Chapter 5 which not only feeds the model with data but also assists in the deeper understanding of the system and hence the constant improvement of the simulation model which represents this system. The computer program should correctly solve its equations and implement its rules and procedures and thus Chapter 6 tests the model to assure verification, validation and ability of the model to conform to reality. Moreover, the simulation model is a tool that can visualise the entire supply chain and allows for the testing of numerous "what if" scenarios in a risk-free environment

(Archibald et al, 1999). Chapters 7 and 8 show how the model is used as "*a vehicle for experimentation, often in a trial and error way, to demonstrate the likely effects of various policies*" (Pidd, 1998).

CHAPTER 5: DATA COLLECTION AND ANALYSIS

5.1 Introduction

This thesis attempts to analyse and model policies for the NBS and the supplied hospitals which will lead to better organisation of the blood supply chain with improved product use and supply and cost savings. Discrete event simulation models were constructed for this purpose, representing in detail the operations shown in the flow diagram of Figure 2.2. The models were developed using the Simul8 software package (www.simul8.com), together with the support of Visual Basic for Applications. Modelling this large system required extensive data. This chapter presents in detail the acquired information which assisted in designing good representations of the system and the necessary data which served as inputs in the simulation models. These are summarised as:

- data collection methods and database description;
- analysis of data relevant to the blood centre and the NBS
    - such as collection teams, processing and testing, product frequencies and shelf-life stocking, supply and demand fluctuations, issuing and distribution;
- analysis of data relevant to hospitals
    - such as physicians' ordering, demand and usage and inventory management and
- wastage analysis and associated loss for both the NBS and hospitals.

Finally, the key observations are summarised at the end of this chapter.

5.2 Data Collection Methods

This study was conducted with the collaboration of the Southampton NBS Centre. This Centre is the smallest of the 10 fully functional, processing, testing and issuing (PTI) Centres of the NBS. It serves 17 hospitals. It collects 130,000 donations per year, around 500 per day. 120,000 units of red blood cells (RBCs), 12,000 units of platelets (PLTs) and 45,000 units of plasma are produced every year. All the information presented in this chapter relates to this particular Centre and its supplied hospitals, unless stated otherwise. Nevertheless, most NBS Centres follow the same general approach but may have slightly different working practices.

Up to nineteen months' data for the Southampton NBS Centre was provided by the NBS information system (PULSE) and analysed in Excel. These data cover the period from 1/4/2003 to 31/7/2004 (16 months) for collections and from 1/4/2003 to 31/10/2004 for processed and issued units, stock holding and discards. The collections and processed units database gives details of the date of collections or processing, method of collection (whole blood or apheresis), ABO and Rh group, if identifiable from returning donors, and the quantity of units collected or processed from each blood group. The issues database provides details about the request form number and line; a request number can have several lines if units from more than one blood group or different products are requested. Additionally, the issues database consists of the request destination code (hospital or NBS Centre), the delivery type of the order, the date of issue, the exact time the units were scanned through the PULSE system for issuing, the product code, the blood group and the quantity of units issued in that blood group. The stock holding and discards databases show the date, product and quantity of units in stock or discarded by group respectively, together with the reason for disposal of the latter. A sample of the provided databases can be found in Appendix A.3. These databases yielded information for both the NBS Centre and the hospital orders and deliveries.

We attempted to gain further insights into the way hospitals request blood products, and information about their stock policies, by contacting the hospital blood banks. A questionnaire was posted and e-mailed to the 17 hospitals supplied by the Southampton NBS Centre. This questionnaire is presented in Appendix A.4. The main points of the questionnaire are the number of weekly physician requests, the size of request, seasonality effects, crossmatching to transfusion ratios, the optimal stock, criteria for placing orders, and the available budget for purchasing blood. Unfortunately, the return rates were low. Only 7 questionnaires were sent back. Moreover, parts of these questionnaires were incomplete, mainly because few blood banks consistently keep records of this sort of information. In other cases some of the answers were vague and inconsistent. However, follow ups and interviews with the contacts of the returned questionnaires significantly assisted in the understanding of the hospital processes. Numerous informal interviews were conducted with NBS staff and hospital blood bank managers for clarification and validation. Moreover, surveys and annual reports from the Blood Stocks Management Scheme (BSMS) greatly helped to acquire awareness and fill in information gaps about hospital processes relevant to blood usage and inventory management. Therefore, hospital data are not only specific to the region under examination but cover a plethora of hospital tactics across England and North Wales.

Consequently, the belief that some generalisation prevails is not unreasonable. The following sections provide insights regarding the data analysis of the collected information and present the data entry requirements of the simulation models.

5.3 NBS Blood Centre

5.3.1 Collections, Processing, Testing and Issues (PTI)

The marketing and collections department plans and collects blood for part of the south region, not solely for the Southampton NBS Centre. Some of the collected blood units return to Southampton for PTI and some go to other southern NBS Centres, for example Bristol. Collections are planned and executed by region rather than by NBS Centre. Each region can include more than one NBS Centre. However, this does not imply that Southampton undertakes all the collections for both Centres. The Bristol Centre collects units for the southwest region. This arrangement is in place because of historically agreed working practices which dictate the workload for each Centre. After PTI, some processed units are sent to the non-fully functional south region Centres for issuing.

The Marketing Department in the Southampton NBS Centre has only been in operation for four years. Before that a public relations (PR) department with limited duties and restricted resources performed this role. Currently the Marketing Department consists of 15 employees, 7 of which are located in Oxford. Nine collection teams operate in the South region. The donation number on the collected bags indicates the place where the particular team reports for processing. The teams operate on a 2-week schedule. The 9 teams carry out around 100-110 sessions per month, according to the needs for supply over the specific period. Some big teams carry out double sessions. Most teams work 9 days per fortnight and the on-site collection department works from Monday to Friday. Each team usually collects around 100 units of whole blood in each session which typically lasts 5 hours. Three of these teams (4 sessions) located closer to the south west send their collections to Bristol for processing. These are around 400 units. The quantity collected depends on factors such as the venue, the number of registered donors in the area, and the weather on the particular day of donation. Appendix A.5 presents the teams' collection plan for 2004/2005.

The teams' working times depend on the category of donation. For industrial sessions (visits to organisations) teams set off from the Southampton blood centre at 08.00 and come back at 18.00. For public collections teams start at 11.00 and come back at 21.00-22.00. The busiest hours of the sessions are in the middle. The latest arrival time for donors at a public session is typically 19.00. Each donation takes on average 30-45 minutes. The collection process, apart from the actual donation process, also includes the following: travelling time to the venue and back, usually 45min - 1hour each route, setting up time (loading/unloading/packing) around an hour, short team briefs and lunch breaks.

At the end of the day, teams which are based in Southampton will bring back the blood units; otherwise the NBS Centre vehicles will collect them. Additionally, there are mid-day pick-ups by the Southampton NBS vehicles which take the units collected up to that time on their way back to the Centre after completing their routine deliveries. The duration of the journey depends on the distance of the particular venue from the Centre and the road congestion. It usually takes no more than 3 hours.

In the Southampton region collections take place from Monday to Friday inclusive Bank Holidays. Other regions, e.g. Midlands, work during weekends too. This is purely based on the working terms and conditions of each region which have been established in the past. In Southampton 64% of the donated units come from public collections, 33% from industrial collections and only 3-4% are collected on-site. The processing department operates from Monday to Saturday. Its employees work from 08.00 to 21.00 on week days and from 08.00 to 15.00 on Saturdays. Therefore, it is possible that late collections from public sessions must wait until the following day to be processed. Processing takes around 2 to 3 hours, depending on the product and the processing method. The processing machines usually have enough capacity to cope with the awaiting workload. On-site testing is carried out as soon as the blood is back at the NBS Centre. The testing department operates from Monday to Friday midnight. Samples of the collected units are also sent for NAT testing to Birmingham next morning around 07.30, and the results are available by 14.00 the same day. At that time, if the results are good, the components are ready for delivery or storage.

Figure 5.1 and Table 5.1 show the monthly differences between collected, processed and issued units from the Southampton NBS Centre during the financial year 2003-2004. The 31%, on average, difference between collections and processed units is due to collections which are sent over to other NBS Centres (Bristol) for PTI. There is also around 8% disparity between processed and issued RBC units. However, the discards database, obtained from PULSE, explains only 0.25% of this 8% loss. 73% of the discards in the database was due to outdating. As a rule of thumb the following equation should apply:

Collections (for PTI in Soton) = Issues + Discards

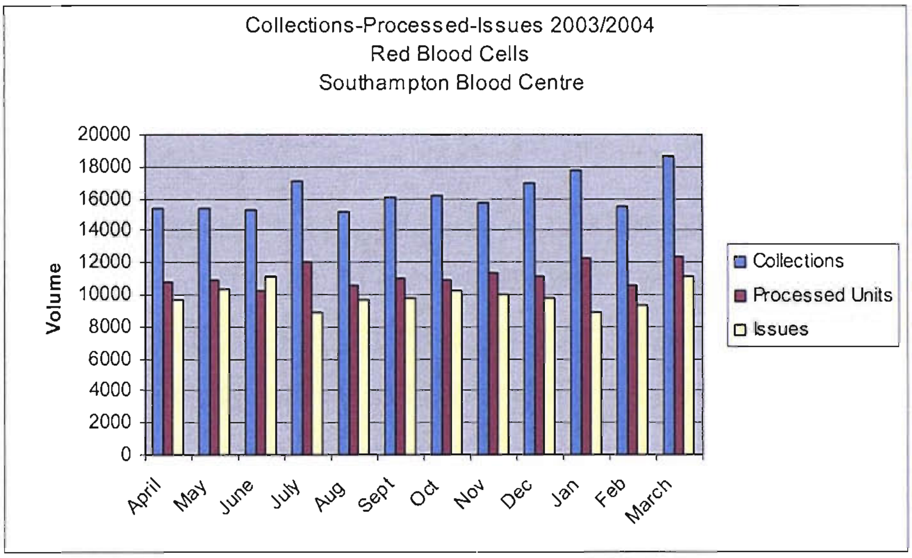

Figure 5.1 Differences between collected, processed and issued RBC units from Southampton Blood Centre, April 2003 – March 2004.

Table 5.1 Collected, processed and issued RBC units from Southampton Blood Centre

Months	Collections	PTI Bristol	PTI Soton	Discards Soton	Issues Soton
April	15400	4660	10740	90	9610
May	15393	4478	10915	70	10315
June	15256	5043	10213	79	11119
July	17097	5032	12065	74	8843
Aug	15133	4543	10590	20	9647
Sept	16066	5075	10991	19	9820
Oct	16132	5271	10861	15	10172
Nov	15742	4356	11386	33	10049
Dec	16963	5786	11177	17	9731
Jan	17742	5496	12246	25	8876
Feb	15543	5005	10538	8	9319
March	18615	6286	12329	19	11092
Total	195082	61031	134051	469	118593
Monthly					
Average	16256.8	5085.9	11170.9	39.1	9882.8
SD	1109.6	565.9	699.2	29.8	729.8
Daily					
Average on WD	774.1	242.2	446.8	1.3	329.4
WD: Working Days	21	25	25	30	30
% of Collections	100.0%	31.3%	68.7%	0.24%	60.8%
Missing= PTI Soton – Discards Soton – Issues Soton =					*7.68%*

Source: PULSE System, April 2003 – March 2004.

Interviews with the BSMS employees justified that typically losses approach 8% from collections to issuing. It was also observed in the database that all discards had identifiable ABO and Rh groups, which indicates that these units have already been through the testing process. In this case it seems that only discards which occur at a late stage are reported. Thus, this particular database was considered inadequate and other sources were used for validating wastage in the model, such as the BSMS annual reports (BSMS, 2002b, 2003b, 2004, 2005). More details about model validation are presented in Chapter 6.

The issues database for the purposes of data analysis was classified by destination of issues, to hospitals and other NBS Centres. The provided information was checked against a private hospital (BUPA hospital in Chalybeate) which kept full records of its blood ordering and delivery status (Appendix A.2). This hospital agreed to provide these electronic reports over a period of time overlapping with the period of the obtained PULSE databases. The quantity of daily receipts of blood units by product from this hospital were compared with the corresponding issues from the Southampton Centre to the hospital between 1/4/2003-13/8/2004. The data were found to be very similar and most of the numbers accurately matched. The means of the two datasets were almost alike and the difference between the standard deviations was less than 2.5 units. This deviation might be caused by human error in data entry or by the inability of the NBS to deliver the whole order. Therefore, it was concluded that issues data from PULSE was of good quality.

From the acquired database it is noted that in a period of 16 months only 49 out of a total of 172,365 requested RBC units did not reach their destination, due to unavailability of product or cancellation of order. Therefore, we assume that NBS issues to hospitals equal hospital orders, and that these names can be used interchangeably. However, interviews with the NBS staff revealed that this phenomenon does not indicate zero shortages. It is an unofficial common practice that hospital orders of specific blood groups which cannot be satisfied by the NBS in a timely manner are substituted by issues of other groups. Before this is arranged, negotiation takes place between the NBS and the hospital, so that the hospital alters its initial order to match the NBS delivery. Thus, this inconsistency between ordered and issued units does not appear in the PULSE system.

5.3.2 Product Frequencies and Shelf-life

Our analysis of the supply chain of blood is limited to the most common products. This is because from the range of 115 blood products offered by NBS, only a few are produced and requested in large amounts. Table 5.2 gives an idea of the quantity of issued blood products in the financial year 2003/2004 and their relative frequencies.

Table 5.2 Frequency of common blood products issued from Southampton Blood Centre

		Southampton NBS **Issues** 1/4/2003-31/3/2004		
	Codes	Products	Units	≥0.5%
1	0050	RBCELLS	118585	74.7%
2	LF10	PLASMA (FFP)	15077	9.5%
3	G050	RBCELLS IRRADIATED	6674	4.2%
4	L531	CRYO	3828	2.4%
5	0B20	RBCELLS NEONATAL	3408	2.1%
6	0378	PLATELETS POOLED	3232	2.0%
7	0370	PLATELETS	2669	1.7%
8	G370	PLATELETS IRRADIATED	1841	1.2%
9	G378	PLATELETS POOLED IRRADIATED	1667	1.0%
1-9		SUM Current Products	156981	98.9%
		TOTAL All Products	158772	100.0%

Source: PULSE System, April 2003 – March 2004.

Only 9 products appear with a frequency of more than 0.5% of issues during that year. These 9 products account for almost 99% of all issues. Moreover, issues of RBC (0050) dominate, comprising about 75% of issues. Plasma (9.5%) and cryoprecipitate (2.4%) can be considered as non-perishable products, since their shelf life extends to 12 months. These two products are not the focus of this research as they do not significantly affect stocking, orders and distribution policies. After meticulous analysis of the data it was concluded that no units of plasma or cryoprecipitate alone ever triggered a delivery to the hospital. Issues of these two products were always accompanied by other perishable products. Hence, it is assumed that hospitals' needs for plasma and cryoprecipitate are fulfilled during deliveries which have primarily been requested to cover requirements of perishable products. Subsequently, they were excluded from the database and from further analysis in this study. Irradiated RBC (G050) comprise 4.3% of Southampton issues. These products derive from RBC (0050) after extra processing and are only produced at the request of the client. RBC units which have been irradiated within 14 days of collection expire 14 days after irradiation and thus on their 28th day after collection at maximum. Those which have been irradiated more than 14 days after collection expire either 5 days after irradiation or at the original expiry date of the pack, whichever comes first (Bryan Lees, 2004; Royal Children's Hospital, 2006). Neonatal

RBC, which comprise 2.1% of issues, are suitable for transfusion until expiry (35 days from collection). However, if an infant is anticipated to undergo massive or rapid transfusion, the use of older red cell units is not recommended and in this clinical circumstance red cells which are less than or equal to 5 days old at the time of crossmatch should be provided.

The four types of platelets that appear in this table all have 5 days of storage life. They all derive from plain platelets (0370) after extra processing. Platelets may be irradiated, pooled, or both at any stage during their 5 days storage life without altering their life span (Royal Children's Hospital, 2006). Hence, for the purposes of this study they can all fall into the same category of platelets with no distinction. Most of the hospitals do not keep stock of platelets and thus, they are produced only after request. Of the hospitals supplied by the Southampton NBS Centre, only one keeps platelets in stock. In general, only 10% of hospitals all across England and North Wales do so (BSMS, 2003a).

In order to analyse and model the supply chain of blood it can be argued that RBC alone are adequate to provide a good understanding of the system performance, as they account for 75% of issues from a range of 115 products. Most researchers have focused their efforts on analysing the distribution of red cells alone. However, by observing the database for RBC issues by the NBS, we soon realised that the large number of daily RBC deliveries could not totally be explained by common practices. High numbers of unexplained ad-hoc RBC orders were observed. After speaking to the Issue Manager and going back to the complete database of all the issued products, it was clear that some RBC are obtained through ad-hoc deliveries, simply because platelets are needed and since a delivery is going to be made, small shortages of RBC can be covered. So, the need for infrequent products which are not kept in stock triggers a large number of ad-hoc deliveries, which also satisfy the requests of small amounts of RBC units.

Subsequently, as the scope of this research includes the analysis of delivery policies of the system, all of the described products but three, are included in the supply chain under examination. Plasma and cryoprecipitate have been excluded as they are not considered to be perishable products. Neonatal RBC have not been included either because they do not adhere to the FIFO issuing order which would greatly complicate the modelling process. The 1.1% of issues, coming from a wide range of products which are omitted from Table 5.3 is also excluded from this analysis. The number of deliveries that might be triggered by their request is assumed to be negligible.

However, in this study 84.9% of all Southampton NBS Centre issues and 96.8% of perishable product issues are included in the analysis and modelling. These products are classified in three categories. These are the red cells with a shelf life of 35 days, the irradiated red cells with a shelf life of 14 days from the moment of irradiation, and platelets with a storage life of 5 days. Each of these three blood products, however, consists of eight sub-products representing the eight different ABO and Rh blood groups, each of which is handled individually in the model. Moreover, irradiated RBC are considered part of RBC and a distinction is only made when it comes to the age differentiation.

In Figure 5.2, harmonisation is observed between the blood group frequencies of Southampton NBS collections, the RBC requests of the supplied hospitals and patients, if it is assumed that patient blood group frequencies follow these of the UK population. The latter assumption is valid since there is no medical evidence for people belonging to a particular blood group to be more prone to any kind of illness than people who belong to any other group. The greatest difference (5%) is detected between the A positive hospital orders and patients' frequency, and between the O positive collections and patients' frequency. The latter is higher in both cases; however, randomness might be the cause of this variation. A general comment is that although donors derive from the population pool and therefore should share the same probability distribution, collections are planned by the NBS, meaning that if there is a shortage of blood of a particular group, the NBS can chase regular donors in this group. Of course, these donors may not appeal to the request. In any event, no major differences were observed.

Platelets are only ordered in 6 out of the 8 blood groups, as Table 5.3 reveals. There is no production of group AB platelets and thus no orders for this group are placed. These patients are usually given A positive, O positive or O negative platelets instead. All rare blood groups seem to have fewer platelet orders placed than RBC. On the other hand, more platelet orders are placed for the common groups, to compensate for the rare ones.

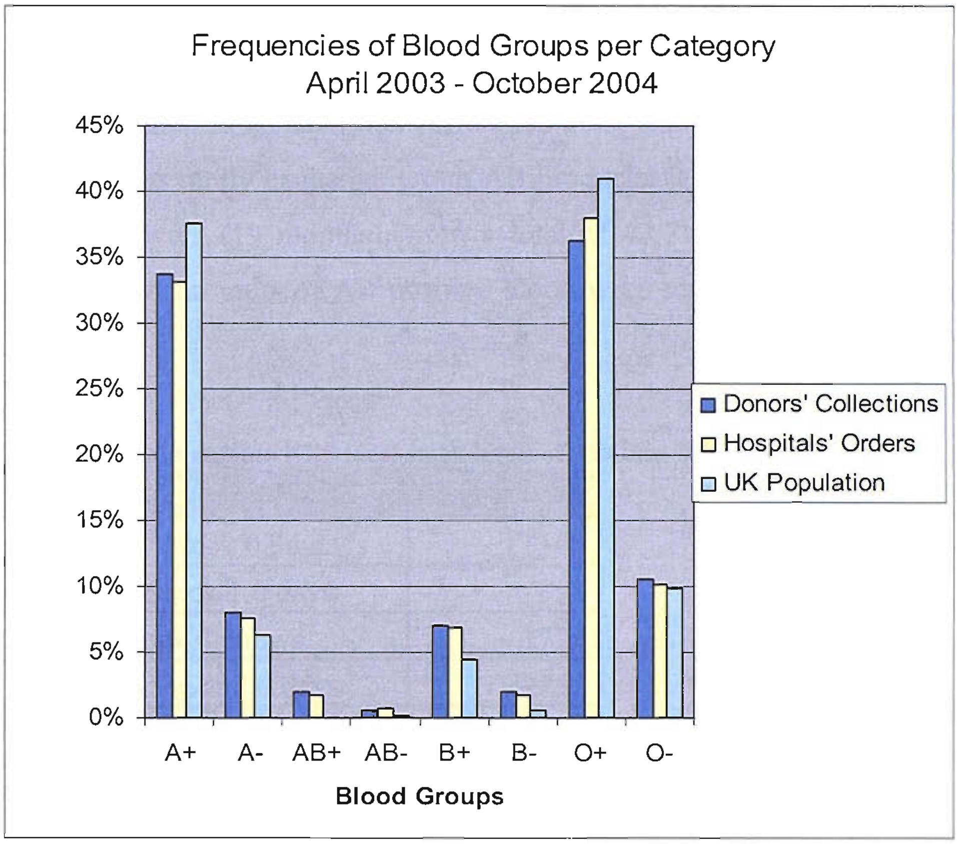

Figure 5.2 Comparison between blood group frequencies of Southampton NBS collections, issues and UK population.

Table 5.3 Comparison between blood group frequencies of RBC and Platelet hospital orders

ABO - Rh Type	Orders	
	RBC	Platelets
A+	33%	38%
A-	8%	6%
AB+	2%	0%
AB-	1%	0%
B+	7%	4%
B-	2%	1%
O+	38%	41%
O-	10%	10%

Southampton Blood Centre, April 2003 – October 2004.

5.3.3 NBS Stock and Issuing Order

As shown in Table 5.4, the ideal stock of RBC units for the Southampton NBS Centre is 4.5 days, which corresponds to about 1800 units. The minimum stock is one day's stock, and the emergency is only half a day's stock. The stock has hardly ever been this low. The maximum is considered to be the stock which covers more than 7 days supplies, from which point on Southampton sends units to other NBS sites to even out the differences with other NBS Centres which experience a deficit. This is a common practice for the Southampton NBS Centre, since it usually has more stock than it needs. During 2004 it held stock of almost 12 days. This is also the case of some other NBS Centres. Southampton and Midlands usually send 600 RBC units to London every week for this reason. London is the area that suffers the most from low collection rates. However, the NBS Centres rarely exchange group AB products. It was observed that in the period the database covers (19 months), from a total of 43,710 units only 60 RBC units of AB negative and no units of AB positive blood were sent from Southampton to other NBS Centres.

Table 5.4 Southampton NBS ideal stock levels of RBC for 2004

Type and Days of stock	Total RBCs
Emergency Stock 0.34 days	149
Minimum Stock 1.0 days	398
Normal Stock 4.5 days	1774
Maximum Stock 7.0 days	2757

Source: Official document, Kirk Beard, National Stock Manager, NBS, 14.5.2004

In Table 5.5 more information about the levels of the Southampton RBC stock per blood group is presented. The actual figures were calculated from the database and the preferred figures were provided by the Southampton NBS official documents. Actual days of stock were computed by dividing the amount of RBC in stock with the issues of RBC during the same period. The average days in stock (bottom line) is a weighted average of the frequencies per blood group and the corresponding actual days in stock. The frequency of blood groups between preferred and actual slightly differs among the groups, apart from A positive and O positive where a substantial divergence is observed. However, the difference in days in stock between preferred and actual hugely varies with respect to the ABO group and Rh type. The major problem centres on groups A positive and AB positive, with 12 and 23 days stock respectively. Especially for AB positive, this number implies that lots of these units were discarded, since the expiry date for the NBS is the 23rd day of the RBC life span, as mentioned in Chapter 2.

Table 5.5 Preferred and actual RBC group frequencies and days in stock of Southampton NBS

RBC Stock Holding					
ABO – Rh	Frequency		Days Stock Cover		
Group	Preferred	Actual	Preferred	Actual	1 Day Units
A+	33%	42%	4.5	11.97	131
A-	9%	7%	4.5	9.05	23
AB+	2%	4%	4.5	23.00	8
AB-	1%	0%	4.5	5.63	3
B+	6%	7%	4.5	9.34	23
B-	2%	2%	4.5	7.94	7
O+	37%	30%	4.5	7.47	147
O-	10%	7%	4.5	6.49	56
Sum/Average	100%	100%	4.5	10.21	398

Source: Southampton NBS Standard Operating Procedures and PULSE System, April 2003 – March 2004.

Taking a wider look, Figure 5.3 shows the days of stock for all the NBS Centres for 3 consecutive financial years. This is called the Issuable Stock Index (ISI). Moreover, Figure 5.4 zooms in on 2001-2002 and analyses the ISI for each blood group except AB. It is apparent that the index of every blood group follows the same pattern of peaks and troughs during the year. It can also be seen that corrective action (increased marketing and donor invitation) is taken when the ISI considerably drops, as in February 2002, to restore stocks which rapidly climb up by the end of March 2002. On the contrary, Figure 5.5 shows that the NBS tries to handle excess days of stock over time by cutting down collections in the following period. In the latter graph it is also noticeable that the total normal days of stock for all NBS Centres combined is 7.8 days, which differs greatly from the 4.5 days of the Southampton Blood Centre.

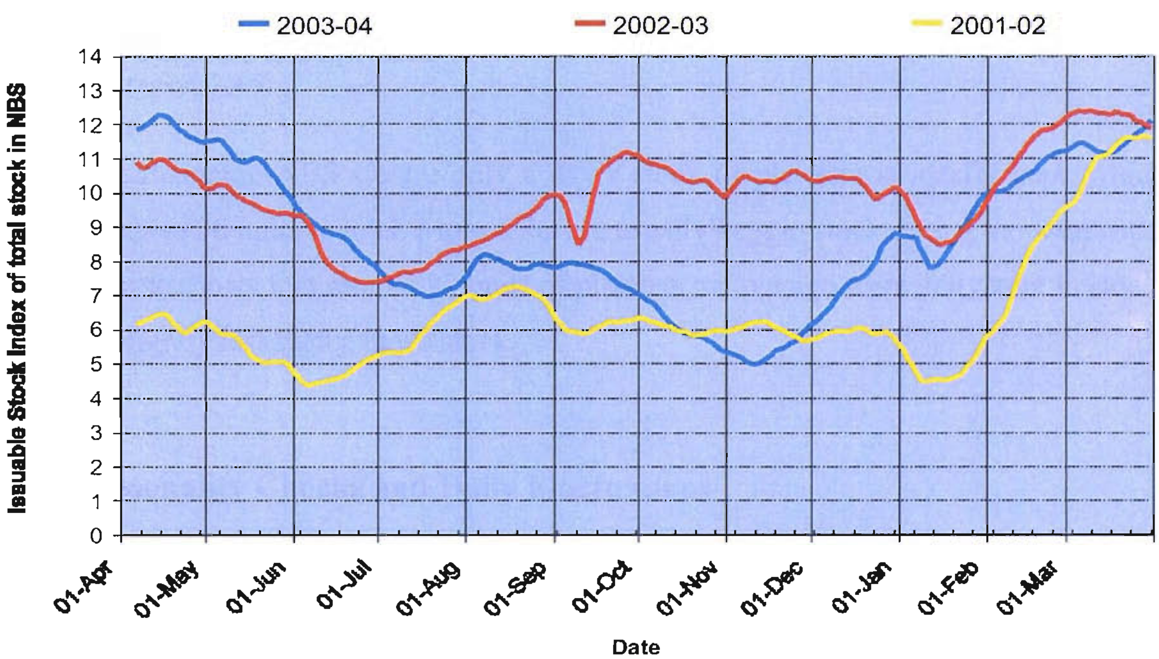

Figure 5.3 Variation in NBS (average of all Blood Centres) issuable stock index of RBCs over time
Source: (BSMS, 2004b)

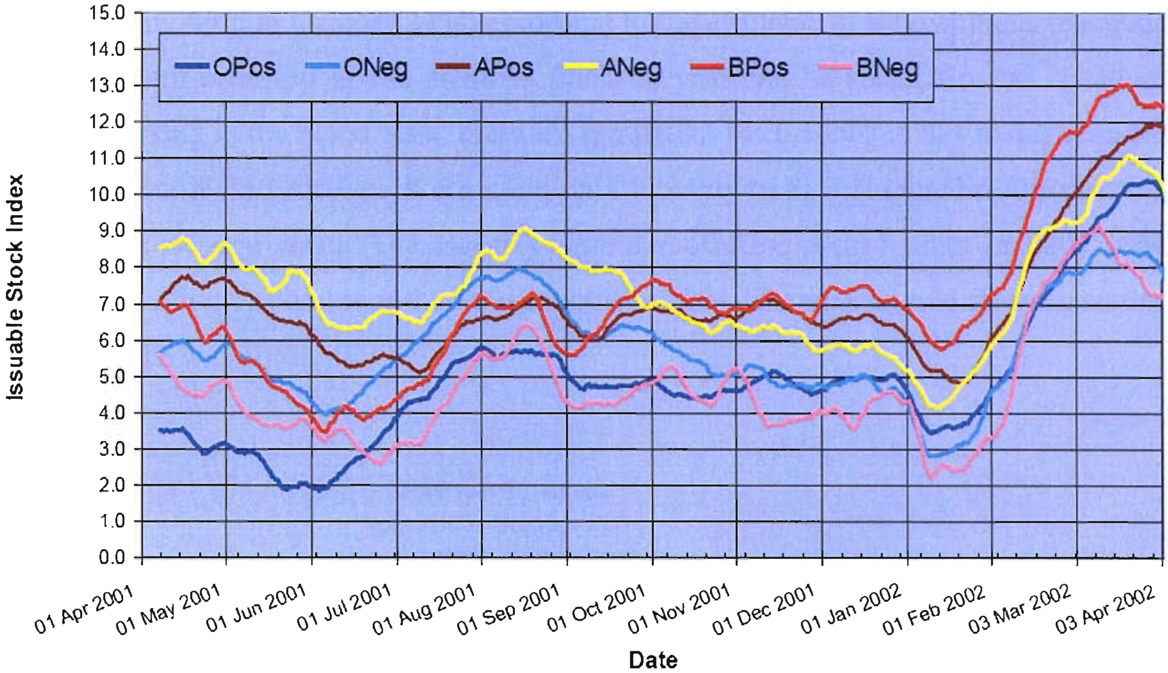

Figure 5.4 Cells Average Age at NBS Issue – Group O, A, & B
Source: (BSMS, 2002b)

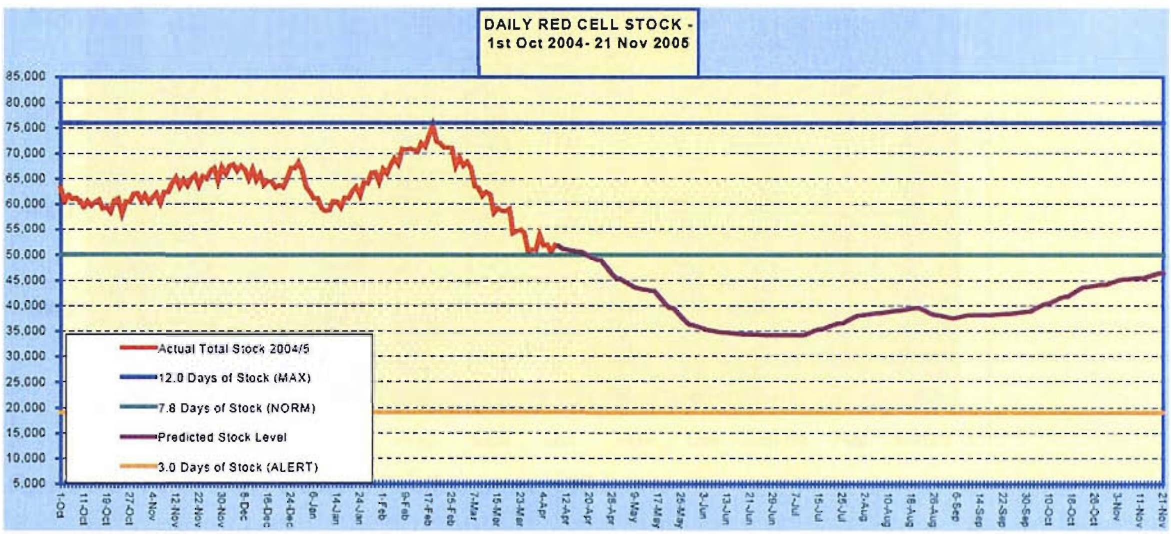

Figure 5.5 Daily NBS Red Cell Stock
Source: (Garwood, 2005)

In the Southampton NBS Centre only a day's stock of platelets is ideally kept, which corresponds to 30 units in total. More units are usually kept in stock during the weekends. The database shows that around 25 units of platelets on average were daily kept in stock, which is slightly less than a day's stock.

5.3.4 Seasonality Checks and Daily Fluctuations

Monthly seasonality in Southampton NBS Centre issues was not observed in the data. As Figure 5.6 shows there are small peaks and troughs during the year, with low issues during July 2003 and January 2004 and peaks in June 03 and March 04. However, for the months from April to October 2004, according to the available data no obvious repetition of the pattern observed in the previous financial year can be seen. Also, as stated by people working in the blood bank, there are significant fluctuations in day to day requests or issues, but these cancel each other out on a monthly basis and therefore the monthly seasonality is very small. The monthly volumes of RBC issued units in 2003 were compared with the volumes of the same months in 2004. The maximum difference among these months was 10%.

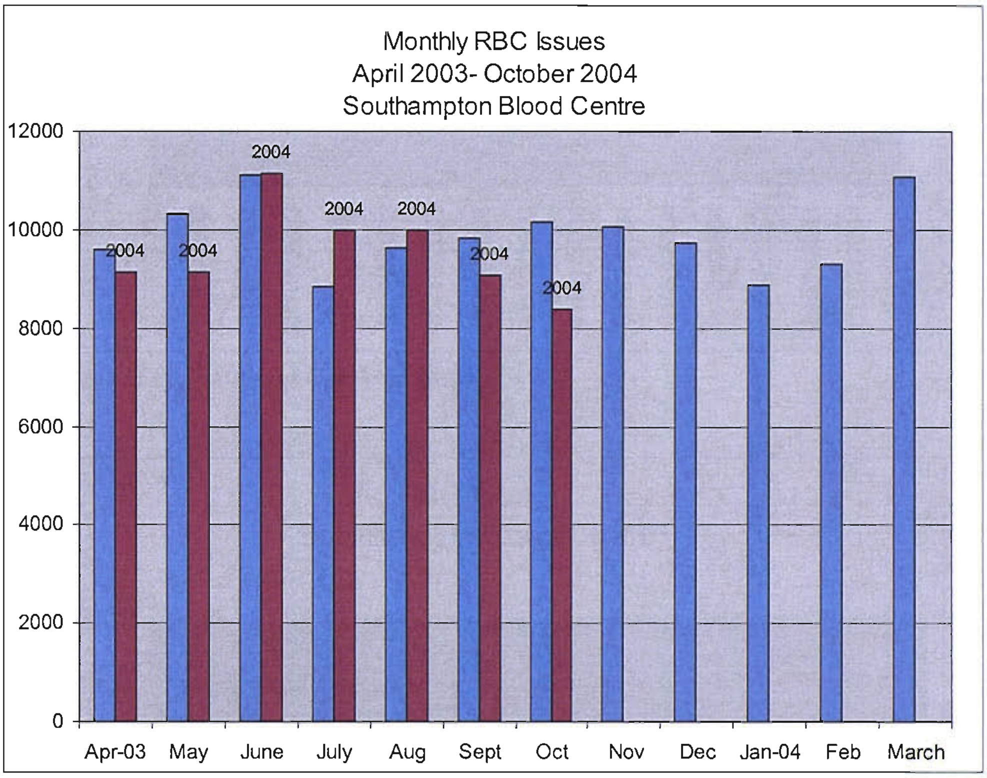

Figure 5.6 Seasonality check of Southampton NBS Issues

The two following Figures 5.7 and 5.8 present the amount of collected units per collection date and the amount of RBC issues per issuing day respectively for the period 1/2/2003 - 31/7/2004. It is apparent that there are days during the year for which high and, most commonly, very low collections are monitored. These are usually bank holidays or the period just after Christmas. For issues, these cases occur more frequently. However, this behaviour is expected as during weekends the hospitals' orders decrease, since they are no Sunday routine deliveries and the whole system is not in full-time occupation.

Furthermore, analysis carried out for collections and issues per blood group illustrated that all blood types follow the same wave of peaks and troughs during the examined period.

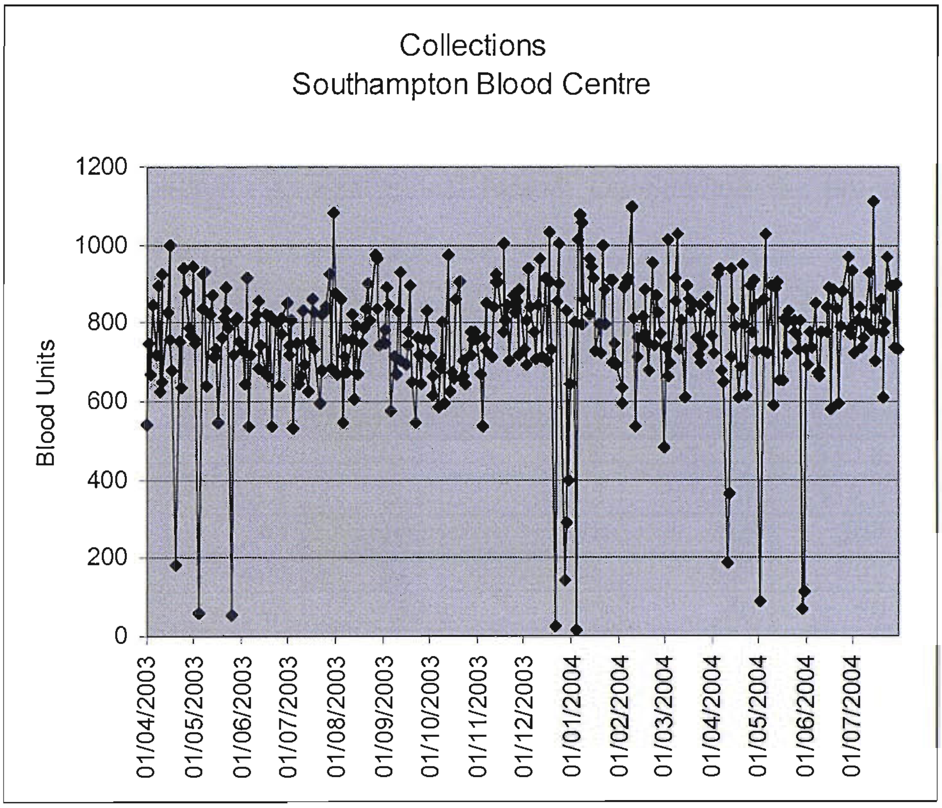

Figure 5.7 Fluctuation of Collected units

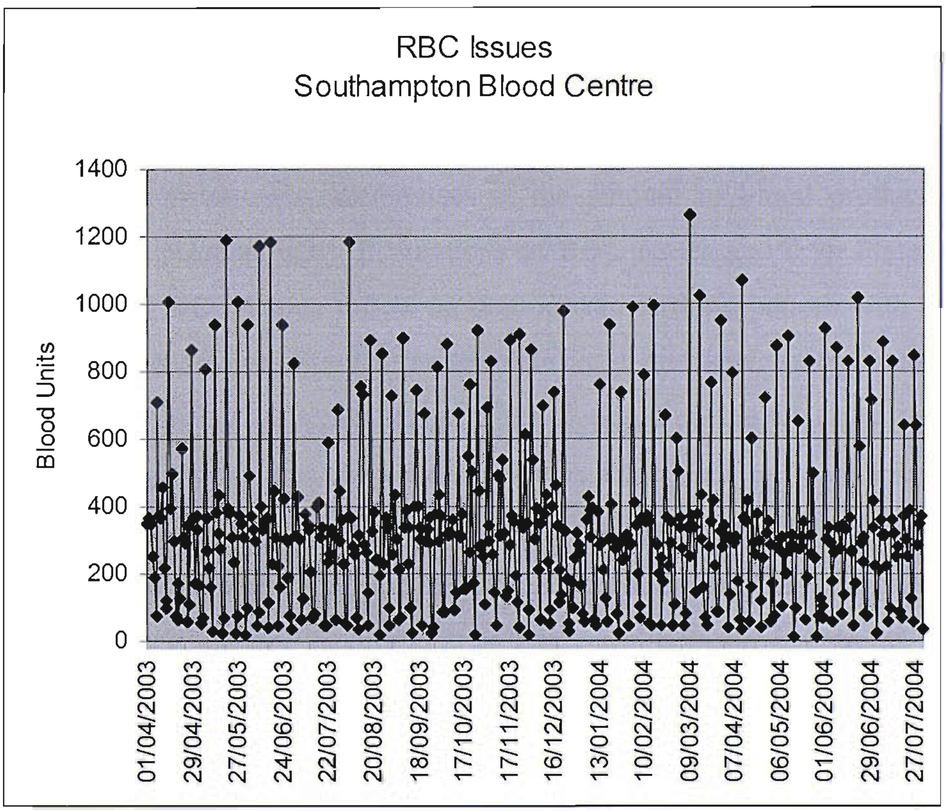

Figure 5.8 Fluctuation of Issued units

Analysis was also performed with respect to the day of week. Collected and processed units as well as issues of RBC, irradiated RBC and platelets were observed for each day of the week. Here the analysis for the processed units and RBC issues is presented in

Tables 5.6 and 5.7 respectively. Appendix A.7 contains all the corresponding tables. Significant daily fluctuations are easily identifiable. In Table 5.6 the Sunday average figure is misleading. There were only two Sundays over the year in which processing took place, probably for an exceptional reason. On Sundays the processing department is usually closed.

Table 5.6 Statistics of daily processed units from Southampton Blood Centre, April 2003 – March 2004

Processed	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	244.9	496.7	529.9	565.3	530.8	255.6	91.0
SD	138.5	313.1	336.5	363.7	339.3	144.0	62.2
Min	143	192	328	315	307	68	48
Max	406	817	861	803	802	394	134
Weeks	48	53	53	50	50	51	2

Table 5.7 Statistics of daily RBC Issues from Southampton Blood Centre, April 2003 – March 2004

RBC Issues	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	327.1	306.0	188.5	192.1	151.0	58.7	54.5
SD	194.6	178.9	95.8	99.8	70.0	6.1	3.9
Min	20	228	169	163	50	8	20
Max	1188	1261	730	828	394	234	283
Weeks	52	53	53	51	52	50	49

Furthermore, the issues of each product under examination are plotted in a graph to clearly demonstrate any differences in the amount of blood products issued per day. Figure 5.9a presents daily fluctuations of RBC issues and 5.9b Platelets and Irradiated RBC issues. RBC issues follow an obvious diminishing pattern with Monday being the most popular day and Sunday the least. In irradiated RBC and platelet issues no pattern can be seen during the week, except at the weekend during which issues are low. A factor which partially explains these behaviours is that RBC units are kept in stock and the deliveries which are made early in the week to recover the lost stock from the weekend satisfy some of the demand for this product for the following days. On the contrary, the other products are not usually kept in stock and demand is covered by daily issues as requests arise. In Figure 5.9c daily hospitals' orders of RBC are plotted. These data have been obtained from a survey (BSMS, 2001a) examining the RBC order patterns of 76 hospitals. The pattern of this graph is not very different from the RBC issues derived from the Southampton Blood Centre database. The differences between Sunday orders and issues can be explained by the fact that Figure 5.9c includes only orders for routine deliveries, and on Sundays mostly ad-hoc and emergency deliveries take place.

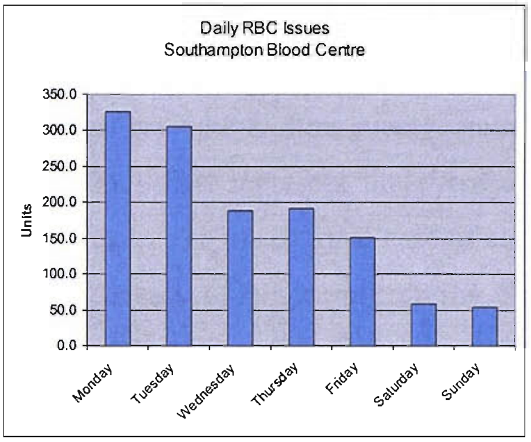

Figure 5.9a Daily average issues of RBC units

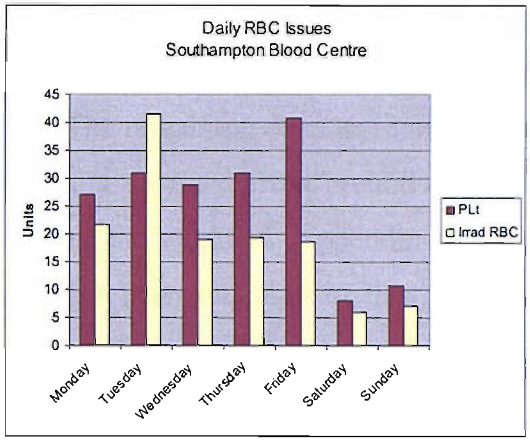

Figure 5.9b Daily average issues of Platelets and Irradiated RBCs

Southampton Blood Centre, April 2003 – March 2004.

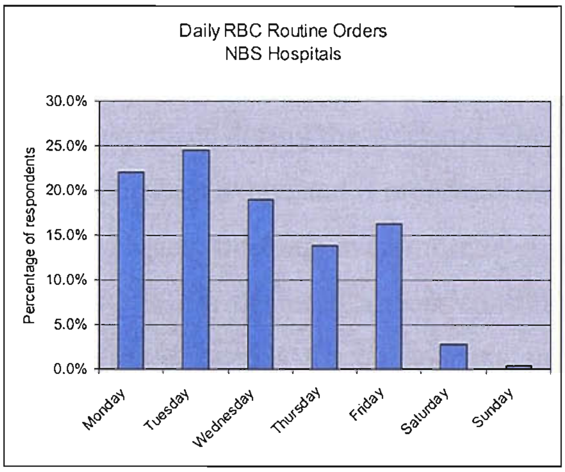

Figure 5.9c Daily average hospital orders of RBC units
Source: (BSMS, 2001a)

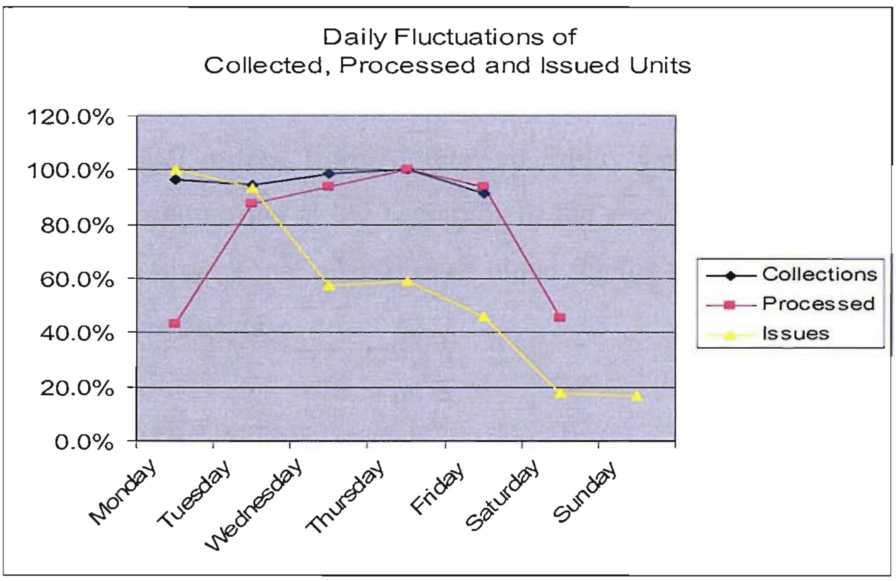

Figure 5.10 Percentage difference of daily fluctuation between collected, processed and issued RBC units
Southampton Blood Centre, April 2003 – March 2004.

Finally, Figure 5.10 demonstrates the percentage fluctuation between different days of the week for collected, processed and issued RBC units. The 100% value relates to the day of the week with the highest average number of units. The remaining days are compared to that. The points represent the average values of units obtained from around 49 to 53 weeks data. The exceptional case of collections during the weekend (Appendix A.7) and the two cases of processing during Sunday have not been included in this graphical representation, to avoid confusion.

The numbers of collected units from Monday to Friday are quite stable. On the contrary, the number of processed units from the Southampton Centre varies significantly. On Mondays and Saturdays a decrease in the units under processing is observed. This is explained by the fact that on Mondays most of the collections arrive at the Centre in the afternoon and no collections take place during the weekend. On Saturdays, moreover, the department is only operational for half a day, and it processes the units that have been left over from Friday's collections. Issues fluctuate even more over the week. From Monday to Sunday the amount of RBC issues decrease almost constantly. On Sundays this is expected as there are no routine deliveries for transporting the units to the hospitals. Furthermore, on Saturdays hospitals do not usually order, for two reasons. The main reason is that because in the past there were no routine deliveries on Saturdays and hospitals have not yet adjusted their practices, and secondly during the weekends fewer hospital staff are working than during week days. This applies to all related employees; from physicians who order blood for their patients to blood bank managers who order blood from the NBS and other related staff. The decreasing trend of RBC issues, and hence hospital orders, from Monday to Friday can only be explained by the fact that hospitals tend to order at the beginning of the week to fill up their inventory and then do not need to order equal quantities of blood for the remaining days since they keep stock for more than one day.

5.3.5 Transport and Deliveries

5.3.5.1 Means of Transport

The Southampton NBS Centre has the following transport mechanisms in place for collecting blood from and delivering it to specific destinations:

- 5 team vehicles properly equipped for collection teams running the sessions

- 2 mini blood vehicles with 3 beds included, which go to organisations and industrial parks for collections
- 1 refrigerated vehicle for transporting components between NBS Centres when the inventory adjustment takes place every week
- 4 transit site vehicles for deliveries and collections
- 5 cars for ad hoc and blue light deliveries
- there are routine flights for the blood delivery of the Channel islands
- a helicopter is hired for supplying the Channel islands in emergency situations
- 11 drivers who work in shifts were employed in 2004. They are appropriately trained to drive any of the NBS vehicles.
- All the vehicles and most of the services are available 24 hours per day. A van can carry many hundreds of units.
- For blue light deliveries taxis or couriers are hired in order to assure rapid delivery.

5.3.5.2 Routine Scheduled Deliveries

Routine scheduled deliveries take place at 10.00 from Monday to Saturday. This time was arbitrarily decided long time ago. At the time of the study all 17 hospitals had one routine delivery per day, with the exception of Southampton General which is on the same site as the NBS centre. A second routine delivery at some point between 14.00 and 16.00 is now under discussion between the hospitals and the Southampton NBS Centre. The outcome of this policy will be tested in the following chapters. The service for ad-hoc and blue light deliveries is available 24 hours a day. NBS team vehicles follow a particular route in order to deliver blood. These are the North, East and West routes. On average not more than 3 to 5 medium hospitals or 7 very small hospitals belong to the same route. Generally, vehicles set off at 10.00 and deliver to the last hospital by 14.00. In the meanwhile these transit site vehicles also collect boxes with blood from the bloodmobile units or from teams who pay visits to organisations for the same purpose. Thus, vehicles are exploited on both legs of their journey. At the beginning of this study some hospitals had their own routine delivery at around midday, which did not belong to a multi-stop route. However, the Issues Manager decided that these favourable treatments were going to stop and all hospitals would be allocated specific routes. Appendix A.6 shows the Southampton NBS Centre's issues by destination. It also indicates the route which each destination belongs to and its distance from the Centre.

Drivers do not always follow the same order when serving hospitals which belong to the same route. The order depends on the traffic or whether a particular hospital urgently requires the delivery. Some hospitals also do not require deliveries every day. In normal traffic a route can take as little as 2 hours or as much as 6 hours.

At the Southampton Blood Centre, hospitals' routine orders should be placed the previous day, overnight or well before the scheduled delivery time at 10.00. Orders which are sent close to 10.00 will be either dispatched at 10.00 or will be delivered with next day's scheduled transport, depending on whether there is sufficient time for preparing and packing the units without delaying the delivery. Other NBS Centres, which usually serve more and bigger hospitals, do not deliver routine orders at the same day. The distribution of the orders is postponed for next day's routine delivery. The Blood Stocks Management Scheme's survey in 2001 (BSMS, 2001a) of a sample of 76 hospitals showed that 51% had routine orders delivered the same day and 49% had deliveries arriving the following day. In this case study both situations are examined with the aid of the simulation model. In the first case, Friday evening and Saturday early morning routine orders can be delivered on Saturday. Saturday late orders and Monday morning orders will be delivered on Monday. In the second case, Friday orders will be delivered on Saturday, Saturday orders will be delivered on Monday, Monday orders will be delivered on Tuesday and so on. In all cases it is common that orders are prepared (scanned and packed) at the issues department as soon as possible after the order arrives, and only rarely is their preparation delayed to just before delivery.

5.3.5.3 Classification of Delivery Types

Statistics on the number of deliveries by type of delivery were obtained from the issues database. However, the size of this large database and some errors in its coding made this analysis difficult.

Deliveries come under 7 codes in the issues database, represented by letters in alphabetical order starting with A. These are: ad-hoc (A) and blue light (B) deliveries, collections of orders with hospital's transport (C), del:stock (D – stock delivery), emergency (E), ad-hoc free (F) and routine delivery (R), as shown in Table 5.8.

Table 5.8 Delivery types

Code	Del Type
A	Ad Hoc
B	Blue Light
C	Collect
D	Del:Stock
E	Emergency
F	AdHoc-Free
R	Routine

However, only four delivery types were clearly identified in Chapter 2. These are routine, ad-hoc, emergency delivery and collection by client transport. We attempted to reclassify the 7 codes into these 4 recognised types. Following advice from the Issues Manager it became apparent that there are no differences between some categories, such as blue light (B) and emergency (E) or Del: Stock (D) and Routine (R). The different coding was due to inconsistency between NBS employees when entering the data. Ad-hoc free (F) deliveries refers to routine orders which, due to an error by the Centre, were delivered as Ad-Hoc (correction of a wrongly sent order, or unavailability of product by the time of routine delivery) and thus no charge was imposed by the NBS on the hospitals. However, it was made known by NBS staff that Saturday routine deliveries were sometimes wrongly coded with F over the period of the acquired database. Hence, for simplification it was assumed that deliveries coded F fall indistinguishably into routine deliveries. Moreover, it was observed that each request number does not always represent a single order or delivery. This is because, for example, hospitals call to place an ad-hoc order and after 30 minutes call again to request more units. In the system this appears as two separate orders for which, however, only one delivery is made. Thus, the number of orders/deliveries was calculated irrespective of the request number by assuming that all the orders that fall under the same destination, delivery type, date, and hour ± 1 belong to the same order/delivery. Table 5.9 shows some descriptive statistics on the number of deliveries by type for the financial year 2003/2004.

Table 5.9 Descriptive statistics on Southampton Blood Centre orders/deliveries, April 2003 – March 2004

Destinations (April 2003-March 2004)	Units	Orders Routine	Orders / Deliveries Ad-Hoc	Emerg.	Collect	Total
Hospitals	Annual	4747	2916	208	1605	9476
	Monthly	395.6	243.0	17.3	133.8	789.7
Other NBS Centres	Annual	9	86	0	70	165
	Monthly	0.8	7.2	0.0	5.8	13.8
Hospitals + Other Centres	Annual	4756	3002	208	1675	9641
	Monthly	396.3	250.2	17.3	139.5	803.3
	SSD	22.7	18.5	6.0	12.2	

The table represents the average number of orders/deliveries with the exception of the routine column. In the routine column only the number of orders is displayed and not deliveries. The exception is made because some of the routine orders might fall into the same multi-stop routine service. So the number of routine deliveries could be overestimated.

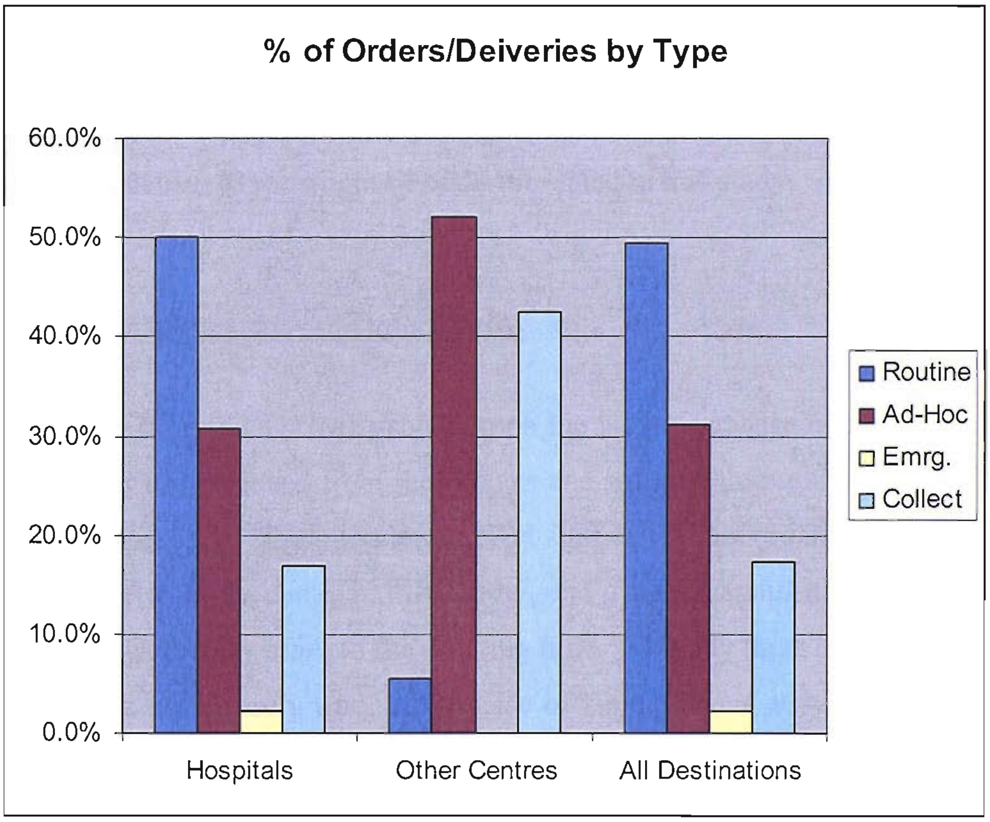

Figure 5.11 Percentage difference of Southampton Blood Centre's orders/deliveries by type and destination, April 2003 - March 2004

As Figure 5.11 demonstrates, almost 50% of all orders are routine, around 30% of deliveries are ad-hoc, less than 2.5% are emergency and less than 17.5%of orders are collected by clients. The pattern of the transport types of blood units that supplement other NBS centres' stock is very different. There are more ad-hoc and collections than routine deliveries, and no emergencies. However, because the number of these deliveries is small, the overall pattern remains approximately the same.

Further analysis on the ad-hoc deliveries was carried out to identify whether daily fluctuations exist. Meticulous checks in the database revealed that ad-hoc deliveries are scattered all over the week and are not exclusively made at weekends when there are no routine deliveries on Sundays.

Another realisation was that the biggest hospital-client (SGH) of the Southampton NBS centre is very atypical in its practices of blood ordering policies, which distorts some of the results. As it is an on-site hospital, blood is collected from the NBS centre instead of being ordered for ad-hoc delivery. Thus, more collections are observed in the Southampton NBS centre than at other centres. In order to avoid fallacies, and since both ad-hoc deliveries and collections are costly delivery types, the two categories were merged under Ad-hoc deliveries. However, the reader should be aware that ad-hoc deliveries generate costs for the NBS and collections for the hospitals. Moreover, the latter is more expensive than the former. Thus, the overall evaluation of costs deriving from this delivery type might be underestimated in this study.

5.3.5.4 Time Frequency of Orders/Deliveries

The exact time (AUDTIME) showing on the issues database literally represents the time the units were retrieved from the shelves and scanned through the system to be assigned to a hospital order. The interviewed NBS staff stated that orders are prepared for delivery as they arrive in the centre in FIFO order, and it can be assumed that the time presented in the database is very close to the ordering time. Naturally there are situations in which this practice is not entirely true. In the case of simultaneous arrivals of ad-hoc and routine orders, ad-hoc orders are prioritised. Also, routine orders can be prepared and scanned through the system any time before the delivery time, which might be the next day. However, there is an attempt to adhere to this FIFO issuing order. Only in cases of shortages in the blood centre will the specific unavailable ordered units be placed into the box for delivery at a later time, when they become available. The simulation models function in line with this logic.

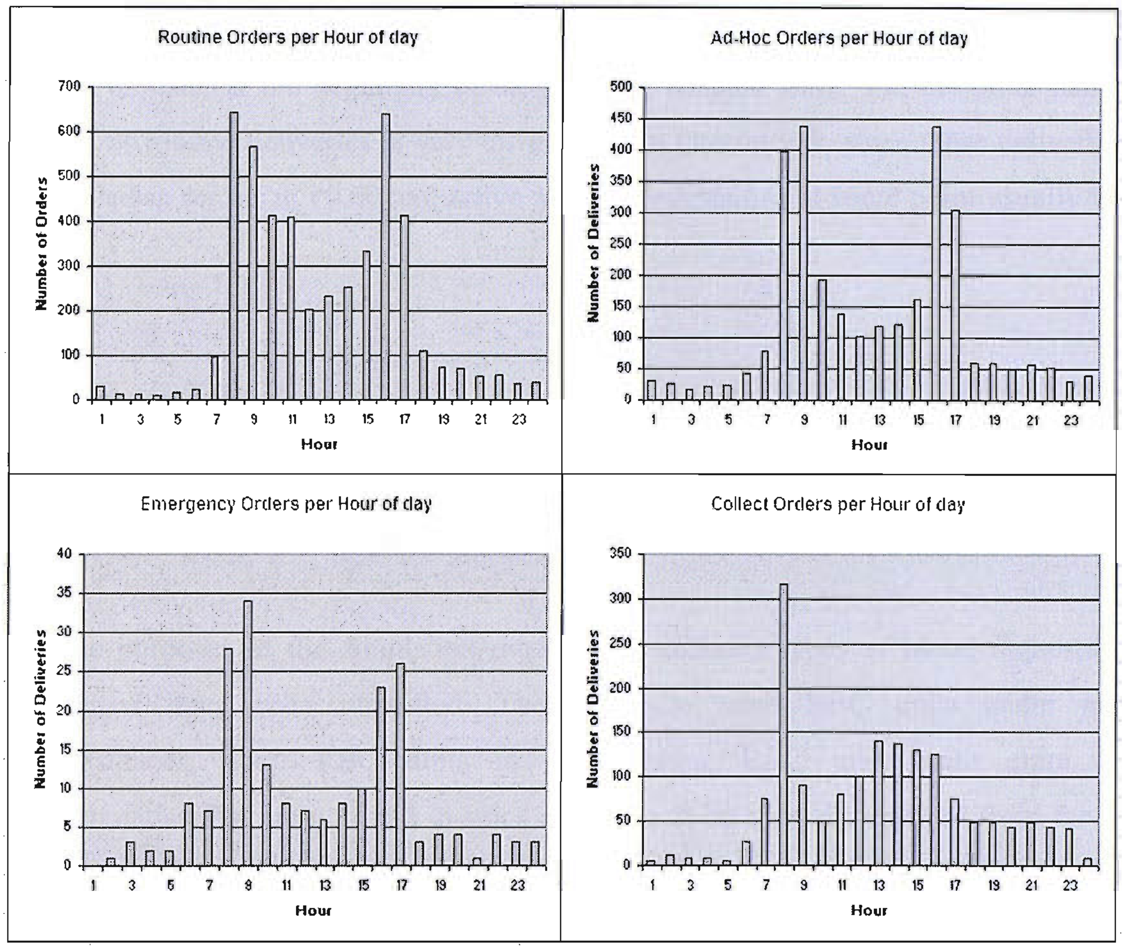

Figure 5.12 Average hourly patterns of orders arriving at Southampton Blood Centre by type for all destinations, April 2003 - March 2004

In Figure 5.12 routine orders appear to have two peaks during the day. This is at 8.00 in the morning and around 16.00-17.00 in the afternoon. This is because different hospitals follow different patterns in placing routine orders, and even within the same hospital this pattern might vary according to the employee who is in charge of blood ordering. Thus, some hospitals count their stock and place orders in the morning, some of them do it in the afternoon or at other times of the day, and a few do not have a standardised pattern and order at random times during the day or night.

Ad-hoc, emergency and collections time patterns are assumed to be similar for orders as well as for deliveries since the time in between these activities is relatively short. The reason for ad-hoc deliveries occurring close to the routine deliveries' time is because hospitals send late orders hoping that they will be included in the routine delivery. Nevertheless, as they come very late and NBS staff cannot prepare them in time for the routine delivery, these orders are finally sent as ad-hoc deliveries and hospitals are charged. Thus, there are two peaks in ad-hoc, closely following the pattern of routine deliveries. The same behaviour is observed in smaller numbers for emergency orders/deliveries. Collections are held at the clients' desirable times, which are usually around 8.00am, at the beginning of the morning hospital shift. On the other hand, the pattern of routine deliveries is very different from their orders, since these deliveries are scheduled to set off at 10.00 and arrive at their destinations at some point usually before 14.00.

5.4 Hospital Processes

5.4.1 Types of Blood Requests from Physicians

For the purposes of the simulation model, five different types of blood requests from physicians have been identified. These include adult RBC units under normal circumstances, adult RBC units in emergencies, RBC units with extra group characteristics that are not held in stock and have to be specially ordered from the NBS, irradiated RBC, and platelets. This classification has been derived from the fact that physicians' requests for these products arrive at different frequencies and have different characteristics in terms of delivery types and product specifications. In particular, adult RBC units that are related to patients for elective surgery or controlled transfusion are the most frequent requests, and the number of units requested slightly varies from patient to patient. Emergency RBC requests are typically requested from the Accident and Emergency (A&E) department for patients with major injuries and heavy bleeding. These more rarely occurring requests come in a substantially higher number of units requested for each patient in comparison to the size of request for ordinary patients. Both of these categories can be satisfied from the hospital blood bank stock, if adequate.

Red cells requests for rare blood groups refers to RBC units for which there are medical needs to comply with additional categories of blood groups on top of the essential ABO and Rh, which are usually the only necessary for most transfusions. Blood bags are labelled with supplementary groups. Thus, when such requests occur, the units in stock are first checked and if none of these satisfy the criteria then an order is placed directly with the NBS. This situation does not occur frequently but influences the number of deliveries from the NBS to the hospitals. If these units are not eventually used they can be assigned to other patients as normal adult RBCs. The irradiated RBCs are especially requested from the NBS and have a different shelf life. However, if not used for the required purpose they can also be given to other people instead of adult RBCs. The size of requested units for each patient of these two categories falls into the same range as for the common adult RBC requests. Platelet requests follow completely different rules in arrival patterns and doses and as such they are treated separately.

5.4.2 Statistical Analysis of Demand and Usage

The stochastic demand pattern of a blood component is totally described using 4 random variables: 1) the number of daily blood requests, 2) the blood group of the request, 3) the size of each request and 4) the number of units used out of the number (size) of units requested, the usage. Most of the above parameters hold different values according to the 5 classified request types.

5.4.2.1 Number of Daily Blood Requests

The first variable is described by the use of a time-dependent Poisson process and use of negative exponential distribution. The selection of the particular distribution has been repeatedly validated by many authors (Elston et al, 1963; Rabinowitz et al, 1970; Yen, 1975). The time-dependent element has been added to this Poisson process because demand for blood products is greater during working hours (8.30–16.30) and is less during evenings and nights. This hours-related pattern is used for all the 5 request types if their arrival frequency allows. Moreover, from the questionnaires and the database it is clear that Sunday requests greatly diminish. Hence, for this day the parameters of the negative exponential distributions change, and the time dependence vanishes if requests become very infrequent. In the PULSE database orders decline on Saturdays and mainly Sundays, and this is partially because of the decrease in physician requests as stated by blood bank managers. In the literature similar patterns were used. Elston and Pickrel (1963) used two negative binominal distributions for each blood type for daily inputs (requests), one valid from Monday to Saturday and the other for Sunday. In some questionnaires, more fluctuations on the daily patterns are indicated, such as high orders on Tuesdays and Wednesdays and very low on Saturdays and Sundays. However, this detailed analysis was left for future research, as here it would further complicate the already complex construction of the simulation model.

Subsequently, all request arrivals follow Poisson processes and each one represents a doctor's order for an individual patient. Hence, each request is for a single blood group since it refers to a particular patient. The values of the parameters defining the Poisson process (with negative exponential distributions) vary from hospital to hospital.

5.4.2.2 Blood Group of the Request

The second variable is described by a probability distribution, which follows the UK population frequency of blood types for red blood cells and the one previously described for platelets (see Table 5.3). These distributions were validated by checking the frequency of the product blood groups of several hospital blood bank orders. Only trivial deviation from the UK population frequency for RBCs between the examined hospitals was observed. Thus, the same distribution is used to describe this variable for all the four classified request types for RBCs in each hospital and for all hospitals. Following a similar approach for platelets the same distribution was used, regardless of the size or characteristics of the hospitals. This probability distribution has been derived from the aggregated orders of all the hospitals under examination.

5.4.2.3 Size of Each Request

The third variable refers to the size of request. This variable can equally be described as the number of crossmatched units per patient. In the latter case only two rare situations are excluded. The general one is the case of an overall shortage of stock in the blood bank, in which case crossmatched units will be none or less than the requested units. The more specific case is the request for O negative units, which cannot be mismatched and for which there is a deficit in the hospital blood bank for the whole period from request to transfusion. In the described case the number of requested units will be greater than the number of crossmatched units. In all other circumstances for which mismatching is allowed, the two terms can be used interchangeably. This parameter varies noticeably from physician to physician and from hospital to hospital. The MSBOS described in Chapter 2 provides some indication; however, it differs between hospitals, is not strictly followed by physicians, and, moreover, is not always accessible to researchers who are not employed by the hospital. Thus, access to actual information relevant to this variable, which will also be adequate to capture a range of hospital practices, is very limited. However, the size of request can be roughly derived from the combination of two other posterior variables. These are the average transfused units per patient and the crossmatching-to-transfusion ratio. From these two variables the number of crossmatched units can be found. According to Varmey et al (2003, p.211) the number of transfused units is on average 2.7 units for red blood cell and 1 dose (unit) for platelet transfusion. If 55% of crossmatched RBC units are transfused (1.8 crossmatching-to-transfusion ratio) then the number of crossmatched units for 2.7 transfused units is 5. If this percentage is 70%, then the size of physicians' requests is on average 3.9 units (obviously in any case only integer number of units are requested). Other authors state that used RBC units vary among institutions between 1 and 5 with a transfusion ratio from 17.1% to 100% (Renton et al, 1997) and among patients from 0 to 6.3 units with a transfusion rate from 16% to 100% (Covin et al, 2003). Hence, if the same method as above is used to define the range of crossmatched units, it can be seen that there is great variability in this parameter.

In this study, when describing a single hospital the variability of requested units from patient to patient is captured by the use of a LogNormal distribution. Other researchers in the past have also used the LogNormal distribution to describe this variable (Elston et al, 1963; Rabinowitz et al, 1970, Brodheim et al, 1980; Yen, 1975). The mean and standard deviation (SD) that define the particular distribution is decided according to the situation. Hospitals with a high transfusion-to-crossmatch ratio will have smaller mean and standard deviation and vice versa. In order to obtain a standard that will help to define the parameters of the LogNormal distribution, the records of the size of various physicians' requests in Southampton General Hospital were manually examined. This information is provided only in handwritten order forms. From around 30 requests none was below 2 units and a mean of 3.7 with an SD of 0.9 was computed for all types of RBCs, with the exception of heavy bleeding, which are typically emergency requests. The latter was found to have a mean of 10 and an SD of 4 units. Finally the request size for platelets per patient was found to have a mean of 1.3 and an SD of 0.5. Figures 5.13 a, b and c show the graphical representation of these distributions. This hospital had an overall transfusion-to-crossmatch ratio of 61%. These graphs were also approved by the BSMS staff.

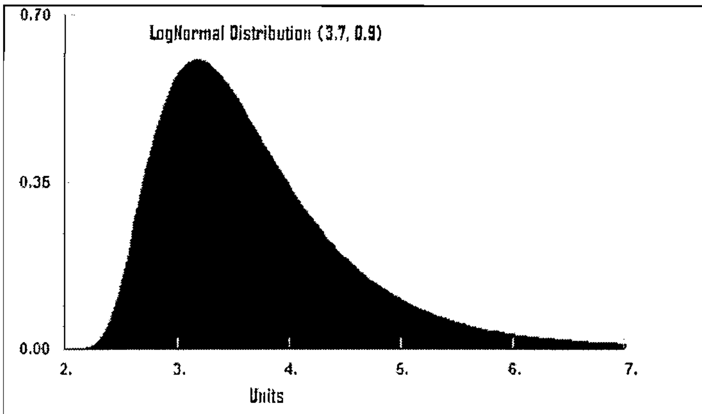

Figure 5.13a Lognormal distribution (3.7, 0.9) describing the number of RBC units requested from physician

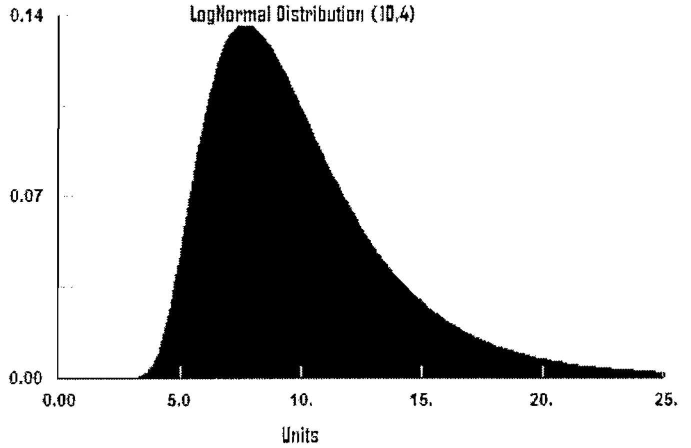

Figure 5.13b Lognormal distribution (10, 4) describing the number of RBC units requested from physician for emergencies (heavy bleeding patients)

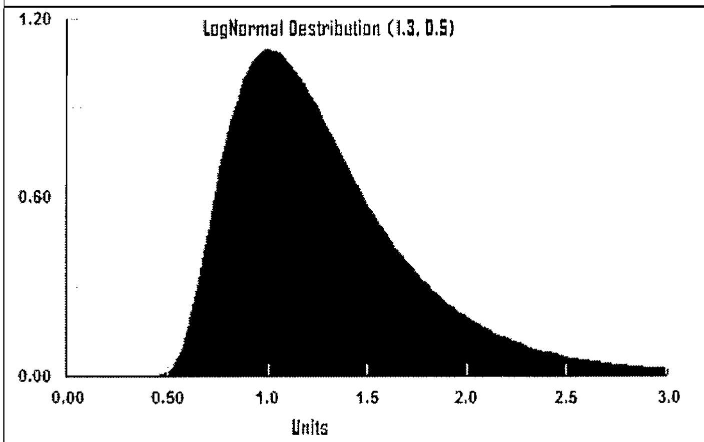

Figure 5.13c Lognormal distribution (1.3, 0.5) describing the number of Platelets requested from physician

The most important observation, which has not been mentioned before in the literature, is the relation between the size of request and usage rate. In general, the more units are requested, above the recommended number, the fewer units are used and vice versa. So, the size of request changes in reverse to the size of used units when aggregated data are examined and not individual cases. Thus, the request size of hospitals which have a transfusion ratio of, for example, 50% could be defined with the following distribution for RBCs: LogNormal(4.2, 1.3), and those with a better rate of 70% by a LogNormal(3, 0.5). The impact of these changes on ordering is assessed in Chapter 7. The request size for platelets and emergencies per patient is assumed to be fixed over the range of 50% to 70% transfusion-to-crossmatching ratio for reasons of simplicity. The infrequent requests for this product mean that this assumption does not have a very negative effect on stock holding and hence on the validity of the model. An important comment at this stage is that the simulation model allows only for integer numbers of units to enter the system and thus the size of request will always be an integer number sampled from the distributions above.

5.4.2.4 Usage Rate (U)

In some previous studies (Rabinowitz and Valinsky, 1970) the complex behaviour of the usage rate meant that only fixed rates or tables with real data were used to describe this variable. Other researchers used a LogNormal distribution (Elston and Pickrel, 1963) or a Poisson distribution (Rockwell et al, 1963) according to the best fit of data, acquired from hospitals they were working with. However, Brodheim and Prastacos (1980) tried to explain the behaviour of this variable by using information and data from a much larger database. They derived to a combined distribution of an inverted triangular distribution $V_1(u,r)$ and a Poisson distribution $V_2(u,r)$, both influenced by a constant "a", which stands for the probability of transfusion.

$$V(u,r) = a * V_1(u,r) + (1-a) * V_2(u,r)$$

The value of "a" was found to be 0.5 for all the examined hospitals. The graphical representation of this distribution produces 3 peaks. Two of them were positioned around the end-points and one in the middle. The end-point peaks were explained by the fact that either all or none (in cases of cancelled surgeries) of the units were used. The middle peak was a result of over-ordering.

In this study the usage rate is described by a probability distribution, which entails further distributions to describe sub-categories, inspired by the example of Brodheim and Prastacos. Ten per cent of all physicians' RBC requests have a usage probability of 1, meaning that all the units are used (defined by a Bernoulli distribution termed "All"). Ten per cent have a usage probability of 0 in which none of the units are used (described in the simulation model by a Bernoulli distribution termed "None"), and 80% have a usage probability related to the particular hospital's crossmatching-to-transfusion ratio, describing the most common case of over-ordering (which is described by a probability distribution termed "Some"). In this latter case some units are transfused, the non-transfused units go back to the bank, and a very small percentage is wasted because units spend a long time (>4 hours) out of the fridge The percentages of 10%, 10%, and 80%

used in the main probability distribution are estimates obtained from the Blood Bank Manager of Southampton General Hospital. Some web search was also performed to ensure consistency of beliefs. Only information about theatre cancellation rates was available. This rate varies considerably, reaching more than 30% but with an average hospital cancelling around 10% of operations (The Guardian, 2002). A 10% transfusion cancellation rate is considered adequate to capture an average situation and was in correlation with the hospital employees' opinions, also bearing in mind that not every single transfusion is carried out in theatre.

In the 80% of cases in which RBC were over-ordered, the probability of transfusion was examined, together with the requested size from physicians. For example, in a teaching hospital, where doctors tend to over-order, a LogNormal(4.2, 1.3) is used to describe the size of an RBC request. For those requests that were over-ordered (80%) a probability distribution of 50% usage, 49.2% returns and 0.8% out-of-fridge discards was used to describe this request. On the contrary, in a hospital which better adheres to the MSBOS, the sizes of RBC requests will fall into the following range of LogNormal(3, 0.5), and the usage is described by the probability distribution of 70% consumed units, 29.2% returned units and 0.8% out-of-fridge discards.

These percentages were empirically derived and validated with some of the hospital blood bank managers. The only most commonly available information from hospitals about RBC usage is the crossmatching-to-transfusion ratio, which was taken into account and was further enriched with other, more realistic approaches, and as such is used in the simulation model.

However, the description of the usage rate of platelets is calculated more simply. This is merely because the average requested size per patient is just above one unit (1.3) and there is little value in using a distribution to determine whether all units will be transfused or none. On the contrary, a percentage rate is used to define the probability of this unit being transfused, returned to unassigned inventory, or expiring due to being out of the fridge for too long. This follows the over-ordering probability distribution which is used for the RBCs, but the transfusion probability is higher because usually only one unit is crossmatched and it is more likely to be used than cancelled. Therefore, a 70% transfusion probability is considered more appropriate for platelets.

In this study, when model experimentation is carried out with policies concerning the usage rate (U), only the parameters of the units transfused or returned of the probability distribution of over-ordering (called "some") are changed; this distribution represents 80% of all cases. The other cases, which describe the usage rate (U) of "none" and "all" units to be used, are assumed to remain steady across hospitals at 10% each.

5.4.3 Blood Bank Inventory Management

Other variables that are important and related to hospital inventory management are 1) days of blood products in stock and stock levels, 2) blood bank ordering policies, 3) issuing order, 4) reservation period and 5) mismatching.

5.4.3.1 Days of Blood Products in Stock and Stock Levels

The first variable, days in stock, refers only to RBC since only these products are usually kept in stock. According to the four identified categories of RBC request types that are useful in the modelling process, basically only two of these can be satisfied by this stock. These are the requests for common (adult) RBC and emergency RBC requests. Units of rare groups of RBCs, irradiated RBCs, and platelet requests cannot be satisfied from the units in stock. They are fulfilled by placing orders as individual requests arise. The only times when these units are actually kept in stock is when previous requests for these products have not been fully consumed and are thus kept in storage until they are used for another request or they time expire. Rare group RBCs and irradiated RBCs in stock can be used for adult RBC requests. Platelets in stock for this reason are checked to see whether they satisfy the arrival of new requests and if they do they are assigned to another patient, and if there are not enough, only the difference between requested and units in stock is ordered.

Hospitals ideally keep anything between 1 to 7 days of RBC stock, but this is not spread evenly across all blood groups. For instance, some hospitals do not keep inventory of groups AB or B negative since these are rare groups. This is common practice in many hospitals. On the other hand, if they keep rare groups in stock these tend to age more than other more frequently used groups. These decisions are determined by the hospital size, its distance from the centre and its blood bank management. Most hospitals keep an average of 4 to 6 days of stock. Figure 5.14 shows the fluctuation of RBC stock cover in a period of 2 months at the end of 2003 for all the 304 hospitals supplied by the NBS. Moreover, Figure 5.15 illustrates the same figure for platelets for those hospitals that keep platelets in stock regularly or keep unused units in the blood bank. Small hospitals may not keep stock or the stock may not be counted in days, as the requests are not daily. Moreover, Figure 5.16 shows the median and variation of days of RBC stock cover per blood group calculated from a survey of 76 NBS hospitals for a period of 16 months (BSMS, 2001b).

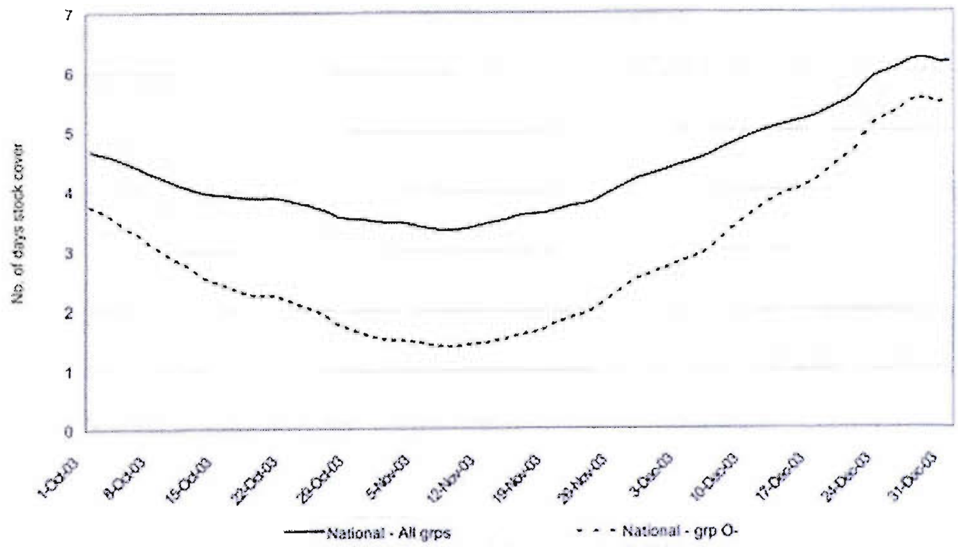

Figure 5.14 Red Cells Stock Cover – All Groups & Group O neg
Source: (Hospital Liaison NBS, 2004)

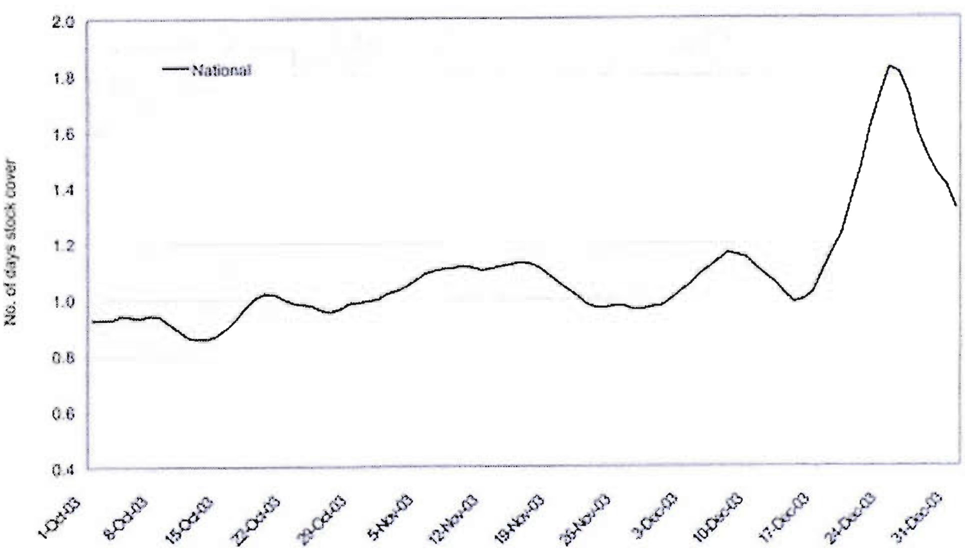

Figure 5.15 Platelet Stock Cover – All Groups
Source: (Hospital Liaison NBS, 2004)

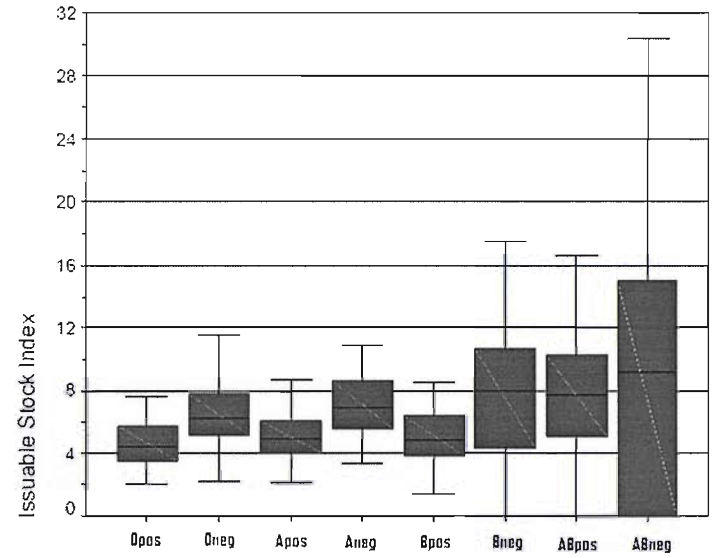

Figure 5.16 Box plots of median number of days RBC stock covers for all blood groups of 76 NBS hospitals
Source: (BSMS, 2001b)

The number of days of stock cover in a blood bank is defined as the issuable stock index. This is the term that Blood Stock Management Scheme (BSMS, 1998) uses to describe this variable. The issuable stock index (ISI) is calculated from the level of unreserved RBC units available for crossmatching, "the issuable stock" divided by the nominal stock which is an approximate value of one day's worth of stock. The one day's worth of stock is the average daily issues from the hospital blood bank, calculated from the previous six months' issues data. The issuable stock usually approximates the ideal stock levels of the hospital, which is the variable that determines the number of orders placed with the NBS. This method of calculating days of stock has been adopted in this study. Ideal stock levels were provided by those hospitals that returned the questionnaires. From those levels the variation between different blood groups was identified. An overall rough average of 5 days stock was initially tested. This value fluctuates between blood groups, following the variation as captured from the actual data, and ideal levels are often rounded to an easily memorised number. Then, the effect of increasing or decreasing this number by approximately 1 or 2 days is demonstrated.

Table 5.10 gives an indication of how the average ISI fluctuates between groups. These values were computed from many hospital blood banks by the BSMS (2004). Nevertheless, the weighted average of these values, taking into account the percentage of issues for each blood group and the dominance of A and O positive groups, is only around 5.5 days, as also stated by the annual BSMS report (2004). Therefore, this case study's experiments on stock holding are in line with actual data from a large sample of hospitals across England and North Wales, and are not specific only to the region under examination.

Table 5.10 Average hospital ISI for each blood group, April 2003 – March 2004

Blood Group	Ave. ISI	Blood Group	Ave. ISI
A Pos	5.3	A Neg	8.3
AB Pos	7.2	AB Neg	10.1
B Pos	5.4	B Neg	9.3
O Pos	4.8	O Neg	7.5

Source: (BSMS, 2004)

Another important parameter in perishable inventory management is the age of stock at issue. The average age of hospital issues of RBCs and platelets for the period October-December 2003 in 304 hospitals was calculated to be 9 and 3.07 days old respectively (Hospital Liaison, 2004). Figure 5.17 presents the fluctuation of the average age over this period, for all groups and group O negative in particular, and Figure 5.18 reveals in detail the percentage of RBC issues for each day of the life of an RBC unit. It can be seen in Figure 5.18 that a surprisingly high percentage of hospital issues are made at days 1 and 2. This figure is quite high considering that usually at day 1 most of the units are still being tested.

Moreover, this average value of 9 days old at time of RBC issues to patients should be considerably higher for the period 2004-2005, as the corresponding age of RBCs at the time of NBS issue was already 10 days or more (Figure 5.3 and 5.17). As it appears from the received questionnaires, the blood bank managers estimate that the average age of RBCs at time of receipt from the NBS lies in the range of 7-14 days old, and the average age of RBCs at the time of crossmatch lies within 10 to 20 days old. Nevertheless, some inconsistencies were identified in these questionnaires, such as that a particular hospital receives blood which is 12 days old but the average age at hospital issue is only 10 days old. This example might be a data entry error, but it could also be a bias that probably derives from the fact that people are prone to complain about the service they receive but appreciate the effort they make in managing their own business.

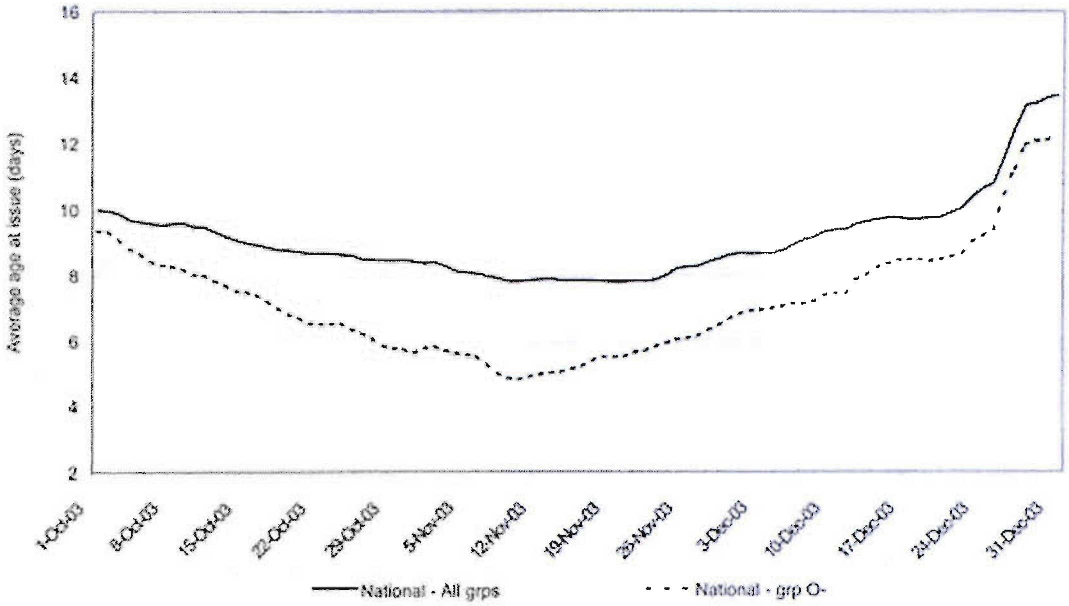

Figure 5.17 Average Age of Hospital Issues of RBC – All Groups, & Group O negative
Source: (Hospital Liaison, 2004)

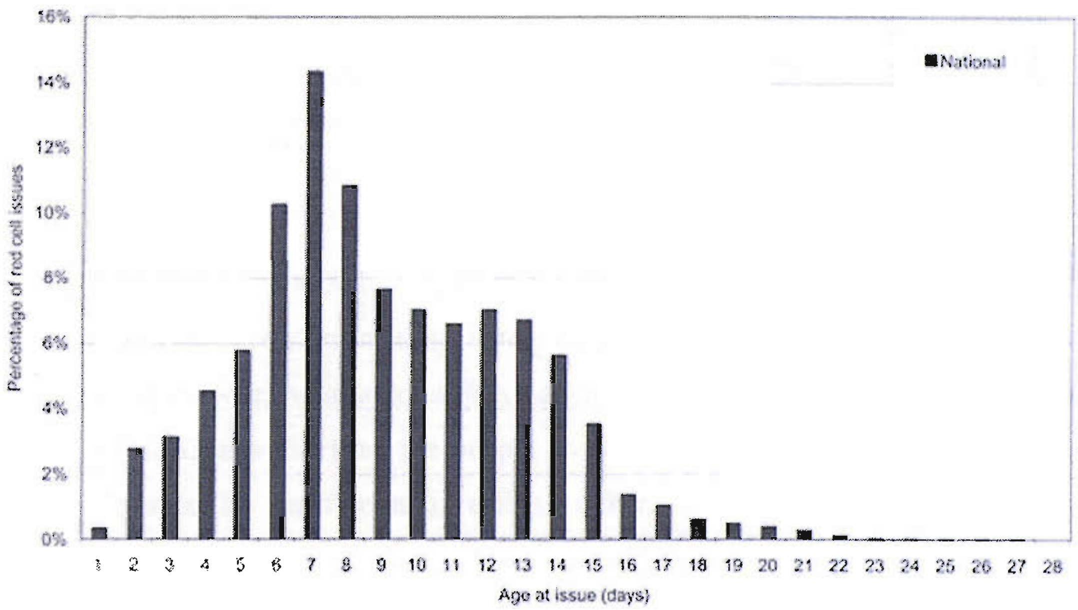

Figure 5.18 Red Cells Average Age Profile of Hospitals Issues – All Groups. October – December 2003
Source: (Hospital Liaison, 2004)

5.4.3.2 Blood Bank Ordering Policies

The blood bank is checked for stock availability every morning or afternoon, as well as whenever necessary following doctors' requests. Checks are done either visually or manually by counting units in the fridge, or electronically if the hospital owns an electronic system with scanners for automatic updates of stocks and status of units. From a survey of 76 hospitals in 2001 (BSMS, 2001a) 38% of hospitals were using a visual review method for calculating stock, 46% were manually calculating and only 19% had an electronic system in place for this purpose. Also, more detailed analysis of these results showed that hospitals that used a visual method were placing more orders per day than those that used a manual or electronic method.

Routine orders with the NBS centre are usually placed either every morning or afternoon from Monday to Saturday as shown in Figure 5.12. Routine orders are placed whenever the RBC inventory is less than the routine re-ordering point. This is commonly around 80% of the ideal stock, and the difference for each blood group is ordered. Also, platelets or rare and irradiated RBC units are ordered at the same time for routine delivery if they are not urgently needed. If their use is urgent then another delivery type will be preferred because the routine delivery can be scheduled for the next day. Ad-hoc or emergency orders are placed when the inventory is low and when urgent deliveries of products not in stock are required. These reasons were validated by blood bank managers and by surveys carried out by the BSMS (BSMS, 2001a). The point of re-ordering RBC stock for each of these two types of delivery depends on the hospital and lies in a range of 30 to 60 and 10 to 25 per cent respectively. Trials with different re-ordering points for ad-hoc and emergency deliveries show the effect of these parameters on the selected performance measures in Chapter 7. Initial trials were with 50% and 15% respectively.

Blood bank managers and doctors do not use well-defined procedures for placing orders, mainly because decision-making tends to be subjective and reliant on individual expertise. Therefore, assumptions about some of the current ordering procedures could not be avoided; nevertheless, the people working in the organisations considered these assumptions to be sensible and realistic either by providing similar figures in the questionnaire or by oral validation. Also, a BSMS survey (BSMS, 2002a) of 76 hospitals found that a substantial majority of respondents (72%) had a documented Standard Operating Procedure (SOP) for red cell ordering; however, more than one in four did not have an SOP. Of those who had one, only 61% were updating it every year, and 91% had a benchmark stock level for each blood group (BSMS. 2001a).

5.4.3.3 Issuing Order

Ideally the units should be kept in the hospital blood banks according to the expiry date. The oldest units should be issued first. However, this is not always the case since first of all doctors believe that fresher blood is better, and secondly sorting the stock according to its age, especially in a big blood bank, is a painstaking procedure to which not all the hospitals devote the necessary time. Issuing the oldest units first is the same as storing inventory in a FIFO order while units arrive from the NBS and in a LIFO (last in, first out) order as they return unused from the assigned inventory. This is because the inventory at the NBS centre is issued in a FIFO order. Specifically, there might be situations in which RBC units delivered on a random day are old and units delivered a couple of days later are very young because there were many requests from other hospitals in between and so the NBS inventory went down. However, the opposite can never happen because blood ages at the same rate in the NBS and in the hospitals. This corresponds to FIFO issuing in the hospital bank when the units arrive, and LIFO issuing of the returned units. The latter should have been the oldest when first issued and, naturally, will have aged at the same rate as the rest of the units in stock.

5.4.3.4 Reservation Period

The total time required for crossmatching ahead of transfusion, plus the duration of transfusion and the time after transfusion until the release of units back to the blood bank, is called the reservation time of a blood unit.

An investigation of 116 hospitals by the Blood Stocks Management Scheme (BSMS, 2002) into routine hospital practices on crossmatching found that 46% of respondents indicated that they crossmatched more than 24 hours in advance, and 54% crossmatched less than 24 hours in advance. Of those who crossmatched more than 24 hours in advance, 60% crossmatched 24-36 hours in advance, 25% crossmatched 36-48 hours in advance, and 15% routinely crossmatched more than 48 hours in advance.

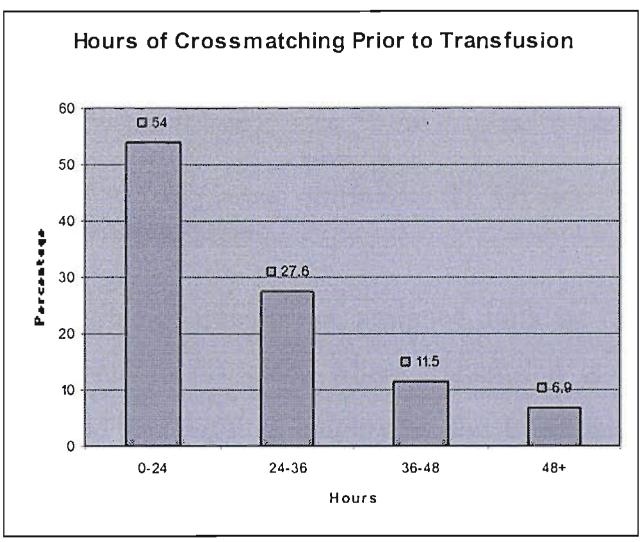

Figure 5.19 Hours crossmatching takes place ahead of transfusion
Source: Survey from 116 NBS hospitals (BSMS, 2002).

The main reasons for early crossmatching were:

a) patients with irregular blood group antibodies for planned transfusion (61%),
b) to use the opportunity of a quieter period in the laboratory (46%),
c) staff shortages at certain times (34%),
d) regularly transfused patients (28%) and
e) planned surgery cases for Monday crossmatched on Friday (19%).

These percentages do not add up to 100% because hospitals gave more than one reason to justify early crossmatching.

However, it was clear from discussions with blood bank managers that the crossmatch period greatly deviates from the mean even for hospitals that routinely try to crossmatch within a certain time in advance. Therefore, a LogNormal distribution was used to model this variable with a mean of 21 hours and a standard deviation of 12 [LogNormal(21,12)]. In the simulation model these numbers are translated into minutes. The time of the actual crossmatching, 30 to 40 minutes, is also incorporated in this period. Figure 5.20 demonstrates a graphical representation of this distribution. In our experiments different parameters of this distribution were tested and their impact on the performance measurements was identified.

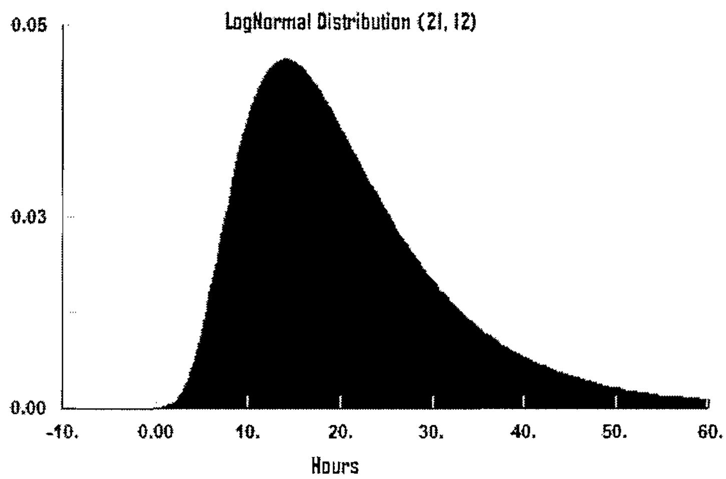

Figure 5.20 Lognormal distribution (21, 12) describing the hours crossmatching takes place ahead of planned transfusion

At the time of transfusion, assigned units are taken out of the reservation fridge and are transferred to the place where transfusion is to take place. According to information provided by hospital employees the transfusion process, which might be part of an operation, can take from 40 minutes up to a maximum of 4 hours in complicated cases, with an average of 2 hours. Using this information, the time blood units spend in the transfusion phase is defined in the simulation model by a Normal distribution with a mean of 120 minutes and a standard deviation of 30, as shown in Figure 5.21. The Normal distribution was preferred to a triangular distribution, for example, because the former can include cases in which the transfusion time is close to zero, meaning that the process was cancelled. Blood that stays out of the fridge for more than 4 hours must be discarded. There is a small percentage of "out of hours" discards of unused units after transfusion. This is defined in the usage rate (U) probability distribution to be around 0.6 per cent overall (80%*0.8).

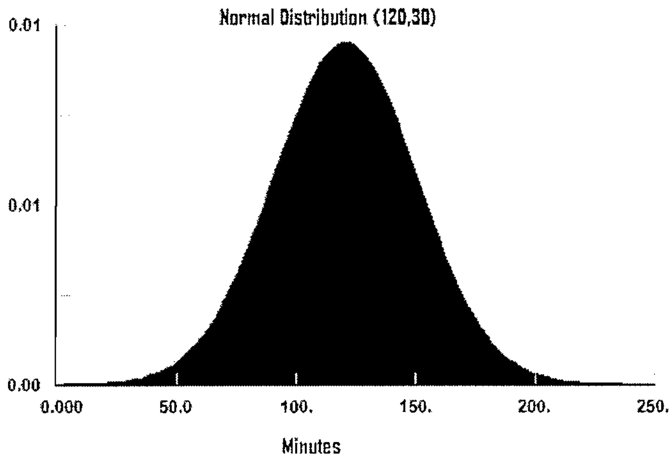

Figure 5.21 Normal distribution (120, 30) describing the duration of transfusion in minutes.

Moreover, information gathered from the questionnaires in this case study and from a BSMS report analysing the crossmatching release period used in 76 hospitals in November 2001 (BSMS, 2001a), indicated that this phase lasts around 24 to 72 hours, depending on the hospital. The great majority of hospitals release unused assigned blood 48 hours after the transfusion time. The actual frequencies were found from the same BSMS study to be 15.8%, 71.1% and 13.2% for reservation periods of 24, 48 and 72 hours respectively. More clarification on the matter was provided by hospital blood bank employees. They explained that this time is not fixed for each blood unit, but depends on the time of day that the unused units are returned from the ward fridges to the main blood bank fridge. Hence, if this time is set to 9.00 in the morning and the transfusion time is at 17.00 then the particular blood units will take 40 hours to physically return into the blood bank, bearing also in mind that units spend almost another day after the transfusion crossmatched to the patient for medical reasons. Other hospitals incorporated this safety period (in anticipation of complications) into the waiting time for the unit to go back to the blood bank. In these cases the same units will return after only 16 hours. Hospitals that used electronic crossmatching and issuing usually followed a policy in which the units theoretically return to unassigned inventory at midnight of the day after transfusion, but physically return to the blood bank the morning after being returned on the system.

The same survey (BSMS, 2001a), showed that all respondents performed one "de-reservation" per day, which is the return of crossmatched blood from the major blood issue fridges to the unassigned blood bank stock, except for one hospital, which performed two "de-reservations". Almost all stock returns were carried out in the morning between 9.00 and 12.00, with the vast majority (78%) returning between 09:00 and 10:00. Another survey by the BSMS (BSMS, 2003a) on the same topic showed that 66 out of 226 examined hospitals (29%) performed a daily morning routine de-reservation and a further 30% performed a Monday to Saturday morning routine release. Thirty-six per cent (83 hospitals) did not, as a routine, perform de-reservation over the weekend. Altogether, 93% of hospitals performed at least one de-reservation per weekday in the morning.

The exact time of this process does not differ much between hospitals, as was shown earlier. However, the fact whether return stock is taken into account for the daily orders affects the number of stock-orders placed with the NBS centre. This will cause variability in stock holding. The first survey (BSMS, 2001a) revealed that 79% of respondents took stock return units into account when placing red cell orders, but 4% took the returns into account in the next day's order. However, the remaining 21%, approximately one in five respondents, did not take returns into account when ordering, which might potentially result in over-ordering. The main reason was that returns take place after blood is ordered.

In the simulation model, different elements are used to describe these complicated variables, crossmatch release period and stock return. The first element is defined by a Fixed distribution which describes the reservation period, after transfusion, for medical reasons, and the second element prevents units returning to the blood bank until the given time. This time was set between 9.00 and 10.00 following the most common practice. The combination of these two modelling processes can effectively capture the real system. The parameter of the Fixed distribution is initially set to 15 hours but then is reduced (to 10) when experimentation is carried out. Also, the routine ordering time is set in different experiments before or after the stock return, to test the impact of this parameter on the holding stock. Analysis of the BSMS survey (BSMS, 2003) suggests that accounting for units returned to stock has no significant effect on the variability of stock level ($p > 0.1$), but does lead to a lower median stock level.

The reservation period for platelets specifically is usually shorter than that of RBCs due to their considerably shorter shelf life. This period before transfusion has been specified to be around 6 hours, described by a LogNormal with a mean of 6 hours and an SD of 2 hours. The period after transfusion is usually limited to the time between the scheduled transfusion and the return of the units to the main hospital fridge, usually at 10.00 in the morning, without any compulsory waiting time.

Several research studies have examined the relationship between hospital issuing practices and the reservation period. It was illustrated by simulation experiments conducted for a large hospital in Philadelphia (Cohen and Pierskalla, 1975; 1979) that increasing the reservation period (λ) consecutively from one to four days severely increased outdating for several shortage rates. They also showed that for low values of λ (reservation period), FIFO yields smaller values of expected outdates than does LIFO. As λ increases to more than six days, LIFO becomes better and FIFO gets worse. Since a reservation period of more than six days is exceptional in the Southampton NBS, a FIFO issuing policy is used in this study, as explained in the section above.

5.4.3.5 Mismatching

Mismatching preferences are also examined in this study. Mismatching is the provision of a compatible blood group when a patient's blood group at the time of request is unavailable. Table 2.4 in Chapter 2 summarises the substitution rules. A survey was conducted in a sample of 99 NBS hospitals (BSMS, 2003a) to investigate the extent of mismatching. The study showed that 5% of issues during the survey period were mismatched in these hospitals and that patients of group A received the highest level of mismatched blood. Around 61,500 units of RBC were issued to these hospitals during the survey period for 25 consecutive days. Three thousand one hundred and five units (5% of issues) were reported as mismatched to 1028 patients. Sixty-nine per cent of those mismatched crossmatched red cell units were finally transfused to 954 patients. The two most common reasons for mismatching were insufficient stock available (57%) and unit time-expiring (26%). Another reason was mismatched units supplied by NBS (4%).

We used this BSMS report on mismatching (BSMS, 2003a, p.3), together with comments from blood bank employees, to derive empirical priority rules on substitution for each blood group. These are included in Table 5.11, which specifies the substitution rules when the patient's particular blood group is not available. Having more than one option for mismatching, wherever possible, is important, because there might be reasons that prohibit choice number one from happening. One such reason could be that none or very little stock of the first proposed blood group substitute is available, although another compatible blood group is available in ample amounts. Moreover, it is common sense that blood bank employees will try to keep enough units of the particular substitute in the bank to cover further requests for the same blood group. In addition, taking a step back, another factor should be examined. This is the possibility that some units of the same blood group as that of the patient have been recently ordered and will arrive soon. In this situation crossmatching can be postponed for a couple of hours, if the request is not urgent. The exact mismatching rules that are used in our models and were also validated by BSMS members are summarised as follows:

1. Mismatching is allowed if same-group blood will not be available in the next 2.5 hours (150 mins).
2. The selection of the compatible group is based on the following criteria:
   a) the oldest compatible blood in the blood bank will be given as long as
   b) there are more than four units of this type in the bank.
   c) The examination of whether each of the compatible blood groups is a feasible option subject to a) and b) follows the order illustrated in Table 5.11.

Table 5.11 Mismatching donor against patient group and preferable substitution options

		Patient							
	Donor	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg
1	Apos			1					
2	Aneg	1		5	1				
3	ABpos								
4	ABneg			2					
5	Bpos			3					
6	Bneg			4	2	1			
7	Opos	2		6		2			
8	Oneg	3	1	7	3	3	1	1	

1: Best substitution option - 7: Worst substitution option

5.5 Wastage

5.5.1 Wastage in the NBS Centre

Wastage figures in both the NBS and hospitals are examined in this section. All the presented information was obtained from the annual BSMS reports covering the years from 2001 to 2005. Wastage is one of the main performance measurements in evaluating the supply chain of blood. Actual data on discards are presented here and act as benchmarks for assessing the validity of the simulation models later on. Wastage is also one of the main defects that can be corrected and improved through better inventory control and supply chain co-ordination.

Table 5.12 illustrates RBC wastage data for the NBS for 4 financial years starting from 2001. Total discards are separated into two categories, which describe the cause of discards; these are "time expiry" and "miscellaneous". The latter category includes factors such as fridge failure and pack label fault. Wastage due to time expiration accounts for 77% of total wastage in 2004-2005 but for only 13% in 2001-2002. Therefore, one cannot conclude that time expiry is always the main reason for wastage in NBS centres. A standard measure for comparison, when referring to discards, is wastage as a percentage of issue. This has the advantage of allowing comparison of discards between different years, regardless of the number of RBC collections and issues. It is apparent that wastage increased dramatically in 2004-2005 compared to previous years, mainly due to time expiry increase. This was largely attributed to the high A positive stock level, reduced demand and subsequent time expiry of excess units (BSMS, 2005).

Table 5.12 Total NBS wastage of RBC by wastage category

RBC Year	Time Expiry	Miscellaneous	Total Discards	Wastage as a % of issues
2004-05	17,348	5,324	22,672	1.1
2003-04	4,955	5,768	10,723	0.4
2002-03	7,374	5,141	12,515	0.6
2001-02	1,402	9,208	10,610	0.3

Source: BSMS, Annual Reports from 2001 to 2005

Table 5.13 shows wastage for platelets. The wastage of platelets as a percentage of issues is much higher than for RBCs. Even the absolute number of actual wasted units is more than for RBC. Clearly, platelets easily outdate since they have a very short shelf life. However, more precautionary measures should be taken by the NBS in order to decrease wastage of this blood product. A suitable suggestion would be that the NBS should produce the larger number of platelets only after clients' requests and not in anticipation of requests, and thus could diminish the amount of product in stock.

Table 5.13 Total NBS platelets wastage by wastage category

Platelets Year	Time Expiry	Miscellaneous	Total Discards	Wastage as a % of issues
2004-05	17,099	10,202	27,301	13%
2003-04	15,780	12,887	28,667	13%
2002-03	16,558	14,518	31,076	14%

Source: BSMS, Annual Reports from 2002 to 2005

5.5.2 Wastage in Hospitals

Wastage of RBCs and platelets also occurs in hospitals, and here wastage is usually greater. Table 5.14 shows the total RBC discards of hospitals that participate in the Blood Stock Management Scheme. Therefore total discards in this table represent only discards from the particular participating hospitals and not from all NBS hospitals. The last column shows the participation percentage. Table 5.15 provides more comparable results of the average wastage per BSMS participant. From both tables it can be seen that time expiration is the main cause of hospital wastage, and this lies in the range of 73% to 80% of total wastage. A more detailed analysis of these figures reveals that group AB has a much larger expiry wastage rate, four to seven times higher than that of any other group. The wastage figures that are presented in this chapter account for all blood groups. Some studies omit group AB wastage, because hospitals do not always have to pay for it when wasted. "Out of hours" represents about 15% of total wastage. Out of hours stands for those units that stay too long at room temperature, out of the refrigerator, when, for example, waiting in the operating theatre, outside the laboratory (hospital blood bank). Overall, an average of 115 to 175 RBC units is wasted in each hospital per annum, which represents 3% to 4.6% of wastage over RBC hospital issues. In 2004-2005 an increase in hospital wastage was observed, which corresponds to the increase in the NBS wastage in the same year (Table 5.12). Table 5.16 shows the time expiry and out-of-hours wastage as a percentage of issues.

Table 5.14 BSMS hospitals wastage of RBC by wastage category

RBC Year	Time Expiry	Out of Hours	Miscellaneous	Total	% of BSMS hospitals
2004-05	38,194	6,883	3,049	48,126	93%
2003-04	23,790	6,097	2,551	32,438	84%
2002-03	23,810	4,915	2,206	30,931	66%
2001-02	13,697	3,675	1,503	18,875	58%

Source: BSMS, Annual Reports from 2001 to 2005

Table 5.25 BSMS hospitals wastage of RBCs by wastage category and average per hospital

RBC Average per BSMS participant	Time Expiry	Out of Hours	Miscellaneous	Total	Wastage as a % of issues
2004-05	139	25	3	175	4.6%
2003-04	91	23	2	125	3.2%
2002-03	103	21	7	135	3.4%
2001-02	82	21	9	113	3.0%

Source: BSMS, Annual Reports from 2001 to 2005

Table 5.36 Hospitals time expiry and "out of hours" wastage as a % of issues

RBC Year	Time Expiry as a % of issues	Out of Hours as a % of issues
2004-05	3.7%	0.7%
2003-04	2.3%	0.6%
2002-03	2.6%	0.5%
2001-02	2.2%	0.6%

Source: BSMS, Annual Reports from 2001 to 2005

Table 5.17 provides similar hospital wastage information for platelets. Only two years of information are available for this product. The wastage as a percentage of issue is relatively higher than for RBCs. For both years 95% of wastage (4.8% out of 5.1% and 4.7% out of 5%) was due to time expiry, and only 5% (0.3% out of 5.1% and 0.3% out of 5%) was due to other reasons. Further analysis of the platelets wastage data reveals that 57% of the wastage of time-expired platelets was due to medically or surgically ordered units that were not used. Sixteen per cent was due to over-ordering. Miscellaneous wastage includes units wasted out of the laboratory as in out-of-hours wastage or fridge failure (BSMS, 2005).

Table 5.47 BSMS hospitals platelets wastage by wastage category and average per hospital

Platelets Year	Time Expiry	Miscellaneous	Total Discards	Wastage as a % of issues
2004-05	8,805	547	9,352	5.1%
2003-04	7,048	438	7,486	5.0%
Average per BSMS participant	32	2	34	5.1%

Source: BSMS, Annual Reports from 2003 to 2005

5.5.3 Discussion

A direct relationship between the stock levels in the NBS, the age of red cells at issue and NBS, and hospital time expiry wastage can be observed over the examined years. The increase in wastage is associated with rises in the NBS stock level and of older red cells supplied to hospitals. Conversely, a decrease in hospital and NBS outdates can be related to the lower NBS stock level and the simultaneous increase in days-to-expiry of the issued RBCs. Variations in time expiry wastage are driven by stock levels and the associated age at issue and are absorbed mainly in the hospitals. NBS outdates are relatively stable. The increase in days of stock in the NBS is the consequence of high collection rates and lower demand from hospitals. Corrective actions that should be taken by the NBS to resolve these problems often require time and thus peaks and troughs in stock and wastage figures are experienced. Figures 5.22a and 5.22b show the fluctuation of NBS and hospital days of stock and wastage over the financial years 2003-2004 and 2004-2005 respectively, in which an increase in wastage was reported.

However, the age of blood in the NBS is not the only problem that causes hospitals wastage. Changes in hospital practice have the potential to improve blood inventory management and minimise wastage regardless of the age of blood at receipt. These potential changes will be shown through experiments with the simulation models.

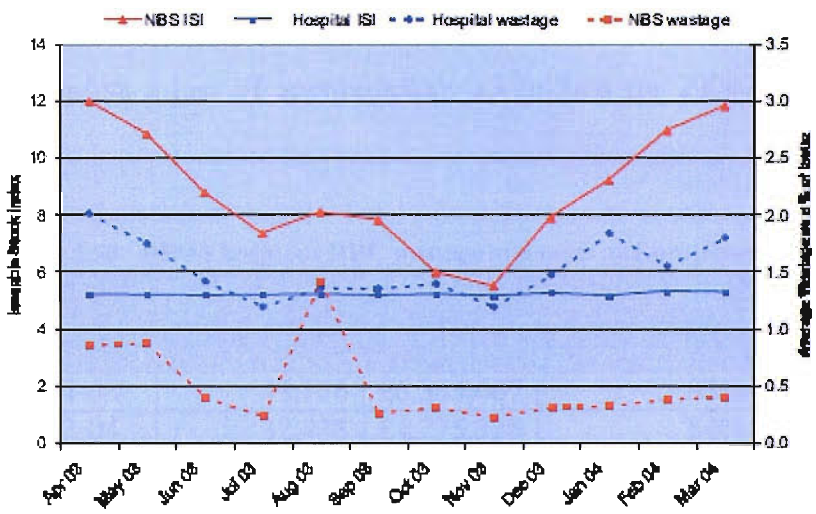

Figure 5.22a NBS inventory level and wastage of RBCs as a percentage of issues, excluding group AB, in 2003/2004
Source: (BSMS, 2004)

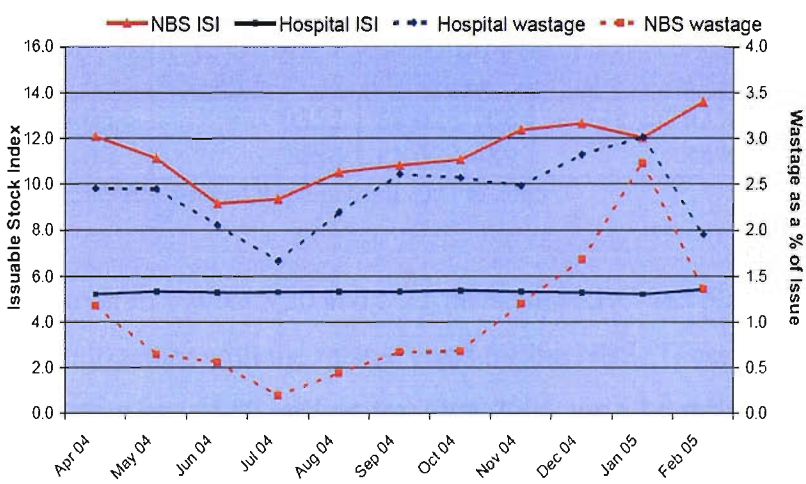

Figure 5.22b NBS inventory level and wastage of RBCs as a percentage of issues, excluding group AB, in 2004/2005
Source: (Bates et al, 2005)

5.5.4 Costs of Wastage

The issue of undesirable wastage is a two-way problem. First of all, units that are wasted might have been very much needed somewhere else, and secondly, blood wastage is a costly waste of money. Since hospitals pay the NBS for the units they receive, they desire optimisation of the blood ordering and inventory system in a way that no excess orders will be made and the acquired units will be utilised in the best possible way. Tables 5.18 and 5.19 show the actual wasted units of RBCs and platelets for the hospitals participating in the Blood Stock Management Scheme. Along with these units, costs are computed in 2005-2006 prices. A red cell unit costs £131.80 and a unit of platelet costs £216.87. Since the approximate proportion of BSMS hospitals in the number of all hospitals in the region of NBS is known, and this is similar to the proportion of BSMS hospitals issues over all NBS issues, estimates were calculated for the wastage of RBC and platelets in all hospitals served by the NBS. The cost of wastage of RBC in all hospitals was found to be over £6.8 million for 2004-2005 and around £2.2 million for platelets. Together this represents a loss of approximately £9 million for 2004-2005 and £7 million for 2003-2004.

Table 5.58 BSMS hospitals RBC wastage and costs and projected values for all NBS hospitals

RBC Year	Total Units Loss in BSMS Hospitals	Total Loss in BSMS Hospitals	% of BSMS Hospitals	Estimated Units Loss in All Hospitals	Estimated Loss in all Hospitals
2004-05	48,126	£6,343,007	93%	51,748	£6,820,437
2003-04	32,438	£4,275,328	84%	38,617	£5,089,677
2002-03	30,931	£4,076,706	66%	46,865	£6,176,827

Source: BSMS, Annual Reports from 2002 to 2005

Table 5.19 BSMS hospitals platelets wastage and costs and projected values for all NBS hospitals

Platelets Year	Total Units Loss in BSMS Hospitals	Total Loss in BSMS Hospitals	% of BSMS Hospitals	Estimated Units Loss in All Hospitals	Estimated Loss in All Hospitals
2004-05	9352	£2,028,168	93%	10,056	£2,180,826
2003-04	7486	£1,623,489	84%	8,912	£1,932,725

Source: BSMS, Annual Reports from 2003 to 2005

Moreover in Tables 5.20 and 5.21 the actual RBC and platelet discards respectively are shown together with the related costs for the NBS. These NBS costs when put together generate a loss of £9 million for 2004-2005 and £7.6 million for 2003-2004.

Table 5.60 NBS RBC wastage and costs

RBC Year	Total Discards	Total NBS Loss
2004-05	22,672	£2,988,170
2003-04	10,723	£1,413,291
2002-03	12,515	£1,649,477
2001-02	10,610	£1,398,398

Source: BSMS, Annual Reports from 2001 to 2005

Table 5.71 NBS platelets wastage and costs

Platelets Year	Total Discards	Total NBS Loss
2004-05	27,301	£5,920,768
2003-04	28,667	£6,217,012
2002-03	31,076	£6,739,452

Source: BSMS, Annual Reports from 2002 to 2005

If the costs raised by hospitals and NBS wastage are added together, they approach a total deficit of £18 million for 2004-2005 and £13.6 million for 2003-2004, which is a considerable sum to be lost.

5.6 Conclusions

The extensive analysis of the data generated interesting observations and decisions about the construction of the simulation model and its inputs. The key points are summarised below:

Collection types and operating times

- Public (64%) from 13.00 to 20.00
- Industrial (33%) from 10.00 to 17.00
- NBS site (3%) from 9.00 to 16.00

Processing

- Main product fabrication analogy: 1 unit of whole blood = 1 unit of RBC
- Department operating times Mon-Fri from 8.00 to 21.00, Sat from 8.00 to 15.00

Frequencies of main products

- RBC (75%)
- RBC Irradiated (4%)
- Platelets (6%)
- Plasma (8.5%)
- Frequencies of blood groups are similar between UK population, hospital orders and NBS collections

Blood products shelf life

- RBC – 35 days
- Platelets – 5 days
- RBC Irradiated – 14 days after irradiation

Testing methods and times

- On site testing in parallel with processing
- NAT testing released 14.00 next day

Stocking

- when NAT test shows negative
- FIFO order
- Ideal stock levels (4.5-7 days)

Orders and issues volume variation in time

- No distinguished monthly seasonality is observed
- Daily and hourly fluctuation of orders and issues is distinctive

Delivery types can be grouped under:

- Routine
- Ad-hoc
- Emergency

Types of Blood Requests from Physicians

- Adult RBC units under normal circumstances
- Adult RBC units in emergencies,
- RBC units with extra group characteristics
- Irradiated RBC
- Platelets

Statistical Analysis of Demand and Usage

- Number of daily blood requests (Poisson process and use of negative exponential distribution)
- Blood group of the request (Probability distribution of UK population blood group frequency)
- Size of each request (LogNormal distribution)

- Usage rate (Probability distribution) dependable on size of request

Blood Bank Inventory Management

- Days of blood Products in stock and stock levels are dependable on hospital rules and hospital size
- Blood bank ordering policies (order up-to quantity function which differs for routine, ad-hoc and emergency orders)
- Issuing order (FIFO and not aged based)
- Reservation period before, during and after transfusion is dependable on hospital rules described by a combination of LogNormal, fixed and time-dependent distributions)
- Mismatching eligibility rules and preferences

Wastage

- RBC wastage as a percentage of issues in NBS (0.3 - 1.1%) in hospital (3 - 4.6%)
- Platelets wastage as a percentage of issues in NBS (13 - 14%) in hospital (5%)

CHAPTER 6: THE SIMULATION MODEL

6.1 Introduction

This chapter portrays the model, the model inputs, and the important conditions of the model's construction and execution. This part is better understood along with the information given in Chapter 5. Further in this chapter, the assumptions of the simulation model are presented. Decisions on the key performance measures of the system and the model output variables are then listed and explained. Moreover, this chapter describes how the model was verified and validated by comparison of output values with real data from a real hospital. It also verifies the choice of simulation run length and iterations.

6.2 Model Description

A snapshot of the Simul8 model with one blood centre and one hospital is demonstrated in Figure 6.1 (next page) as it was initially modelled. At Appendix D a snapshot of the model with one blood centre and three hospitals can be found. Moreover, in Chapter 6 (Figure 6.1) one can see the same model as it was designed for display to non-experts, where details are hidden under sub-windows.

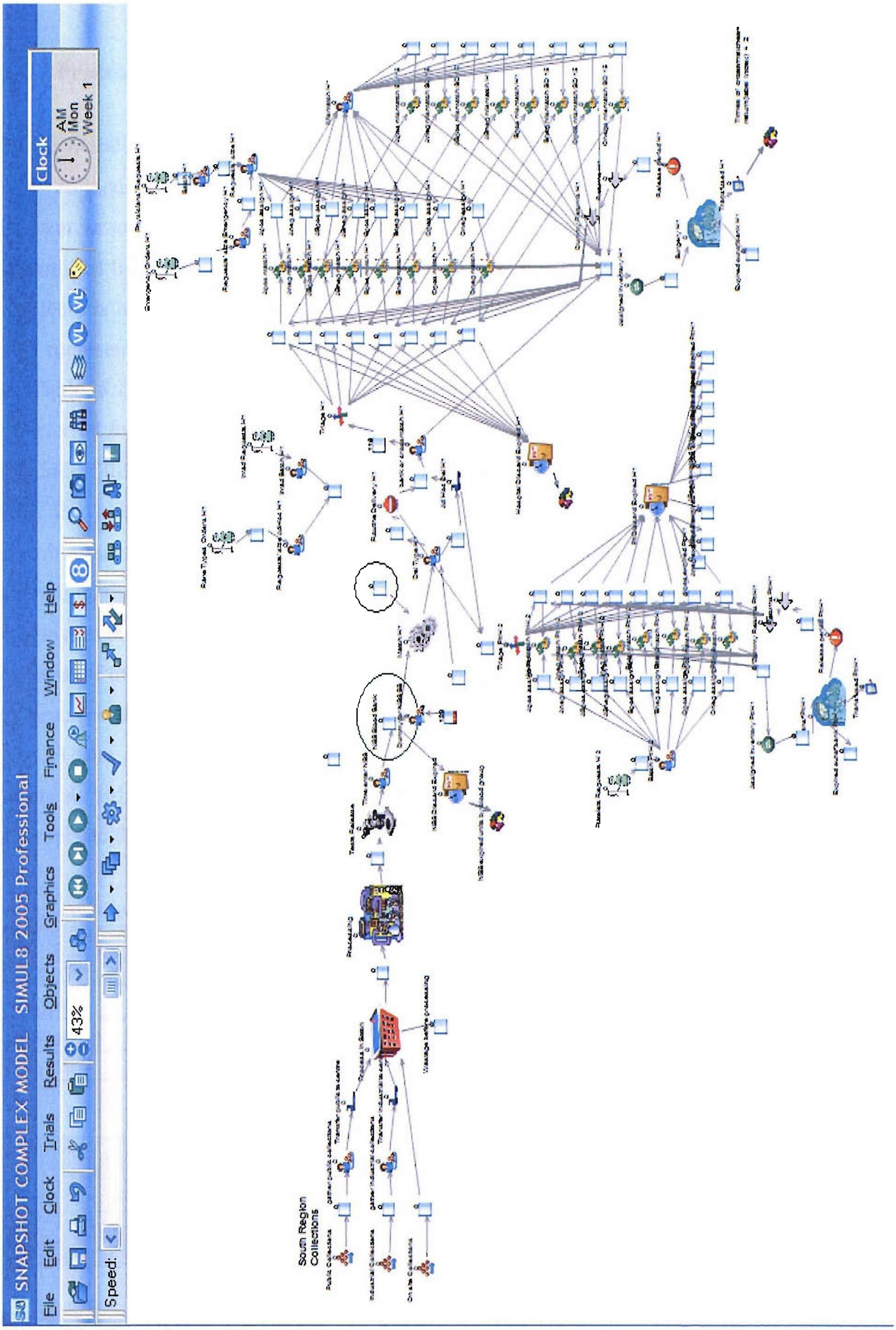

Figure 6.1 Simulation model snapshot

6.2.1 Processes and Inputs

Whole blood units (entities) arrive in the system from three entry points, representing the three collection modes, i.e. public, industrial and on-site. Each one is described by a Poisson process (exponential inter-arrival time). The frequency of blood groups is determined by a probability distribution following the UK population frequency of ABO and Rhesus blood types. The entry points of collections operate at different times of the day, representing the collection sessions as described in section 5.3.1 and clearly shown in Table 6.1. Units from the first two collection modes accumulate until they are transferred to the centre for processing twice per day, via a mid-day pick up and one at the end of the session. Transport of collected blood to the site for processing takes place with the help of vehicle resources. Table 6.1 summarizes the times of events and distributions used to describe the duration of certain events. The distributions of journey and processing times were derived after consultation with the Transport manager and with employees working in the processing department respectively; unfortunately actual data for both of these durations are not recorded. In particular, a uniform distribution was used to describe the duration of processing because the two processing methods (BAT and whole) take different times to be completed; nonetheless, these are within the specified limits according to staff experience and therefore a uniform distribution considered more appropriate than others that have one pick point.

Table 6.1 NBS Centre operating times and distributions of processes

Collections Sessions	%	Operating Times	Pick Ups	Duration of journey (in minutes)
Public	64%	13.00-20.00	16.00 & 20.00	Triangular Distribution [15, 170, 50]
Industrial	33%	10.00-17.00	13.00 & 17.00	
On-site	3%	9.00-16.00		
				Duration of processing (in minutes)
Processing Department	Weekday	8.00-21.00		Uniform Distribution [110, 180]
	Saturday	8.00-15.00		
Testing Results Release	Next day	~14.00		

Whole blood for which the group has already been determined at collection by the UK population probability distribution is processed as RBC. The length of processing is defined by a uniform distribution of 110 to 180 minutes. A pack of whole blood gives a pack of RBC (see Table 2.3) so there is no actual transformation of the model entities.

The tests are released next day at 14.00 (or the day after the next for late public collection returns, see section 5.3.1) and each unit is stored in the centre's bank until an order arrives matching its blood group. There is a mechanism (minimum waiting time) in place to ensure that units have stayed enough time in the processing and testing department for all their tests to be completed, taking into account the department's working times.

Orders arrive in the centre's blood bank and are matched with the units in stock according to the blood group. Each requested item that is part of an order is represented by an individual entity (work item) in the model. Thus, the order and the required unit merge to become a single entity that waits to be transported to the hospital bank (or straight to assigned inventory, if the order is for a rare or irradiated RBC). The time that the unit will be transported and the travel time depend on the order's status (routine, ad-hoc, emergency). A routine delivery is dispatched at 10.00 every morning except Sunday. An ad-hoc or emergency delivery will be dispatched as soon as the units are prepared and the transportation vehicle is available. There are two types of vehicles (resources). The vehicles that belong to the first type are used for scheduled deliveries and for mid-day public and industrial pick-ups, while the second type is dedicated to ad-hoc and emergency deliveries.

Each entity (blood unit), when it enters the processing phase, is stamped with a "label" that specifies the exact simulation time at which the particular unit expires. Simul8 software incorporates algorithms that allow the counting down of the remaining life of a unit when this is in a "storage area" (queue); when it gets to zero the unit is discarded. The remaining life of each unit is updated in the system just before the unit enters the blood bank, either CBB (centre blood bank) or HBB (hospital blood bank) by subtracting from the scheduled expiration time the simulation time at the time it enters the bank (storage area). When a unit expires, it is removed from the system by transferring it to another area, which collects expired units. This occurs on the 23rd day of its life in the centre's bank, preventing very old blood from being given to hospitals where there are limited chances of using it. On the other hand, expiration takes place in the hospital blood bank on the 35th day for RBCs and the 5th for platelets. For irradiated RBCs, the age of the unit is changed at the time of issue to 14 remaining days of shelf life. If, however, the age of the unit at the time of issue is more than 20 days then the shelf life is not changed. Thus, in the former case irradiated RBCs expire on the 14th day of their shelf life (after irradiation) or on the 35th in the latter case.

The centre keeps enough stock to satisfy expected demand for 4.5 days or more. In the model this is succeeded by the daily collection of blood units, which gradually accumulate in the CBB storage area since not all the stored units are issued to hospitals at once (see section 6.4.1).

Platelets production is not considered in the model in such detail as for RBC units. Platelets production planning is a complicated issue with many ad-hoc policies involved. It was believed to be difficult to capture this adequately in the model. Moreover, there is a lack of published information on platelets production planning and a shortage of academic papers in the literature. Future work should be pursued in this field. Nonetheless, platelets issues from the NBS centre to hospitals are easier to comprehend. The main information that could be obtained is that platelets are produced at a client's request, but that centres also produce platelets in anticipation of hospital requests; the latter trigger the high rate of platelets wastage in the NBS. In this model only the first point is taken into consideration. It is assumed that platelets are produced only on request and thus no wastage occurs in the centre, yet unused units generate platelets wastage in hospitals. Therefore, only RBC units can be found in the centre blood bank (storage area), but not platelets, and thus orders for platelets are not matched with the units in the CBB. Instead, they are placed in an individual queue and are presumed to be automatically fulfilled and to proceed to the waiting area for transportation to the hospital together with the other RBC products. Their delivery type is defined the same way as for RBC orders. So, under our model logic, no shortage of platelets can be observed, as production is assumed to be done automatically. The age of platelets at issue is fixed at one day, and thus there are 4 days left for use in the hospital. Other researchers (Sirelson and Brodheim, 1991) have also selected this age value at issue.

There are five different types of blood requests from physicians, as also explained in section 5.4.2, which are represented by five entry points. These include adult RBC units under normal circumstances, adult RBC units in emergencies, RBC units with extra group characteristics which are not held in stock and have to be specially ordered from the NBS, irradiated RBC, and platelets. All request arrivals follow time-dependent distributions and represent a doctor's orders for an individual patient. Demand for blood products is greater during working hours and less during the evening and night and on Sundays. Hence, requests are more frequent during a weekday and Saturday between 8.30-16.30. Poisson process is used to describe this variable. Outside these working hours, a Normal distribution is used to describe the arrival of the requests at these entry points, as these are more infrequent and appear to have a larger variation. Therefore, the use of a Normal distribution with a bigger average (inter-arrival time of requests) and SD value was indicated. A Normal distribution was preferred at this stage to a negative exponential because it gives more control over the number of requests placed within a day. On Sundays, when physicians' requests are rare, the time dependence disappears and a negative exponential distribution is in place to produce these infrequent doctors' requests. In small-volume hospitals blood requests for each of these categories of products typically only arrive occasionally, and as such the time element does not make any actual difference. In these cases a negative exponential distribution alone is enough to describe the arrival of request. Moreover, in the same hospital this case may be applicable to some of the categories of doctors' requests. Principally, requests for adult RBC units under normal circumstances are very frequent and time-dependence can be successfully applied, but the rate of occurrence of requests in the remaining categories can accurately be described with the use of a simple negative exponential distribution. The values of the parameters that define the distributions of these entry points differ significantly both in the same hospital and from hospital to hospital.

Each request is for a single blood group. The probability distribution of requested blood groups also follows the UK population frequency of blood types for all RBC requests. For platelets the blood groups' occurrence is described by the probability distribution that was shown in Table 5.3 and was acquired by investigating the patterns from all the hospitals in the database. These probability distributions stay the same between different hospitals. The size of the request is described by a LogNormal distribution, as also explained in section 5.2 and displayed in Figure 5.2, depending on the product or category of request. Each requested unit of adult RBC and emergency RBC is matched with the stock in the hospital bank and then proceeds to crossmatching as a single entity. The remaining requests (rare blood types RBCs, irradiated and platelets) are ordered from the NBS and matched with the stock in the centre's bank only. Then, when delivered to the hospital, they proceed to crossmatching without passing through the blood bank (unassigned inventory) because they have been obtained for particular patients.

Hospitals keep an ideal stock in their banks for each blood group, which may be counted in days of stock, yet the latter is not spread evenly across all blood groups (see section 2.8 and 5.4.3.1). In the model each blood group is kept in a different storage area inside the hospital blood bank, mainly for visibility of stock fluctuation. Every hour, the hospital blood bank is checked for stock availability by counting the entities in each of the storage areas. Every Monday to Saturday at a predefined time routine orders are placed whenever the RBC inventory is less than 80% of the ideal stock, and the difference for each blood group is ordered. Also, platelets or rare RBC units might be ordered if requested at that time by the doctors. This order will be prepared by NBS staff as soon as possible after its arrival, but it will be delivered the same day or the day after according to the policies in place for routine deliveries, as explained in section 5.3.6. If at the time of the order's preparation in the NBS not all the requested units are in stock, then these units will be supplied later on when they become available before the delivery time of the order. Ad-hoc or emergency orders from the hospital blood bank to the centre, for recovering stock, are also placed when, for example, stock is 50% or less of ideal stock (according to the hospital's policy), at any time (whole hour) of the day. Moreover, ad-hoc orders are placed with the NBS when products not in stock are requested. When physicians request such products then a check is made to see whether their request is urgent or not. If it is urgent then an order will be placed with the centre at the next opportunity and the units will be matched and delivered as soon as possible. In such cases small amounts of missing RBC stock can also be recovered, since a delivery will be made anyway. If the request is not urgent then the order for the delivery of these units will be made at the same time as the routine order. Blood bank managers have stated that usually 40% of such product requests are very urgent. The remaining 60% can wait until the time of the routine schedule delivery to be satisfied (crossmatched and transfused). If a hospital that places routine orders at 9.00 has an arrangement with the centre for next day delivery, then for particular products (irradiated, platelets and rare group RBCs) an exception is made and these products go into the same day's routine delivery if it has not already set off by the time of the order. This is possible in the real system since there are usually only a few units of these products requested and NBS staff prioritise their preparation. This is also considered in the model. Placement of ad-hoc orders is prohibited at times near the scheduled delivery or very close to previously placed ad-hoc orders, which have not been delivered yet, to avoid over-ordering.

The units are kept in FIFO order in the centre and hospital blood banks. Ideally the unused returned crossmatched units should follow a LIFO order if they are to be sorted according to the expiry date. However, this is not always the case, as explained in section 5.4.3.3. In the baseline model only a FIFO order is used.

Blood is crossmatched roughly a day in advance of surgery, but this time could easily be much more or much less than a day, determined by a LogNormal distribution. It goes through the transfusion process, which is described by a Normal distribution of 120 minutes mean and 30 minutes SD for all hospitals, and if unused, it stays assigned to the patient for some time determined by the parameters of a LogNormal or fixed distribution. Then it waits to be returned to the bank at 10.00 the following morning (for the selection of the particular distributions see section 5.4.3.4). During this process either some of the units under the same request are consumed, or all of them or none if the transfusion is cancelled (see section 5.4.2.3). All RBC categories follow the same rules of usage rate if in the same hospital. However, platelets follow their own rules. Both usage rules differ from hospital to hospital. Unused units of rare groups of RBCs and irradiated RBCs are also kept in storage together with the adult RBCs until they are used from another request or they time-expire. These products are advantageous because they can also be used to satisfy normal adult RBC requests and this fact enhances their chances of being transfused in the end. Subsequently, when unused, they return into the hospital's storage areas where RBC stock is kept according to their blood group.

In particular for platelets, a different storage area in the hospital exists in the model. This storage area consists in fact of 8 different storage areas (queues) which host each of the 8 blood groups (6 in reality, as the AB group storage areas are "dummy", which means that they exist only for modelling purposes since the AB group is never requested). The ordered units arrive in the storage area and are matched with physicians' requests and then move on to crossmatching. The unused units go back to the storage area and wait to satisfy another request for the same group if this arises within their shelf life. If a suitable request arrives, they are assigned to another patient, but if these units are not enough to satisfy a whole request, only the difference between requested and in-stock units is ordered. In any other case these platelets soon expire.

Finally, the model allows for mismatching if the same blood group will not be available within 2.5 hours. The selection of the compatible group is based on the following criteria: the oldest compatible blood in the blood bank will be given as long as there are more than 4 units of this type in the bank. In the model this means that when these conditions are true the entity that represents the requested unit will leave the waiting area of its group and will be transferred to the storage area of the suggested group for "order to unit matching". From that moment the single entity carries the group of the unit in stock and it is treated like a genuine match.

In the hospital blood banks there is no such substitution mechanism for platelets. However, the platelets mismatch procedure is partially incorporated in the physicians' request activity. Since the physician is aware of the fact that there is no production of group AB platelets a substitute will be given, no matter whether the patient is of group AB. This substitution is usually an A positive or O negative unit as demonstrated in section 5.3.2. In the model, this is incorporated into the physicians' request logic by allowing zero possibility of a group AB request to enter the system. The selected group ABO probability distribution (Table 5.3), which the model entails in the requests entry point for platelets, clearly illustrates this primary substitution. Furthermore, as the model assumes that any given request for platelets, other than group AB, can be automatically satisfied from the centre, there is no medical reason for mismatching. The only reason that a process like this would be desirable in a hospital would be to avoid the time expiration of compatible unused units. This potential is not captured in the model, mainly for purposes of simplicity and also because the chances of occurrence of such an event, given the short shelf-life of platelets and the infrequency of orders, is so small.

6.2.2 Model Conditions

When entities are introduced to the model, whether these are collected units, physicians' requested units or stock orders from the hospital to the centre, they are all stamped with "labels" that define their special characteristics and, in a way, make them unique and distinguishable to the modeller. These entities acquire more labels, as needs arise, as they proceed through the different phases of the model. For a collected unit these labels define the ABO and Rh group, the time it entered the system (processing phase), the simulation time when the unit is due to expire in the CBB (= time entered system + 23 days) and in the HBB (= time entered system + 35 days) and the times the CBB and HBB were entered. Physician-requested units carry attributes such as product type (adult RBC, Irrad. RBC, platelet), ABO and Rh group, urgency of request (for not-in-stock products) and usage status (to be transfused, cancelled, over-ordered). Finally, ordered units hold all the labels of physician requests plus delivery type and HBB location (blood bank or crossmatching). When an entity that represents an ordered unit (RBC) is matched with the entity in the CBB (actual unit) they are both merged into a new entity and all the labels of the two different entities are carried forward to the new entity. Therefore, it is guaranteed that valuable information is not lost during this process. Other mechanisms are in place to ensure that these labels accurately capture the correct information. That is to say, if the product type is for an irradiated unit then the label of the simulation time of expiration (= time entered system + 35 days) will be adjusted to the correct one (= time of request + 14 days). Such control mechanisms have been used throughout the simulation model to ensure obedience to the rules. These rules and equations are either located in the Visual Logic of the Simul8 model, or in the VBA code that is activated by the Simul8 model as appropriate. The same label merging process occurs when the entity of a doctor's requested unit is matched with the entity of a unit in the HBB. If labels have the same name, overwriting takes place. If these are not the same, the highest value is kept.

Generally, Simul8 Visual Logic (the software's internal programming language), VBA and the Excel spreadsheets facilitate testing, modification, and documentation of assumptions, such as facilities' start and stop hours and days, ordering times or shortage assumptions, capacities and many others. They also assist in the monitoring of selected results and make verification and validation plausible. An analytic presentation of the conditions, rules and logic used in the simulation model can be found in Appendix B.

The model runs in minutes to encapsulate the detailed timings and variations in the duration of all the processes in the supply chain. However, this also enforces other functions that would be better off counted in hours or days to also be computed in minutes, such as the shelf life of the blood units. This fact slows down the execution time of the simulation model. Nevertheless, there is a fair trade-off between execution time and detail, as the latter implies the model is more realistic.

Moreover, the ability of the software to group blocks into larger hierarchical structures is used extensively during and mainly after model development and helps the comprehension of the model by non-experts, in particular blood managers.

6.3 Assumptions

6.3.1 One Centre – One Hospital Model

As Pinson stated (1973) a valuable basis of such studies of regional systems is first of all an accurate model of an individual hospital blood bank. The basic model can then be used as a building block of the regional blood bank system model. Thus, this chapter focuses on the detailed description of an accurate supply chain involving the NBS centre and one medium-sized hospital. The purpose of focusing on one hospital is to ensure verification and validation of the model with one of the existing hospitals for which detailed data exist in the acquired database. Moreover, it is easier to describe fundamental elements of the supply and the causal relationships between the centre and the hospital blood bank. In contrast, the latter is difficult to understand when numerous reactions take place at the same time in a model in which many hospitals participate. Similarly, internal factors in the centre blood bank and hospital blood bank that influence the system's performance measurements are identified individually .

However, the attempt to capture in a simulation model a blood centre that supplies only one hospital carries some dangers. These are basically summarised as the problem of keeping a balance between the centre's input (blood collections) and output that is supplied to the particular hospital on request. The main consideration is to hold enough blood in stock to only satisfy orders from one hospital without observing more shortages than exist in reality or, on the contrary, facing too many outdates because collected units are more than needed. In the latter case, the consequence of the ageing blood in the CBB will also have an additional impact on the hospital outdates as it gives little opportunity for use (see section 5.5.3). The desired balance is achieved by reducing the centre's inputs to cover the demand of this hospital, so that overall supply and demand stay in balance. In particular, this is achieved by adjusting the collected units according to the orders from the hospital blood bank. However, because the latter is an unknown variable of the system, which takes values following certain rules and equations, it cannot be measured before running the simulation model. Nevertheless, the database from PULSE provides the actual number of issues from the centre to each hospital by product, and thus an approximation of these issues to the chosen hospital was used as inputs. In order for the model entry points to produce the required amount of collected units, calculated over a period of time, a trial and error method was used. The number of collected units is, however, slightly higher than that of ordered units in order to absorb unexpected behaviours and to have most of the requested units in stock at any time. This does not mean that all the extra units are wasted. They are just transferred to other centres once a week to maintain the equilibrium and prevent excess stock from accumulating in the CBB. Only middle-aged stock is transferred, which does not greatly affect the average age-range of blood sent to the hospital. However, units of group AB are not transferred. These are normal processes of all NBS centres as observed in practice.

In fact in the model the units in the CBB are counted every Monday at 11.00 and the transfer of units to other NBS centres takes place if more than a certain number of units are in the CBB. This threshold is a number close to the maximum days of the centre's stock (7 days) which has previously been adjusted to the approximate percentage of issues to that particular hospital. Therefore, a combination of information from Appendix A.6 (Southampton NBS issues to clients) and Table 5.4 (Southampton ideal stock levels of RBC) is needed to compute this value. The difference between this threshold and the total quantity of stock in the CBB is the number of units that will be transferred to other centres. However, only middle-aged blood is suitable for moving. Therefore, the physical movement of middle-aged stock is carried out in the model by subtracting entities that lie in the middle of the CBB storage area (queue), bearing in mind that blood units are sorted in a FIFO order in the CBB. Group AB units are skipped.

Having this device in place guarantees some control over balancing NBS inputs once a week. On top of this, percentage adjustments and a trial and error method can identify suitable input parameters for the NBS collections that will keep the CBB issuable stock stable during the week.

6.3.2 List of Assumptions

During the development of the model, several key assumptions were made in order to provide simplicity while preserving the actual physical effects. Moreover, assumptions are made for calibrating and quantifying human behaviours and translating actions under certain circumstances into mathematical rules and logical conditions. These assumptions are listed below.

1) Wastage that occurs between collections and testing (almost 8%) has been excluded from the model by subtracting these quantities before the collected units enter the system.
2) Platelets are not kept in stock in the CBB. They are only produced on request and there is always availability of primary components for their production.
3) The available remaining shelf-life of platelets at time of receipt by the hospital is fixed at 4 days.
4) Outdated units are only disposed of when they wait at or return to the HBB or CBB.
5) Delivery types are reduced to three. Collections with client transport are considered the same as ad-hoc deliveries. F coded (wrong) deliveries are merged with routine deliveries.

6) Physicians' requests are aggregated under 5 categories without considering the type of surgery or patients' condition.
7) Collections follow the UK blood group probability distribution in the same way as physicians' requests (patients).
8) The blood group frequency distribution for platelets applies in all hospitals.
9) Usage percentages concerning how many of the crossmatched units are transfused and how many are returned to the unassigned inventory (probability distribution of over-ordering, "some") are based on hospital practices.
10) Usage rate (U) of none (10%) and all (10%) units transfused, which are used in the model, remain the same across hospitals.
11) Selection of the LogNormal distribution parameters for the reservation time is made based on the hospitals' policies.
12) Selection of the LogNormal distribution parameters for the request size is made based on the hospitals' policies.
13) The weekly pattern of physician blood requests is based on the hospital volume. (The same time-dependent Poisson processs are used for Mondays to Saturdays and different distributions are used for Sundays.)
14) Blood bank checks are made every hour, on the hour.
15) Moves of stock are only allowed from this blood centre to other centres but not vice versa. It is assumed that if this centre does not have adequate stock to serve its hospitals then there is a general deficit of stock in all centres.
16) The probability distribution parameters for urgency of platelets, irradiated RBC and rare blood RBC requests are the same in every hospital.
17) Hospital routine, ad-hoc and emergency ordering points are determined based on hospital policies.
18) Back-orders are allowed.
19) CBB follows FIFO issuing.

It may seem that numerous assumptions surround the simulation model. Nevertheless, none of the previous models was capable of considering these assumptions. They usually used aggregated data as inputs without taking account of blood groups or request sizes and usage rates. Therefore, this model tries to capture many more interactions than any of the previous models could.

6.4 Model Performance Measurements and Outputs

While the model runs, data are reported in an Excel file, such as the day and time of placing an order with the centre, the type of order (routine, ad-hoc or emergency), the requested product and the amount by blood group. Moreover, information is reported on the time and number of units returned to the HBB. Comparisons between this information determine future decisions and actions of the model, but they also calculate useful results to measure the performance of the system under examination, such as shortages, number of deliveries by type, mismatches by patient's and recipient's group and age of blood by group when entering the hospital blood bank. At the end of the run more output measures are available from Simul8, including wastage figures by product and blood group both from the CBB and HBB, number of crossmatches in the hospital and many others. These features also help the verification process by identifying errors in the modelling, and the validation process by comparing the outputs of the model with the real data given from PULSE and blood bank managers.

For clarity the model outputs are categorised in two sections: a) the main performance indicators that assess the performance of the whole simulated system when different policies apply, and also enable validation of the initial model with the real system, and b) the model outputs that are used for verification and evaluation of internal relationships between model variables. The second can be further classified into i) intermediate outputs that assist in decision making while the model runs, ii) end-run outputs that assess the accuracy of initial assumptions, and finally iii) end-run results that reveal information about internal relationships between model variables, which are usually valuable for one participant (echelon) in the supply chain, either the centre or the hospital. Some overlapping between these categories exists.

6.4.1 Main Performance Indicators

Before the model is run and further experiments are performed, evaluation metrics should be carefully selected. However, a rational decision on these metrics necessitates some background research into the relationships between variables in the real system and also in the way the model has been developed.

An obvious performance measure would be the number of outdates in CBB and HBB. Wastage is an undesirable outcome of bad coordination of the centre and/or the hospital blood bank processes. On top of the physical loss of a valuable and scarce resource, outdates also incur money loss for both the NBS and the hospitals. However, in section 5.5.3 it is noted that the number of outdates in the centre depends on the number of outdates in the hospital. If the hospital manages its processes better and has fewer expired units, it can satisfy the same demand with fewer orders. In the current model, since the number of units in the system stays the same in a single trial, this will result in fewer outdates in the hospital and more in the centre (or more units moved to other centres). Nevertheless, the whole system can operate with fewer donations overall. In reality decreasing the number of collections would be the correct course of action, which is highly desirable, and thus an increase in the centre's wastage would not be observed. Therefore, wastage in the centre was not considered to be a crucial performance indicator since it could be misleading. Nevertheless, it is presented in the model output for verification, under this assumption. Hospital wastage was considered to be a more representative measure for evaluating the supply chain's performance. In addition the number of outdates as a percentage of total issues is reported. This measure is more representative when it comes to comparison between different hospitals.

Product and blood group shortages are another crucial performance measure, and can lead to unpleasant situations, such as cancellation of surgery or compulsory mismatching. According to the conceptual model a shortage occurs when the required blood group is not available from the centre at the time of ordering and/or by the time the remaining ordered units, available in the centre stock, are transported to the hospital. Shortages are rarely reported in the real system. However, this is not because there are always available units in the centre blood bank, but mostly because hospitals change the orders placed with the NBS to match the centre's available stock and possibly mismatch the units. Nevertheless, the simulation model counts the shortages occurring in the system according to some rules which can be summarised as follows. If an ad-hoc or emergency order is placed for a particular product and it is not delivered in the hospital blood bank with the next ad-hoc delivery or within, for example, 3 hours of the ordering time, for a hospital an hour away from the centre, the product is assumed to be out of stock and a shortage is recorded. In the case of a routine order the blood unit is considered unavailable when it is not delivered with the next routine delivery or the following day's scheduled delivery, according to the hospital's arrangement about routine deliveries with the centre. More details on these rules can be found on the pseudo-code presented in

Appendix B. The number of shortages and the proportion of shortages as a percentage of total orders are computed from the model.

Another significant indicator of the provision of bad quality service in the hospitals is the mismatching of patient blood groups, which is undesirable (even though not fatal) and thus is considered bad practice. This measure is partially related to the occurrence of shortages from the centre but it can also be caused as a result of a hospital's deliberate decision, such as denial of stocking group AB red cells. The overall number of mismatches is reported by the model, but also mismatches per patient and per recipient group are examined for further analysis. In addition, mismatches as a percentage of total issues is calculated.

Finally, the number of deliveries from the centre to the hospital is considered significant, as increased deliveries incur extra transportation and staffing expenses for the centre. More vehicles are needed to deal with excess deliveries in different directions, which subsequently leads to excessive vehicle mileage and maintenance costs and an increased number of drivers to provide this transport. Moreover, staff in the Issues Department are occupied in taking orders and preparing blood units for delivery at all times. On the other hand, excessive deliveries also incur expenses for the hospital due to the compensation associated with ad-hoc and emergency deliveries (or collections with associated taxi expenses) on top of the product costs. Routine deliveries are preferable to ad-hoc and emergency since they are scheduled for a certain time, meaning that staff can arrange the workload in their own time and several hospital orders can be satisfied in the same delivery. Moreover, there is no extra cost for the hospitals. On the contrary, ad-hoc and emergency deliveries are counter-effective. However, these are seen as desirable by hospitals because they easily solve problems arising from poor management, and the assigned cost is quite low when compared with the consequences of a shortage or even with the real cost of hiring a taxi or a courier company for the delivery.

Summarising, the key performance targets for determining the cost-effectiveness and quality of the system are the following:

Table 6.2 Output measures for performance evaluation in experiments

Key Performance Indicators	Effect of Improvement	Source of Result
1. Number of hospital RBC and Platelet outdates by group 2. RBC and platelet outdates as a % of total RBC and Platelet issues respectively	The smaller the better – saves money	Simul8 output
1. Number of RBC shortages 2. RBC shortages as a % of total RBC ordered units	The smaller the better – saves lives	VBA and spreadsheet output
1. Number of RBC mismatches 2. RBC mismatches as a % of RBC issues	The smaller the better – saves lives and money	Simul8, VBA and spreadsheet output
1. Number of total deliveries to the hospital 2. Number of routine/ad-hoc/emergency deliveries to the hospital	The smaller the total number of deliveries the better, but routine deliveries are more cost-effective and well organised from the Centre so the problem lies largely with ad-hoc and emergency deliveries	VBA and spreadsheet output

6.4.2 Model Outputs

The simulation output results are analysed in this section. Together with the help of the built-in Simul8 functions, the Visual Logic and the VBA, data are reported in the Simul8 results summary sheet and several Excel spreadsheets for evaluation. Some of these outputs are further manipulated to produce new, more meaningful results.

Intermediate outputs are reported, while the simulation model runs, every time an important event takes place. These events are:

- The placement of an order from the hospital to the centre for which the simulation day, hour, order/delivery type, product, blood group, amount are recorded.
- The occurrence of a shortage which is the difference between the above information and the amount of delivered units.
- The occurrence of a mismatch for which the patient's group is recorded together with the group of the substitute unit.
- The age of units at receipt from the hospital. Fifteen per cent of randomly selected units are chosen of which the age is recorded.

At the end of each run, outputs are listed in the following numerical format. These variables' performance is monitored after the end of a run. Their performance provides practical information for validation and evaluation of processes. Some of the desirable information is obtained after additional calculations are carried out on the end-run outputs.

1. Issuable HBB stock index per blood group (number of stock days in the HBB) = average stored RBC units (before crossmatching) per blood group (Simul8 output) / one day's worth of stock of the particular blood group.
    - One day's worth of stock = total issues from HBB (Simul8 output) over the simulation run / number of simulated days.

Or

Issuable HBB stock index per blood group = average waiting time of RBCs in the HBB (Simul8 output).

2. Issuable CBB stock index = average age of RBCs in CBB = average waiting time in CBB (Simul8 output).
3. The number of RBC outdates by group in the centre (Simul8 output).
4. The average age of RBCs in the HBB = average age of RBCs on arrival in the HBB (Excel output) + average waiting time of RBCs in the HBB (Simul8 output).
5. The average number of RBCs in CBB/HBB by blood group (Simul8 output).
6. The average number of RBCs/Platelet crossmatches during their shelf-life (Simul8 output + VBA check per transfused, expired and "out of hours" item).
7. The average reservation period of RBCs/platelet = Average before surgery crossmatch period (Simul8 output) + average transfusion period (Simul8 output) + average after transfusion crossmatch release period (Simul8 output).
8. Total RBC mismatches per patient/recipient groups (Excel output).
9. "Out of hours" RBC hospital wastage as a % of issue = Number of "out of hours" RBC/ Platelet wasted units (Simul8 output) / number of hospital RBC issues (Simul8 output).
10. Platelet hospital outdates as a % of issue = Number of Platelet outdates (Simul8 output) / number of Platelet issues (Simul8 output).
11. Total transfused RBC and Platelet units (Simul8 output).
12. Total returned RBC and Platelet units to the unassigned inventory (Simul8 output).
13. Total number of collections (Simul8 output).

14. Total physician RBC requests (for all 4 RBC categories) (Simul8 output).
15. Total physician RBC requested units (for all 4 RBC categories) (Simul8 output).
16. Total Platelet requests (Simul8 output).
17. Total Platelet requested units (Simul8 output).
18. Total ordered RBC/Platelet units (Simul8 output).

These results are presented together with the key performance metrics in Chapter 6, where experimentation takes place and the model outputs are analysed.

6.5 Initial Contents, Warm-up Period, Length and Number of Runs

Before running the model the warm-up period and the results collections period need to be decided together with the number of runs over a trial for getting statistical results.

A warm-up period is required to ensure that biases due to initial conditions are removed to achieve a steady state system. This setback is due to the lack of initial stock in the centre and hospitals, which raise orders and shortages unrealistically. An obvious remedy is to run the simulation for a period long enough to remove the effect of the initial bias without collecting results. Figure 6.2 shows the transient period of the model starting with zero stock; it can be seen that the hospital's units in stock and age of stock reaches a steady state after approximately 90 days. The blood centre's age of stock is achieved more quickly, as shown in Figure 6.3a, but the units in stock suffer for a long period (Figure 6.3b). The warm-up period should be driven by the longest delay, since the whole system should be balanced. However, instead of running the model for 90 days before starting the collection of results a quicker way of bringing the system in a representative state has been followed, which combines the introduction of initial aged stock and a shorter warm-up period of only 18 days.

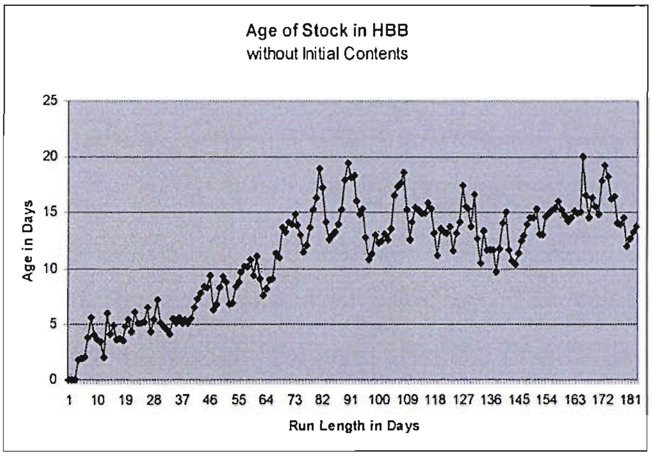

Figure 6.2a Fluctuation of the average age of stock in the HBB in a simulation run without initial contents

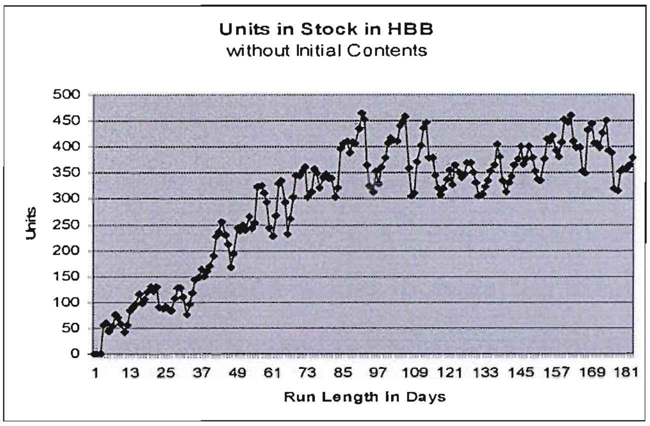

Figure 6.2b Fluctuation of the number of units in stock in the HBB in a simulation run without initial contents

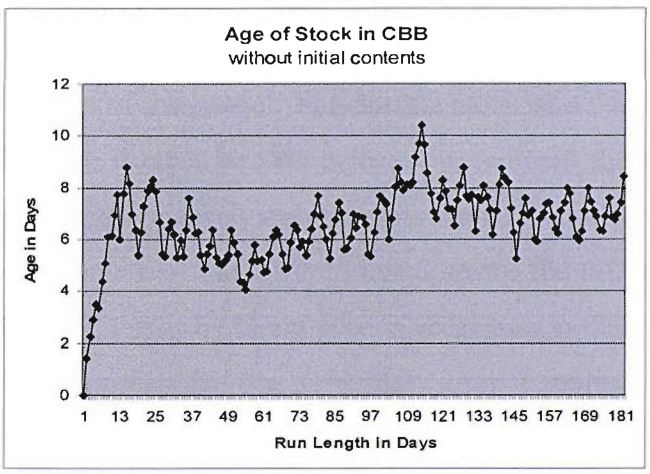

Figure 6.3a Fluctuation of the average age of stock in the CBB in a simulation run without initial contents

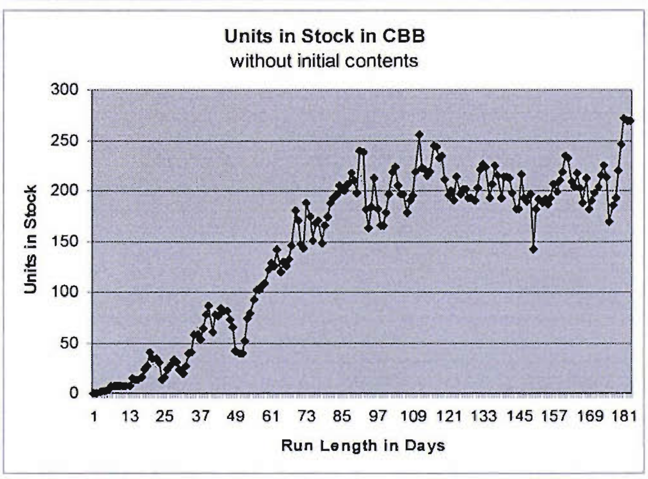

Figure 6.3b Fluctuation of the number of units in stock in the CBB in a simulation run without initial contents

Initial contents, representing RBC stock, have been inserted in the model, both in the CBB and HBB. This stock has an age of 5 days for units in the CBB and 7 days for the HBB. These values represent a lower age than the average age range (6-9 for CBB and 14-18 for HBB) when the system reaches the steady state. This is because all the new entries of blood will begin with zero age and a gap in ages between the age of stock and that of the new units will build up. The selection of the low values irons out these differences more quickly and after the first 18 days the system runs smoothly. The results of this alternative way of balancing the system are shown in Figures 6.4 and 6.5 for both the number of units in stock and the age of stock in the HBB and CBB respectively. The graphs demonstrate that the system becomes balanced in 18 days, from which point on results are collected. This method is preferable because it minimizes the length of the model. Due to the complexity of the system, the model takes a considerable time to run (63min in a desktop PC with a 2.8GHz processor and 512MB of RAM). The addition of a long warm-up period would increase the execution time to unacceptable levels. It is believed that this method is a satisfactory way of bringing the model into a steady state as quickly as possible.

The centre's initial stock is calculated from the actual stock data of the centre, adjusted to the size of the model. The normal stock of 4.5 days is used as a starting point. However, because it takes two days from the moment the first collections take place until the test results are released and the units are stored, one more day of stock has been added to the initial stock of the CBB to make up for the difference. The actual values are taken from Table 5.4 split by blood groups according to the Southampton NBS data, and are adjusted to the percentage the particular hospital represents. These numbers are added as initial contents into the CBB increased by one day's stock as previously explained. On the other hand, the hospital's initial stock is the ideal stock of the particular hospital under examination.

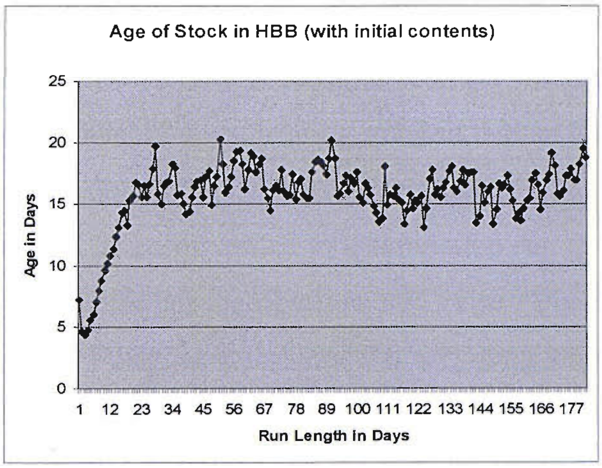

Figure 6.4a Fluctuation of the average age of stock in the HBB in a simulation run with initial contents

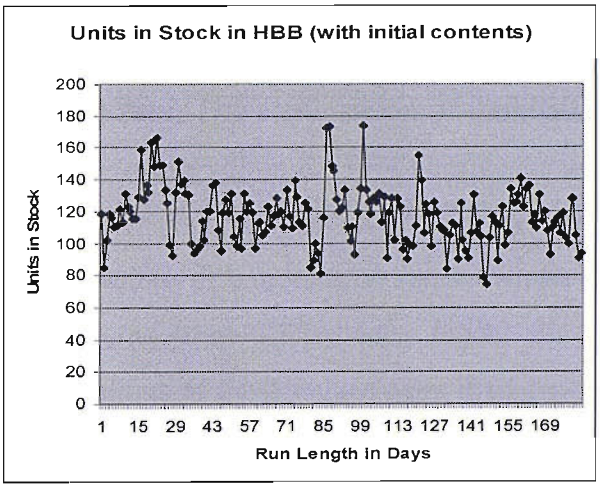

Figure 6.4b Fluctuation of the number of units in stock in the HBB in a simulation run with initial contents

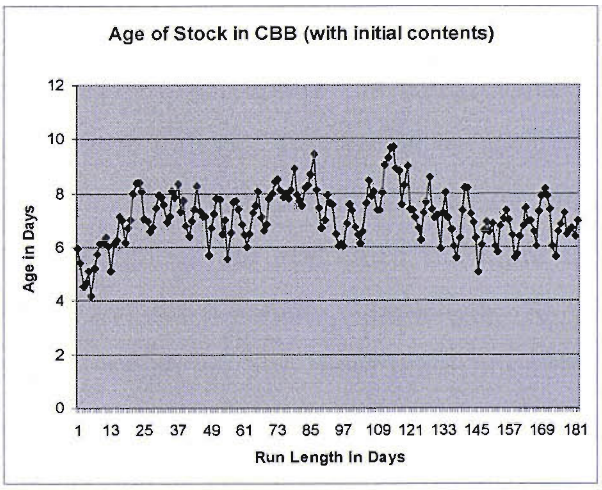

Figure 6.5a Fluctuation of the average age of stock in the CBB in a simulation run with initial contents

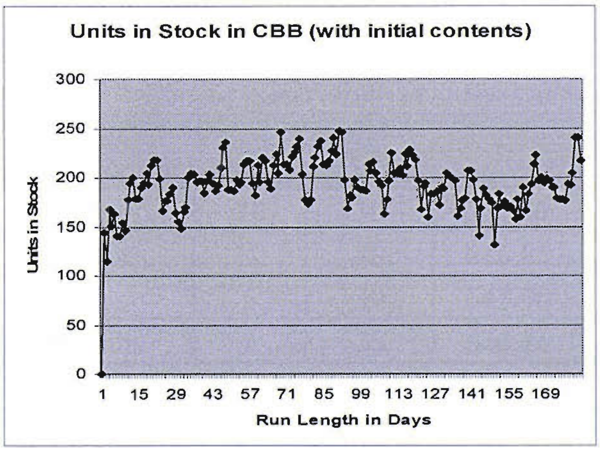

Figure 6.5b Fluctuation of the number of units in stock in the CBB in a simulation run with initial contents

Further to the warm-up period or initial contents the model's results collection period should be defined. A sensible decision will assume that the length of run should be much more than 35 days, bearing in mind that an RBC unit completes its cycle in the system at maximum 35 days when it time-expires. It is also important to consider that several weeks should be incorporated in a simulation run to capture the effects of weekends, which run under different distributions and rules. Nevertheless, because the execution time is an issue in this particular model a very long length of run was prohibited. A run-length of 6 months was selected, a sufficiently long period to capture all the required variability in the processes and also a time period easily converted to an annual figure. Additionally, averages are taken over 5 iterations for each policy to capture the possible variability of different runs. The combination of the run-length and the number of iterations provides accurate results within the 95% confidence interval.

Five iterations of 6 months' duration (which took just over an hour to run) were chosen as a pragmatic trade-off between model run-time and accuracy. Nevertheless, different combinations of these values were tried out to confirm the adequacy of the results. Table 6.3 shows some alternative run lengths and number of iterations for some combinations of runs for the number of total orders. It is apparent that one of the equivalents for 6 months of 5 runs, i.e. 3 months and 10 runs (both combinations represent 30 simulated months), is not adequate to capture the actual value of ordered units (651.51) within the 95% confidence interval. This would be achieved with more runs but the time taken to run these iterations is much longer than for the first option. One reason is the fact that the more iterations are performed the more times the warm-up period is also executed. Moreover, for 4 months' run-length, 10 iterations are needed to accurately produce results, which are also more time consuming. For 12 months, 3 runs produce adequate results but this is done again at the expense of a longer execution time. Therefore, 6 months' run of 5 iterations was considered the best solution.

Table 6.3 Validated model results of ordered units according to run-length and number of runs

Run Length	Runs	Total months	-95%	Average Ordered Units	95%	Run-Time in min
3 months	10	30	651.67	660.86	670.05	78
4 months	10	40	646.85	656.73	666.60	100
6 months	5	30	643.90	655.23	666.56	63
12 months	3	36	646.26	655.03	663.79	130

6.6 Model Validation

A simulation model needs to undergo several forms of validation before, during and after its construction in order to be accurate. These forms are summarised as follows: conceptual model validation, data validation, white-box and black-box validation (Robinson, 1997). Conceptual model validation confirms that the scope and level of detail of the model fulfils its purpose and assures that the assumptions made are correct. For the particular blood supply model, this process has already been accomplished in this thesis. Previous chapters analysed the conceptual model (Chapter 2), defended the level of detail in order for the model to produce accurate results (Chapter 3) and justified the correctness of the assumptions made (Chapter 5 & 6) as well as the translation of the conceptual model into a computer simulation program (Chapter 4 & 6).

The second form of validation, data validation, confirms the accuracy of the required data for the model construction. This form of validation was carried out in detail in Chapter 5. White-box validation determines that each component of the computer model accurately represents the corresponding real world elements. In this study, this form of validation was undertaken with the support of the real users who are the NBS staff and hospital blood bank employees. The model was at first demonstrated to managers working for the Southampton NBS Centre to validate the part of the model which represents this echelon of the chain. Then, it was shown to blood bank managers and doctors of the Southampton General Hospital seeking approval for the way specific hospital tactics were depicted in the model. The model received enthusiastic responses mainly due to its friendly interface and its performance was easily explained. Amendments and improvements to the model were suggested and soon adopted to ensure better representation of the real system.

Finally, black-box validation justifies sufficient, overall accuracy of the model against the real world. This form of validation was achieved by simulating a particular hospital for which information was available, from both the NBS database and the hospital itself, and the model results were tested against the actual data. The results were analysed for compliance with some of the key performance measures and other results.

The processes and policies that were known about the hospital and served as inputs to the model were:

- The ideal stock level (40 units of A positive, 10 of A negative, 4 of AB positive, 4 of AB negative, 10 of B positive, 0 of B negative, 40 of O positive, 10 of O negative).
- The percentage of the Southampton blood centre issues to this particular hospital (7% of all Southampton NBS issues to all destinations or around 8000 annual ordered units of RBC) according to which volume of collections were reduced to reflect collections adequate for this hospital and also normal and maximum stock holding for CBB.
- The overall transfusion rate (55%) which is used for the over-ordering probability distribution of 55% transfused units, 44.2% returned and 0.8% out of hours' wastage.
- The range of daily doctor requests (7-12) and requested units (30-40) from which the number of daily requests per patients and the size of request were derived for each request category.
- Routine orders are placed at 8.00 in the morning and are distributed from the blood centre with the scheduled delivery which sets off at 10.00 of the same day.
- The re-ordering point of stock for placing routine orders is 80% of the ideal stock, for ad-hoc orders 50%, and for emergency orders 10% of the ideal stock.
- Hospital issues follow a FIFO order in all cases (and for returned RBC units). However, platelets are sorted according to their age (FIFO for new arrivals and LIFO for returned units) because they are few and their sorting is easy.
- The hospital is located approximately 40 minutes away from the centre.

Appendix C.1 lists all the inputs of the model with their values and the specific processes of this particular hospital. Moreover, the first table of this appendix refers to these model inputs, which are assumed to stay the same in all the simulated hospitals.

The performance indicators derive from complex processes of input distributions and in-built conditions and they are not produced using a straightforward relationship. Consequently, if the model outputs on these criteria converge with the real data they validate that the distributions and logic of the model are realistic. These are:

- Average monthly ordered units of RBC, irradiated RBC and platelets, acquired from the PULSE database over 19 months' daily data.
- Average monthly routine, ad-hoc and emergency deliveries, acquired from the PULSE database over 19 months' daily data.

- The hospital expired RBC units as a percentage of total issues for the year 2003-2004, acquired from that particular hospital.

Table 6.4 shows the average values and the 95% confidence intervals that were acquired for the above three measures from the five runs of the model. Each run covers 182 simulated days (6 months). Furthermore, in the same table these values are compared with the values obtained from the real system (last column). It is obvious that the actual values of all the performance measures fall within the confidence intervals of the model results, except for routine deliveries, for which, however, the difference is very small. Moreover, it can be noticed that the range of number of deliveries is quite small and only the number of ordered units fluctuates slightly.

Table 6.4 Validation of model results against actual data

Performance Criteria	Low 95% CI	Average	High 95% CI	Actual Value
Average monthly ordered units	643.90	655.23	666.56	**651.51**
Average monthly RBC ordered units	604.22	616.17	628.11	613.62
Average monthly Irrad. RBC ordered units	8.96	11.33	13.71	11.42
Average monthly Platelet ordered units	24.35	27.73	31.12	26.47
Average monthly deliveries	49.34	51.43	53.52	**49.63**
Average monthly routine deliveries	20.57	21.36	22.15	19.32
Average monthly ad-hoc deliveries	24.45	26.47	28.48	27.26
Average monthly emergency deliveries	3.15	3.6	4.05	3.25
Expired RBC units in hospital as % of issues in 2003-2004	2.10%	2.34%	2.57%	**2.50%**

Unfortunately, shortages are rarely recorded in the real system as previously explained and thus validation cannot be performed on this measure because no real reported data exist. Also, platelet outdates and mismatched RBC figures were, unfortunately, not available from the particular hospital. However, some of them were validated by checking:

- Expired average per BSMS participant platelet units as a percentage of platelet issues, acquired from the BSMS report as shown in Table 5.17.
- "Out of hours" hospital wastage as a percentage of issues as presented in Table 5.16 with data taken from the BSMS annual reports.
- Mismatches as a percentage of issues as indicated from the BSMS survey of 99 hospitals (BSMS, 2003a).

Table 6.5 Validation of model results against averaged data from other hospitals

Performance Criteria	Low 95% CI	Average	High 95% CI	Actual Value
Expired Platelets as % of Issues	10.86%	14.07%	17.28%	5.1%
"Out of hours" RBCs as % of Issues	0.64%	0.73%	0.81%	0.6%
Mismatches as % of Issues	2.42%	3.01%	3.61%	5%

The number of platelet discards that were generated from the model for this particular hospital is more than the actual average platelets wastage. After consultation with the hospitals' blood bank manager it seemed that the number of platelet outdates (24 units over 6 months or 49 annually) was reasonable according to his experience, without though having any statistical results to validate his opinion. He also believed that the 5% overall platelets wastage, which according to the survey corresponds to 32 platelet units over the year (see Table 5.17) was underestimated. The model's "out of hours" RBC wastage (48 units) as a percentage of issue comes closer to the average actual value of all the hospitals participating in the BSMS. The lower 95% interval is very close into incorporating the actual value of this figure. On the other hand, the number of mismatches as a percentage of issues is under the average figure of the hospitals participating in the survey. It is, however, assumed to be within acceptable levels.

For the particular measures, the actual values were not expected to be within the model outputs range since these values do not exclusively derive from the examined hospital but represent aggregated average values of many NBS hospitals. Nevertheless, the comparison was made to assure that the model generates realistic values.

The model generated several other results that were very interesting to the blood bank manager and blood centre staff. For instance, the model shows that the particular hospital keeps approximately on average five days of stock, and this was also validated by the blood bank manager. However, the days of stock fluctuate considerably between blood groups. The average weighted days of stock according to the daily issues is only 3.4 days, as shown from the model. Furthermore, the frequencies of the model delivery types (51% routine deliveries, 42% ad-hoc and 7% emergencies) are similar to those of Figure 5.11 (50% routine, 47.5% ad-hoc and collected, 2.5% emergencies), which represent the corresponding values of all hospitals in the PULSE database. Only emergencies deviate, and are quite high in the model. Moreover, the pattern of the daily fluctuations of ordered units (Figure 6.6) is not very different from that shown in Figure 5.9a of the total Southampton NBS issues (orders). However, the daily differences in the latter case are more distinctive. More information about the model results is thoroughly examined and discussed in Chapter 6 for the case of hypothetical hospitals with different characteristics.

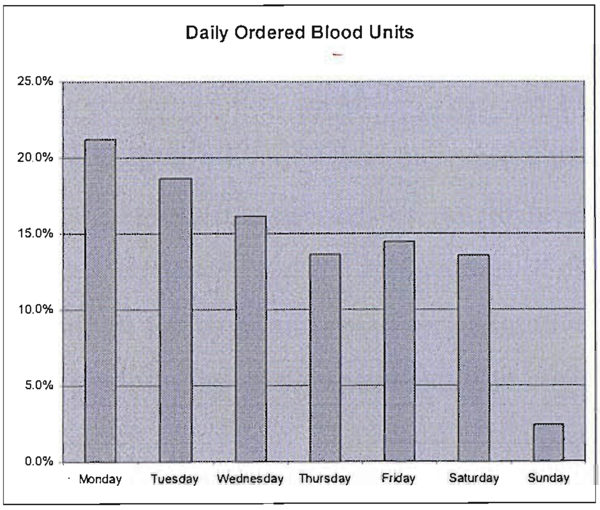

Figure 6.6 Daily average differences between ordered RBC units for the validated hospital

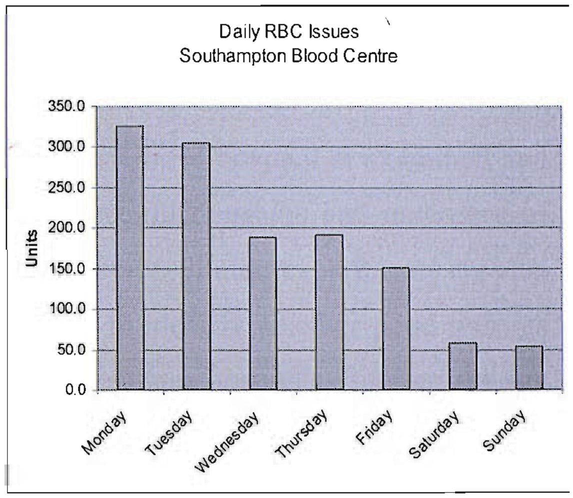

Figure 5.2a Daily average issues of RBC units

CHAPTER 7: EXPERIMENTATION

7.1 Introduction

In this chapter a hypothetical but representative medium-sized hospital is examined and several experiments are carried out to reveal the direct relationships and outcomes of "what if scenarios" and the applications of different policies. Similar experiments are also performed for large and small representative hospitals to identify whether good policies for a medium volume hospital can also apply to different size hospitals. Similarities and differences are sought. The blood centre that is used in the model imitates the working patterns of the Southampton blood centre as described in Chapters 5 and 6.

As a starting point, the hospitals for which information is available from the PULSE database and the questionnaires were categorised according to the volume of blood issues from the Southampton centre, as Table 7.1 shows. This volume depends on the number of units issued from the Southampton NBS to the particular hospital (column 2) out of all hospital issues (column 3). Issues to other NBS centres were not included in the calculations. However, since this particular blood centre is small, although it is a full PTI centre, many of the hospitals that this centre serves are also small in size and thus have low blood consumption. Therefore in Table 7.1 two categories of small and very small hospitals are presented. Nevertheless, only one small hospital is simulated and examined, so these categories are combined.

Fortunately, questionnaires were returned by at least one of the hospitals in each category and thus ideal stock levels, estimations of arrival of physicians' orders and other details were provided combined with the detailed data from the NBS for issues to any of these hospitals. Blood units' arrival rates from the centre and hospital as well as stock levels were adjusted to give a good representation of each category. Several parameters are altered and their impact on the performance criteria is tested. Relationships between the model's outputs are discussed in detail.

Table 7.1 Classification of hospitals according to their blood consumption. Southampton Blood Centre, April 2003 – October 2004

Size	Range of Annual RBC Issues	Range of % of RBC Issues	Number of Hospitals	Hospital Codes*
Very Small	1 - 2250	0%-2.5%	7	SO23, SO27, SO28, SO21, SO24, SO19, SO22
Small	2250 - 4500	2.5%-5%	4	SO18, SO12, 9926, SO10
Medium	4500 - 9150	5%-10%	3	SO17, SO15, SO20
Large	9150 -	10% -	4	SO13, SO11, SO14, SO16

*Hospital codes represent the name of the particular hospital in the database (appendix A.6)

7.2 Medium Volume Usage Hospital

The model whose results will be described represents the processes of a hypothetical but representative medium-sized hospital located approximately 1 hour away from the centre. The baseline model incorporates common blood-ordering policies from several hospitals. The model does not represent an identifiable hospital, but these policies are all in use in one or more of the hospitals from where data were collected.

A snapshot of the simplified model interface is demonstrated in Figure 7.1. The black arrows represent blood units flow and the thick blue arrows represent information flow, i.e. orders. This interface was designed in an attempt to resemble the blood units' flow diagram as presented in Figure 2.4. The snapshot reveals only the top level of the model construction. This simplifies the representation of the system and makes it comprehensible to non-experts, such as NBS and hospital staff.

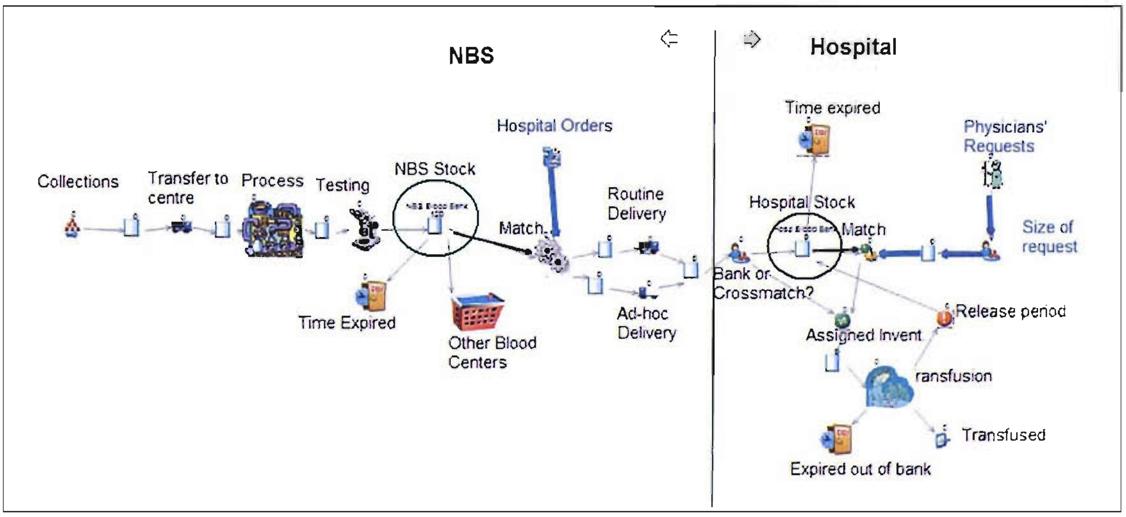

Figure 7.1 Top level simulation model snapshot

The inputs and policies of the baseline scenario of the model that describes the hypothetical hospital are listed below:

- The ideal stock level is 50 units of A positive, 12 of A negative, 4 of AB positive, 4 of AB negative, 10 of B positive, 0 of B negative, 55 of O positive, and 15 of O negative: 150 units altogether.
- The percentage of the Southampton blood centre's issues that this hospital accounts for, and according to which the volume of collections is downsized to reflect collections and stock holding adequate for this hospital only, is 7% (around 8000 ordered units per year).
- The range of daily requests is 7 to 12, which accounts for 30-40 requested units. Following these figures the distribution parameters that describe arrival time of request per patient and size of request were derived for each request category.
- The size of RBC orders, with the exception of emergency requests, follows a LogNormal distribution with a mean of 4.2 units and an SD of 1.3.
- Routine orders are placed by the hospital at 9.00 in the morning. Their delivery from the blood centre sets off at 10.00 on the following day.
- The ordering point for placing routine orders is 80% of the ideal stock, 50% for ad-hoc orders and 15% of the ideal stock for emergency orders.
- The parameters of the over-ordering probability distribution are 50% transfused units, 49.2% returned and 0.8% "out of hours" wastage.
- Unused units return to the unassigned inventory at 10.00 and are not taken into account for routine orders that are placed at 9.00 of the same day.
- The reservation period is variable; however, after transfusion the units are kept at least 15 hours with the patient. The distributions that are used to describe each part of the reservation time are as follows (the values are in minutes): before transfusion - LogNormal (1260, 720); at transfusion - Normal (120, 30); after transfusion - Fixed (900) plus the time difference between the end of the fixed period and the returns at 10.00 in the morning.
- Hospital issues follow a FIFO order for newly arrived RBC units and also for returned units. However, platelets are sorted according to their age (FIFO for new arrivals and LIFO for returned units).
- The distribution time from the centre to the hospital depends on the type of delivery. For routine deliveries this time varies considerably, since it depends on which order the multi-stop NBS transport serves the hospitals. The ad-hoc or emergency delivery times are closer to the true distance from the centre to the

hospital. The following distributions were used to describe the routine and ad-hoc/emergency delivery times respectively (the values are in minutes): LogNormal (120, 40), LogNormal (60, 10).

Appendix C.2 shows the distributions and their parameters that were used for all the inputs of the simulation model.

Table 7.2 shows the average values and the 95% confidence intervals of the key performance indicators that were acquired from the five runs of the model. Each run covers 182 simulated days (6 months). The blood centre's expired RBC units are also included in the table, although this is not considered one of the main criteria, as explained in section 6.4. However, the particular results are meaningful in some ways.

Table 7.2 Model results on performance criteria for a Medium-sized hospital (Baseline scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	336.13	347.60	359.07
Expired RBC units as % of issues	5.17%	5.18%	5.19%
Expired Platelets in hospital	19.50	27.80	36.10
Expired Platelets as % of Issues	13.62%	15.80%	17.29%
Mismatched RBC units	118.82	160.00	201.18
Mismatches as % of Issues	1.75%	2.31%	2.83%
Shortages	133.90	151.00	168.10
Shortages as % of Issues	2.06%	2.25%	2.43%
Expired RBC units in Centre	59.69	101.80	143.91
Expired RBCs in Centre as % of issues	1.68%	2.77%	3.79%
Average deliveries	304.41	313.40	322.39
Routine deliveries	132.50	138.40	144.30
Ad-hoc deliveries	137.17	146.80	156.43
Emergency deliveries	20.75	28.20	35.65

At first glance, it can be noticed that the range of the number of deliveries is rather tight but the ranges of the remaining indicators is wider. Looking at average values, there are 348 expired RBC units in the hospital over 6 months or 58 per month, under the listed hypotheses, generating losses of £45,866 or £7,644 respectively. This figure represents 5.18% of issues and is above the average (2.7%, see Table 5.16). Table 7.3 shows that the hospital issues in the examined period are almost 6,970 units. Around 28 units of platelets are expired (4.5 units in a month's period). This number might not seem high, yet it accounts for 15% of issues, which were 177 platelets, as Table 7.3 demonstrates. The term "*issues*" refers to the number of crossmatched units. The same unit might be crossmatched more than once in its shelf life and therefore the number of issues is usually higher than the number of orders. On average a unit is crossmatched almost 3 (2.86) times before it is transfused or wasted. For platelets this figure is lower (2.15) due to the much shorter shelf life and the infrequency of crossmatches, hence orders. A more in-depth analysis of the simulation output data reveals that the number of crossmatches for the transfused units is 1.7 for RBC and 1.15 for platelets, and the number of crossmatches for the expired units is higher: 4.1 for RBC and 3.15 for platelets.

Mismatches form approximately 2.3% of issues. There are 160 mismatched units, most of which are caused by the substitution of group B negative which is not kept in stock (Table 7.5). Also, unavailability of the rare AB positive units increased the number of mismatches. Shortages represent 2.25% of hospital RBC issues or 4.1% of NBS issues. This figure is close to the 4% mismatched units supplied by the NBS, as reported by the BSMS report (2003a) (see p. 104) and a connection between these two parameters can be identified. One hundred and fifty-one shortages were observed during the run-length. This number reflects the number of requested units that were unavailable from the blood centre at the time of request or by the time of delivery. This figure is not affected by the fact that these units might have been eventually delivered at a later stage when they became available. There are 102 expired units in the blood centre, representing 2.77% of issues. This figure is lower than the equivalent for the hospital. Most of the hospital discards come from the outdating of B negative units, as Table 7.5 reveals, which are not requested from this hospital as they are not kept in stock, and in this model there are no other hospitals served by the blood centre to absorb some of these units.

Three hundred and thirteen deliveries took place in total. Of these 138 were routine deliveries, 147 were ad-hoc and 28 emergency. Ad-hoc and emergency deliveries together account for 56% of all deliveries, and routine deliveries account for 44%. Emergency deliveries alone represent 9% of all deliveries. Routine deliveries to the hospital were highly utilised. One hundred and thirty-eight routine deliveries in 6 months means that 88% of the times that scheduled deliveries were available from the blood centre served this hospital. The availability of routine deliveries in a 6-month period is 158 days; Sundays are excluded. Also, one ad-hoc or emergency delivery was made to the hospital on 96% of days, almost one per day. The number of individual deliveries to the hospital is quite high and the hospital has to pay at least £2,625 for them over the 6 months in addition to the cost of the units. On the other hand, the blood centre expenses for these deliveries are even higher, though not quantifiable. Moreover, the hospital has to pay £51,938 for those RBC and platelet units that were not used because they expired. Three thousand eight hundred and sixty-three orders were placed with the NBS centre, of which 94.3% were for RBC units, 4% for platelet units and only 1.7% for irradiated RBCs. These percentages matche the frequency of products as they appear in the PULSE database for all the NBS issues (see Appendix A.1). Collections from the NBS were 4,115 units, little higher than the number of ordered units.

Table 7.3 Various model results in blood units and as a percentage of total issues for a Medium-sized hospital (Baseline scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	6714.2	
RBC Transfusions	3301.8	49.18%
Hospital RBC Returns	3361.2	50.06%
Hospital RBC Outdates	347.6	5.18%
Hospital RBC Out of Hours Wastage	49.4	0.74%
Hospital Platelet Issues	176	
Platelet Transfusions	123.8	70.34%
Hospital Platelet Returns	51	28.98%
Hospital Platelet Outdates	27.8	15.80%
Hospital Platelet Out of Hours Wastage	1.2	0.68%
Centre RBC Issues	3678.4	
Centre RBC Outdates	101.8	2.77%
All RBC Requests	1596.6	
All RBC Requested Units	6968.2	
Platelet Requests	135.6	
Platelet Requested Units	176.8	
All Ordered Units	3862.6	
RBCs (stock)	3644	
Irradiated and Rare types RBCs	64.6	
Platelet	154	
Collections	4115.6	

The rate of returned, transfused or out-of-hours expired units for RBC and platelets, as Table 7.3 shows in the % of issues column, resembles the respective rates of the over-ordering distribution. The distributions for all the RBC units under the same request to be transfused or none cancel each other in the long run since they are both 10%.

Moreover, 1597 RBC requests were reported, corresponding to 6968 requested units. This means that the average size of each request was 4.3 units overall, which is validated by the mean value of the LogNormal distribution that defines this variable. For platelets, there were 136 requests, which correspond to 177 requested units (1.3 request size). The blood centre collections were 4115 units, of which 338 (8.2%) were transferred to other centres.

Table 7.4 Model outputs related to stock holding in the HBB per blood group for a Medium-sized hospital (Baseline scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	50	47.23	3.59	9.4	3.6
A negative	12	13.04	4.59	13.1	4.7
AB positive	4	5.49	5.06	6.0	5.0
AB negative	4	4.31	13.67	9.4	13.2
B positive	10	11.60	4.05	12.2	4.1
B negative	0	0.20	3.24		3.1
O positive	55	51.78	3.57	14.7	3.6
O negative	15	12.76	3.99	2.6	4.1
Total	150	146.41			
Average per group	18.75	18.30	5.22	9.63	5.18
Weighted Average			3.85	11.21	3.89

The hospital's actual average units in stock per blood group are close to the ideal stock, as Table 7.4 illustrates in columns 2 and 3, since the ordering policy always tries to balance stock around the ideal figure. The particular hospital keeps approximately 5.2 days of stock on average. However, the days of stock significantly fluctuate between blood groups (column 4). The outlier is AB negative inventory, for which 13.7 days of stock are kept. This figure increases the total average days of stock. Nevertheless, the weighted average days of stock, based on the daily issues per blood group, is only 3.8 days, which better reflects the true value of this variable. Days of stock per blood group (column 4) are calculated as presented in section 6.4 and are validated by the Simul8 output regarding the average waiting days of stock in the HBB (column 6). From the model it is also known that around 200 units are in stock on average at the CBB, which accounts for 8.7 days of stock.

The average age of RBC on arrival to the hospital from the CBB varies according to the blood group from 2.5 days to 15 days, with an overall average age of just less than 10 days. The young age of some groups, like O negative, shows that these units are not aged by waiting at the CBB but are distributed as soon as they are collected, so no outdates of these units are acknowledged in the CBB, although shortages are possible. On the other hand, units of blood groups that are old at the time of arrival in the hospital and when the waiting time (days of stock) in the HBB is also long have a high probability of outdating in the HBB.

Table 7.5 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Medium-sized hospital (Baseline scenario).

	Hospital			NBS
6 Months Data	RBC Outdates	Platelet Outdates	Mismatches by patient group	RBC Outdates
A positive	101.60	10.20	0.00	0.40
A negative	36.60	4.20	0.00	4.20
AB positive	15.80	0.00	38.00	2.00
AB negative	19.20	2.60	5.00	7.40
B positive	33.20	2.60	2.00	15.00
B negative	3.40	0.40	115.00	72.60
O positive	111.60	7.40	0.00	0.00
O negative	26.20	3.00	0.00	0.20
Total	347.60	30.40	160.00	101.80
Average per group	43.45	3.80	20.00	12.73

Moreover, Table 7.5 shows RBC and platelet outdates by blood group in the HBB and RBC outdates in the CBB. It is apparent that groups A and O positive have the largest number of discards in the HBB, yet rare groups like AB negative and B positive appear to have far too many outdates in proportion to their issues. Outdates in the CBB come mainly from B negative units (71% of all outdates) as they are rarely requested by the hospital. Also B positive outdates represent 15% of total NBS outdates. For B positive it is clear that ideal hospital stock is greater than necessary since in both blood banks outdates are monitored. At Table 7.5 the mismatches by blood group are also reported (column 4). One hundred and fifteen substitutions of B negative (72% of all mismatches) are observed since this group is not kept in stock. Yet there are also 38 substitutions of group AB positive even though outdated units are also observed in the HBB at the same time. It seems there is a lack of co-ordination between available stock and physicians' requests.

Furthermore, Figures 7.2a and b show the number and average age of units in this HBB, and Figures 7.3a and b show these for the CBB respectively. The first 18 days of the warm-up period have been omitted from the graphs. The range of age in the CBB stock is 6 to 8 days and in the HBB it is 15 to 20 days. The fact that blood is relatively young in the CBB but old in the HBB shows that the hospital can better arrange its processes to improve the age of blood and decrease outdates. The majority of units in stock in the HBB are roughly between 125 and 175 and in the CBB between 160 and 220. A balance is kept during all the run-length in both age and number of units either in the HBB or in the CBB. The largest fluctuation is observed in the number of units in stock in the CBB. The stock drops at distinct points in the graph. These are the days that movements of stock between the blood centre and other centres take place and thus the units in stock notably decrease.

The reservation period of units from the time of crossmatch to the time of release in the unassigned inventory is on average 49.1 hours, which is just above two days. Twenty-one hours is the average waiting time before scheduled transfusion, as defined by the LogNormal distribution, two hours is the average transfusion practice defined by the Normal distribution, and 15 hours is the fixed time that blood stays with the patient in this hospital. The remaining 11 hours is the average time that a unit will have to wait from the moment the compulsory time finishes until the time the unit is returned to the main hospital fridge at 10.00 in the morning. Certainly, there is a huge variation in this waiting time from unit to unit. Accordingly, the reservation period for platelets is on average 22 hours, which is broken down to 12 hours' waiting time before transfusion, two hours' transfusion practice and eight hours' safety stay after transfusion. There is no difference between the last waiting period and the return of platelet units to the HBB, as platelets are closely controlled by hospital staff due to their short shelf life.

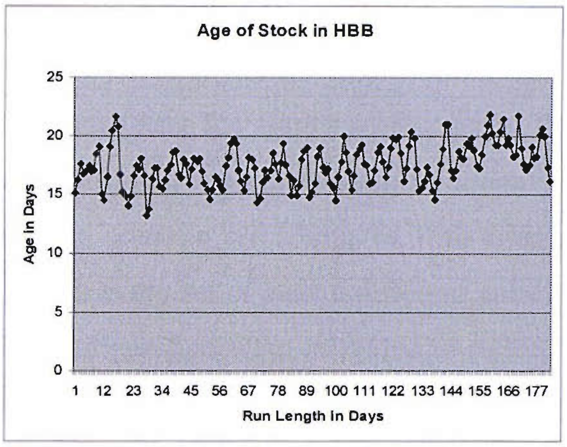

Figure 7.2a Fluctuation of the average age of stock in the HBB (Medium-sized hospital, Baseline Scenario).

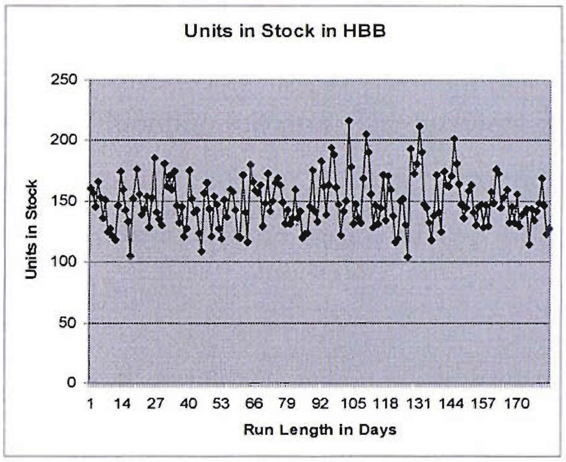

Figure 7.2b Fluctuation of the number of units in stock in the HBB (Medium-sized hospital, Baseline Scenario).

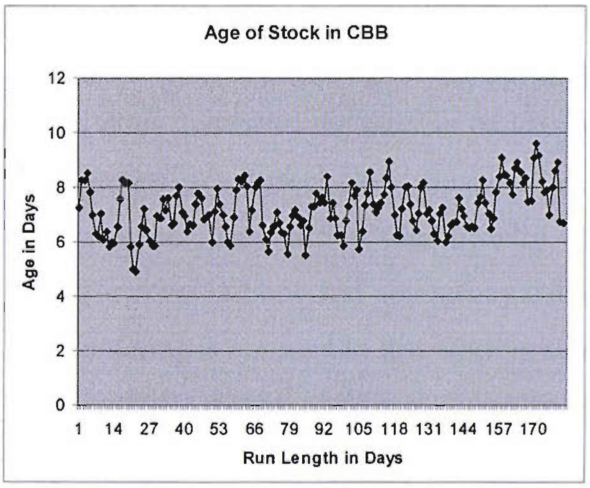

Figure 7.3a Fluctuation of the average age of stock in the CBB (Medium-sized hospital, Baseline Scenario).

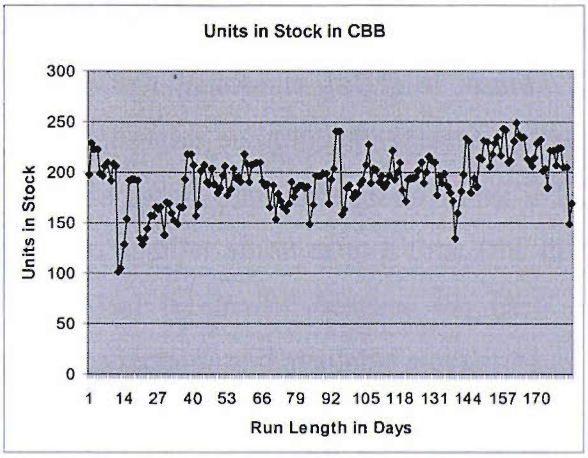

Figure 7.3b Fluctuation of the number of units in stock in the CBB (Medium-sized hospital, Baseline Scenario).

7.3 Experimentation with Medium Volume Hospital

After analysing the results of the model that represents the hypothetical medium blood usage hospital, experimentation for identifying better practices follows. The results of the baseline scenario are compared with alternative policies proposed by hospital and NBS staff. In every set of runs a different policy is tried one at a time. The model parameters and configuration were amended to reflect the new policy and the results are compared with the baseline model against the main performance criteria. Table 7.6 shows, in actual numbers, aggregated results from all the scenarios while Table 7.7 illustrates the actual results of the baseline model and the percentage change of the tested policies compared with the baseline scenario. The numbers in bold indicate that the actual and percentage difference is significant at the 95% confidence level (by conducting one-tailed paired t-test for comparing the means of two samples). Each tried policy is demonstrated and analysed below.

- Policy 1, holding 4 units of B negative in stock, radically decreases the cases of mismatches but slightly increases the expired units, as this group is infrequently requested. Moreover, the blood centre's expired units decrease since B negative units are now regularly distributed to the hospital.
- Policy 2 reduces the number of ideal stock by 20-30 per cent except for the rare groups. Ideal stock now accounts for 4.74 days on average or 3.12 on weighted average. This action significantly reduces the number of expiries by 31%. However, ad-hoc and emergency deliveries increase by 18% since more frequent ordering is required as less stock is kept.
- Policy 3 makes additional reductions to the level of "ideal" inventory, by more than 30% discount for groups A, O and B positive and by 25% for group AB. The outcome is far less expired stock in the HBB; only 199 units out of the initial 348, which represents 2.95% of issues. On the other hand, ad-hoc and emergency deliveries substantially increase, although the number of routine deliveries stays the same. Shortages go down by 29%, possibly because orders to the CBB come in smaller amounts at a time (the difference between the existing stock and the ideal is smaller because the ideal level is less) and better co-ordinate with collections and available stock.
- Policy 4 decreases the average reservation period to 37 hours from 49, by reducing the average crossmatch period before transfusion to 12 hours from 21 and the after-transfusion compulsory reservation time to 10 hours from 15. The

average waiting period, after transfusion and until returns take place, still remains close to 11 hours in spite of these changes. Under this policy all the performance measures look good. There is a significant reduction of expired units in the HBB. Units stay in the assigned inventory for a shorter time and thus return faster to the blood bank if unused.

- Policy 5 assumes that better transfusion estimates are made for each patient and as a consequence smaller batches of ordered units are requested on average (3 units) in each physician's request and increased transfusion to crossmatch ratio is achieved (70%). This policy is possible under either of the following recommendations: better adherence from doctors to the MSBOS and allowance of double or multiple crossmatching as presented in section 2.8. The outcome of this policy is very positive for all key measures. Outdates are considerably reduced, and shortages and mismatched units are reduced too, also fewer ad-hoc and emergency deliveries to the hospital are made. RBC units are only crossmatched 2.4 times in their shelf life compared to the 2.86 times of the baseline scenario. Obviously there is more opportunity for the units to be transfused rather than outdated. The blood bank is more up to date with less distortion from the returned inventory and ad-hoc deliveries are less frequent since fewer units are requested for each operation as a result of more accurate requests from doctors. This also leads to less shortage from the CBB as fewer orders are placed in total.
- Policy 6 uses a lower ad-hoc stock ordering point of 30% (from 50%) and a lower emergency point of 10% (from 15%). These obviously decrease the number of ad-hoc and emergency orders placed with the centre (by 27%) even though bigger orders are now placed with the CBB, causing a small but insignificant increase in the shortage rate. Moreover, routine deliveries slightly increase.
- Policy 7 adopts a LIFO order for returned units in the hospital bank and FIFO for those entering for the first time. This age-based classification leads to a huge drop in the number of outdates, of 66%. All the other performance measures also look good but no considerable changes are reported.
- Policy 8 considers the case of placing routine orders at 16.00, instead of 9.00, keeping the same delivery time. This scenario implies a smaller lead time, which however, hardly affects any of the criteria apart from shortages. Shortages are increased by 15% because there is less time for the right units to become available from the time of order to the time of delivery. This scenario also implies that units returned to the HBB are taken into consideration when orders are placed.

- Policy 9 looks at the effect of an even smaller lead time between routine orders and deliveries, which at present is available to small blood centres only or on less busy days. It assumes that a routine order placed at 8.00 is delivered at 10.00 on the same day. Surprisingly this policy has different outcomes than the previous one. Shortages go down instead of up. There are notably fewer ad-hoc deliveries because of the almost instant routine delivery, which keeps the HBB stock levels close to the optimal. Possibly as a result of the latter, shortages, which should have otherwise increased due to the short lead time, are overshadowed by the fact that fewer orders are placed overall. In addition, fewer expired units are reported because of the balanced HBB.
- Policy 10 introduces two routine deliveries on weekdays: one in the afternoon (14.00) to satisfy the orders placed in the morning (9.00), assuming there is enough time for the centre's staff to prepare the orders, and one in the morning (10.00) to satisfy the routine orders placed at 16.00 on the previous day. Saturdays, though, still have one morning routine delivery. Additionally, the routine stock ordering point drops to 70% of the ideal instead of 80% of the initial scenario, as there are more chances over the day to recover stock in this way. This policy drastically decreases the ad-hoc and emergency deliveries, by 22%. Nevertheless, routine deliveries are almost doubled and apparently the overall number of orders increases by 31%. (More trials were carried out with two routine deliveries and lower or higher re-ordering points. The best outcome was the ordering point of 70% of the ideal stock for the particular size hospital and for all the following tested hospitals, as shown later on. An ordering point of less than 70% in a double daily routine delivery, when compared with the ordering point of 70%, increased the number of total deliveries due to an increase in ad-hoc deliveries followed by only a slight reduction in routine deliveries. This outcome was not considered desirable. The remaining results did not show any significant change with respect to the change of the ordering point.)
- Policy 11 prolongs the life of RBC units in the CBB before discard from the 23rd day to the 30th. This policy does not seem to have a significant impact on the system. Nevertheless, fewer expired units are observed in the CBB followed by a small increase in expired units in the HBB. The most important change is that fewer shortages are detected because more units are available in the CBB's inventory.
- Finally, policy 12 examines the case of an earlier release of test results, at 8.00 instead of 14.00, which enables greater availability of blood units in the CBB at

the time of routine ordering. As expected, shortages go down (by 26%) and also expired units in the HBB lessen by 5%.

- An additional policy which is not presented in any of the Tables is regarding platelets. The impact of decreasing the reservation period of platelets by 5 hours (from 22 hours to 17) was tried out by reducing pre-transfusion time and after-transfusion waiting time. However, the results did not lead to a great change in the number of expired units. Only two fewer expired units were observed, which was not a significant change. Unfortunately, no more "what if scenarios" for platelets were examined since some of their NBS processes are not part of this model and no complete control over their supply chain exists. Future work in this field will be able to throw more light on specific requirements.

Table 7.6 Performance criteria results under different tested policies. Medium hospital.

Policies	**NBS Expired**	**HBB Expired**	**Mismatches**	**Shortages**	**All Orders**	**Ad-hoc & Emerg. Deliver.**	**Routine Deliver.**
0) Baseline, actual results	101.8	347.6	160	151	313.4	175	138.4
1) Keep stock of B negative (4 units)	**40**	**387**	**61.4**	166.2	322.6	180.8	141.8
2) Reduced ideal stock (A+40,A-8,AB+4,AB-4,B+8,B-0,O+40,O-10)	107	**238.8**	133.2	155.6	**342.8**	**206**	136
3) Further reduced ideal stock (A+32,A-6,AB+3, AB-3,B+6,B-3,O+34,O-7)	118.6	**198.6**	174.2	**107.2**	**390.6**	**250.8**	139.8
4) Reservation period 37h	100	**275.6**	150.6	129.86	305.6	167.2	138.4
5) 70% Transfused, smaller size request [LogNormal(3,0.5)]	110.6	**188.4**	**108.8**	**81.6**	**293.2**	**150**	143.2
6) Ad-hoc order = 30% of Ideal Stock Emergency order =10% of Ideal Stock	110.4	337.8	157.6	169.2	**274.2**	**127.6**	**146.6**
7) Blood Bank FIFO +LIFO for returns	120	**118.6**	130	143.4	306.4	168.8	137.6
8) Order at 16.00	94.8	333.2	131.6	**173.6**	314.4	173.4	141
9) Order at 8.00 Delivery same day	104.4	**309.2**	155.8	**119.2**	**286.6**	**142.4**	**147.2**
10) 2 Routines(order at 16.00 delivery at 10.00 next day/order at 9.00 delivery at 14.00 same day	103.2	333.4	157.6	160	**411.8**	**137.2**	**274.6**
11) NBS RBCs expire on day 30	73.6	361	156.2	**126.8**	312.2	172.8	140.4
12) Tests Release at 8.00	98.4	**329.4**	158	**111.8**	324.6	192	138.6

Table 7.7 Percentage change of performance criteria under different tested policies. Medium hospital.

Policies	NBS Expired	HBB Expired	Mismatches	Shortages	All Deliver.	Ad-hoc & Emerg. Deliver.	Routine Deliver.
0) Baseline, actual results	101.8	347.6	160	151	313.4	175	138.4
1) Keep stock of B negative (4 units)	**-61%**	**11%**	**-62%**	10%	3%	3%	2%
2) Reduced ideal stock (A+40,A-8,AB+4,AB-4,B+8,B-0,O+40,O-10)	5%	**-31%**	-17%	3%	**9%**	**18%**	-2%
3) Further reduced ideal stock (A+32,A-6,AB+3,AB-3,B+6,B-3,O+34,O-7)	17%	**-43%**	9%	**-29%**	**25%**	**43%**	1%
4) Reservation period 37h	-2%	**-21%**	-6%	-14%	-2%	-4%	0%
5) 70% Transfused, smaller size request [LogNormal(3,0.5)]	9%	**-46%**	**-32%**	**-46%**	**-6%**	**-14%**	3%
6) Ad-hoc order = 30% of Ideal Stock Emergency order =10% of Ideal Stock	8%	-3%	-2%	12%	**-13%**	**-27%**	**6%**
7) Blood Bank FIFO +LIFO for returns	18%	**-66%**	-19%	-5%	-2%	-4%	-1%
8) Order at 16.00	-7%	-4%	-18%	**15%**	0%	-1%	2%
9) Order at 8.00 Delivery same day	3%	**-11%**	-3%	**-21%**	**-9%**	**-19%**	**6%**
10) 2 Routines(order at 16.00 delivery at 10.00 next day/order at 9.00 delivery at 14.00 same day	1%	-4%	-2%	6%	**31%**	**-22%**	**98%**
11) NBS RBCs expire on day 30	-28%	4%	-2%	**-16%**	0%	-1%	1%
12) Tests Release at 8.00	-3%	**-5%**	-1%	**-26%**	4%	10%	0%

Only some of the tried policies resulted in beneficial outcomes for all the chosen criteria (policies 5, 6, 7 & 10). The combination of these policies also gave very positive results; however, policy 10 was not considered very realistic by the blood centre's staff. The remaining policies did not show the simultaneous improvement of all the criteria, which complicated the recognition of a bad or a good policy. Certainly, the criteria do not have the same significance; for example, the risk to human life because of mismatch is far more important than cost savings. A weighted average could be a good solution to this problem. However, the combination of several policies had a different outcome overall. Hence it was attempted by trial and error to make realistic combinations of policies, following the suggestions of the NBS staff and blood bank managers. Tables 7.8 and 7.9 represent some of the best tested combinations, which are also compared with the baseline scenario.

- Scenario 1 combines policies 1, 2, 4, 5, 6, 7 and 10 as illustrated in Tables 7.7 and 7.8. These are summarised as follows: "ideal" stock holding of A positive 40 units, A negative 8, AB positive 4, AB negative 4, B positive 8, B negative 4, O positive 40, O negative 10, average reservation period of 37 hours, smaller batches of requested units [LogNormal(3,0.5)], transfuse-to-crossmatch ratio of 0.7, ad-hoc stock ordering point is 30% of ideal stock, and emergency stock ordering point is 10% of ideal, HBB keeps RBC units in FIFO order on arrival from the centre and returning units from assigned inventory in LIFO order, and two routine orders and deliveries are made each weekday. The outcome of this experiment has a great impact on all the performance measures, as Tables 7.8 and 7.9 show. The expired units in the blood centre did not significantly change; however, the number of units transferred to other centres has considerably increased from 337 units, as in the baseline scenario, to 658. These 658 units (16% of issues) could help other centres to meet their needs, or in the ideal world where all the centres follow optimal policies there would be no need for collecting them in the first place. This outcome is greatly desirable since the donors' pool constantly shrinks in the light of new transmitted diseases, as explained in Chapter 1.
- Scenario 2 slightly diminishes the blood centre's collections (by 260 blood units over 6 months) to monitor the consequence of lower supply on the criteria, taking also into consideration the decrease in the age of blood sitting in the centre's stock. Looking at Table 7.9, the effects are not significant when compared with the previous scenario, but, as expected, outdates in the HBB are slightly reduced (2%) and all types of deliveries have improved, although shortages and

mismatches have a smaller improvement compared with scenario 1 because of the reduced availability of stock.

- Scenario 3 adopts scenario 2 with the addition of policy 11, units in the NBS are discarded after 30 days. Under this scenario the blood centre's expired units are drastically reduced; however, the improvement in hospital's expired units diminishes by 10%. Shortages look slightly better than before but total deliveries further increase in comparison to scenario 2, because routine deliveries increase more than non-routine deliveries decrease.
- Finally, scenario 4 is based on scenario 2 incorporating policies 11 and 12 together with the release of blood units test results at 8 in the morning. The effects are the same as for scenario 3.

Table 7.8 Performance criteria results of different combined policies. Medium hospital.

Scenarios	CBB Expired	HBB Expired	Mis-matches	Shortages	Total Deliver.	Ad-hoc & Emer	Routine Deliver.
0) Baseline, actual results	101.8	347.6	160	151	313.4	175	138.4
1) Combine 1, 2, 4, 5, 6, 7,10	77.4	**48.8**	**36**	**80**	**369.6**	**92.6**	**277**
2) Combine 1, 2, 4, 5, 6, 7,10, 260 fewer collections	68.4	**45.2**	**40**	**84.6**	**360.8**	**89.4**	**271.4**
3) Best 2 with 30 day NBS expiry and fewer collections	**10.8**	**75.2**	**38.6**	**77**	**376.2**	**83.2**	**293**
4) Best 2 with 30th day NBS expiry& 8.00 Tests and fewer collections	**9.8**	**74.6**	**38.2**	**73**	**373.8**	**82.4**	**291.4**

Table 7.9 Percentage change in the performance measurements achieved with different combined policies. Medium hospital.

Scenarios	CBB Expired	HBB Expired	Mis-matches	Shortages	Total Deliver.	Ad-hoc & Emer	Routine Deliver.
0) Baseline, actual results	101.8	347.6	160	151	313.4	175	138.4
1) Combine 1, 2, 4, 5, 6, 7,10	-24%	**-86%**	**-78%**	**-47%**	**18%**	**-47%**	**100%**
2) Combine 1, 2, 4, 5, 6, 7,10, 260 fewer collections	-33%	**-88%**	**-75%**	**-44%**	**15%**	**-49%**	**96%**
3) Best 2 with 30 day NBS expiry and fewer collections	**-89%**	**-78%**	**-76%**	**-49%**	**20%**	**-52%**	**112%**
4) Best 2 with 30th day NBS expiry& 8.00 Tests and fewer collections	**-90%**	**-79%**	**-76%**	**-51%**	**19%**	**-53%**	**111%**

Scenario 2 is believed to be the best of the tested combinations. Scenarios 3 and 4 were ruled out because they involved further changes in the blood supply system which did not show remarkable benefits. Taking into account also the fact that public systems are usually slow adopters of changes, it was decided that it would be better to keep it simple.

More results related to scenario 2 are presented here in the same way as for the baseline. Table 7.10 shows that routine deliveries are almost doubled, meaning that all the added routine deliveries are utilised. This phenomenon, although it increases the number of total deliveries, is not necessarily unfavourable since routine deliveries are well organised and serve many clients at once. However, ad-hoc and emergency deliveries, which are costly, decrease by almost 50%. Furthermore, it is notable in Table 7.13 that, although optimal stock has decreased by 32 units compared with the initial scenario, the days of stock have increased on average to 6.44 days from 5.22 (weighted average to 3.92 from 3.85). This has possibly been caused by the need for fewer requested units to satisfy the same number of patients, as Table 7.12 illustrates. This is also apparent from the fact that the number of all RBC requests from the physicians is the same between Tables 7.3 and 6.11 (1597 units) but the number of requested RBC units is 1916 units less in the second case (best scenario) over the 6 months. Additionally, the total ordered units have decreased from 3863 to 3510, which therefore causes less increase in the number of deliveries, when compared with the increase in deliveries of policy 10, which allows for two routine deliveries (increase reduced by 16%). Moreover, as Table 7.12 shows, the age of units on arrival has decreased from 9.63 to 5.46 on average.

Table 7.10 Model results on performance criteria for a Medium-sized hospital (Best scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	25.08	45.20	65.32
Expired RBC units as % of issues	0.53%	0.93%	1.30%
Expired Platelets in hospital	17.88	28.00	38.12
Expired Platelets as % of Issues	12.44%	15.86%	18.20%
Mismatched RBC units	10.27	40.00	69.73
Mismatches as % of Issues	0.22%	0.82%	1.39%
Shortages	69.3	84.6	99.8
Shortages as % of Issues	1.47%	1.74%	1.99%
Expired RBC units in Centre	41.51	68.40	95.29
Expired RBCs in Centre as % of issues	1.26%	2.02%	2.72%
Average deliveries	343.19	360.80	378.41
Routine deliveries	269.31	271.40	277.49
Ad-hoc deliveries	52.57	65.00	77.43
Emergency deliveries	19.05	24.40	29.75

Table 7.9 Various model results in blood units and as a percentage of total issues for a Medium-sized hospital (Best scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	4864	
RBC Transfusions	3315.2	68.16%
Hospital RBC Returns	1517.8	31.20%
Hospital RBC Outdates	45.2	0.93%
Hospital RBC Out of Hours Wastage	34.6	0.71%
Hospital Platelet Issues	176.6	
Platelet Transfusions	124	70.22%
Hospital Platelet Returns	51	28.88%
Hospital Platelet Outdates	28	15.86%
Hospital Platelets Out of Hours Wastage	1.2	0.68%
Centre RBC Issues	3394	
Centre RBC Outdates	68.4	2.02%
All RBC Requests	1596.6	
All RBC Requested Units	5052.53	
Platelet Requests	135.6	
Platelet Requested Units	176.8	
All Ordered Units	3510	
RBCs (stock)	3310.4	
Irradiated and Rare types RBCs	45.6	
Platelets	154	
Collections	3853.4	

Table 7.10 Model outputs related to stock holding in the HBB per blood group for a Medium-sized hospital (Best scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	40	32.02	3.53	4.6	3.5
A negative	8	8.53	4.41	8.4	4.5
AB positive	4	4.45	5.86	5.9	5.9
AB negative	4	3.67	15.60	6.9	15.2
B positive	8	8.68	4.41	6.6	4.5
B negative	4	4.72	9.33	2.3	9.3
O positive	40	31.66	3.13	5.6	3.2
O negative	10	10.00	5.22	3.4	5.3
Total	118	103.73			
Average per group	14.75	12.97	6.44	5.46	6.42
Weighted Average			3.92	5.32	3.95

Table 7.13 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Medium-sized hospital (Best scenario).

6 Months Data	Hospital			NBS
	RBC Outdates	Platelet Outdates	Mismatches by patient group	RBC Outdates
A positive	0.00	11.40	0.00	2.60
A negative	2.20	3.40	0.00	12.00
AB positive	4.60	0.00	16.00	3.20
AB negative	15.40	1.60	12.00	6.00
B positive	5.40	1.60	6.00	25.20
B negative	11.80	0.40	6.00	7.00
O positive	0.00	6.40	0.00	0.00
O negative	5.80	4.80	0.00	12.40
Total	45.20	29.60	40.00	68.40
Average per group	5.65	3.70	5.00	8.55

Furthermore, the graphs in Figures 7.4 and 7.5 prove that the solutions obtained in the best scenario derive from a balanced model. The age of blood in the HBB has decreased by 2 to 3 days throughout the run. One can observe that in Figures 7.4a and 7.5a there is some possible prevalence of initial transient data for the first 20 days or so. However, since the value differences and the transient period are small and the phenomenon was not repeated in any of the other similar graphs, the warm-up was not changed.

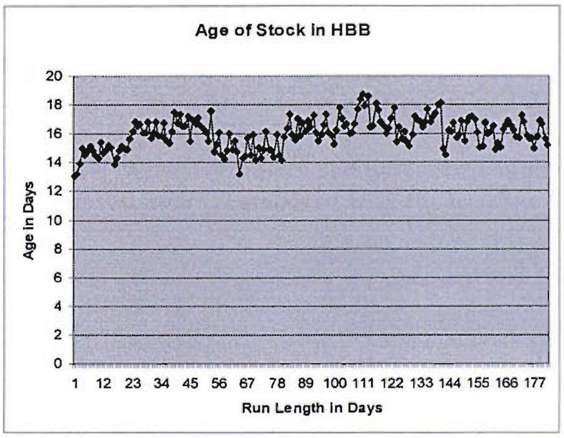

Figure 7.4a Fluctuation of the average age of stock in the HBB (Medium-sized hospital, Best Scenario).

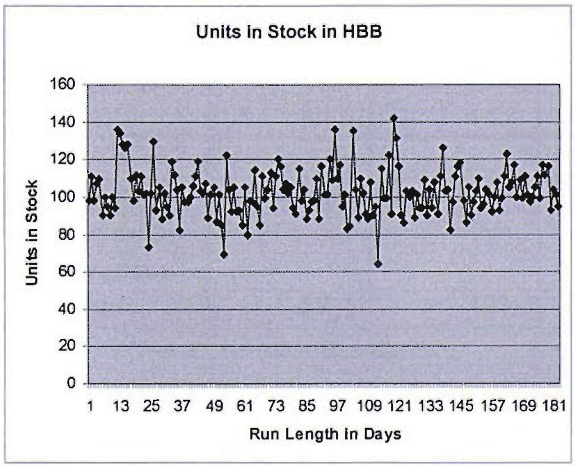

Figure 7.4b Fluctuation of the number of units in stock in the HBB (Medium-sized hospital, Best Scenario).

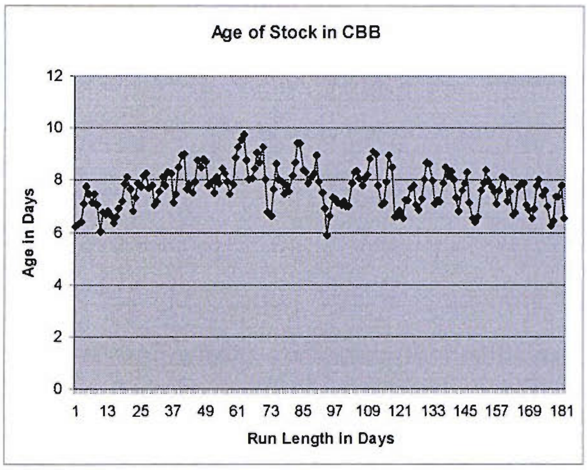

Figure 7.5a Fluctuation of the average age of stock in the CBB (Medium-sized hospital, Best Scenario).

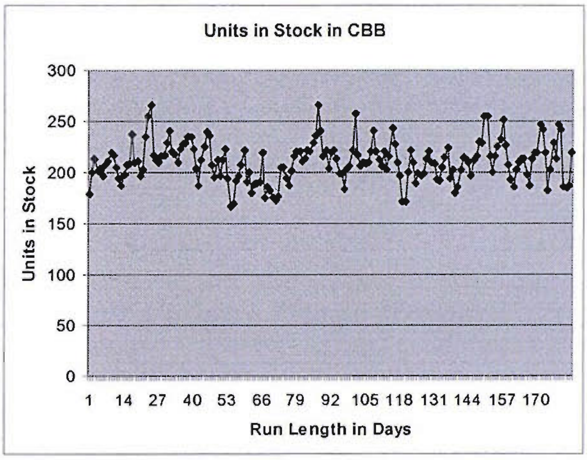

Figure 7.5b Fluctuation of the number of units in stock in the CBB (Medium-sized hospital, Best Scenario).

Table 7.14 shows the results of the enhanced model in actual values and percentage improvement in the performance measurements, comparing the current practices of the sample hospital with the best combination of policies recommended for adoption.

Table 7.14 Actual numbers and percentage improvements in the performance indices by applying the improved policy, compared with the baseline of a Medium hospital.

Performance Measurement	Actual Number	% improvement	Savings	
			£	%
Expired RBC units	68.4	88%	£38,500	9.1%
Mismatched units	45.2	75%	Lives	
Shortages in units	84.6	44%	Lives	
No. of All Deliveries	360.8	-15%	£1,360	49%
No. of Ad-hoc & Emergency Deliveries	89.4	49%		

In adopting the recommendations of the improved scenario, the total system will gain:

- 88% (297 units) fewer RBC outdates, which corresponds to a cash saving of £38,500. Moreover, the cost savings in buying 353 fewer units from the NBS will cut costs by £46,500 in total from the hospital budget. This is a 9.1% saving overall.
- 75% (115 units) less mismatching, resulting in avoidance of possible medical complications and potential health risk.
- 44% (66 units) fewer shortages from the centre.
- 49% (86) fewer ad-hoc and emergency orders from the hospital, with 49% savings (£1,360) on the money charged for deliveries from this hospital alone, and uncounted savings for the NBS by reducing the number of occupied drivers, staff and transport outside of the routine deliveries specified times.

7.4 Small Volume Usage Hospital

Further experiments were carried out for a hypothetical small hospital with similar characteristics in terms of hospital proximity to the centre and initial ordering policies. Again in this case the model does not represent an identifiable hospital, but these policies are all in use in one or more of the hospitals from where data were collected.

The inputs and policies of the baseline scenario of the model that describes the hypothetical small hospital are listed below:

- The ideal stock level is 18 units of A positive, 5 of A negative, 0 of AB positive, 0 of AB negative, 4 of B positive, 0 of B negative, 20 of O positive, and 5 of O negative: 52 in total.
- The percentage of the Southampton blood centre's issues that this hospital accounts for, and according to which the volume of collections is downsized to reflect collections and stock holding adequate for this hospital only, is 2.6% (around 2800 ordered units per year).
- The range of daily requests is 2 to 4, which accounts for roughly 5 to 20 requested units. Following these figures the parameters of the distributions that describe arrival time of request per patient and size of request were derived for each request category. These orders do not follow a time-dependent distribution because they are infrequent.

The remaining points are the same as for the medium size hospital presented in section 7.2. A list with the exact distributions used in the simulation model of this hospital is given in Appendix C.3.

Under these circumstances, looking at average values in Table 7.15, 136 expired RBC units were reported in the hospital, most of them deriving from groups A, B and O positive, as Table 7.18 shows. This number of outdates represents 5.9% of RBC issues, i.e. 2312 units (Table 7.16). Only 11 units of platelet outdated over the 6 months, which however represents almost 21% of issues, as only 55 units of platelet were issued in total. RBC outdates cause a waste of almost £18,000 and platelets a loss of £2,400; altogether this is a loss of £20,400. Mismatched units are extremely high, higher than in the medium-sized hospital, and account for 7.4% of issues. This is obviously because no stock of groups AB and B negative is kept in the HBB. Most of the mismatching comes from group AB positive, and also there are mismatched units for patients with group B positive, even though there are usually 4 units of this group kept in stock. Only 54 units were not delivered in time from the CBB, corresponding to 2.3% of issues, almost the same proportion as for the medium hospital. The model generated 1380 units of orders with the CBB, which were transported in 201 deliveries. This means that the average size of delivery approaches 7 units. This figure was 12 units for the medium hospital. Forty-seven per cent of the deliveries were scheduled routine deliveries, 37% ad-hoc and 16% emergency. The latter figure is very high. Routine deliveries are utilised only at the rate of 59% out of all (158) available scheduled deliveries. On average around 5.4 days are held in stock and the weighted average is 4.1 days. In the CBB the same figure is about 7.3 days. In the NBS 100 units of RBC were again outdated. Almost all of these come from the groups not in stock in the HBB and especially from AB negative. Groups A and O seem to have almost no outdates (Table 7.18) because they are ordered frequently and they also compensate for the groups not in stock.

On average an RBC unit has been crossmatched just less than twice in its life (1.74) before being transfused or wasted. The average number of crossmatches for the transfused units is 1.64 and for the expired units 3.55. For platelets, these figures are 1.05 and 2.05 respectively. On average a platelet gets crossmatched 1.13 times regardless of its final destination.

Table 7.13 Model results on performance criteria for a Small hospital (Baseline scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	96.98	136.00	175.02
Expired RBC units as % of issues	4.35%	5.88%	7.30%
Expired Platelets in hospital	5.28	11.40	17.52
Expired Platelets as % of Issues	13.25%	20.73%	24.97%
Mismatched RBC units	148.37	171.20	194.03
Mismatches as % of Issues	6.66%	7.40%	8.09%
Shortages	41.9	54	66.1
Shortages as % of Issues	1.88%	2.34%	2.76%
Expired RBC units in Centre	71.57	100.40	129.23
Expired RBCs in Centre as % of issues	5.83%	7.83%	9.67%
Average deliveries	192.24	201.40	210.56
Routine deliveries	89.53	93.80	98.07
Ad-hoc deliveries	69.94	75.40	80.86
Emergency deliveries	30.30	32.20	34.10

Table 7.14 Various model results in blood units and as a percentage of total issues for a Small hospital (Baseline scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	2312	
RBC Transfusions	1143	49.44%
Hospital RBC Returns	1157.6	50.07%
Hospital RBC Outdates	136	5.88%
Hospital RBC Out of Hours Wastage	17.4	0.75%
Hospital Platelet Issues	55	
Platelet Transfusions	37.8	68.73%
Hospital Platelet Returns	17	30.91%
Hospital Platelet Outdates	11.4	20.73%
Hospital Platelets Out of Hours Wastage	0.2	0.36%
Centre RBC Issues	1281.8	
Centre RBC Outdates	100.4	7.83%
All RBC Requests	556.6	
All RBC Requested Units	2501.92	
Platelet Requests	41.2	
Platelet Requested Units	55.2	
All Ordered Units	1379	
RBCs (stock)	1301.8	
Irradiated and Rare types RBCs	27.2	
Platelets	50	
Collections	1445.4	

Table 7.17 Model outputs related to stock holding in the HBB per blood group for a Small hospital (Baseline scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	18	19.90	4.15	10.3	4.1
A negative	5	5.90	6.49	7.2	6.6
AB positive	0	0.28	4.76		5.4
AB negative	0	0.10	8.65		6.5
B positive	4	5.62	5.77	12.1	6.0
B negative	0	0.21	6.29		6.6
O positive	20	20.41	3.91	11.4	3.9
O negative	5	1.65	1.48	3.1	1.6
Total	52	54.06			
Average per group	6.5	6.76	5.19	8.82	5.09
Weighted Average			4.12	9.94	4.17

Table 7.18 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Small hospital (Baseline scenario).

6 Months Data	Hospital			NBS
	RBC Outdates	Platelet Outdates	Mismatches by patient group	RBC Outdates
A positive	37.60	4.00	0.00	0.60
A negative	15.80	1.00	2.00	1.60
AB positive	4.40	0.00	85.00	15.60
AB negative	1.20	0.20	11.00	42.40
B positive	27.20	0.20	38.00	13.60
B negative	3.80	0.00	36.00	24.80
O positive	42.00	4.80	0.00	0.20
O negative	4.00	1.40	0.00	1.60
Total	136.00	11.60	172.00	100.40
Average per group	17.00	1.45	21.50	12.55

Figures 7.6a and b show the number and range of the average age of units in this HBB and Figures 7.7a and b show these for the CBB respectively. The graphs are much more variable than the corresponding graphs for the medium-sized hospital. The average age of blood in the HBB ranges between 14 and 24 days. However in the CBB it seems to fall at first but then stabilises at about 7 days. The age of units on arrival in the HBB is roughly 8.8 days (Table 7.17). The 1.5 days difference between the average age of stock in the CBB and at the time of arrival in the HBB is due to the FIFO NBS issuing (the oldest units are shipped first from the top of the pile and not those of average age from the middle). In addition, there is around one day waiting in the reserve mode in the CBB from

the moment routine orders arrive and get prepared (at 9.00) in the CBB until they are delivered to the HBB the following day (after 10.00). This intermediate period in which the units are reserved in the CBB is not included in the days of stock in the CBB. The units in stock are even more erratic. They lie within the range of 60 to 80 in the HBB and from 30 to 120 in the CBB. Some of the fluctuation in the number of units in stock in the CBB is explained from the movements of stock between the blood centre and other centres at discrete points of time, when the stock notably drops. Moreover, this variation is explained by the fact that collections arrive at the CBB at specific times from the collection sites, and the stock that acts as a cushion is not enough to absorb all the gaps between arrival of new stock in the CBB and delivery of orders.

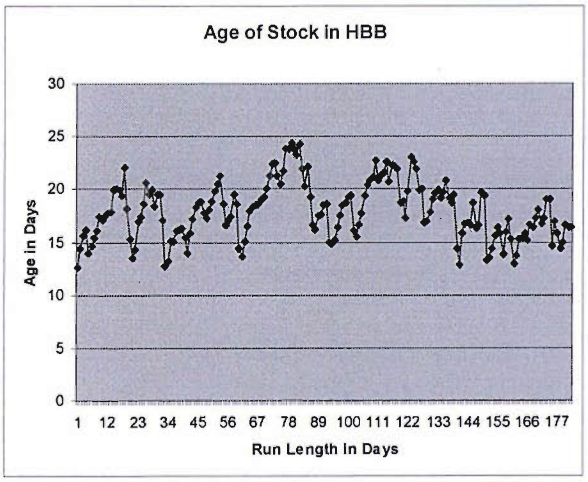

Figure 7.6a Fluctuation of the average age of stock in the HBB (Small hospital, Baseline Scenario).

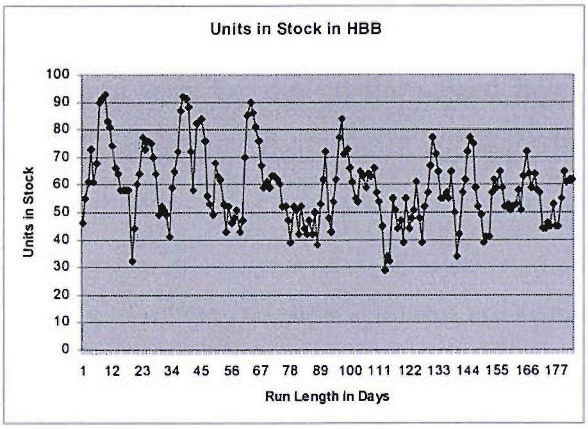

Figure 7.6b Fluctuation of the number of units in stock in the HBB (Small hospital, Baseline Scenario).

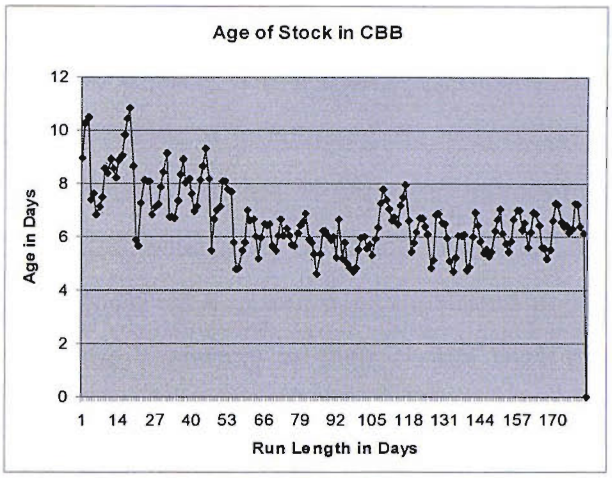

Figure 7.7a Fluctuation of the average age of stock in the CBB (Small hospital, Baseline Scenario).

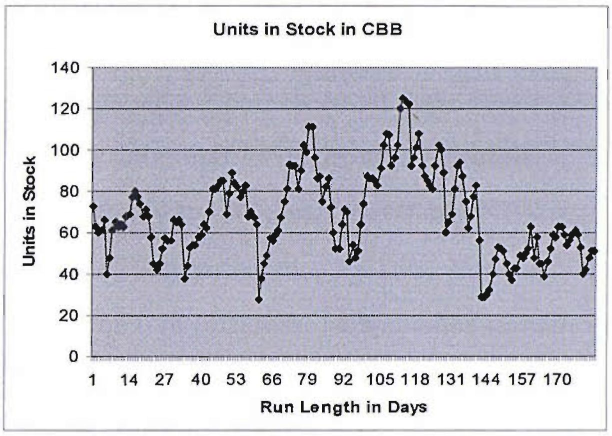

Figure 7.7b Fluctuation of the number of units in stock in the CBB (Small hospital, Baseline Scenario).

7.5 Experimentation with Small Volume Hospital

Experimentation for identifying better practices in the small hospital was less time-consuming than for the medium-sized hospital. It was soon realised that most of the policies that improved outcomes in the medium-sized hospital were equally good for the small hospital.

The results of the baseline scenario are compared with some of the alternative policies. Table 7.19 shows, in actual numbers, results from all the presented scenarios, while Table 7.20 illustrates the actual results of the baseline model and the percentage change of the tested policies compared with the baseline scenario. The numbers in bold indicate that the actual and percentage difference was significant at the 95% confidence level. Each policy is demonstrated and analysed below.

- Policy 1 considers the issuing order in the HBB. It assumes that FIFO order is kept for new arriving RBC units and LIFO is used for returning units. This policy decreases the number of outdates by 42%, which is smaller than the corresponding reduction of 66% for the medium-sized hospital. All the other key outputs also look good, with a significant drop in shortages by 13 units (24%).

- Policies of minimising the reservation period to 37 hours on average, requests for smaller batches of units and increasing the transfusion rate to 70%, using ad-hoc and emergency ordering points of 30% and 10% of ideal stock respectively (policies 4, 5 and 6, as illustrated in Tables 7.7 and 7.8) were adopted right from the beginning as their results were beneficial for all main criteria. Apart from policy 1, which was presented for confirming the improvements that this policy also brings to the small hospital, the results of the remaining policies are not presented one by one but only in combination, together with policy 1. Thus, scenario 2 combines all these four policies and also minimises A negative stock to 4 units and O positive to 15 units. The outcome is that expired RBC units drop hugely by 86% and inevitably NBS outdates increase. Also ad-hoc and emergency deliveries decrease by 15%; however, routine deliveries increase by 13%, which is positive progress. Mismatches remain the same, as no stock of three of the blood groups is kept, and shortages also do not present significant change.
- Scenario 3 adopts scenario 2 but also adds 4 units of stock to each of group AB and group B negative. This obviously reduces the number of mismatches to only 42 units (75% reduction) but decreases the improvement in expired units from 86% to 50%, because stock from the rare groups also outdates from the HBB. Shortages also decrease because orders are spread between all the blood groups and are not gathered in groups A and O only. Thus, the CBB can now satisfy smaller orders of groups A and O and also has fewer expired units because units of groups AB and B are ordered. The advantage, though, of scenario 2 of fewer ad-hoc deliveries is now lost, as more ad-hoc deliveries are initiated than in the previous case in order to replace the rare groups' stock. Routine deliveries are also increased by 23% over the baseline scenario.
- Scenario 4 adopts scenario 3 and slightly changes the A negative stock from 18 to 15 units, in an attempt to find the "best" stock level for this HBB to trigger the ordering process. There was no significant change from the previous scenario except for expired hospital units, which decreased by 52% (2% more than before).
- Scenario 5 adopts scenario 4 and adds a second routine delivery service as in the case of the medium-sized hospital. A routine order is placed at 16.00 the previous day and is delivered at some point after 10.00 the next morning, the time that the NBS transport sets off from the blood centre. The second routine order is placed at 9.00 and is delivered after 16.00 the same day. Also the routine ordering point is

reduced to 70% of the ideal stock, instead of 80%. The outcome is that ad-hoc and emergency deliveries drop by 24% in comparison with the baseline scenario, but routine deliveries increase by 71% and thus the total number of deliveries increases by 20%. One hundred and sixty routine deliveries are now made, representing around one delivery per day of available NBS routine transport. The remaining criteria get better in comparison to the baseline scenario but stay the same when assessed against the previous scenario. Only the improvement in shortages is reduced, because more orders are now placed with the centre and thus the NBS is more frequently short of some of the requested units.

- Finally scenario 6 copies scenario 5 with the difference that routine re-ordering point is 60% of the ideal stock. Results are similar to those of scenario 5 except for deliveries. The improvement in ad-hoc and emergency deliveries decreases by 8%, and although routine deliveries are 14% lower than in scenario 5, the benefit in the total number of deliveries is only a 2% decrease. Since decreasing ad-hoc and emergency deliveries is more important, scenario 5 was judged to be slightly better overall than the current one.

Scenarios 4 and 5 are believed to bring the best improvement out of the scenarios that were tried. The difference is whether one or two scheduled deliveries are available from the NBS, and also changes the routine ordering point from 80% with one delivery to 70% with two. Nevertheless, the decision about the number of provided deliveries from the centre would not be evaluated solely from the benefits this policy brings to the particular hospital, but will be assessed on the general advantage offered to all hospitals supplied by the NBS. Therefore, since even for the small hospital a second delivery is fairly advantageous, then this is also so for all the bigger hospitals. In section 7.3 it was proven that two routine deliveries are beneficial for the medium-sized hospital.

Table 7.17 Performance criteria results under different combined policies. Small hospital.

Scenarios	CBB Expired	HBB Expired	Mismatches	Shortages	No. of Orders	Ad-hoc &Emerg D.	Routine Deliver.
0) Baseline, actual results	100.4	136	171.2	54	201.4	107.6	93.8
1) Blood Bank FIFO +LIFO for returns	112.4	**79.4**	155.8	**41.2**	196	105.8	90.2
2) Best stock (A+18,A-4,AB+0,AB-0,B+4,B-0,O+15,O-5)	**377.8**	**19.2**	168.8	52.6	199.8	**91.8**	**106.4**
3) Best stock (A+18,A-4,AB+4,AB-4,B+4,B-4,O+15,O-5)	**57.8**	**67.6**	**42.2**	**21.2**	**217.4**	104.4	**115.6**
4) Best stock (A+15,A-4,AB+4,AB-4,B+4,B-4,O+15,O-5)	**58**	**64.8**	**43.4**	**21.6**	**220**	105.2	**114.8**
5) 2 Routines(order at 16.00 delivery at 11.00 next day/order at 9.00 delivery at 15.00 same day	**60.6**	**62.8**	**44.2**	**33.4**	**242**	**82**	**160**
6) 2 Routines routine orders at 60% of ideal stock	**61.8**	**62.4**	**44.4**	**32.2**	**237.4**	**90.2**	**147.2**

Table 7.18 Percentage change of performance criteria under different combined policies. Small hospital.

Scenarios	CBB Expired	HBB Expired	Mismatches	Shortages	No. of Orders	Ad-hoc & Emerg D.	Routine Deliver.
0) Baseline, actual results	100.4	136	171.2	54	204.9	107.6	93.8
1) Blood Bank FIFO +LIFO for returns	12%	**-42%**	-9%	**-24%**	-3%	-2%	-4%
2) Best stock (A+18,A-4,AB+0,AB-0,B+4,B-0,O+15,O-5)	**276%**	**-86%**	-1%	-3%	-1%	**-15%**	**13%**
3) Best stock (A+18,A-4,AB+4,AB-4,B+4,B-4,O+15,O-5)	**-42%**	**-50%**	**-75%**	**-61%**	**8%**	-3%	**23%**
4) Best stock (A+15,A-4,AB+4,AB-4,B+4,B-4,O+15,O-5)	**-42%**	**-52%**	**-75%**	**-60%**	**9%**	-2%	**22%**
5) 2 Routines(order at 16.00 delivery at 10.00 next day/order at 9.00 delivery at 14.00 same day	**-40%**	**-54%**	**-74%**	**-38%**	**20%**	**-24%**	**71%**
6) 2 Routines routine orders at 60% of ideal stock	**-38%**	**-54%**	**-74%**	**-40%**	**18%**	**-16%**	**57%**

More results related to scenario 5 are presented in Tables 7.21 to 7.24. It can be seen that expired RBC units in the HBB as a percentage of issues is still quite high (3.7%). In the medium-sized hospital the adoption of the new policies brought a greater advantage in this sector (0.9%). This is mainly because outdates from the rare groups, which under the improved scenario are also kept in stock, are unavoidable (Table 7.24). Most of the mismatches are still occurring from group AB positive and some from group B positive, although they are significantly reduced in comparison with the baseline scenario. Days of stock have grown to 9.9 on average because of the addition of rare groups in stock, but the weighted average is still down to 5.5 days (Table 7.23). The days of stock in the CBB are almost unchanged. Emergency deliveries have only gone down by three. Ad-hoc and emergency deliveries account for 33% of all deliveries, 21% less than the initial scenario. Outdates in the CBB are down to 60 units which are spread across all blood groups with the biggest number being with B positive. No attempt was made in this scenario to reduce the number of collections. This is because the number of ordered units has been reduced by only 20 units to 1359 (Table 7.22) and the increase in the number of units that were moved to other NBS centres (around 100 units) was not that great.

Overall it was shown that the same policies can successfully apply to both medium and small hospitals. Only the extent of benefit between the performance measures changes.

Table 7.19 Model results on performance criteria for a Small hospital (Best scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	47.79	62.80	77.81
Expired RBC units as % of issues	2.92%	3.69%	4.41%
Expired Platelet in hospital	5.73	12.00	18.27
Expired Platelet as % of Issues	14.17%	21.66%	25.96%
Mismatched RBC units	14.71	44.20	73.69
Mismatches as % of Issues	0.90%	2.60%	4.17%
Shortages	25.39	33.56	41.62
Shortages as % of Issues	1.55%	1.97%	2.36%
Expired RBC units in Centre	42.05	60.60	79.15
Expired RBCs in Centre as % of issues	3.53%	4.89%	6.14%
Average deliveries	236.35	242.00	247.65
Routine deliveries	150.95	160.00	169.05
Ad-hoc deliveries	47.56	53.00	58.44
Emergency deliveries	24.98	29.00	33.02

Table 7.20 Various model results in blood units and as a percentage of total issues for a Small hospital (Best scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	1702.2	
RBC Transfusions	1167	68.56%
Hospital RBC Returns	522	30.67%
Hospital RBC Outdates	62.8	3.69%
Hospital RBC Out of Hours Wastage	15.6	0.92%
Hospital Platelet Issues	55.4	
Platelet Transfusions	37.4	67.51%
Hospital Platelet Returns	17	30.69%
Hospital Platelet Outdates	12	21.66%
Hospital Platelets Out of Hours Wastage	0.2	0.36%
Centre RBC Issues	1240.4	
Centre RBC Outdates	60.6	4.89%
All RBC Requests	556.6	
All RBC Requested Units	1812.04	
Platelet Requests	41.2	
Platelet Requested Units	55.2	
All Ordered Units	1359.6	
RBCs (stock)	1290.2	
Irradiated and Rare types RBCs	19.2	
Platelets	50.2	
Collections	1445.4	

Table 7.21 Model outputs related to stock holding in the HBB per blood group for a Small hospital (Best scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	15	15.18	4.60	13.5	4.6
A negative	4	4.54	7.05	14.1	7.2
AB positive	4	3.41	11.46	3.5	11.5
AB negative	4	2.32	22.02	2.0	21.4
B positive	4	4.77	7.24	8.8	7.5
B negative	4	2.89	17.41	5.7	16.8
O positive	15	14.80	4.18	12.4	4.3
O negative	5	4.15	5.43	6.2	5.7
Total	55	52.06			
Average per group	6.875	6.51	9.92	8.27	9.88
Weighted Average			5.49	11.63	5.57

Table 7.24 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Small hospital (Best scenario).

6 Months Data	Hospital RBC Outdates	Hospital Platelet Outdates	Hospital Mismatches by patient group	NBS RBC Outdates
A positive	1.20	4.60	3.00	7.20
A negative	9.20	0.40	3.00	10.20
AB positive	10.00	0.00	24.00	1.60
AB negative	13.20	0.40	0.00	2.80
B positive	12.80	0.40	12.00	19.80
B negative	10.00	0.00	3.00	0.80
O positive	1.40	5.20	0.00	14.20
O negative	5.00	1.40	0.00	4.00
Total	62.80	12.40	45.00	60.60
Average per group	7.85	1.55	5.63	7.58

Figure 6.8a and b show once more the number and range of the average age of units in this HBB and Figures 6.9a and b show these for the CBB respectively. The graphs of the CBB are much less variable than for the baseline scenario with fewer peaks and troughs. Nevertheless, for the HBB, the graphs fluctuate considerably. This is especially apparent for the units in stock, which vary from below 20 to 120.

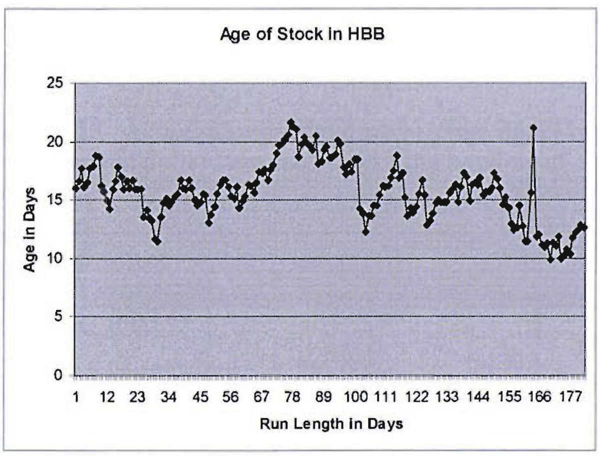

Figure 7.8a Fluctuation of the average age of stock in the HBB (Small hospital, Best Scenario).

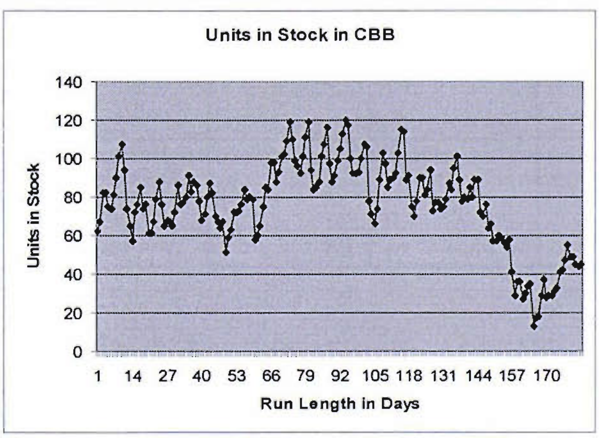

Figure 7.8b Fluctuation of the number of units in stock in the HBB (Small hospital, Best Scenario).

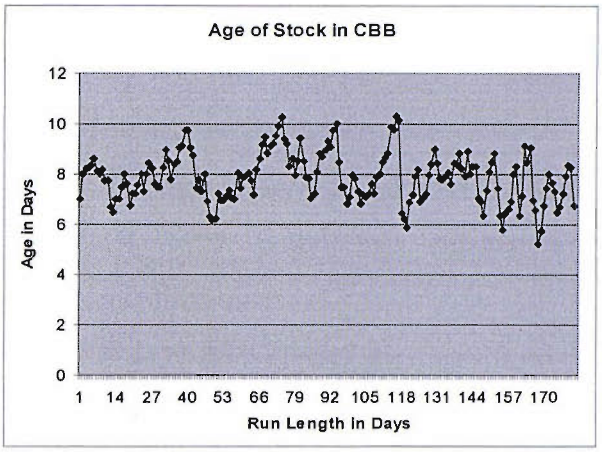

Figure 7.9a Fluctuation of the average age of stock in the CBB (Small hospital, Best Scenario).

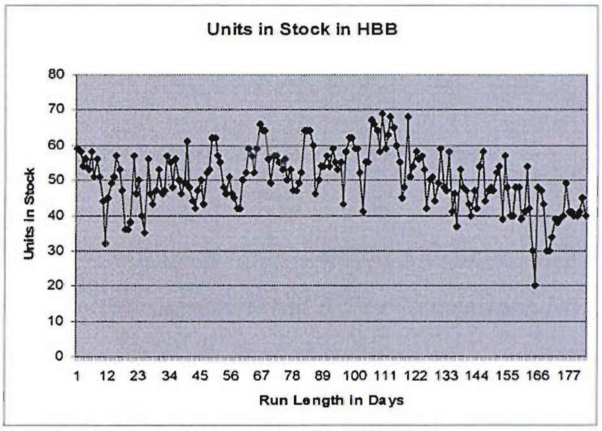

Figure 7.9b Fluctuation of the number of units in stock in the CBB (Small hospital, Best Scenario).

Table 7.25 shows the results of the improved model in actual values and percentage improvement in the performance measurements of comparing the current practices of the example hospital with the best combination of policies recommended for adoption.

Table 7.25 Actual numbers and percentage improvements in the performance indices by applying the improved policy, compared with the baseline of a Small hospital.

Performance Measurement	Actual Number	% improvement	Savings	
			£	%
Expired RBC units	62.8	54%	£9,620	1.6%
Mismatched units	44.2	74%	Lives	
Shortages in units	33.5	38%	Lives	
# of All Deliveries	242	-20%	£360	24%
# of Ad-hoc & Emergency Deliveries	82	24%		

In adopting the recommendations of the improved scenario, the total system will gain:

- 54% (73 units) fewer RBC outdates, which translates to £9,620 less wasted expenditure. However, since only 20 fewer units were ordered in total the actual difference in savings is 1.6% (£2,640).
- 74% (127 units) less mismatching, resulting in avoidance of possible complications.
- 38% (21 units) fewer shortages from the blood centre.
- 24% (26) fewer ad-hoc and emergency orders from the hospital with £360 savings on the money given for charged deliveries from this hospital alone.

7.6 High Volume Usage Hospital

More experiments were carried out for a high volume hospital. The inputs and policies of the baseline scenario that differ from those for the previous two hospitals are listed below:

- The ideal stock level is 95 units of A positive, 25 of A negative, 8 of AB positive, 8 of AB negative, 15 of B positive, 4 of B negative, 105 of O positive, and 30 of O negative: 285 in total.
- The percentage of the Southampton blood centre's issues that this hospital accounts for, and according to which the volume of collections is reduced to reflect collections and stock holding adequate for this hospital only, is 15% (around 15,000 ordered units per year).
- The range of daily requests is 16 to 20, accounting for roughly 65 to 85 requested units. The doctor's requests for adult RBCs follow a time-dependent distribution due to their high frequency.

The remaining assumptions are the same as for the medium-sized hospital (section 7.2). A list of the distributions that were used for this model and are different from the previous models is included in Appendix C.4.

Table 7.24 Model results on performance criteria for a Big hospital (Baseline scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	661.07	685.80	710.53
Expired RBC units as % of issues	5.16%	5.25%	5.34%
Expired Platelets in hospital	32.29	38.20	44.11
Expired Platelets as % of Issues	11.17%	11.35%	11.48%
Mismatched RBC units	39.63	56.80	73.97
Mismatches as % of Issues	0.31%	0.44%	0.56%
Shortages	286.9	312.8	338.7
Shortages as % of Issues	2.24%	2.40%	2.55%
Expired RBC units in Centre	4.86	37.80	70.74
Expired RBCs in Centre as % of issues	0.07%	0.53%	0.97%
Average deliveries	401.4	414.8	428.2
Routine deliveries	142.6	150.2	157.8
Ad-hoc deliveries	208.0	220.6	233.2
Emergency deliveries	33.7	38.6	43.5

Under these conditions 686 units of RBC and 38 units of platelets expired, accounting for 5.25% and 11.35% of issues respectively. The money spent on products that were finally discarded is £90,415 for RBCs and £8,240 for platelets, which adds up to around £98,700. Groups A positive and O positive are the most expensive, with around 150 discarded units each (Table 7.29). On the other hand, only 57 units were mismatched, a very low value which represents less than 1% of issues. This is because in a big hospital units of rare blood groups are kept in stock and thus almost all requests are satisfied from the appropriate group. AB and B positive were basically the mismatched patients' groups which were mainly substituted with O positive and some A negative. Shortages climbed to 313 units (2.4% of issues). Only 38 units of RBC expired in the NBS, although more units are kept in stock overall (427 on average). The stock corresponds to 10 days of supplies, which is much higher than the ideal of 4.5 days as presented in section 5.3.3. The age of units on arrival in the HBB was around 10.6 days old. The hospital stock of blood units approached 260 units, which last for 3.5 days (weighted average, Table 7.28). Only the stock of AB negative represents a considerably higher number of days in stock (8.5) than the average, which is again not outrageous when compared with the number of rare groups' days in stock for the small hospital (above 22 days for AB negative, best scenario).

Table 7.27 Fluctuation of the number of units in stock in the HBB (Big hospital-Baseline Scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	12813.8	
RBC Transfusions	6292.4	49.11%
Hospital RBC Returns	6401.0	49.95%
Hospital RBC Outdates	661.1	5.16%
Hospital RBC Out of Hours Wastage	81.6	0.64%
Hospital Platelet Issues	289.0	
Platelet Transfusions	202.5	70.06%
Hospital Platelet Returns	83.7	28.98%
Hospital Platelet Outdates	32.3	11.17%
Hospital Platelets Out of Hours Wastage	0.8	0.26%
Centre RBC Issues	7077.7	
Centre RBC Outdates	4.9	0.07%
All RBC Requests	3088.0	
All RBC Requested Units	13060.8	
Platelet Requests	253.4	
Platelet Requested Units	336.8	
All Ordered Units	7503.8	
RBCs (stock)	7089.0	
Irradiated and Rare types RBCs	133.8	
Platelets	281.0	
Collections	7464.0	

A total of 415 deliveries were made to the hospital. Only 36% were routine deliveries, and the remaining 64% were individual deliveries to the hospital of which 53% were ad-hoc and 11% emergency. Almost every simulated day a routine delivery was made to the hospital, apart from Sundays, which are not used for routine deliveries. Seven thousand five hundred and four units were ordered in these 415 deliveries, hence about 18 units in each order/delivery. As Table 7.27 reveals, 7223 RBC units were ordered in total (RBC in stock, rare group units and irradiated RBC) until the end of the simulation run, but only 7077 were actually delivered on average in the five runs. This means that 146 ordered units were not satisfied until that point and 167 or slightly more had a delay in delivery, since 318 shortages were reported in total. Some of the undelivered units might not count as "real" shortages because orders that were placed on the last simulated day may have not been due for delivery yet.

Table 7.28 Model outputs related to stock holding in the HBB per blood group for a Big hospital (Baseline scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	95	85.09	3.32	11.9	3.3
A negative	25	21.64	4.10	14.9	3.9
AB positive	8	8.91	4.21	9.5	4.1
AB negative	8	5.59	8.50	1.8	8.2
B positive	10	15.88	2.75	17.9	2.8
B negative	4	5.24	3.82	6.7	3.7
O positive	105	88.84	3.15	15.1	3.2
O negative	30	27.77	5.06	6.8	4.7
Total	285	258.96			
Average per group	35.625	32.37	4.36	10.57	4.24
Weighted Average			3.47	13.17	3.44

Table 7.29 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Big hospital (Baseline scenario).

6 Months Data	Hospital			NBS
	RBC Outdates	Platelet Outdates	Mismatches by patient group	RBC Outdates
A positive	148.79	9.16	0.00	0.00
A negative	33.69	2.48	0.00	0.00
AB positive	18.05	0.00	23.00	0.00
AB negative	13.18	1.48	2.00	1.74
B positive	23.70	1.48	32.00	0.00
B negative	8.47	0.00	0.00	0.00
O positive	152.44	5.35	0.00	0.00
O negative	48.89	2.65	0.00	0.00
Total	447.20	22.60	57.00	1.74
Average per group	55.90	2.83	7.25	0.22

Figure 7.10b confirms that the HBB is balanced in terms of available (unassigned) stock, but Figure 7.11b reveals the existence of some turbulence in the centre's blood stock, with a decreasing trend over the last couple of months. The age of stock in the CBB (Figure 7.10a) fluctuated between 5 to 8 days and in the HBB between 15 to 20 days (Figure 7.10a). The age of blood at the time of arrival in the HBB is however 10.6 days. A RBC unit was crossmatched around twice in its shelf life on (weighted) average. This is split over 1.8 crossmatches of transfused units and close to 5 times for expired units, which is the highest that has been observed over the different hospitals. Platelets were crossmatched 1.4 times in total: 1.2 crossmatches for transfused units and 2.1 for expired ones. Overall, the number of units that were crossmatched is higher in the medium-sized

hospital for both RBCs and platelets, followed closely by the big hospital, and finally the small hospital appears to have the least crossmatches (1.74 for RBCs and 1.13 for platelets) under the baseline scenario. Apparently, these units stay longer in the HBB before their first crossmatch. Moreover, for the best scenarios there are no great changes observed to the number of times an RBC unit is crossmatched in its shelf life in any of the hospitals. The effect of the higher transfusion rate (70% instead of 50%) which translates to fewer crossmatches is balanced by the fact that the non-transfused units move faster through the loop from the unassigned to assigned stage due to the reduction of the reservation period, which gives more opportunities for crossmatching.

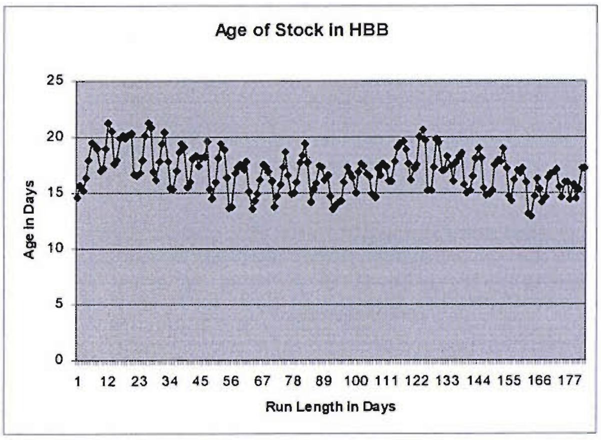

Figure 7.10a Fluctuation of the average age of stock in the HBB (Big hospital-Baseline Scenario).

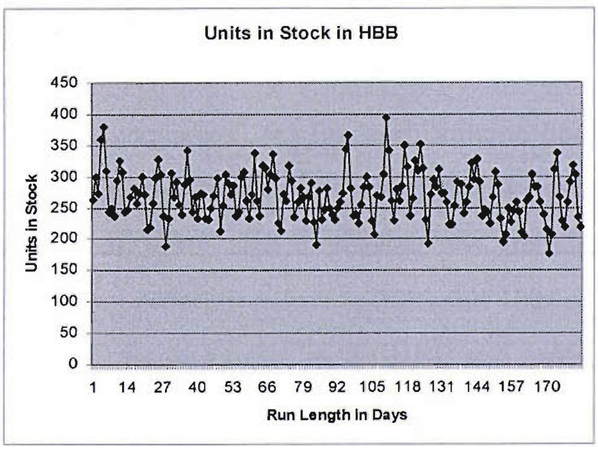

Figure 7.10b Fluctuation of the number of units in stock in the HBB (Big hospital-Baseline Scenario).

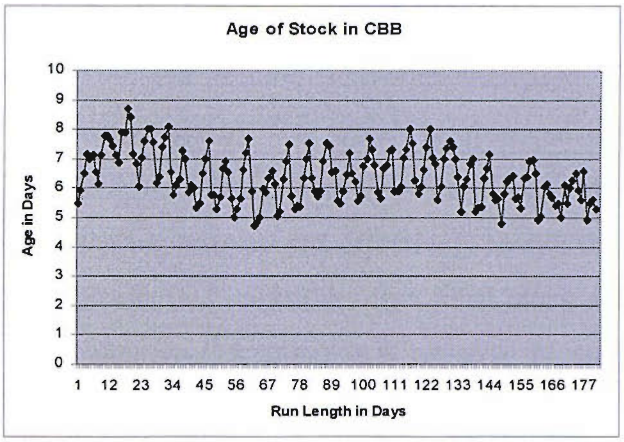

Figure 7.11a Fluctuation of the average age of stock in the CBB (Big hospital-Baseline Scenario).

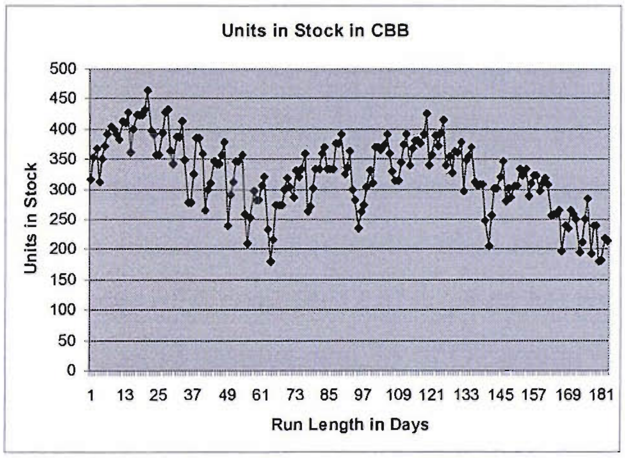

Figure 7.11b Fluctuation of the number of units in stock in the CBB (Big hospital-Baseline Scenario).

7.7 Experimentation with High Volume Hospital

"What if scenarios" for the high volume hospital start by directly adopting policies of minimising the reservation period to 37 hours on average, placing requests for smaller batches of units and increasing the transfusion rate to 70%, reducing ad-hoc and emergency ordering points to 30% and 10% of ideal stock respectively, adhering to FIFO and LIFO issuing order in the HBB and having two routine deliveries by decreasing the routine ordering stock level to 70% of the ideal (policies 4, 5, 6, 7 and 10, as presented in Tables 7.7 and 7.8). Each policy was tried out in one simulation run and beneficial results were produced for all the criteria. In this section the outcomes of the baseline scenario are compared with scenarios that incorporate the above-mentioned policies and experimentation is limited to some other characteristics, such as the ideal stock level and re-ordering points.

- Scenario 1 considers the above mentioned policies. Ideal stock is kept at the baseline scenario levels. As Tables 7.30 and 7.31 show, expired RBC units in the HBB have greatly decreased to 100 units. As a counter-effect NBS expires went up. Mismatches went down by 58% and shortages also decreased, but not significantly. Ad-hoc and emergency deliveries decreased greatly, from 260 to 100, but routine deliveries increased. The overall effect is a decline in total deliveries by 7%, which is observed for the first time, since for the other size hospitals the outcome was an increase in the total number of deliveries. However, the big hospital can effectively absorb the increase in routine deliveries.

- Scenario 2 considers less ideal stock for some of the blood groups, such as A negative (18 units), AB negative (4 units) and O negative (20 units). The ideal stock is now 269 units in total instead of 285. As a result the units that expire in the HBB decrease even further by 91%, increasing the expiries in the CBB. Mismatches are still down but with a smaller difference compared with the previous scenario, and shortages are also down by 32%. The outcomes in deliveries are exactly the same as in scenario 1.
- A further reduction in the ideal stock was attempted in scenario 3 with only 65 units of A positive, 12 of A-, 4 of AB positive, 4 of AB-, 10 of B positive, 4 of B-, 65 of O positive, and 15 of O-, a total of 179 units. The consequence is a further decrease of expired units in the HBB to only 43 units. However, mismatches do not look as good as in the previous scenarios. Shortages, on the other hand, also decrease as small batches of orders arrive at the centre's bank each time. Routine deliveries increase to the maximum possible: 293 routine deliveries are the maximum available in a period of 182 days, as Sundays are excluded and only one delivery is offered on Saturdays. As a result of this, ad-hoc and emergency deliveries decrease in comparison with the previous scenarios.
- Finally, scenario 4 adopts scenario 2 and explores the effect of further reducing the routine ordering point to 65% of the ideal. Although this is a small change, it undesirably influences most of the key criteria. The reduction in mismatches and shortages as well as in ad-hoc and emergency deliveries is much lower than the equivalent figures for scenario 2.

Table 7.30 Performance criteria results under different combined policies. Big hospital.

Scenarios	CBB Expired	HBB Expired	Mis-matches	Shortages	No. of Orders	Ad-hoc &Emer	Routine Deliver.
0) Baseline, actual results	37.8	658.8	56.8	312.8	414.8	259.2	150.2
1) Best, same stock	97.4	100.4	24	266.2	384.8	100.2	284.6
2) Best, stock (A+95,A-18,AB+8,AB-4,B+15,B-4,O+105,O-20) 70%Routine	126.2	57.2	28.2	211.4	387.2	102.8	283.2
3) Best, stock (A+65,A-12,AB+4,AB-4,B+10,B-4,O+65,O-15)	124.8	42.6	47.2	177.8	426	149	293
4) Best same stock 65% Routine	120.5	65	52.8	232.4	402.6	129.2	289.4

Table 7.31 Percentage change of performance criteria under different combined policies. Big hospital.

Scenarios	CBB Expired	HBB Expired	Mis-matches	Shortages	No. of Orders	Ad-hoc &Emer	Routine Deliver.
0) Baseline, actual results	37.8	658.8	56.8	312.8	414.8	259.2	150.2
1) Best, same stock	**158%**	**-85%**	**-58%**	-15%	**-7%**	**-61%**	**89%**
2) Best, stock (A+95,A-18,AB+8,AB-4,B+15,B-4,O+105,O-20) 70%Routine	**234%**	**-91%**	**-50%**	**-32%**	-7%	**-60%**	**89%**
3) Best, stock (A+65,A-12,AB+4,AB-4,B+10,B-4,O+65,O-15)	**230%**	**-94%**	-17%	**-43%**	**3%**	**-43%**	**95%**
4) Best, same stock 65% Routine	**219%**	**-90%**	**-7%**	**-26%**	**-3%**	**-50%**	**93%**

Scenario 2 proves to be the best since there are significant improvements to all the main criteria. More results related to this scenario are presented in Tables 7.32 to 7.35.

In Table 7.32 is apparent that expired RBC units account only for 0.61% of issues after the implementation of the new policies and in actual number expiries have fallen from 659 units to only 57. Table 7.35 shows that only group O negative has a considerable number of outdates. However, a further reduction in the ideal stock of O negative did not greatly reduce outdates of this group when tried out (scenario 3). Also, AB negative outdates are a bit high with respect to the total number of issues, but this is the sacrifice the HBB needs to make if mismatches are to be kept low. Mismatches represent only 0.30% of issues under this scenario, which results from shortages of groups AB positive and B negative. Shortages have decreased, but they still represent 2.3% of issues. Nevertheless, as Table 7.33 illustrates, ordered units have decreased to 6813 out of 7504 units. The movements of units from the blood centre to other centres have also increased from 193 to 807 units. Also, because of the reductions in the ordered units, there is on average more stock remaining in the CBB (475 units on average), which corresponds to 11.5 days of stock. This is also obvious from Figures 7.12a and b. Therefore a reduction in collections, as was tested in the medium volume hospital, would have reduced outdates and unwanted stock in the CBB. Also the age of blood on arrival in the HBB would be slightly younger, preventing even more units from outdating. Currently the average age of units on arrival in the HBB is 12.7 days (15.7 on weighted average). The number of ad-hoc and emergency deliveries is down to 103, representing only 26% of all deliveries, and emergency deliveries account for less than 5% overall.

Table 7.30 Model results on performance criteria for a Big hospital (Best scenario).

Performance Criteria	Low 95% CI	6 Months Average	High 95% CI
Expired RBC units in hospital	32.03	57.20	82.37
Expired RBC units as % of issues	0.35%	0.61%	0.86%
Expired Platelets in hospital	37.29	41.80	46.31
Expired Platelets as % of Issues	12.83%	12.38%	12.04%
Mismatched RBC units	15.96	28.20	40.44
Mismatches as % of Issues	0.17%	0.30%	0.42%
Shortages	196.2	211.4	226.6
Shortages as % of Issues	2.13%	2.25%	2.36%
Expired RBC units in Centre	76.29	126.20	176.11
Expired RBCs in Centre as % of issues	1.20%	1.94%	2.64%
Average deliveries	369.57	387.20	404.83
Routine deliveries	276.31	283.20	340.09
Ad-hoc deliveries	74.42	84.80	95.18
Emergency deliveries	12.74	18.00	23.26

The stock kept in the HBB is enough to cover requests for about 4 days (weighted average), which is higher than the days in stock covered in the baseline scenario (3.47), even though the actual stock has decreased (by 6%). The same situation was observed for the medium and small hospitals. In the former the stock decreased by 21% and the days in stock slightly increased from 3.85 to 3.93 days. In the latter the stock increased by 6% and the days in stock also increased from 4.12 to 3.95, always referring to the weighted average. This phenomenon can be explained by the fact that stock levels alone (the nominator) are not enough to determine the days in stock. The latter is also decided by the number of daily issues (the denominator). Hence, because this figure has been reduced by approximately 27% in the best scenarios (smaller size requests, better transfusion rate, etc.) for all the hospitals, the figure for days in stock has also increased.

Table 7.33 Various model results in blood units and as a percentage of total issues for a Big hospital (Best scenario).

6 Months Average:	Units	as % of Issues
Hospital RBC Issues	9413.6	
RBC Transfusions	6396.8	67.95%
Hospital RBC Returns	2948.4	31.32%
Hospital RBC Outdates	57.2	0.61%
Hospital RBC Out of Hours Wastage	71.8	0.76%
Hospital Platelet Issues	337.6	
Platelet Transfusions	237.8	70.44%
Hospital Platelet Returns	98.2	29.09%
Hospital Platelet Outdates	41.8	12.38%
Hospital Platelets Out of Hours Wastage	1.8	0.53%
Centre RBC Issues	6520	
Centre RBC Outdates	126.2	1.94%
All RBC Requests	3103.2	
All RBC Requested Units	9707.16	
Platelet Requests	253.4	
Platelet Requested Units	336.8	
All Ordered Units	6812.6	
RBCs (stock)	6548.4	
Irradiated and Rare types RBCs	62.4	
Platelet	201.8	
Collections	7464	

Table 7.34 Model outputs related to stock holding in the HBB per blood group for a Big hospital (Best scenario).

Hospital RBC	Ideal Stock	Average Units in Stock	Days of Stock	Average Age on arrival	Average waiting days in HBB
A positive	95	73.29	4.03	16.4	4.2
A negative	18	16.49	4.12	19.8	4.8
AB positive	8	8.53	5.45	11.1	5.7
AB negative	4	4.09	7.44	3.6	8.8
B positive	15	14.12	3.40	18.8	3.6
B negative	4	5.18	4.85	6.9	5.4
O positive	105	80.36	3.99	16.0	4.1
O negative	20	17.92	4.31	9.0	4.8
Total	269	219.99			
Average per group	33.625	27.50	4.70	12.70	5.17
Weighted Average			4.09	15.66	4.32

Table 7.35 Model outputs of outdates in the HBB and the CBB and mismatches in the HBB per blood group for a Big hospital (Best scenario).

6 Months Data	Hospital RBC Outdates	Hospital Platelet Outdates	Hospital Mismatches by patient group	NBS RBC Outdates
A positive	0.60	14.00	0.00	12.00
A negative	4.60	5.80	0.00	25.00
AB positive	5.20	0.00	12.00	8.20
AB negative	10.40	2.60	3.00	16.20
B positive	1.80	2.60	0.00	39.20
B negative	5.40	1.40	13.00	8.60
O positive	0.20	9.80	0.00	5.20
O negative	29.00	8.20	0.00	11.80
Total	57.20	44.40	28.00	126.20
Average per group	7.15	5.55	3.50	15.78

Figures 7.12 and 7.13a and b reveal how much more balanced the system is under the new policies.

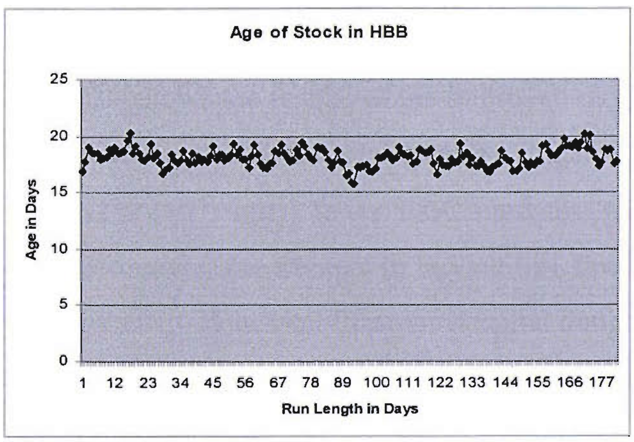

Figure 7.12a Fluctuation of the average age of stock in the HBB (Big hospital-Best Scenario).

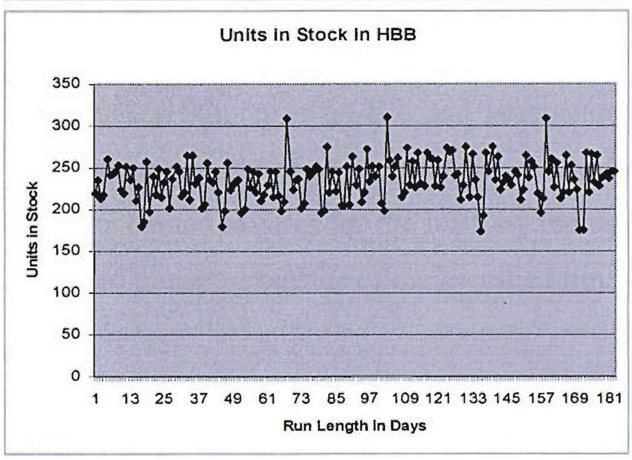

Figure 7.12b Fluctuation of the number of units in stock in the HBB (Big hospital-Best Scenario).

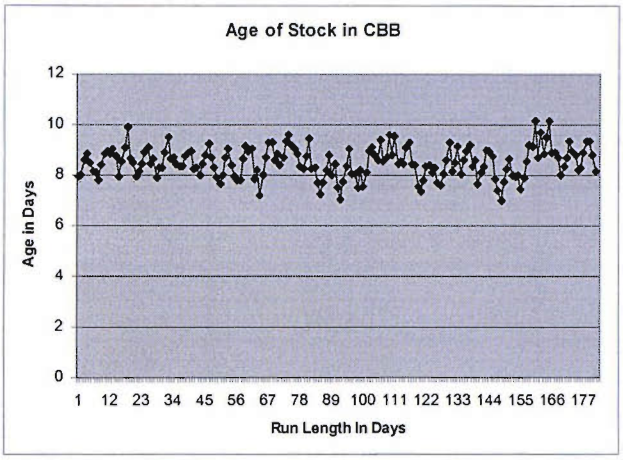

Figure 7.13a Fluctuation of the average age of stock in the CBB (Big hospital-Best Scenario).

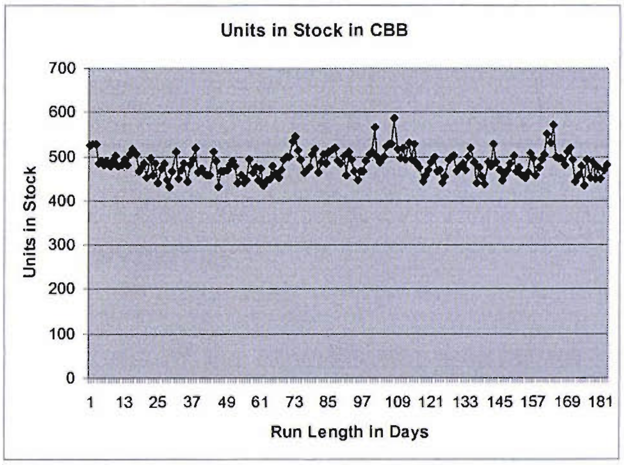

Figure 7.13b Fluctuation of the number of units in stock in the CBB (Big hospital-Best Scenario).

Table 7.36 shows the results of the improved model. In adopting the recommendations of the particular scenario, the total system will gain:

- 91% (601 units) fewer RBC outdates, resulting in £79,300 less wasted money. Moreover, the savings in buying 691 fewer units from the NBS will reduce costs by £91,075 in total from the hospital budget. This represents a saving of 9.2%.
- 50% (29 units) less mismatching, resulting in avoidance of possible medical complications.
- 32% (101 units) fewer shortages from the centre.
- 60% (156) fewer ad-hoc and emergency orders from the hospital with £2,345 savings on the money given for charged deliveries from this hospital alone, and uncounted savings for the NBS by reducing the number of occupied drivers, staff and transport outside of the specified times of routine deliveries.

Table 7.34 Actual numbers and percentage improvements in the performance indices by applying the improved policy, compared with the baseline of a Big hospital.

Performance Measurement	Actual Number	% improvement	Savings	
			£	%
Expired RBC units	57.2	91%	£79,300	9.2%
Mismatched units	28.2	50%	Lives	
Shortages in units	211.4	32%	Lives	
# of All Deliveries	387.2	7%	£2,345	60%
# of Ad-hoc & Emergency Deliveries	102.8	60%		

7.8 Conclusions

The analysis of the experimental policies reveals that the joint effect of some of these policies is beneficial for all hospitals, regardless of their size in terms of blood usage. Therefore, all hospitals should revise their policies in relation to ordering decisions, ideal stock, reservation period of blood units, and the order that stock is kept in their blood bank. Blood centres, on the other hand, should also consider adopting a second routine delivery, which will better co-ordinate their activities in terms of staff working patterns and transportation services. This discussion will further evolve after the analysis of additional policies examined in a more complicated environment, where several hospitals are considered together in one model and multiple results are reported from the same simulation run. This analysis follows in Chapter 8. Furthermore, the effect of all the observed relationships that were observed under these scenarios will be presented in Chapter 9 together with those from Chapter 8.

CHAPTER 8: DISTRIBUTED SIMULATION

8.1 Introduction

This chapter focuses on the methods and results of simulation models of the blood supply chain that incorporate more than one hospital. This attempts to provide a more realistic picture of the actual system. The aim is to examine the effect that grouping hospitals in the same supply chain will have on blood centre stock and hospital activities. More policies which were not tried out in Chapter 7 can be tested under the new conditions.

However, the discrete event simulation model that was developed for the purposes of this study is a very complex and detailed model. The attempt to expand the model by incorporating more hospitals encountered runtime problems. The increase in the execution time of a model with two hospitals resulted in unacceptable waiting periods and it was not possible to run a version with three hospitals on a desktop PC with a 2.8GHz processor and 512MB of RAM. Other solutions were sought in order to circumvent this problem without the model losing the complexity and detailed approach of its initial design.

Obtaining a more powerful computer (3.2 GHz processor and 1GB RAM) improved the situation slightly, but did not really address the fundamental issue. Fortunately, in recent years technological advances have sought to tackle these problems, namely parallel and distributed simulation. These approaches are still evolving according to the applications for which they are used. Thus, this model was employed as a case study in which one of these technological approaches developed by Taylor et al (2005b, 2006) was examined in a real problem that uses a Commercial Off-The-Shelf (COTS) Simulation Package. Distributed simulation is the approach used. Some general information about the technique, emerging from papers in the literature, is provided next.

8.2 The Distributed Approach

Distributed simulation has been used to overcome problems arising from big, complex and mainly supply-chain-related simulation models, which are difficult to handle with the processing resources of one computer (Taylor et al, 2002; Lendermann et al, 2001; Gan et al, 2000; Robinson, 2005). This method emerged in the last decade and is still evolving.

Parallel or distributed simulation refers to the execution of discrete event simulation programs on a multiprocessor system or network of workstations. Fujimoto (2002) defines a parallel/distributed simulation technology to be "a technology that enables a simulation program to be executed on parallel/distributed computer systems, namely systems composed of multiple interconnected computers". As this definition suggests, there are two key components to this technology: 1) simulation and 2) execution on parallel or distributed computers. A simulation program executes on a computing system containing multiple processors, such as personal computers, interconnected by a communication network. Parallel simulation executes on a set of computers confined to a single box or machine room, while distributed simulation executes on machines that are geographically distributed across a building or even the world. The second approach was decided to be more appropriate for this study.

There are several general advantages for the use of distributed simulation. Some of them are summarized in the following points:

- Scalable performance enabling the accommodation of systems that expand in size and complexity.
- Maintaining the same execution speed for bigger models/virtual environments by using more CPUs.
- Geographically distributed users and/or resources (e.g., databases, specialized equipment).
- Integrated simulations running on different platforms (networks).
- Fault tolerance methods for avoiding system failures and achieving high reliability.
- Enable simulation of big models.
  - Initialize simulation from situation database.
  - Faster-than-real-time execution to evaluate effect of decisions.

(Fujimoto, 1999, 2003).

It is apparent that the advantages offered by distributed simulation are strongly related to the problem under examination. The general approach of distributed simulation is to divide and modify a model so that parts of the model reside on different computers linked together by a communication network. These "model parts" become *Logical Processes* (LPs) that interact using time-stamped messages that represent the interaction of one part of a model with another (say, when an entity leaves one part of a model and arrives at another) (Chandy and Misra, 1979; Fujimoto, 2001). More recently, the "practice" of distributed simulation has been focused on a wide scale on attempts to standardise approaches. These standardisation efforts took place in the middle to late 1990s and resulted in the IEEE 1516 standard *The High Level Architecture* (HLA) that supports the general needs of distributed simulation (IEEE 2000). This is rooted in the early work of Chandy and Misra but considerably updates it with advances in distributed computing. HLA defines the runtime infrastructure (HLA-RTI) software and the format of the data that is used by a collection of interacting models running on different computers. Such a collection of models is termed a federation.

There have been several attempts to create distributed simulations of manufacturing systems and supply chains. The first major work in the area was done by Straßburger (2001). Various strategies have been investigated since then. For example, Mertins et al (2000), Rabe and Jakel (2003), Hibino et al (2002), McLean and Riddick (2000) and Linn et al (2002) discuss the use of HLA to support the distributed simulation of manufacturing systems. Lenderman et al (2001), Straßburger et al (2003) and Taylor et al (2005a) also discuss strategies for HLA use in the same domains. Non-HLA based approaches include work done by Taylor et al (2002) with the *Generic Runtime Infrastructure for Distributed Simulation* (GRIDS) to support the distributed simulation of supply chains and automotive engine production; Fuji et al (2000) in the distributed simulation of virtual factories; and Zülch et al (2002) with the hierarchical distributed simulation of manufacturing systems. Boer et al (2002) discuss the use of the FAMAS backbone (a distributed simulation architecture) to support the distributed simulation of a port; Roy and Arunachalam (2004) discuss the development of a novel distributed simulation algorithm for manufacturing supply chains; and Gan et al (2000) compare the HLA with an alternative technique extended from a protocol described in Gan and Turner (2000).

This work, while contributing to the development of distributed simulation, presents a problem. Virtually every author cited above uses a different approach to distributed simulation of manufacturing and supply chains. In an attempt to "standardise" the approach, the Simulation Interoperability Standards Organisation's COTS Simulation Package Interoperability Product Development Group (CSPI PDG) (www.cspi-pdg.org), has produced a set of draft standards in this area, which are described in Taylor et al (2005b) and Taylor et al (2006). Wang et al (2005) discuss a general experimental test-bed used to investigate these standards. Gan et al (2005) present a case study in the use of the standards to support semiconductor supply chain analysis using Autosched AP™.

The approach adopted in our case uses a similar method modified according to implementation limitations (as described in Mustafee and Taylor 2006). In this work the HLA-RTI is presented as a black box. Figure 8.1 shows an illustration of the "conventional" simulation model and the relationships between a blood centre and multiple hospitals simulated on a single computer. In contrast, Figure 8.2 shows the conventional model using a distributed simulation approach. Each part model (federate) represents either the NBS blood centre or a hospital running in a separate copy of Simul8 running on a separate computer. A Manager federate (not shown), a special program required by the HLA which coordinates the execution of the federation through registration of synchronisation points (Kuhl et al, 1999)29

, runs with the HLA-RTI process on the same computer as the NBS model. In this investigation, interaction between the models/Simul8 and the HLA-RTI is via an Excel file. For example, entities representing orders are written into the file by Simul8 and VBA during the execution of the hospital models. The HLA-RTI, augmented by the CSPI PDG standards, then correctly transfers this information to the NBS Centre model. The incoming orders from each hospital are collected into their corresponding queues in the NBS model and the orders are matched with the available stock of blood. The resultant matched units are written into an Excel spreadsheet in the NBS federate. This information is then sent to the different hospital models in a similar manner.

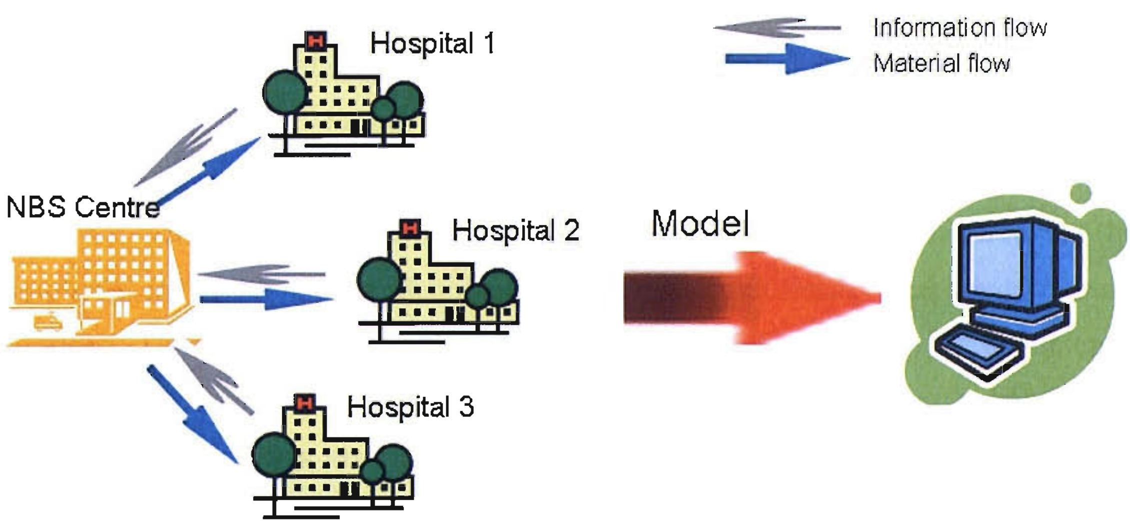

Figure 8.1 Conventional simulation approach.

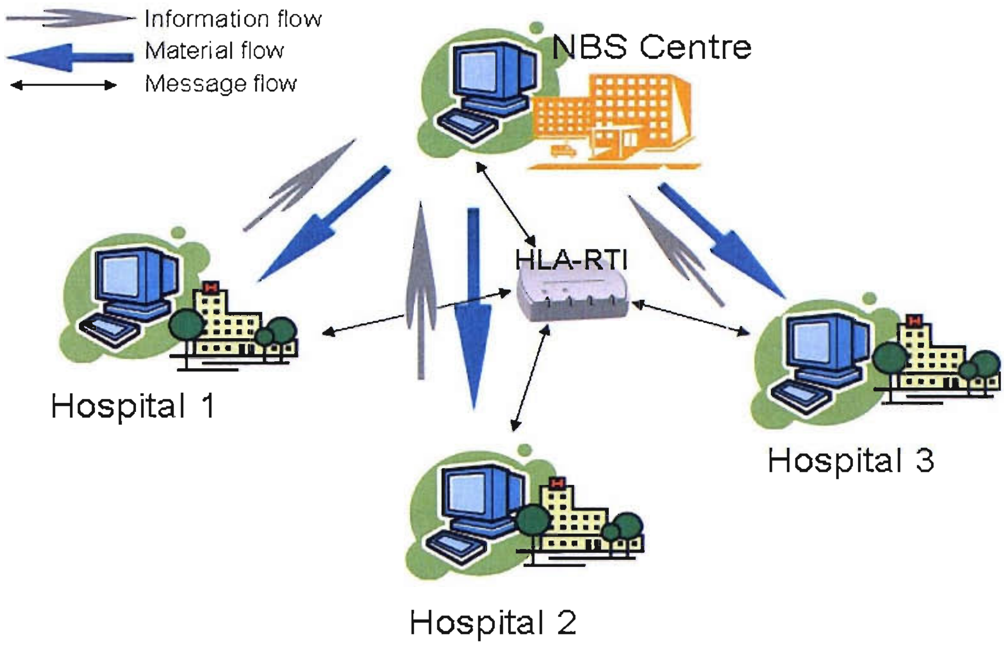

Figure 8.2 Distributed simulation approach.

8.3 Testing Distributed Simulation Vs. Conventional Simulation

This method is used in the final part of this study. However, before the technique was adopted a feasibility study was carried out for adapting a standard, widely used simulation package (Simul8) for use in a distributed simulation model.

To examine the distributed approach compared with the conventional approach, four scenarios were investigated. These was one NBS centre serving one, two, three and four hospitals respectively. Before experimentation commenced, the outputs for the conventional and distributed models were compared to check that the same results for a year's run were produced. This was done to check that the minor modifications to link Simul8/Excel/HLA-RTI in the distributed model did not artificially increase/decrease the workload. Only insignificant difference in the 95% confidence level between the output (ordered and shipped units per hospital) of the conventional simulation method and the distributed method was observed. All experiments were conducted on Dell Inspiron laptop computers running the Microsoft Windows XP operating system with 1.83GHz processors and 1GB RAM connected through a 100Mbps CISCO switch. The same computer specifications were used to guarantee consistency in runtimes. The results of the execution times for each of the models are based on an average of 5 runs. The run length of the models changed from 6 months to a year for the purposes of the experiments between the two methods.

Furthermore, the hospitals that were added to the models were all of the same volume (medium). For instance, the physicians' requests were around 1000 blood units for each hospital per month with each hospital diverging by a small percentage (≤5%) from the mean. Accordingly, the distribution parameters for every hospital were slightly different. Also, every hospital complied with its own rules about routine ordering times, re-ordering stock points, ideal stock levels, etc. The reason for this imprecision was to ensure a spread of courses of action happening during the day, such as the time the orders are matched with the units, a fact that affects the performance of the models including the runtime.

The conventional model with one hospital took approximately 14 minutes to run for a whole simulated year. The runtime rose to 78 minutes when the model ran with two hospitals and to 17.5 hours approximately with three hospitals. The addition of the fourth hospital rocketed the execution time to 35.8 hours. The distributed model with one NBS centre and one hospital ran in approximately 8.5 hours, with two hospitals in 9.8 hours, with three hospitals in 12.7 hours and with four hospitals in 16.5 hours. Figure 8.3 shows these execution times in seconds for both methods.

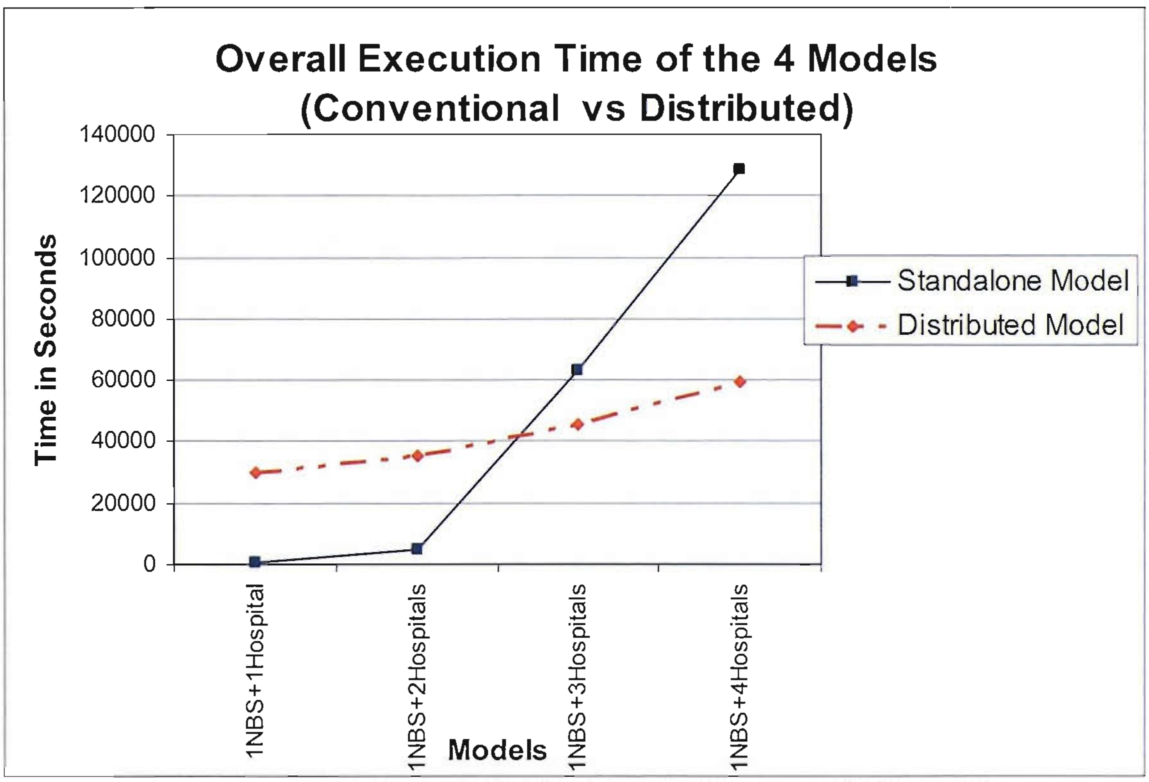

Figure 8.3 Runtimes of conventional and distributed method for one NBS Centre with one, two and three hospitals.

Even after considerable help and advice from the package vendor it was not possible to decrease the runtime of the conventional models. The enormous number of entities in the system, each of which carries many attributes, increases the computation time exponentially even though there is no exponential element in the functions of the model.

This exponential increase (which is actually linear after the addition of the second hospital as Figure 8.3 reveals) results from a combination of two different factors. Firstly, the massive amount of information generated by the model cannot be accommodated in the random access memory (RAM) alone, and hence the operating system has to keep swapping information to the hard disk. The part of the hard disk which is kept aside for use as swap space is called virtual memory. It takes much more time for the processor to recall information from virtual memory compared to RAM. Thus, as the models get bigger, more information is generated, resulting in more swaps between RAM and virtual memory, thereby contributing to an increase in execution time. Secondly, the behaviour of the system being modelled is such that all entities (blood units) in the system have a limited shelf life. This behaviour is modelled in the NBS simulation by continually scheduling events that decrease the shelf life of each entity by the minute. This results in more computations as the number of entities flowing through the system increases. As these models get bigger, the overhead of continually recalling data from virtual memory to perform these computations accounts for an exponential increase in model runtime.

It is apparent that the versions with one or two hospitals are less time-consuming to run using the conventional approach. Conversely, when a third and fourth hospital are added then the distributed method betters the runtime of the conventional approach. There also appears to be an exponential escalation of the runtime in the conventional version when increasing the number of hospitals in the model. This is quite a contrast to the substantially smaller and smoother rise in the runtime in the distributed method. Further, a more exhaustive analysis of the results reveals another significant feature. Every model for each method was monitored for its execution time per simulated month until the end of the run (1 year) as Figure 8.4 shows. The graph clearly demonstrates that for the conventional method there is an upwards incremental trend in the runtime per added month. Especially for the model with one NBS supply centre and three hospitals, the monthly runtime climbs up from month 10 and over, and for the model with four hospitals this trend is apparent from the first until the last month for the reason previously explained. The ups and downs in the runtimes between consecutive months are due to random variation.

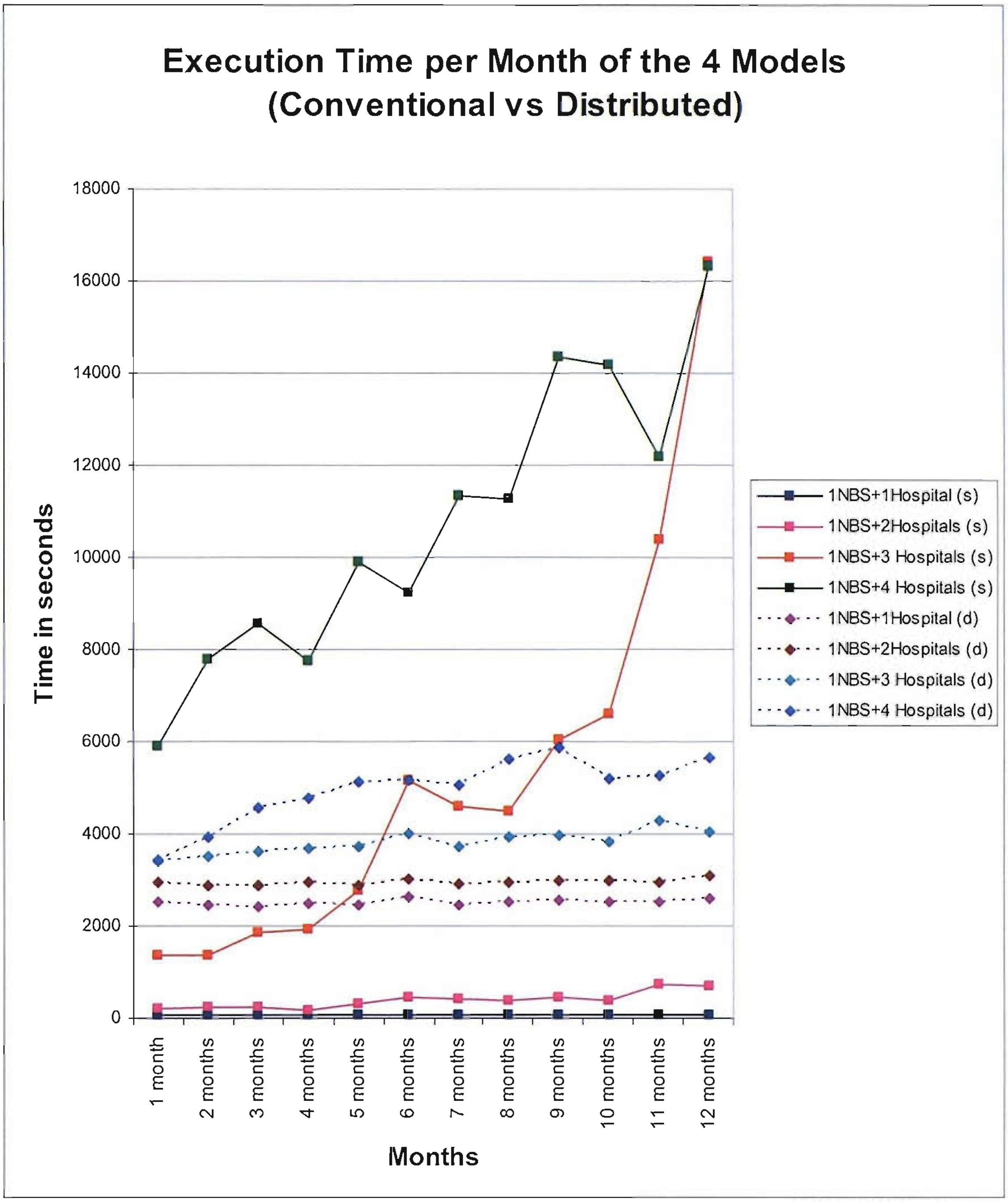

Figure 8.4 Execution Time per Month of the four Models [(Conventional (s) & Distributed (d)].

An in-depth observation of this graph shows the percentage difference in the time taken for the conventional models to execute every consecutive month of the year versus the corresponding difference of the distributed models. Figure 8.5 shows, for the conventional models, the percentage difference in the runtime between each month and the month that took the least time to run. The latter is equal to 0%. The month that took the least time to run in the first two models (with one NBS centre and one or two hospitals) is month four, while for the three-hospital and four-hospital models it is the first month. It can be seen that the Y axis scale takes values from 0% to 1100% while in Figure 8.6 the equivalent range for the distributed models is from 0% to 71%. The maximum percentage differences for one- to four-hospital models using the conventional method against the distributed method are 53% to 5% (10.6:1), 315% to 8% (39.4:1), 1100% to 26% (42.3: 1) and 176% to 71% (2.5:1) respectively. The small ratio observed in the last case is due to the fact that the model takes considerably more time to run right from the first month.

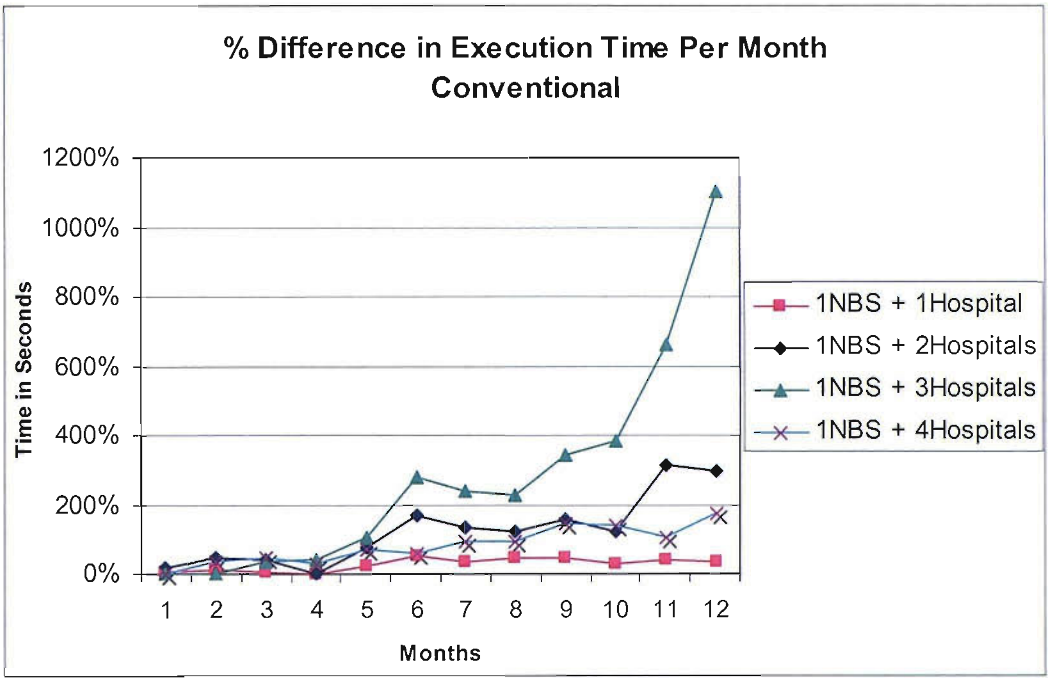

Figure 8.5 Execution time per month of the four models for the Conventional method.

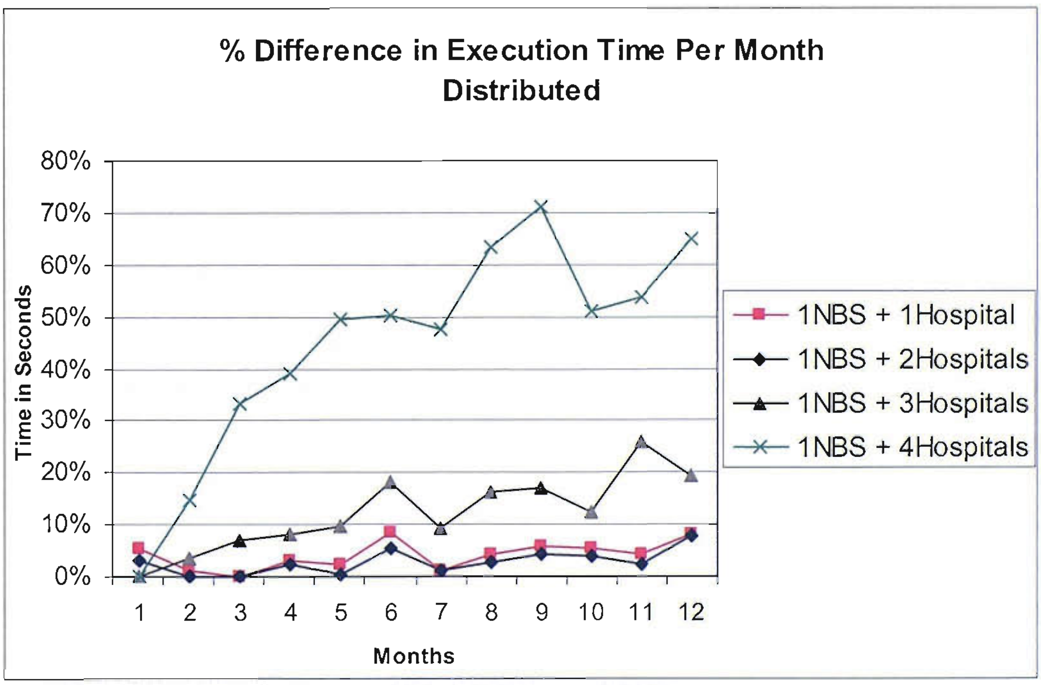

Figure 8.6 Execution time per month of the four models for the Distributed method.

These findings indicate that for the conventional method an expansion in model size will be accompanied by an exponential increase in both the total runtime and the time between iterations when the results are being collected. On the other hand, for the distributed method an increase in the number of hospitals (and therefore of computers) will be followed by a much smaller increase in total runtime, with no extensive increase in runtime between iterations. Therefore, if more than two hospitals are added to any model the distributed method would be a better platform on which to develop and run the simulation experiments. Overall, the distinctive trend that the two methods follow concerning runtimes seems to be continuous, meaning that the more hospitals we add to the model the differences in the runtimes between the two methods would be by far in favour of the distributed one. As noted in the discussion of the conventional approach, the increase in runtime appears to be primarily due to a large event list caused by a combination of the volume of entities and the "counting down" of the shelf life. The large event list in turn causes swapping between RAM and virtual memory, which further causes long runtimes. The results suggest that the distributed approach allows the processing and memory demands made by large event lists to be shared over several computers.

8.4 Model Results for a Blood Centre Supplying Three Hospitals

Following the results of the feasibility study, distributed simulation was adopted wherever possible in the attempt to explore a supply chain with one blood centre and three hospitals, namely the three hospitals as presented in Chapter 6. The models' run lengths were switched back to 6 months for the purpose of experimentation and thus the time differences between the two simulation methods were not as large as for the one-year run. However, distributed simulation was much preferable, where it could be used, because of the fault tolerance mechanism it contains. Runs of the conventional model were usually delayed by "warning" messages for specific variable values or low virtual memory, which could not be switched off without human intervention, necessitating constant attention to the model while running. This was not necessary in the distributed approach in which the models ran smoothly with no halts.

The first experiment pulls the medium, big and small hospitals together and explores their behaviour under the initial stage as defined in their baseline scenarios. Adjustments to the size of collections from the blood centre are made to match the requirements of all the three hospitals together. Collections now represent 25% of the Southampton NBS issues to the hospitals (around 26,000 collected units per year) and the stock levels are changed accordingly. Appendix C.5 provides all the necessary details of the model inputs.

Table 8.1 shows results for the three hospitals on the key performance measures under the policies of the baseline scenario. Values represent averages of 5 simulation runs. Confidence intervals, which are not reported here, were similar to these presented for the one-to-one models.

The expired units in the HBB of the medium volume hospital are exactly the same (347) as presented in section 6.2, Table 6.2, for the one-to-one model (one blood centre – one hospital). Six hundred and seventeen units are expired for the big hospital, less than the value presented in Table 6.26 (686). On the other hand, 224 expired RBC units are counted at the small HBB, a huge increase compared to 136 outdates reported in Table 6.16. Both differences in the values of expired units of the big and small hospitals are significant. A thorough look at the models' results shows that for the big hospital the average age of the blood units on arrival from the CBB is somewhat younger (9.57 days) than for the small hospital (11.63), in addition to the fact that these units spend less time in the HBB (3.42 days on weighted average against 4.47 for the small). Mismatches for all the three hospitals are much more related to the corresponding values of Chapter 6 and no significant differences are noticed; under the baseline scenario not all hospitals keep stock of all blood groups and thus mismatches are unavoidable. Shortages, however, are less for all three hospitals. Even though values overlap in the 95% confidence interval with those of Chapter 6, the fact that the trend is constant for all the participating hospitals shows that there is a tendency for fewer shortages. One possible explanation is that more stock is available at any time in the CBB and individual enquiries are better satisfied. The number of orders is higher for the small hospital; more ad-hoc deliveries are observed, which is the result of having more expired units and therefore additional orders being placed to substitute for the loss. In general, when hospitals are considered together and have to compete for resources from the same CBB, important differences from the single models are detected only in the number of expired units in the big and small volume hospitals, and also there is a propensity for fewer shortages.

Table 8.1 Performance criteria results of the model with the three hospitals supplied by the blood centre (Baseline scenario).

Policies	HBB Expired	Mismatch	Shortages	No.of Orders	Routine Deliver.	Ad-hoc Deliver.	Emerg Deliver.
0) Baseline							
Medium Hospital	347.6	150.6	122.4	323.2	143	149.8	30.4
Big hospital	617.5	55.6	288.6	406.6	138	223.8	44.8
Small Hospital	224.2	160	37.2	213	84.4	97.2	31.4
	1189.3	366.2	448.2	942.8	365.4		577.4

Next, the models were run with the application of policies from the best scenarios as presented in Chapter 7. Two routine orders and deliveries per weekday were available for all the three hospitals. The results are reported in Table 8.2.

Table 8.2 Performance criteria results of the model with the three hospitals supplied by the blood centre (Best scenario).

Policies	Expired	Mismatch	Shortages	No.of Orders	Routine Del	Ad-hoc	Emerg
1) Best							
Medium Hospital	45.4	33	75.4	365	267.2	68.8	29
Big hospital	27.2	34.4	172.2	385.8	281.8	76.8	27.2
Small Hospital	89.4	36.2	26.6	255.6	162	61.4	32.2
Total	162	103.6	274.2	1006.4	711		295.4

Expired units are far fewer, by more than a thousand overall in relation to the baseline models. This saves the three hospitals around £135,400 in total. Compared with the results of the one-to-one best models presented in Chapter 6 (see Tables 6.10, 6.32, and 6.19 respectively), the medium-sized hospital generates the same amount of outdates, while for the big hospital there are 30 units fewer outdates (52%), and for the small hospital outdates increase by 42% (27 units). Mismatches are far fewer than in the baseline scenario, as all blood groups are now kept in stock. Nevertheless, these are more for the small hospital than for either of the others. Shortages correspond to the size of the hospital, but are again less than for the best scenarios in Chapter 6. A small increase in the general number of orders by 6.7% is observed between the best and the baseline scenario, caused by the introduction of the second routine order/delivery. In reality, though, the total number of routine deliveries is not 711 but can only go up to 283, corresponding to two routine deliveries per weekday plus one every Saturday over the 6-month period. Subsequently, 711 is the number of routine orders but 283 or less is the number of routine deliveries in a multi-stop delivery service, if it is assumed that all the three hospitals belong to the same route and are served from the same NBS transport. If two hospitals belong to the same route and the third to a separate one then the number of deliveries will be 566 at maximum, and if all the three hospitals are in different routes then 711 routine deliveries will be made (849 is the maximum routine orders that can be placed under this scenario). Under the baseline scenario, under which only one routine delivery is available, the equivalent number goes only up to 158 for one multi-stop delivery service. Nevertheless, ad-hoc and emergency deliveries are half what they used to be in Table 8.1. The total number of deliveries is the sum of ad-hoc and emergency deliveries (295.4) plus the maximum number of routine deliveries (283), i.e. around 578 deliveries. The corresponding number of the initial scenario was 735 deliveries; this is a 21% decrease. A comparison with the results of Chapter 6 shows that there are insignificant differences in the number of deliveries; however, the same trend of fewer ad-hoc deliveries for the big hospital and more for the small continues, probably because of the respective changes in the number of outdates.

In both of the examined scenarios the models are balanced in terms of number of blood units in stock and age of stock in the CBB and all the three HBBs. The number of units in the CBB inventory is 684.2 in the initial scenario, increasing to 762 after the implementation of the new policies. This has the parallel effect of increasing the range of the age of units in stock from 5-8 days to 6-10 days respectively. Moreover, the number of units transferred to other centres drastically increases from 586 units to over 1629 units, because fewer units are requested overall in the best scenario. By decreasing the number of collections, the age of the CBB stock will be reduced, bringing better results to the performance criteria of the hospitals, subject to the fact that the decrease in collections will not significantly increase shortages.

Additionally to the key performance criteria, the utilisation of NBS transport was also measured in these models and some alternatives were tried out. It was assumed that the three hospitals are served by the same multi-stop routine delivery transport. The same means of transport, which is usually an NBS transit site vehicle (section 5.3.5), is also used at the mid-day public collection picks-ups on the way back to the centre after delivering the routine orders to the hospitals. Ad-hoc and emergency orders are delivered by another NBS vehicle, which is typically a car. Furthermore, because timely delivery is guaranteed for these types of orders, more than one vehicle is usually employed to deal with deliveries of simultaneous orders from different hospitals. All vehicles are available 24 hours a day, 7 days a week. Drivers for scheduled transport and mid-day collections and pick-ups are available at the times these take place, namely Monday to Friday from 10.00 to 18.00 and Saturdays from 10.00 to 14.00. Drivers for ad-hoc and emergency deliveries work in shifts covering 24 hours, since this service is available at all times. Little modification to the models was necessary to cater for all the required transport measurements and in particular new distributions were added to include the time vehicles take to return to base after delivery or the time a vehicle needs to serve hospitals one after the other. The travel times were approximated based on estimations from the Transport Manager of the Southampton NBS. These times were somewhat shorter than the corresponding times for deliveries from the centre to each hospital, as presented in Appendices B.2, B.3 and B.4, but, because of the addition of the return time, the overall duration is much longer. More details about these inputs are shown in Appendix C.5.

Table 8.3 shows results on vehicle utilisation and delivery waiting times for different transport arrangements for the baseline scenario.

Table 8.3 NBS transport utilisation and delivery waiting times for different transport options. Baseline scenario.

Baseline	**No. of Vehicles**	1	2	
Routine Vehicle	Utilisation %	17.44	13.92	
Collections Vehicle	Utilisation %	0	3.52	
Return Collections to Centre	Average Queuing Time	2.35	0	
	Maximum Queuing Time	61.46	0	
Baseline	**Ad-hoc/Emerg. Vehicles**	1	2	3
	Utilisation %	24.14	12.07	8.05
Queue for Medium Hospital Deliveries	Average Queuing Time	10.08	0.44	0
	Maximum Queuing Time	174.77	48.35	0
Queue for Big Hospital Deliveries	Average Queuing Time	7.04	0.15	0
	Maximum Queuing Time	153.61	29.67	0
Queue for Small Hospital Deliveries	Average Queuing Time	11.28	0.38	0
	Maximum Queuing Time	158.28	44.42	0

If the same vehicle is used for routine deliveries to the three hospitals and mid-day public collection pick-ups around or before 16.00, then this vehicle is utilised at 17.5%. However, the maximum vehicle utilisation in a whole week (24 hours, 7 days) is up to 86%, since on Sundays this service is not available and the maximum driver utilisation is 33%, if it is assumed that one driver is employed to cope with this workload and is occupied only during the times of routine deliveries. Under these conditions, however, there is a chance of small delays on the public collection pick-ups. Usually, these are only a couple of minutes but there might be occasional delays of up to an hour. If a different transport is used for the pick-ups then the routine vehicle utilisation drops to 14% and the collections vehicle is used at 3.5% only. The latter vehicle can of course be utilised for other operations as well. Under this scenario zero waiting times are observed. The utilisation of vehicles that are used for ad-hoc and emergency deliveries is also illustrated in the same table. The table shows the utilisation rates of having one, two or three cars available at any time for this operation and the corresponding waiting times of orders ready for delivery. The last column demonstrates that for 3 available vehicles, one for each hospital, there are no waiting times, but the utilisation of all the vehicles together is down to 8%. For the case of two vehicles, the utilisation rate increases to 12% and delays can be up to three-quarters of an hour but on average are zero. If only one vehicle is used for ad-hoc and emergency deliveries the utilisation rises to 24% and waiting times also increase to almost 3 hours maximum, although they are usually about 10 minutes. In this case the utilisation of the drivers is actually 72%.

The equivalent results for the best scenario are shown in Table 8.4.

Table 8.4 NBS transport utilisation and delivery waiting times for different transport options. Best scenario.

Best	**No. of Vehicles**	1	2	
Routine Vehicle	Utilisation %	30.77	27.24	
Collections Vehicle	Average Queuing Time	0	3.52	
Return Collections to Centre	Average Queuing Time	25.34	0	
	Maximum Queuing Time	93.59	0	
Best	**Ad-hoc/Emerg. Vehicles**	1	2	3
	Utilisation %	12.33	6.16	4.11
Queue for Medium Hospital Deliveries	Average Queuing Time	5.25	0.00	0
	Maximum Queuing Time	103.36	0.00	0
Queue for Big Hospital Deliveries	Average Queuing Time	6.11	0.28	0
	Maximum Queuing Time	134.59	13.23	0
Queue for Small Hospital Deliveries	Average Queuing Time	4.50	0.05	0
	Maximum Queuing Time	110.86	4.83	0

The best scenario includes two routine deliveries from Monday to Friday at 10.00 and 14.00 and one on Saturday. If it is assumed there is one vehicle and one driver for both daily routine deliveries to the three hospitals, also catering for the mid-day pick ups, then the vehicle utilisation goes up to 31%, which is almost the maximum rate at which one driver can be utilised. However, waiting times for collections also increase to 25 minutes on average and up to an hour and a half maximum, which is the case when all three hospitals require the second daily delivery and the vehicle is busy there. If, however, another transport is used for collections then these waiting times fall to zero. Under the best scenario delays might also be observed at the start of the second delivery, if the vehicle has not managed to finish the morning delivery within 4 hours due to traffic congestion between the three hospital locations. Moreover, the serious reduction of ad-hoc and emergency deliveries under the best scenario has decreased the utilisation of these vehicles to almost half of what it used to be for the baseline scenario in any case. No delays are observed with the employment of two vehicles and even with one vehicle average delays are only of 5 minutes with maximum delays of two and a quarter hours for the big hospital. This last figure will look better in reality, where more hospitals are supplied by the same centre and more cars are used to transport blood to these hospitals. For example, if there are 15 medium supplied hospitals and five cars to cater for all their non-routine deliveries, the maximum delay will be much less. Under these circumstances it would be reasonable for one vehicle to be used for routine deliveries and collection pick-ups, and only one more to handle all the non-routine distributions. Nevertheless, it would also be recommended that only up to three or four medium-sized hospitals belong to the same multi-stop, routine service. For any other case the same vehicle will not be able to handle the second delivery at 14.00 and the mid-day collection pick-ups without long delays.

Furthermore, an alternative solution could be the use of the routine vehicle to cater for ad-hoc and emergency requests before and after the routine shifts to maximise its utilisation. More than one driver would of course be required to drive this vehicle to cover deliveries on a 24-hours basis. As Table 8.5 shows, if three vehicles are used, one NBS transit site vehicle and two cars, these are utilised at a rate of 20% and waiting times average less than 2 minutes with maximum delays of about an hour. If only two vehicles are available, these are 30% utilised, waiting times are in general around 6 minutes and maximum delays are less than 2 hours. A comparison between this and the previous scenario of Table 8.4 reveals that delays are less in Table 8.5 with one NBS transit site vehicle which also delivers non-routine orders and an extra car for the latter. Nevertheless, the number of drivers increases.

Table 8.5 Experimentation with different NBS transport arrangements under the best scenario.

Best	No. of Vehicles	2	3
Vehicles	Utilisation %	29.77	19.85
Queue for Medium Hospital Deliveries	Average Queuing Time	6.04	2.33
	Maximum Queuing Time	111.38	66.39
Queue for Big Hospital Deliveries	Average Queuing Time	5.52	1.81
	Maximum Queuing Time	94.02	53.17
Queue for Small Hospital Deliveries	Average Queuing Time	6.53	2.00
	Maximum Queuing Time	99.30	38.44
Return Collections to Centre	Average Queuing Time	8.43	0.30
	Maximum Queuing Time	56.66	11.86

8.5 Experimentation with Redistribution Policies

Using the same model with one blood centre and three hospitals and applying the best scenario, additional experimentation was carried out aiming at further improving results if possible. The attempts focused on scheduled returns and redistributions, via the blood supplier's transport, of unused blood to the blood centre and then to other hospitals. Redistributions have never been permitted by the U.K. National Blood Authority, yet these policies are occasionally utilised in the U.S. Many studies in the past have shown the benefits of these policies (Yahnke et al, 1972; Graf et al, 1972; Jennings, 1973b; Brodheim and Prastacos, 1979a, 1979b; Prastacos and Brodheim, 1979), as presented in the literature review (section 3.3.8). This study attempts to show whether a redistribution policy can further improve an already well-organised system, assuming that the best scenario of the simulation experiments as suggested by their stakeholders has been implemented. The selection of the particular criteria for reallocation policies, which will be illustrated together with each set of experiments, is a mixture of new and old rules that have been tried out in these past studies and yielded positive results and which also, in total, appealed to people who have studied the blood supply system.

Unfortunately, for the blood reallocation scenarios the use of distributed simulation was not possible as the method has been programmed to handle only one-way shipping of blood units from the centre to the hospitals and not the other way around. This drawback is likely to be overcome with further development of this technologically advanced tool; however, this was not possible in the limited time available. In order to generate results within the available time the conventional simulation method was used. New code was added to the model to support the redistribution process and only small changes to the model configuration were required according to the demands of each scenario. Apart from the key performance metrics, information was also gathered regarding the number of redistributed units and the number of routine deliveries that were utilised to return these units back from the hospitals to the NBS. The model was run for 6 months and results for each scenario were collected from five runs. The ranges of the 95% confidence intervals of each of the key performance measures were similar to these presented for the one-to-one models. This partially justifies the adequacy of the selection of five runs for producing accurate results from the model with one blood centre and three hospitals, taking into account also the fact that the long execution time of the model limits experimentation in this area.

The first set of experiments tests a policy that allows all the hospitals to send blood units for redistribution back to the CBB. The rules of this scenario are summarised below:

- All the policies of the best scenario apply.
- All hospitals are allowed to send units back to the blood centre.
- Hospitals send those units back to the NBS that have been in the HBB for more than 10 days from their day of arrival and are more than 20 days old.
- Returns take place only at the times of routine scheduled deliveries and are transferred to the blood centre with the NBS transport.
- Returned units are re-distributed from the NBS on an age-based order (the oldest units are issued first).
- Units are discarded from the CBB on scenario (a) the 30^{th} day of their life, scenario (b) the 27^{th}, and scenario (c) the 23^{rd}.
- Units older than the specified age for removal from the CBB are not returned from the hospital.
- Money is refunded to the hospitals for each of the returned units.

Table 8.6 illustrates the most important results of the three scenarios.

Table 8.6 Results of redistribution policy. RBC returns to blood centre from all three hospitals

Redistribution Scenarios	HBB Expired	Mismatch	Short-ages	No. of Orders	Routine Deliver.	Ad-hoc	Emerg	Moved Units
a) Units expire the 30^{th} day from NBS								
Medium	58.4	27.2	54.8	379.4	250	77.4	52	219
Big	44.2	30.2	153.6	402.6	280	82.4	40.2	304.2
Small	93.8	29.4	15.6	286.4	151.4	76.4	58.4	372.6
Total	196.4	86.8	224	1068.4	681.4		386.8	895.8
b) Units expire the 27^{th} day from NBS								
Medium	55.8	31.4	64.6	376.6	252.4	75.8	48.4	202.4
Big	41.2	34	166	398.2	279.2	80.6	38.4	274.4
Small	90.8	33.2	18.8	280	151	73.6	55.4	350.8
Total	187.8	98.6	249.4	1054.8	682.6		372.2	827.6
c) Units expire the 23^{rd} day from NBS								
Medium	45.8	33.8	73	375.2	250.8	79	45.4	174.2
Big	41.2	35.6	175.4	393.8	281.4	76	36.4	215.8
Small	90.8	38	27.2	282.2	152	77.4	52.8	298.8
Total	177.8	107.4	275.6	1051.2	684.2		367	688.8

To begin with, an extension of the shelf life of blood units at issue from the CBB before they are discarded seemed reasonable since units will be at best 20 days old when they are returned from the HBBs and some time should be allowed for redistribution. Thus, the first scenario gives them a time period of up to 10 days to get a chance of being distributed to another hospital or even the same one under request.

Nevertheless, when comparing the results of scenario (a) with Table 8.2 (best-scenario), some advantages and disadvantages of this policy can be identified. First of all, by looking at the sum of column 4 it is noticed that shortages are much fewer under this scenario. This is due to the fact that more units are available from the CBB for issuing since they are discarded much later than they used to be. Therefore, hospital requests are better satisfied. This has also a moderate impact on the number of mismatches, which also decreases. The reasoning behind this is that mismatches are caused by unavailability of the particular units in stock in the HBB, which in turn is caused by shortages of these units in the CBB, as long as hospitals keep stock of all groups. Hence, since fewer shortages occur, fewer mismatches will also take place. Moreover, outdates in the CBB are very few; only 5.6 units expire, because their life duration in the CBB has been extended but, on the other hand, expired units in the hospital banks have increased by 34.4 units irrespective of the reallocation of old units. The age of RBCs on arrival from the centre is greater than it used to be due to the fact that the CBB holds a lot of old blood because of the delay in discarding units and also because of the returned old units. However, the time the units spend in the HBB, and subsequently the average age of blood in the HBB, both decrease because old units are removed from the hospital and are sent back to the centre. Nevertheless, the latter activity cannot compensate for the entire amount of old blood the HBB receives. Furthermore, the total number of orders also goes up, due to the increase in ad-hoc and emergency deliveries caused by the fall in the stock level when returns take place and its replacement with ad-hoc deliveries. Overall, 896 units were returned from hospitals back to the centre in 144 routine deliveries. More units were returned from the small hospital (373) than from any other. The big hospital returned 304 units and the medium returned the least units (219). So, this scenario generated rather undesirable results and no straightforward benefit was achieved that could make the redistribution policy attractive under these circumstances.

Scenario (b) considers the effect of holding blood units in the CBB until the 27th day only. Hence, it gives up to a week for redistribution. The overall results look better than those of scenario (a) apart from the shortages and mismatches for which the previously observed benefit somewhat declines. Additionally, the number of redistributed units falls by around 8.5%. The 827 returned units are transferred back to the centre in 137 routine deliveries. Outdates in the CBB rise to 79 units.

Finally, scenario (c) better matches the policies of the best scenario of Chapter 6 without changing the life span of blood units in the CBB, which expire on the 23rd day. This restricts redistribution to up to 3 days and means that returned units will have more chance of expiring in the CBB than in the hospital. However, if units are distributed soon after they return to the CBB this effect is limited. The results show that the benefit in shortages and mismatches is completely lost since these numbers return to the levels they were at in Table 8.2 (best scenario); these are 275 and 107 units of shortages and substitutions respectively. Expired units in the hospital banks fall to 177 but, nevertheless, this number is not as low as the number of expired units in the best scenario (162 units), even though the difference between them is not significant. In contrast, outdates in the CBB increase to 190 units. Ad-hoc and emergency deliveries slightly diminish but returned units considerably decrease to only 689 units overall, a 30% decrease from scenario (a). These units are transferred in 115 routine deliveries. The small hospital again has the largest number of returns to the centre, in which most of the units arrive at the HBB before or close to the age of 10 days and stay without being transfused for more than 10 days until they become eligible, at the age of 20 to 23 days, for returning to the centre.

Therefore, one can argue that the application of none of these policies is worthwhile since no great advantages have been observed, but on the contrary much time and effort needs to be consumed to deal with the controversy and complexity that modification of rules would bring for allowing redistribution policies to be implemented.

The second set of experiments applies a similar policy with the difference that only the small hospital is allowed to return units back to the centre for redistribution. This low blood usage hospital has been chosen for redistribution because it encounters the bigger problem in outdates in relation to the amount of its blood issues. The remaining rules apply, as presented above, to this scenario too.

Table 8.7 shows the results of the three versions of this scenario. The results again are compared with results of Table 8.2. The most important changes take place in the small hospital. For scenario (a) the sum of outdates at the hospital banks increases as a result of the escalation of outdates at the medium and big hospital. However, the small hospital generates fewer outdates under this scenario than in the best scenario. Shortages are roughly the same for each hospital, even though there is an overall decrease of approximately 20 units; nevertheless, there are fewer mismatches for the big and small hospitals. Total orders stay the same apart from a fall in routine deliveries, which is followed by an increase in emergencies for the medium and small hospitals. Three hundred and thirty-five units were returned from the small hospital to the blood centre in 78 routine transfers. This scenario does not seem to have any clear benefits either.

Scenario (b), which assumes that discards in the CBB take place on the 27th day of the RBC life, does not seem to bring any big changes to the number of outdates except for the medium-sized hospital for which expired units decrease. Shortages and mismatches increase compared with scenario (a) in the same way as in the previous set of experiments. Orders and deliveries also stay at relatively similar levels, apart from emergency deliveries for the small hospital, which decrease. There were 323 returned units from the small hospital, which were transferred in 72 routine deliveries. The restriction on the number of days the hospital is allowed to return units to the CBB did not significantly decrease the number of returns from the small hospital.

The last scenario, which further limits the number of days that blood units can stay in the CBB or returned from the hospital, has different effects overall. Surprisingly, shortages and mismatches decrease, instead of increasing, for all the involved hospitals. Outdates, on the other hand, fall further in the hospital banks which, as expected, increases the CBB outdates to 217 units. Outdates in the hospitals are now even less than those of the best scenario by 27 units, which represents a significant change because the fall in the total number of expired units derives solely from a fall in the small hospital's expired units from 89 to 63, an approximate 30% decrease. Routine orders stay at the same levels as they did over all these three scenarios. However, ad-hoc and emergency deliveries fall slightly to 313; nevertheless, they are still more than those of the best scenario (295). Emergency deliveries in the small hospital decrease considerably in comparison to the previous scenario (Table 8.2). Finally, the number of units returned to the centre has radically been reduced to 256 units, which were returned in 62 routine deliveries, around 4 units per delivery.

The last scenario in this set of experiments has an obvious advantage in comparison with the other two, as also happened with scenario (c) of the previous experiments in which all hospitals were allowed to return units to the centre. However, the results of scenario (c) for the latter set of experiments are much better. Outdates in the small hospital bank seem to be going down, which is the challenge that the redistribution policy was employed to beat. The scenario under discussion also produces better results in comparison with the best presented scenario of Table 8.2. Only ad-hoc and emergency deliveries seem to worsen (by 6%), which is however an important factor in the overall performance of the recommended policy.

It is up to the National Blood Service to decide whether the results that the model illustrates by adopting this additional course of action are worthwhile, taking into account the necessary changes in the system this policy requires. If the particular policy were tried out in the baseline scenario it is possible that some of the outputs would perform much better. This is not likely to happen in an already upgraded system where there is not much space for further improvement.

Table 8.7 Results of redistribution policy. RBC returns to blood centre from small hospital only

Redistribution Scenarios	**Expired**	**Mismatch**	**Short-ages**	**No. of Orders**	**Routine Deliv.**	**Ad-hoc**	**Emerg**	**Moved Units**
a) Units expire the 30th day from NBS								
Medium	64.8	30.2	61.2	354	245	67.0	42	0
Big	46.2	20.2	170.2	388.4	283	74	31	0
Small	73.2	25.4	24	257.2	143	59.2	55	335.4
Total	184.2	75.8	255.4	999.6	671		328.2	335.4
b) Units expire the 27th day from NBS								
Medium	61.2	38	65.4	361.8	245	72	44.8	0
Big	35.2	48.8	179.2	386.6	281	73	32.6	0
Small	74	28.2	32.2	243	145.8	60.4	36.8	323.2
Total	170.4	115	276.8	991.4	671.8		319.6	323.2
c) Units expire the 23rd day from NBS								
Medium	46.6	18	51.8	365.2	246	69.2	50	0
Big	25.2	27.2	170.8	377	275.8	61	40.2	0
Small	63.2	24.2	27	241.2	149	54	38.2	256.2
Total	135	69.4	249.6	983.4	670.8		312.6	256.2

Considering the positive results that the previous experiment produced for scenario (c) (units discarded the 23rd day of their life in the NBS) a final experiment was carried out in which the small hospital does not hold units of rare groups in stock but gets them from other hospitals or the NBS under request. The rules of this scenario are the following:

- All the policies of scenario (c) of Table 8.7 apply.
- Small hospitals do not hold stock of group AB and group B negative.
- Requests for these groups are satisfied through emergency deliveries from other hospitals or the NBS.

- Orders for units of groups which are not held in stock are placed first with the big hospital. If they cannot be satisfied the medium-sized hospital is then asked, and if the orders are still not satisfied, orders are placed to the blood centre for emergency delivery. If none of these options is available, the request will be mismatched.
- An order from the small hospital for units of groups not in stock are only satisfied from other hospitals if these hospitals have units of the particular groups that are more than 20 days old.
- Payments will be made to the supplying hospital for the units at a lower cost than the official value of the acquired products. The requesting hospital will provide transport for the transfer of the units to its blood bank.
- Proximity of the small hospital to the other hospitals is assumed.

The results of this scenario are presented in Table 8.8

Table 8.8 Results of redistribution policy with returns from small hospital which orders units from other hospitals as well as from the NBS. Units are discarded on the 23rd day from the NBS.

Policies	Expired	Mismatch	Shortages	No. of Orders	Routine Del	Ad-hoc	Emerg
1) Best							
Medium Hospital	44	21	55.2	364	242.8	73	48.2
Big hospital	21.8	35.2	164.4	378.8	276	62.8	40
Small Hospital	29	12	19.2	282.2	147	51.8	63.4
Total	94.8	68.2	238.8	1025	665.8		339.2

Under this scenario, 234 units were returned from the small hospital to the blood centre in 80 scheduled deliveries, about three units per delivery. Eighty-three units of groups AB and B negative were requested in 26 physicians' requests, which produced 25 claims to the collaborating hospitals. Of these 21 were satisfied. The big hospital satisfied 14 requests, the medium hospital satisfied four, and three requests were delivered by the NBS. Four requests remained unsatisfied. These unsatisfied requests were mismatched; one request was for three units of AB positive, another for three units of AB negative, and two requests were for six units of B negative. Nevertheless, even though it seems that the number of mismatches in the small hospital decreased, it is apparent that the mismatched units in the big hospital increased. One explanation is that units of rare groups are held in stock in small amounts in the big hospital. Therefore, by giving them away, a request for these units in the near future will find the bank empty and substitution will follow. Thus, the one effect cancels the other and the overall outcome is the same as in the last scenario of the previous Table (8.7), scenario (c). Looking at the other criteria, a further decrease in the number of outdates at the hospital blood banks is observed, which exclusively derives from the reduction of the expired units in the small hospital by 54%, compared with the previous scenario (Table 8.7c). This is due to the lack of stock of rare groups, which previously generated most of the outdates. Nevertheless, routine deliveries fall, but unfortunately ad-hoc and emergency deliveries rise by 9% compared again with scenario (c) of Table 8.7, and by 15% compared with the best scenario (Table 8.2), because of an increase in the number of emergencies in the small hospital. The number of emergency deliveries incorporates the 25 deliveries of AB and B negative units from either a hospital or the NBS. The small hospital is burdened with the cost of these transfers. This cost is variable and might exceed the cost of an ad-hoc or emergency delivery, as it depends on the proximity of the hospital to the other hospitals or blood centre and the type of transport selected for this service. Excluding these rare group transfers, the number of ad-hoc and emergency deliveries would be about the same as in scenario (c) of Table 8.7.

The adoption of this policy is controversial, and raises conflicting issues, which are concentrated, on the one hand, on the gain from fewer outdates, but on the other hand on the complication of the system with more arrangements for deliveries, and the safety implications of the returned and transhipped units. Furthermore, in a supply chain where there are relatively more small hospitals compared with big or medium-sized hospitals, as is the case for the Southampton blood centre, the results of such a policy with requests of un-stocked units from other hospitals might be very different. The most likely outcome would be that most of these units would be satisfied via emergency deliveries from the NBS or, eventually, would be mismatched. This case resembles the baseline scenario and perhaps implies that results will be quite similar.

Overall, no extensive improvements are found for the use or redistribution and transhipment policies in a system which is already well organised, apart from the small volume hospital. Nevertheless, reallocation policies can improve the blood supply chain in systems where there is more room for improvement. In this particular study, which concerns the processes and policies of blood centres and hospitals in the U.K., it is reasonable to assume that policies like the ones presented in Chapter 6 have more to offer in such a system. The implementation of a redistribution policy will require changes in safety rules and regulations, which the NBS would be reluctant to take on at present. However, if major supply problems ever occur in the future, and redistribution policies are considered necessary, then the "what-if" scenarios examined here show that these will only be beneficial when small hospitals return to the centre fairly old units that can be redistributed to other hospitals almost immediately after their return.

CHAPTER 9: CONCLUSIONS AND POTENTIALS

9.1 Summary of this Research

In this study a computer simulation model was constructed to test, in a risk-free environment, the effects of several policies while managing the supply chain of blood products. The model captures all the activities from donation to transfusion and shows how changes in the current practices of blood centres, physicians and hospital blood banks could improve service levels and the budget of the stakeholders involved. Moreover, the model demonstrates how adoption of these changes enables the system to cope easily with future threats of increased demand or diminished supply.

An overview of the National Blood Service (NBS) and the supplied hospitals was presented. The conceptual model of the blood supply chain was then analysed, including related issues about donations and collections, processing, testing and storage, issuing and delivery, hospital inventory management and demand, and financial planning. The literature review illustrated the areas of the subject in which research has previously been conducted, and outlined the merits of the particular study in contrast to the literature. The analysis of data relevant to the blood centre and hospitals was essential for the construction of the simulation model, and this generated the inputs for the model. Data were obtained from several sources and with a variety of collection methods. The selection of the Operational Research technique that was employed to tackle the problem was justified, and the assumptions for the development of the model were laid down. The simulation model was described and validated and key performance metrics specified. Moreover, all the computer facilities and programmes used to develop the model either in the conventional or distributed simulation method were described.

Certain policies suggested by NBS and hospital staff were tried out for different size hospitals. The hospital size was determined by the volume of its blood usage. Hospitals were classified as small, medium and big, and a representative hospital that applied common observed practices was simulated for each of the categories. A set of "what-if" scenarios was tested to monitor the effects of certain policies on the hospital and blood centre practices. Combinations of policies proposed by the involved stakeholders were then examined to identify improved scenarios which brought better results. The best combination of policies for all the different size hospitals was determined from the set of tested scenarios. Subsequently, the model with one blood centre and a single representative hospital was expanded to incorporate all the three characteristic hospitals, by placing the isolated models into an interactive and more realistic environment. The purpose of this attempt was to observe the relationships between hospitals as they compete for resources from the blood centre, and to inspect whether the identified policies had the same impact on the performance criteria as for the single models. Furthermore, redistribution and transhipment policies were tested under the expanded model to check the effects of these practices on the key criteria.

9.2 Conclusions and Recommendations

This PhD study attempted to address five research questions, which were communicated at the beginning of this thesis (at the end of section 1.2). In retrospect, we can see how these questions can be answered after the completion of this study.

A) Compared with previous studies on the topic, how far can we extend this research and make more realistic models with the tools available today?

Compared with previous studies on the topic, which mainly took place 30 years ago, the research area of perishable goods inventory systems and supply chains and in particular the supply chain of blood can be further extended and analysed. The tools available today are capable of producing more detailed and realistic models, which are larger in size and better depict the simultaneous influences and interrelationships of critical factors of the blood supply system's behaviour.

This study and the main model presented here have achieved several advances from previous models:

1) It represents and mimics a detailed vertical part of the blood supply chain from donor to patient, considering the consequences a decision taken in one echelon of the chain will have on another echelon.

2) It incorporates in a single model products with different shelf lives which affect the ordering status of the system.

3) It includes mismatching, which influences the inventory levels of specific blood products.

4) It includes the time a unit spends in the assigned inventory stage and therefore calculates the correct shelf life of products at all stages.

5) It expands by introducing more hospitals into the model and shows the way this more realistic situation affects the quality and quantity of the service offered by the provider (NBS).
6) It considers different sizes of clients (hospitals) and obtains satisfactory policies for each size separately and for all hospitals in the same supply chain together.

B) Is it possible to use simulation to thoroughly explore the supply chain of blood?

Discrete event simulation provides both the theoretical background and the computational support to investigate a complex supply system like this of a perishable product such as blood. Observation of the system, problem formulation and model conceptualisation are essential steps for understanding the system's behaviour and identifying the bottlenecks that prohibit good performance. Unarguably, other operational research techniques like soft systems methodology and system dynamics could have offered a more analytical view of the system's relationships and interactions. However, these techniques would probably fail to capture all the complex quantitative aspects of the problem, which involve substantial mathematical and logical processing. Computer simulation is in a position to offer this service to system modellers together with a great range of experimental capabilities in a risk-free environment. Other attempted "hard" operational methods have only displayed a very limited exploratory level (as seen in Chapter 3).

A discrete event simulation model can be built in several ways. This could either be with a high level programming language or a commercial off-the-shelf package (COTS), which is usually a data-driven software system in which the model is specified using user-defined and default data items (Ball, 2006). It could also be a combination of these two methods by using a COTS package interface and user-friendly environment and expanding its capabilities by connecting it to a high level programming language. We have adopted the last method, which we found more suitable in order for the clients (NBS and hospitals) to easily comprehend the model by looking at the computer screen, yet to allow the construction of a model which is flexible and captures all the necessary logic of the system.

Nevertheless, under these circumstances, as the size and complexity of the model increases, the running times become unbearable and experimentation becomes a time-consuming task. However, this model and similar models of large supply chains can benefit from distributed simulation, which is a method of distributing parts of the simulation model to other computers and synchronising their clocks, activities and mathematical interactions through middleware. The trade-offs in runtime have been explored in a feasibility case study showing that the particular model, running for a year long, can benefit from distributed simulation when three hospitals or more are added to the supply chain. The reduction in runtime by using the distributed method in comparison to the conventional model is 27.4% in the model with three hospitals and 54% in the model with four hospitals, and this difference increases exponentially. Another important benefit of the use of distributed simulation is the fault tolerance mechanism it contains, which prohibits the generation of warning messages, due to short communication difficulties between Simul8 and VB, from stopping the running process. This allows the model to run in the absence of the modeller. Nevertheless, distributed simulation is constantly evolving through experimentation with the hope that eventually it could be applied in a wider range of simulation models with less specific characteristics and as a result the lack of flexibility will be overcome.

Runtime problems might not have been encountered if a high level programming language alone had been used; however, this would have probably sacrificed the advantages of using a comprehensive, user-friendly interface. The use of a more powerful computer or an alternative COTS package, to the best of our knowledge, could only slightly improve the runtimes though without mitigating the problem.

C) Can a simulation model answer crucial questions about the management of a supply chain of a perishable product?

The simulation model that was built for the purposes of this study successfully answers crucial questions about the management of the supply chain of blood and potentially of many other perishable products. Overall, the particular system can be improved by adopting the following policies:

- Holding stock of rare blood groups of RBC, as also proposed by the BSMS survey (BSMS, 2003a).
- The introduction of two routine deliveries in working hours, to improve the management of orders from the NBS and grouped transport to hospitals.
- A more insensitive routine ordering point for RBCs, corresponding to 70% of the optimal stock level when a second routine order per weekday applies.
- A more insensitive ad-hoc ordering point for RBCs, corresponding to 30% of the optimal stock, and to 10% for emergency stock ordering.

- Reducing the total crossmatch release period (before and after transfusion) to less than 1.5 days.
- Increasing the transfusion-to-crossmatch ratio to 70%, either through stricter compliance with the recommended ordering system leading to more accurate orders placed by doctors, or by applying multiple crossmatching techniques.
- Hospital blood bank strictly adhering to FIFO order when crossmatching for units coming from the centre, and to LIFO order for unused returned units from the other wards. This corresponds to FIFO order according to the collection/production date of the unit.
- Holding stock of a weighted average of approximately four days after the implementation of the above mentioned policies.
- A cluster of at most three to four hospitals (less than 850 routine orders in total per semester) under the same routine delivery service which delivers twice a day and utilises one vehicle and one driver.
- Using the routine NBS transit site vehicles to cater also for non-routine deliveries before and after the scheduled distributions.

These policies can be applied to all hospitals, regardless of the volume of blood consumption.

Moreover, systems open to re-distribution and transhipment policies can further benefit by allowing returns of RBC units from small hospitals (with approximately less than 4500 requested units per annum) to the blood centre subject to the following rules:

- RBC units are sent back to the centre by routine transport.
- Units should be between the age of 20 and 23 days, and should have stayed at the hospital blood bank for more than 10 days.
- Redistribution of these units from the centre to the hospitals will be prioritised and done before the units reach the age of 24 days, at which they should be discarded by the centre.
- Small hospitals should be refunded by the NBS for the number of returned RBC units.

In adopting these recommendations, the total system will experience:

- Cost savings in the hospital budget by encountering fewer outdates and requesting fewer RBC units overall.
- Fewer shortages from the blood centre.

- Less mismatching, resulting in the avoidance of possible medical complications.
- Fewer ad-hoc and emergency orders from the hospital with savings on the money charged to the hospital for deliveries, and further savings for the NBS by reducing the number of occupied drivers, staff and transport.
- Increased availability of RBC units at the blood centre to cover possible supply shortfalls, for whatever reasons may these occur, in the region covered by the centre or anywhere in the nation or abroad.

Furthermore, the simulations identified specific interactions between certain parameters of the model. These are summarised as follows:

- Expired units are determined a) by the age of blood on arrival from the blood centre; b) by the length of time that stock stays unused in the HBB (days of stock) which is also determined by the frequency of physicians' requests for the particular blood group; c) by the time stock remains in the assigned inventory stage; and d) by the probability of transfusion.
- If the number of outdates is high, more deliveries will be required to replace the lost inventory and reach the ideal stock. These will usually be ad-hoc deliveries rather than routine, because loss of stock happens at any time and not necessarily near the routine order time. However, this is also affected by the amount of loss and the level of stock compared with the optimal.
- Routine, ad-hoc and emergency deliveries are affected by the defined ordering point for stock, which is in turn determined by the frequency of physicians' requests for the particular blood group.
- Mismatches are caused by unavailability of the particular units in stock in the HBB, which in turn is caused by shortages of these units in the CBB in cases where hospitals deliberately keep stock of all groups. Therefore, if the number of shortages is high eventually the number of mismatches will increase because units will not be available at the time needed.
- Reducing outdates in the hospital banks increases outdates in the CBB and vice versa, provided that everything else stays the same. However, the first direction of this relationship is much more useful, since the extra units in the centre bank can avoid expiration by being moved to support regions where demand is greater and supply cannot cope. The possibility of having additional stock can also provide a way to deal with the future threat of increased demand or decreased supply. On

the other hand, an excess of units in the hospital blood banks inevitably leads to outdates.

- The more units are requested above the recommended number, the fewer units are used, and vice versa. So, the total volume requested changes in inverse proportion to the number of used units when aggregated data are examined and not individual cases.
- An increase in days of stock in the NBS, which also increases the age of blood on arrival in the hospitals, is the consequence of a high collection rate that is not balanced by corresponding demand from hospitals.
- Hospital practices have the potential to improve blood inventory management and minimise wastage, regardless of the age of blood at receipt. This improvement can be achieved through the policies mentioned at the beginning of section 9.2. In addition, these improved transfusion practices suggest that hospitals can satisfy the same level of patient demand with fewer ordered units.
- The young age of some blood groups at the time of arrival in the hospitals shows that these units do not wait at the CBB but are distributed as soon as they are collected, meaning that either their demand is great or they are sparsely collected. Hence, no outdates of these units will be seen in the CBB, although shortages are possible. On the other hand, units that are old by the time of arrival in the hospital and for which the waiting time (days of stock) in the HBB is also long, have a high possibility of outdating in the HBB.
- Blood that is quite young in the CBB but old in the HBB indicates that the hospital can better arrange its processes to improve the age of blood and decrease outdates.
- If outdates but no mismatches of a particular group are observed in the HBB then a reduction in the hospital's optimal stock level of this blood group is recommended. On the other hand, if a high number of mismatches are reported for this group an increase in its stock level is required.
- If orders of bigger size are placed with the NBS centre more shortages are likely to be observed in the centre, especially if the ordered units are of the same group.
- When no stock of a particular group is kept in the hospital banks, then other groups have to compensate for their shortage in the HBB and thus consumption of other substitute groups increases. Consequently, more orders for the substitute groups are made and in larger quantities. This can lead to increased shortages for

these units from the NBS if collections have been planned according to the distribution of blood groups in the population.

- The utilisation of NBS transport considerably increases when routine deliveries go up and ad-hoc and emergency deliveries decline.

Additional recommendations that derive from a general analysis of the blood supply system and not solely from the simulation experiments are as follows:

- Standardisation of working patterns across the NBS centres could make the structure of the system more "lean" and assist control throughout the chain. National standards should apply regarding working times and shifts, delivery schedule and exchange of stock. However, some legal variations would still be possible amongst the regions depending on pressure to cover demand.
- Blood centres could better be managed as self-sufficient parts of the system. These should incorporate all the basic functions of a complete centre, such as collections, processing, testing and issuing, together with marketing and finance services for minimising unnecessary interaction in the system. However, communication between centres is definitely encouraged with stock movements and product exchange to even out regional supply needs.
- Hospitals should also standardize some of their processes, as suggested by the simulation experiments. Better stock management in hospital blood banks can be achieved with the implementation of rules that usually apply to manufacturing and other profit-driven companies, such as determined stock ordering points, updated optimal stock levels, specified ordering and delivering policies, substitution rules, transhipment regulations, etc.
- An online, real-time stock control and ordering system of all the blood banks would benefit this supply chain. Access to this database by blood centres and hospitals will result in a better co-ordinated supply and demand chain, where information about inventory levels and ordering processes are transparent to all members of the chain.

D) Are such models useful to real life users?

The simulation model as such can offer useful pieces of advice to the stakeholders of the system. The main use of the model, which has been thoroughly displayed in this thesis, is experimentation with different sets of scenarios, which identified improved ordering, stocking and distribution policies for adoption by the NBS and the supplied hospitals. The list of scenarios that have been tested is not exhaustive but covers the ones that were particularly emphasized by the NBS and hospital blood bank managers. Therefore, these policies were considered as feasible recommendations for immediate implementation. However, the experimental capabilities of the model are vast, meaning that many more scenarios can be tested on request. Nevertheless, the model needs some form of adaptation in order to accommodate every new scenario. The number of changes required for the model to successfully portray the new scenario defines whether specific programming skills are essential or not. Changes in the configuration of the model and the arrangement of the simulation building blocks or the Visual Basic logic will demand the intervention of the modeller. Thus, policies such as the induction of a second routine delivery or more than one hospital in the model or redistribution activities require the brief intervention of an expert. However, the actual users of the model can still test a substantial range of scenarios without the presence of the modeller after receiving only a basic tour of the software. So, hospital blood bank and NBS managers can experiment, for example, with the "ideal" blood stock level and identify more satisfactory "ideal" stock levels than the ones that their experience alone dictates. Moreover, they can easily test different blood reservation periods or stock re-ordering points and crossmatching-to-transfusion ratios.

The selected software (SIMUL8) has in-built tools that allow the user to make changes to the model parameters by typing different numbers in pop-up boxes before each run. The modeller needs to activate these features and work out the set of questions that the user needs to answer in order to change the chosen parameters each time. After the end of each run (or set of runs) a pop-up window presents the results summary. The users found this tool very "*handy*" and seemed excited with the idea of playing around with the software "*like it was a video game*" and at the same time get useful answers about the efficiency of the blood system in few minutes' time. Runtime was not a big issue in the set of experiments that the users could test alone, as the model with one centre and one hospital completes a single run in about 10 minutes and five runs in approximately one hour. However, the users acknowledged that they would ideally prefer the run process to last no more than a couple of minutes.

E) Can we apply the method used for blood products to the supply chain of other perishable products?

Finally, the same methodology and modelling approach can apply to various supply chains of perishable products, such as the food industry, horticulture and floristry, pharmaceuticals, transplants, and other perishable goods. Likewise, non-perishable product supply chains with comparable configuration and/or characteristics can benefit from a similar simulation model. Some of the functions that have been examined in this thesis, such as ordering, stocking and distribution, are common to any supply chain and consequently it is possible that parts of this model could be used and/or integrated in the simulation models of other supply chains. At the very least, modelling ideas can be gained by examining the way this model was built.

9.3 Limitations, Potentials and Future Work

At this stage, a critical evaluation of the whole study is essential. The quality and strengths of this research has been discussed in the previous section. However, the present work has certain limitations that need to be acknowledged when considering the study and its contributions. Some of these limitations can be seen as fruitful avenues for future research under the same theme.

There are two major limitations. The first limitation concerns the selection of a single case (Southampton blood centre) to study the NBS part of the designed supply chain, which naturally brings forth many restrictions as far as the generalisation of the results of the study is concerned. The second constraint relates to the modelling technique which is characterized by inherent limitations. By nature, the process of using of a computer-generated system to represent the dynamic responses and behaviour of a real system carries with it a number of major assumptions. If these assumptions do not hold, the study can be limited in its usefulness. The main concern is that the human behaviour is difficult to be completely understood and captured in a set of logical rules. Thus, assumptions regarding ordering, stocking and mismatching, which are based on staff experience in the real world, might be misleading. However, these limitations were mitigated by sound statistical analysis to produce acceptable distributions of order frequencies, order size, etc. deriving from NBS and hospital data, with the further assumption that these data are accurate.

Moreover, there are a few, specific limitations in this research which should be addressed as a means of improvement or potential strategies for further study. One of these is the assumption of the platelets age on arrival to the hospital. Taking the model forward, in-depth information about the production of platelets and other special components by the NBS and their use by hospitals would lead to a better understanding of their supply chain. Details of this process could be incorporated into the model in order to consider shortages and stock holding and assist in the management of these increasingly needed blood products.

Next, a further expanded model with more hospitals supplied by an NBS centre could be built and even additionally enlarged to incorporate more blood centres in order to capture and mimic the real system on a national level with all the stakeholders involved. The expanded model could illustrate how hospitals and centres compete for resources and whether an amended structure of the system with a different number of blood centres would prove better than the existing one. This is very relevant nowadays since politicians are discussing a possible reform of the whole British blood supply system, in which only four "mega" NBS centres would exist to supply the whole nation's hospitals (Northcott, Head of Southampton NBS Centre, interview 31.5.2005). Also, additional experimentation could show whether centres could better manage the whole supply chain by exercising more control over the hospitals' supplies in a transparent system. Thus, alternative system configurations and general policies could be recommended and standardised processes could be applied. However, all these raise issues of computation time due to the generation of a very large number of entities.

Nevertheless, the investigation undertaken in this thesis has revealed possible solutions to tackle the problem. The feasibility study on the use of conventional or distributed approaches to better and faster simulate the expanded model of the blood system showed that when the supply chain grows in size and complexity, distributed simulation appears to offer a viable alternative to conventional simulation by sharing the processing and memory requirements of the simulation across multiple computers.

The potential for such an approach in healthcare simulation modelling is huge. There is an increasing recognition that healthcare systems do not exist in a vacuum and that even seemingly well-defined subsystems such as emergency departments, operating theatres or out-patient clinics have complex interconnectivity with other parts of the overall healthcare system, both within the hospital and outside its walls. This can lead either to the development of enormous models that attempt to capture these relationships, or to oversimplification by ignoring them and making the model boundaries artificially narrow.

Distributed simulation offers a viable solution to this problem, using low cost off-the-shelf software which is widely available and increasingly used in the National Health Service (NHS).

In terms of further work, the question is whether all large, complex simulations could benefit equally. The development of metrics to indicate what could be distributed and what should not be distributed will help bring this technology closer to the simulation practitioner. If this endeavour is worthwhile and a substantial number of complex simulation models with lengthy runtimes can be distributed, then future work ought to make this process more user friendly and with expanded experimental capabilities for the end user.

Moreover, recalling the limitations that Nahmias (1982) identified in all previous research of blood inventory management (see section 3.5) it can be seen that the present study was able to address some of them. In particular, we proved that discrete event simulation could handle this complex problem and present useful results unlike a single mathematical model. Our model successfully separated the assigned and unassigned inventory taking also into account the ageing of blood inside the loop of assign-unassigned inventory. Finally, our model also considered mismatching as well. However, the limitation regarding the need to incorporate into the model the practical medical limitations of requests of fresh blood for some certain transfusion was not tackled. Further developments of the elements of the model would be able to deal with this issue. This could be another opportunity for future research.

Finally, our model was also capable of examining distribution scheduling, with the development of heuristic algorithms for scheduling the distribution of multiple blood products from the centre to the hospitals. This was one of the open research questions on blood management identified by Prastacos in 1984 (section 3.5). His remaining questions about optimal component processing policies, optimal organisational structures of regional blood systems and inter-regional collaborations are still unanswered and evergreen for potential research.

APPENDIX

A: DATA COLLECTION

A.1 Blood Products

Table A.1 Southampton NBS Issued Products with more than 0.1% frequency, April 2003 – October 2004.

Products	Description	Issued Units	Percentage
0050	RCELLS LEUCO DEP	185484	74.50%
0064	RCELLS WASHED LD	3	0.00%
0370	PLTS LEUCODEPLETED	4612	1.90%
0378	PLATELETS POOLED LD	5133	2.10%
0390	PLTS APH WASH/PAS	31	0.00%
0420	PLTS APH IN PAS	17	0.00%
0872	WATER INJECTION 20ML	12	0.00%
0932	PRALIDOXIME MESYLATE	10	0.00%
0933	ATROPINE	12	0.00%
0934	SALINE 0.9% IV 5ML	9	0.00%
0935	OBIDOXIME 1ML	1	0.00%
0B20	RBCS OA L.DEP NEO	5099	2.00%
0N81	HYPER CONC PLATELETS	1	0.00%
0Y50	AUTOLOGOUS BLOOD	10	0.00%
G050	RCELLS LEUCO DEP GI	10465	4.20%
G064	RCELLS WASHED LD GI	75	0.00%
G350	LEUCOCYTES GI	147	0.10%
G370	PLT LEUCODEPLETED GI	3407	1.40%
G378	PLATELETS POOL LD GI	2943	1.20%
G390	PLT APH WASH/PAS GI	1	0.00%
G420	PLTS APH PAS GI	59	0.00%
GB20	RBCS OA LD GI NEO	232	0.10%
GN81	PLTS HYPER CONC GI	12	0.00%
GU10	PLTS APH LD GI NEO	44	0.00%
GY30	RED CELLS GI IUT	17	0.00%
L376	PLT POOL LD EXLIFE	30	0.00%
L531	LEUCODEP CRYO	5886	2.40%
L551	LD FFP PK1 300ML	15	0.00%
L552	LD FFP PK2 300ML	12	0.00%
L561	LD CRYO DEP PLASMA	757	0.30%
LF10	LEUCODEPLETED FFP	23941	9.60%
LF11	LEUCODEP FFP PK1	2	0.00%
LF12	LEUCODEP FFP PK2	2	0.00%
LF60	FFP MBREMOVED NEO	327	0.10%
LF70	FFP(NUK)MBREM PAED 1	102	0.00%
LF80	FFP(NUK)MBREM NEO	184	0.10%
	TOTAL	249094	100.00%

GLOSSARY

RCELLS = Red Cells	FFP = Plasma	L.DEP = Leucodepleted
RBCS = Red Cells	CRYO = Cryoprecipitate	GI = Irradiated
PLTS = Platelets	NEO = Neonatal	G – Irradiation of the corresponding code

A.2 Maximum Surgical Blood Ordering Schedule - MSBOS

Table A.2 Maximum Surgical Blood Ordering Schedule (MSBOS). Southampton University Hospitals NHS Trust Haematology and Blood Transfusion Department, Version 1.0

General Surgery	Units
Oesophagectomy	2
Liver resection	2
Cardiac and Thoracic Surgery	
Redo cardiac surgery	2
Extended bypass	Requiremts for patients undergoing extended by pass should be discussed with BT (Blood Transfusion?)
All adult cardiothoracic procedures are G&S except the above Paediatric procedures – at the discretion at the clinician.	
Orthopaedics	
Arthroplasty: Total Hip Revision	2
Arthroplasty: Total Knee Revision	2
Scoliosis correction	6
Neurosurgery	
All routine neurosurgery should be for G&S Complex neurosurgery will be XM'ed at the discretion of the clinician	
Urology	
Cystectomy	2
Obstetrics	
Placenta praevia	
This is repeated every 7 days or as advised by the lab	
Extensive surgery requests will vary and are at the discretion of the clinician.	
All other procedures are for G&S	
NB: For any surgical procedures not mentioned under any directorate, a G&S sample is sufficient.	
This MSBOS relies upon samples being submitted to the BT lab in a timely manner, so that an antibody screen can be performed pre-operatively to exclude the presence of clinically significant atypical antibodies. If potentially clinically significant antibodies are found blood will need to be cross-matched before surgery takes place to cover the procedure. A "full cross-match" is required taking a minimum of 45 minutes, but may take much longer depending on availability of suitable blood.	

* Information valid on 20/7/2004

* G&S = Group and Save

A.3 NBS Data Sample

Table A.3 Southampton NBS Collections database

Date	Type	Group	Units
01-Apr-03	A	A+	8
01-Apr-03	A	A-	1
01-Apr-03	A	B+	1
01-Apr-03	A	B-	2
01-Apr-03	A	O+	8
01-Apr-03	W	A+	172
01-Apr-03	W	A-	32
01-Apr-03	W	B+	28
01-Apr-03	W	B-	5
01-Apr-03	W	O+	225
01-Apr-03	W	O-	50
01-Apr-03	W	AB+	5
01-Apr-03	W	AB-	3
02-Apr-03	A	A+	12
02-Apr-03	A	O+	9
02-Apr-03	A	O-	4
02-Apr-03	W	+	1
02-Apr-03	W	A+	227
02-Apr-03	W	A-	56
02-Apr-03	W	B+	66
02-Apr-03	W	B-	15
02-Apr-03	W	O+	275
02-Apr-03	W	O-	64
02-Apr-03	W	AB+	17
02-Apr-03	W	AB-	1

Source: PULSE System

Note: "W" stands for Whole Blood and "A" for Apheresis*
Apheresis regards only Platelet collections.
Database covers the period from April 1, 2003 to October 31, 2004 (5,856 rows).

GLOSSARY for Issues database

Titles Abbreviations

RQNO = Request Number
REQLINE = Request Line
PRDCD = Product Code
LOCCD = Location code
AUDDATE = Date (yy/mm/dd)
ABORH = ABO Rh Group
DELTY = Delivery Type
AUDTIME = Time
REQAMNT = Requested Amount

Deliveries Notations

Code	Notation	Explanation
A	Ad Hoc	
B	Blue Light	
C	Collect	No NBS transportation is used
D	Del:Stock	Routine delivery
E	Emergency	
F	AdHc-Free	Routine delivery which by NBS mistake was delivered as Ad-Hoc or Saturday Routine Delivery which had been wrongly entered as Ad-hoc free delivery by NBS employees
R	Routine	Routine delivery

Table A.4 Southampton NBS Issues database

REQNO	LOCCD	DELTY	REQLINE	AUDDATE	AUDTIME	PRDCD	ABORH	REQAMNT
S072822	S011	A	1	20030401	0036	0378	A+	2
S072823	S016	C	1	20030401	0750	0370	A+	1
S072824	S016	D	1	20030401	0801	0050	A+	10
S072824	S016	D	2	20030401	0801	0050	O+	10
S072824	S016	D	3	20030401	0802	0050	O-	14
S072824	S016	D	4	20030401	0802	0050	O-	6
S072824	S016	D	5	20030401	0820	0370	A+	4
S072824	S016	D	7	20030401	0801	LF10	A+	9
S072824	S016	D	8	20030401	0801	LF10	O+	3
S072824	S016	D	9	20030401	0803	LF50	AB+	2
S072825	S018	D	1	20030401	0804	0B20	O-	6
S072826	S013	F	1	20030401	0818	0370	O+	1
S072826	S013	F	2	20030401	0815	LF10	A-	2
S072826	S013	F	3	20030401	0815	LF10	O+	4
S072826	S013	F	4	20030401	0816	LF10	AB-	4
S072827	S014	D	1	20030401	0842	0370	O+	1
S072827	S014	D	2	20030401	0841	0378	A+	1
S072828	S019	D	1	20030401	0845	0050	A+	4
S072828	S019	D	2	20030401	0845	0050	A-	3
S072829	S015	D	1	20030401	0846	0050	A+	18
S072829	S015	D	2	20030401	0848	G050	O+	2
S072830	S020	D	1	20030401	0849	G370	O+	1
S072831	S017	D	1	20030401	0853	0370	A+	1
S072832	S020	F	1	20030401	0906	0050	B-	4
S072833	S011	D	1	20030401	0920	0050	A+	15
S072833	S011	D	2	20030401	0920	0050	B-	1
S072833	S011	D	3	20030401	0919	0050	O+	10
S072833	S011	D	4	20030401	0920	0050	O-	4
S072834	S012	D	1	20030401	0923	0050	A+	2
S072834	S012	D	2	20030401	0923	0050	O+	11
S072834	S012	D	3	20030401	0924	0050	AB+	2
S072835	S018	F	1	20030401	0929	0378	O+	1

Source: PULSE System

Note: Database covers the period from April 1, 2003 to October 31, 2004 (43,814 rows).

Table 0.5 Hospital's receipts of blood products from the Southampton Blood Centre

Date	RCLD	FFPLD	PLAT	Cryo	RCLDI	BP250	BP500	Other	Comments	Returns
01/04/2004	12									
05/04/2004	6									
06/04/2004	12	8								
07/04/2004	8		2				8		4 from SGH, 4 from Aventis	
13/04/2004			1							
14/04/2004	6	2	2							
15/04/2004	7									
19/04/2004	5									
20/04/2004	8									
21/04/2004	8									
26/04/2004	5									
27/04/2004	3									
28/04/2004	6	4	2							
29/04/2004	9									
TOTALS	**95**	**14**	**7**	**0**	**0**	**0**	**8**			

Source: BUPA Hospital Chalybeate

Note: Database covers the period from April 1, 2003 to August 31, 2004

Table A.6 Discards database of the Southampton Blood Centre

Wastage Date	PRD CD	RSDSC*	ABO RH	Units
1-Apr-03	0371	PST	A+	1
01-Apr-03	0378	PST	A-	1
01-Apr-03	0378	PST	A+	5
01-Apr-03	0054	PST	AB+	19
01-Apr-03	0378	PST	O+	4
01-Apr-03	0372	PST	A+	1
01-Apr-03	0378	PFL	O+	1
02-Apr-03	0054	PST	AB+	7
02-Apr-03	0372	PST	A-	1
02-Apr-03	0378	PST	O+	1
02-Apr-03	0372	PST	O+	1
02-Apr-03	0378	PST	A+	1
02-Apr-03	0371	PST	A-	1
02-Apr-03	G371	PST	A+	1
02-Apr-03	0378	PFL	O+	1
02-Apr-03	0371	PST	O+	1
02-Apr-03	0378	PST	O-	1
02-Apr-03	0378	SMB	A+	2
02-Apr-03	0378	PST	A-	1
03-Apr-03	0378	TDA	O+	1
03-Apr-03	0378	PST	A+	1
03-Apr-03	0378	PST	A-	1
03-Apr-03	0054	SMB	B+	1
03-Apr-03	0372	PST	O+	1
03-Apr-03	0371	PST	O+	2
03-Apr-03	0378	PST	O+	1
03-Apr-03	0054	PST	AB+	16
04-Apr-03	0054	SMB	A+	1
04-Apr-03	0054	PST	AB+	1
05-Apr-03	0378	PFL	A+	1
07-Apr-03	0371	PST	B-	1
07-Apr-03	0054	PST	AB+	3
08-Apr-03	0378	PST	A-	1

Discards Notations

Code	Notation
AFF	MANUFACT'RE PROBLEM
ALF	PACK LABEL FAULT
APF	PACK SYSTEM FAULT
CDU	UNDERWGT COLLECTION
COL	LABEL ERROR
COO	OVERWGT COLLECTION
COP	CONTAMINATED PACK
COR	WRONG PACK
COS	Empty/Missing Tubes
COT	CLOTTED UNIT
CTC	T CRUZI TEST
MAT	MALARIA
NAT	Await Test Results
PDV	VISUAL ABNORMALITY
PEC	CENTRIFUGE PROBLEM
PEP	PRESS ERROR
PFL	LAB PROBLEM
POE	EXCESS RED CELLS
POH	HANDLING DAMAGE
POL	PROCESS LABEL ERROR
POO	OVERWGT COMPONENT
POP	OPERATOR ERROR
POS	LEAKING SEAL/CLIP
POT	PRODUCT OUT OF TIME
POU	UNDERWGHT COMPONENT
PSI	PENDING INVESTIGN
PSR	RETURNED PRODUCT
PSS	STORAGE ERROR
PST	EXPIRED
PWU	BYPRODUCT
PYT	TRIAL/RESEARCH
QAF	QA DISCARD
SMB	D63 DISCARD
TDA	ANTIBODY
TDB	MEDICAL DISCARD

Source: PULSE System, * RSDSC: Reason of Discard
Note: Database covers the period from April 1, 2003 to October 31, 2004 (1,540 rows).

A.4 Hospital Blood Bank Questionnaire

University of Southampton

Blood Bank Hospital Questionnaire

SURVEY CONSENT FORM: This survey is designed to collect data concerning the blood bank procedures in hospitals supplied by the Southampton NBS centre. The information that you will provide will be incorporated in a wider study as part of my PhD research project. The project is being carried out in collaboration with the National Blood Service, and involves analysing the supply chain of red blood cells from donor to patient, hopefully leading to improvements through the use of mathematical techniques such as computer simulation. More specifically, I am seeking information about transfusions, blood stock levels, ordering policies and costing in your hospital. This survey is vital for the fulfilment of the project, and as such your participation is very important. All the information gathered in this project is completely confidential and will remain anonymous if you wish so. The resulting information will be used only for research purposes.

INSTRUCTIONS: The following questionnaire contains 30 questions about your blood bank operations and red cells transfusions. Please start by entering the name of your hospital, your details and your NBS centre, and then respond to the questions below. If you feel that you can provide a sample of your collected data on the following matters I would be very grateful to receive any files in order to enable my understanding and analysis to be more accurate. Also, if you would like additional information about this research, please contact me at korina@soton.ac.uk. You are also very welcome to contact my PhD supervisor, Dr Sally Brailsford, tel. 023 8059 3567 or email scb@soton.ac.uk. Thank you very much.

1. Please enter the name of your Hospital:

[ ]

2. Please enter your name, job title, e-mail and phone number:

[ ] Name:

[ ] Job Title:

[ ] Email:

[ ] Phone:

3. To which NBS Centre does your Hospital belong?

[ ]

Transfusion – Crossmatches

4. How many units of red cells do you transfuse per day, on average, by blood group? If there is significant variation from day to day, please give the approximate range [1 2]. If you have carried out a statistical analysis of your data, please give the standard deviation instead of the range.

Blood Group	Average daily transfusions (e.g. 20 units)	Daily range (e.g. 10-25 units) or standard deviation (e.g. 5 units)
A+		
A -		
B+		
B -		
AB+		
AB -		
O+		
O -		

5. If there is a seasonality effect, please indicate the busiest month(s) and also the month(s) with the lowest transfusion rates, and say by how much they differ from the average:-

Highest:-

Lowest:-

Please also indicate the day(s) of the week with the highest and lowest transfusion rates, and say by how much they differ from the average:-

Highest:-

Lowest:-

If you have any illustrative daily data, I would be very grateful to receive it.

6. Do your surgeons comply with the Maximum Surgical Blood Ordering Schedule (MSBOS)? Please circle one answer:-

Y / N / Sometimes.

If not, why not?

What are your surgeons' average daily requests for red cells, by blood group? Please give a range (or standard deviation if you know it) as before, if there is any daily variation.

[1] Calculate the average by considering a prolonged period of time (e.g. year)
[2] If you believe that weekly transfusions better describe the situation in your hospital, then change daily to weekly.

Blood Group	Average daily requests	Range / standard deviation
A+		
A -		
B+		
B -		
AB+		
AB -		
O+		
O -		

7. What is the transfusion to crossmatch ratio? (The probability of a crossmatched unit for a surgery to be transfused in that surgery.)

8. What is the average crossmatch release period (in hours)? (The period between the crossmatching of a unit and its returning back to the unassigned inventory, if not transfused.)

9. What is the average age of the red cells that you receive?

Does this differ from blood group to blood group? Y / N.

If yes, please indicate this number for each blood group.

Blood Group	Average Age of red cells (e.g. 7 days)
A+	
A -	
B+	
B -	
AB+	
AB -	
O+	
O -	

10. How often do you check for expired units? (e.g. every morning at 9, when we check for stock levels and orders, etc.)

11. Does your issuing policy follow the order of oldest blood being crossmatched first?

Y / N.

If No, what rule do you use?

12. How many times is a unit of red cells cross-matched in its lifetime, on average?

Does this number vary according to blood group? Y / N

If yes, please indicate this number for each blood group:-

Blood Group	Average no. of crossmatches
A+	
A -	
B+	
B -	
AB+	
AB -	
O+	
O -	

13. What is the average age of a unit of red cells when it is cross-matched for the first time?

14. What is the average time (in hours) from the first crossmatch until the unit is used?

Is there any variation in this? Y / N.

If yes, please specify the range or better still, the standard deviation:-

15. What is the average time (in hours) from a unit's arrival in the hospital blood bank until it is first crossmatched?

Is there any variation in this? Y / N.

If yes, can you specify the range that this time varies or the standard deviation?

16. Is multiple cross-matching allowed? (Assigning the same unit of red cells to more than one patient at the same time). Y / N.

If yes, is this effective, and how does it work in practice?

What is the average number of multiple crossmatches?

What is the maximum allowed number?

Stock Levels

17. What are your optimal (target) stock levels by blood group?

Blood Group	Optimal Stock Levels (in units)
A+	
A -	
B+	
B -	
AB+	
AB -	
O+	
O -	

18. What are your <u>average</u> stock levels by blood group?

Blood Group	Average Stock Levels (in units)
A+	
A -	
B+	
B -	
AB+	
AB -	
O+	
O -	

19. How many days of stock do you aim to keep, if any?

20. How many times per day (or week/ month) do you check the blood bank stock and at what times?

21. How many times per day (or week/ month) do you order red cells from the NBS and at what times? Of these, how many are routine orders, how many emergency and how many ad hoc?

	Number per Day/Week	Times of the day
Orders for Routine Deliveries		
Orders for Ad Hoc Deliveries		
Orders for Blue light Deliveries		
Other (specify)		

22. How long, on average, does it take for an Ad Hoc/blue light delivery to arrive (in hours)?

23. What is the percentage (or quantity) that you will wait for your blood stock levels to fall below the target/optimal, until you place an order with the NBS centre for replenishment?

24. Do you telephone, fax or both in order to place an order with the NBS centre?

25. Do you keep electronic records of crossmatches, transfusions, etc.? Y / N

If yes, then in what format (e.g. in which software)?

Costs

25. Do you find the prices for the blood components acceptable? Y / N

Comments:

26. How much do you usually spend annually on purchasing blood?

27. Is the hospital's budget for blood products sufficient? Y / N / Usually

Approximately, what is the budget for the year?

28. Can you please describe your financial transactions between your hospital and the NBS?

- Frequency of payments
- Payer-payee
- Payment method (check, cash, in advance or after receipt of goods, etc.)
- Additional charges for ad hoc/emergency deliveries per delivery or item.

Further comments:

29. Approximately how many employees are currently occupied in your hospital blood bank?

30. Do you have a costing policy for shortages and wastages? Y / N

If yes, please describe how it works:-

See the following :
Outdate cost = average costs of ordering, processing, storing and transporting one unit + bag cost, record keeping and hours of work.

Shortage cost = cost for processing a unit on an emergency basis and for recruiting donors + cost of postponing a surgery (extra administration job) + the risk the patient is put under.

Any additional comments:

Thank you for taking the time to respond to this research survey.

Please send by e-mail to:
korina@soton.ac.uk

Or return to:

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A.5 Blood Collection Scheme

Southampton Collection Department

9 Collection Teams

1. Reading are based on Reading
2. Milton Keynes based on Bristol
3. Swindon based on Bristol
4. Oxford *2 sessions based on Bristol
5. Southampton North based on Southampton
6. Southampton West based on Southampton
7. Portsmouth based on Portsmouth
8. Isle of Wight (work 1 or 2 days over 15) based on the Isle of Wight
9. Bloodmobiles *2 sessions based on Southampton

Teams collect only whole blood. Apheresis collections take place only at PTI sites.

Table A.7 Blood collection scheme of the Southampton Blood Service

Southampton NBS Centre Collection Schedule						
Collection Teams South East	Based on	PTI in	Working days per fortnight	no. of sessions	Collection Target 2004/2005	Collection Target 2005/2006
Portsmouth	Portsmouth	Southampton	9	1	23,855	
Southampton North	Southampton	Southampton	9	1	21,646	
Southampton West	Southampton	Southampton	9	1	23,163	
Bloodmobiles (2mini)	Southampton	Southampton	9	2	13,718	
Isle of Wight	Isle of Wight	Southampton	1 or 2	1	6,574	
Oxford	Bristol	Bristol	9	2	38,223	
Milton Keynes	Bristol	Bristol	8	1	18,404	
Reading	Reading	Southampton	8	1	19,378	
Swindon	Bristol	Bristol	8	1	20,300	
Southampton static (on-site)	Southampton	Southampton	10	1	4,663	
Oxford static (on site)	Oxford	Southampton	10	1	1,789	
Sum					191,713	182,217
					Annually	Monthly
Collections to Bristol for PTI					76,927	6411
% of total collections sent to Bristol					40.1%	

A.6 Southampton Blood Service Clients and Issues

2003/2004 19 months	Code	Location	Issued RBCs	Issues	Delivery Time	Route - Distance
1	SO10	BASINGSTOKE DISTRICT	7100	3.7%	10	North 48m
2	SO11	BOURNEMOUTH GEN.	15281	8.0%	12	W 48m
3	SO12	ST. MARY'S NEWPORT (IOW)	6018	3.1%	12	1h
4	SO13	POOLE GENERAL HOSP	14726	7.7%	10	W 1h +5m
5	SO14	QUEEN ALEXANDRA	19044	9.9%	10	E 41m
6	SO15	ROYAL HAMPSHIRE CTY.	11659	6.1%	10	N 30m
7	SO16	SOUTHAMPTON GENERAL	28780	15.0%	9.30 14.30 16.30	4m
8	SO17	SALISBURY DISTRICT	10331	5.4%	10	W 50m
9	SO18	ST. MARY'S PORTS.	5590	2.9%	10	E 45m
10	SO19	ROYAL NAVY HOSPITAL HASLAR	2033	1.1%	10	E 58m
11	SO20	WEST DORSET HOSPITAL	12500	6.5%	10	W 1.38h
12	SO21	BOURNEMOUTH NUFFIELD	1655	0.9%	12	W 51m
13	SO22	CHALYBEATE	1609	0.8%	No Routines	
14	SO23	ORCHARD HOSPITAL	42	42		
15	SO24	JERSY STATE HOSP.	O 404	0.2%	No	
16	S027	PRINCESS ELIZABETH GUERSNEY	117	0.1%	No	
17	S028	WESSEX NUFFIELD	866	0.5%	12	N 20m
18	9926	ARMY BLOOD SUPPLY	6903	3.6%	Any	N 1h
19	9905	NBS SHEFFIELD	100	0.1%	Any	N
20	9911	NBS BRENTWOOD	33478	17.4%	Any	N 2,35h
21	9914	NBS MANCHESTER	810	0.4%	Any	
22	9916	NBS SOUTH THAMES(Tooting)	6090	3.2%	Any	N 1,55h
23	9922	NBS NORTH LONDON (Colindale)	330	0.2%	Any	
24	SO19B	BRISTOL, PLYMOUTH, OXFORD	6401	3.3%	Any time	
		TOTAL	191885	100.0%		

A.7 Statistics on Daily RBC Data

Table A.8 Statistics of daily collected units from Southampton Blood Centre, April 2003 – March 2004.

Collections	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	766.1	748.5	780.5	792.3	722.8	156.5	163.0
SD	507.8	491.8	514.4	524.9	475.7	109.2	113.8
Min	465	376	508	516	521	143	48
Max	1078	1058	1063	1042	898	170	278
Weeks	48	53	53	50	50	2	2

Table A.9 Statistics of daily processed units from Southampton Blood Centre, April 2003 – March 2004.

Processed	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	244.9	496.7	529.9	565.3	530.8	255.6	91.0
SD	138.5	313.1	336.5	363.7	339.3	144.0	62.2
Min	143	192	328	315	307	68	48
Max	406	817	861	803	802	394	134
Weeks	48	53	53	50	50	51	2

Table A.10 Statistics of daily RBC issues from Southampton Blood Centre, April 2003 – March 2004.

RBC Issues	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	327.1	306.0	188.5	192.1	151.0	58.7	54.5
SD	194.6	178.9	95.8	99.8	70.0	6.1	3.9
Min	20	228	169	163	50	8	20
Max	1188	1261	730	828	394	234	283
Weeks	52	53	53	51	52	50	49

Table A.11 Statistics of daily Irradiated RBC issues from Southampton Blood Centre, April 2003 – March 2004.

Irrad. RBC Issues	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	21.8	41.6	19.1	19.3	18.6	6.0	7.1
SD	19.9	1.1	23.3	21.0	22.2	1.4	14.8
Min	4	22	4	5	5	2	2
Max	43	62	38	41	35	10	16
Weeks	50	40	52	49	50	4	28

Table A.12 Statistics of daily Platelet issues from Southampton Blood Centre, April 2003 – March 2004

Platelet Issues	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	27.2	31.0	28.8	30.9	40.8	8.0	10.8
SD	6.5	11.3	8.4	10.6	20.3	4.9	27.0
Min	11	19	12	17	18	8	4
Max	39	38	39	52	58	8	37
Weeks	18	15	17	16	12	1	49

B: MODEL LOGIC (PSEUDO-CODE)

In this section an outline of the logic which was used to model and program the system is presented. It includes all the modelling steps which were conducted in Simul8 Visual Logic, VBA and the Excel worksheets in order the model to be capable of producing meaningful results. It is written in a form that can be easily understood and converted into real programming statements. However, it is free of syntactic details of the programming language and therefore it cannot be compiled nor executed as it is. The benefit of the use of the pseudo-code is to provide to the programmer and reader of this thesis the ability to check the model's internal relationships and judge their realism and relevance to the system. It can also be manipulated by another modeller to reproduce the model. A short glossary is provided in the begging in which the reader can refer back while reading the pseudo-code. Also the latter is organised by event. Headings, in bold, briefly describe the part of the logic that will be examined.

Preliminary Information

Simulation Clock runs in minutes

Time Checks take place every hour

Request = Request of one blood unit (bag) at a time

Communication of VBA with SIMUL8 is done via Signals

Signal is a text

Simul8 Time Check VL for setting the working patterns of the NBS Centre and of each simulated hospital (excluding the VBA Signals)

<u>Simul8 – Time Check VL</u>

FOR each hospital

IF Simulation Day is Sunday

SET Simul8 Entry Point "Physicians' Requests H#" Inter-arrival Time Distribution to Exponential with average 9-10 hours

ELSE IF Simulation Day is Monday

SET Simul8 Entry Point "Physicians' Requests H#" Inter-arrival Time Distribution to Time Dependent "Requests H#"

END IF

END FOR

```
IF Simulation Hour is 8a.m AND Day is not Sunday
    Start "Processing"
ELSE IF Simulation Hour is 9a.m
    Return unused units from wards to Hospital Blood Bank, "Returns H#"
    IF Day is not a weekend day
        Start "On site Collections" Entry point
    END IF
ELSE IF Simulation Hour is 10a.m
    Breakdown Simul8 workstation "Returns H#"
    IF Day is not a weekend day
        Start "Industrial Collections" Entry point
    END IF
ELSE IF Simulation Hour is 1p.m AND Day is not a weekend day
    Start "Public Collections" Entry point
    Start mid day pick-up for Industrial Collections, "Transfer industrial to centre"
ELSE IF Simulation Hour is 2p.m AND Day is not Sunday
    Start routing processed units to NBS Blood Bank after "Tests' Release"
ELSE IF Simulation Hour is 3p.m
    IF Simulation Day is not Sunday
        Breakdown routing to NBS Blood Bank wait for "Tests' Release"
    END IF
    IF Simulation Day is Saturday
        Breakdown "Processing"
    END IF
ELSE IF Simulation Hour is 4p.m AND Day is not a weekend day
    Start mid day pick-up for Public Collections, "Transfer public to centre"
    Breakdown "On site Collections" Entry point
ELSE IF Simulation Hour is 5p.m AND Day is not a weekend day
    Breakdown "Industrial Collections" Entry point
    Start end of day pick-up for Public Collections, "Transfer industrial to centre"
ELSE IF Simulation Hour is 8p.m AND Day is not a weekend day
    Breakdown "Public Collections" Entry point
    Start end of day pick-up for Public Collections, "Public industrial to centre"
ELSE IF Simulation Hour is 9p.m AND Day is not a weekend day
    Breakdown "Processing"
```

* The exact VL code contains some more Starts and Breakdowns of auxiliary workstations which are not included here for simplification

VL SECTION: Define the expiration Simulation Time of each unit according to the place of expiry

<u>VL SECTION: "Process in Soton" Action Logic</u>

SET Expiration Time of HBB = Time Entered System+35 days

SET Expiration Time in NBS = Time Entered System+23 days

VL SECTION: Define the time left to expiry when blood unit enters the HBB

<u>VL SECTION: Dummy for time enter bank Action Logic</u>

SET "Expiring in NBS after" = Expiration Time in NBS-Time Entered NBS Bank

VL SECTION: Define the time left to expiry when blood unit enters the HBB

<u>VL SECTION: "bank or crossmatch H#" Action Logic</u>

FOR each blood unit arrival in the "bank or crossmatch H#" workstation

SET "Expiring after" = Expiration Time in HBB -Time Entered HBB

IF Product = Irradiated RBC

SET "Expiring after" = 13 days

SET Time Entered System = initial value-9 days (to decrease its expiration life to a maximum of 26 days instead of 35 because it should be only up to 14 days old to be Irradiated)

END IF

END FOR

VL SECTION: Define the transfusion to crossmatching ratio for each request

<u>VL SECTION: Entry Logic</u>

Entry Point Label Actions-VL of

Physicians' Requests H#

Emergency Orders H#

Irrad Requests H#

Rare Types Orders H#

Platelet Requests H#

FOR each blood unit's arrival in the Entry Point

GENERATE a Random number

IF Random number < 0.1

SET text label “Usage” to Probability Distribution “All” (all units of this request will be transfused)

ELSE IF 0.1 < Random number < 0.2

SET text label “Usage” to Probability Distribution “None” (this request will be cancelled, none unit will be transfused)

IF 0.2 < Random number < 1

SET text label “Usage” to Probability Distribution “Some” (i.e. 55% of the units of this request will be transfused, 44.2% won’t and 0.8% will stay out of bank for too long)

END IF

END FOR

VL SECTION: Update the time of Expiration. Applies to both RBC and PLT Returns

VL SECTION: Returns H# On Exit Logic

IF blood is about to return in HBB for a second time or more

READ Simulation Time of Previous Return

END IF

INITIALIZE “Usage”

VL SECTION: Dummy Returns H1 Action Logic

IF blood is about to return in HBB for the first time

SET Time elapsed =Simulation Time Now – Simulation Time when unit first entered HBB

ELSE IF blood is about to return in HBB for a second time or more

SET Time elapsed =Simulation Time Now – Simulation Time of Previous Return to HBB

END IF

UPDATE “Expiring after” = Previous “Expiring after” - Time elapsed

VL SECTION: Units waiting for Routine transport should be separated to stock orders which are delivered the following day and those which are at the same day

VL SECTION: Differ H# Work Complete Logic

IF Product = PLT

IF Delivery is Urgent

SET Route = immediate

```
    ELSE
        SET Route = next day
    END IF
ELSE IF Product = RBC
    SET Route = next day
ELSE IF Product = Irradiated RBC
    IF Delivery is Urgent
        SET Route = immediate
    ELSE
        SET Route = next day
    END IF
END IF
```

VL SECTION: Route blood products to the right storage or usage area

<u>VL SECTION: Where H1 Work Complete Logic</u>

```
IF Product = PLT
    SET Route = PLT Bank
ELSE IF Product = RBC
    SET Route = RBC Bank
ELSE IF Product = Irradiated RBC
    SET Route = RBC Bank
END IF
```

Count pc runtime per simulated month

<u>Simul8 – Time Check VL</u>

```
FOR Simulation Time = 0 and for the beginning of every simulated month Signal VBA
    Signal = "PC Clock"
END FOR
```

<u>VBA</u>

```
IF Signal = "PC Clock"
PRINT PC time in Excel worksheet "Optimal Stock"
END IF
```

Setting initial conditions for the Simul8 model, for the VBA code and for the results' collections.

<u>Simul8 – On Reset VL</u>

On clicking the Reset button from the menu bar Signal VBA

Signal= "Reset"

<u>VBA</u>

IF Signal= "Reset"

Call the Names of the SIMU8 Objects which will be used in the VBA code

INITIALIZE all the auxiliary variables related to counting

Clear the Excel worksheets from results of previous runs

Breakdown the Collection Entry Points in the Simul8 model

READ the optimal stock values for each hospital in the model from the Excel worksheet "Optimal Stock"

FOR each hospital
    FOR each blood group
        Add work items to Queue before HBB
        Set Attribute value "Blood Group" to blood group
        Set Attribute value "Expiring after" to 26 days
        Set Attribute value "Time Entered System to 7 days before the start of the simulation run
    END FOR
END FOR

READ the Re-Ordering percentage point for Routine Orders and Ad-hoc Orders for each hospital in the model from the Excel worksheet "Optimal Stock"

READ the adjusted normal stock values for the NBS Centre from the Excel worksheet "Optimal Stock"

FOR each blood group
    Add work items to NBS Blood Bank
    Set Attribute value "Blood Group" to blood group
    Set Attribute value "Expiration time" to 35 days

Set Attribute value "Time Entered System" to: 5 days before the start of the simulation run

Set Attribute value "Expiring from the NBS Centre after" to 18 days

Set Attribute value "Product" to RBC

END FOR

END IF

Average age and number of units of RBC inventory in CBB and HBB per simulated day. Validation of the average amount and age of initial contents for both the CBB and HBB and Warm-up period.

<u>Simul8 – Time Check VL</u>

```
FOR Every simulated day at midnight Signal VBA
    Signal= "Validation"
ENF FOR
```

<u>VBA</u>

```
IF Signal= "Validation"

FOR each blood unit in NBS Blood Bank
    COMPUTE Blood unit age = Simulation Time Now – Time Entered System
    PRINT Blood unit age on Excel worksheet "AgeStockNBS"
    INCREMENT Row
END FOR

    READ NBS Blood Bank stock size from Simul8 object
    PRINT NBS Blood Bank stock size on Excel worksheet "Stock"
    INCREMENT Row

FOR each hospital
    FOR each blood group's Storage area in HBB
        PRINT stock size on Excel worksheet "Stock"
        INCREMENT Column
     END FOR
     INCREMENT Column by 2 after the last written Column of the previous hospital
END FOR
```

INCREMENT row

FOR each hospital

FOR each blood group' Storage area of RBC in HBB

FOR each blood unit

COMPUTE Blood unit age = Simulation Time Now – Time Entered System

PRINT Blood unit age on Excel worksheet "AgeStockH#"

INCREMENT Row

END FOR

END FOR

INCREMENT Excel worksheet "AgeStockH#"

END FOR

INCREMENT Column

END IF

Move excess stock from this NBS Centre to other Centres

<u>Simul8 – Time Check VL</u>

FOR Every simulated Monday at 11a.m. Signal VBA

IF NBS Total stock is near to maximum stock

Signal= "Moves"

END IF

ENF FOR

<u>VBA</u>

IF Signal= "Moves" AND Simulation Time is not the first Monday of the Run

INITIALIZE units to be moved

FOR each blood unit in NBS Blood Bank from the mid of the pile to the end

IF the blood unit group is not ABpos OR ABneg

INCREMETN units to be moved

IF units to be moved are less than the units in excess (above the normal/maximum stock)

Move units to Simul8 Storage area "Other NBS"

END IF

END IF

```
    END FOR
END IF
```

Order Blood Products

Simul8 –Object- HBB Storage Area -Routine In -VL

```
FOR each hospital
    FOR each blood unit arrival in the Storage area of RBC in HBB by blood group
        IF "Delivery Type" = Routine
            INCREMENT Total Routine RBC Deliveries
        ELSE IF "Delivery Type" = Non-Routine
            INCREMENT Total Non-Routine RBC Deliveries
        END IF
    END FOR
END FOR

FOR each hospital
    FOR each blood unit arrival in the Waiting area of Physicians' PLT Requests in HBB
by blood group
        INCREMENT Total PLT units' Requests
    END FOR
END FOR
```

Simul8 – Time Check VL

```
FOR Every Time Check Signal VBA
    FOR each hospital
        FOR each blood group
            SET in Excel worksheet "OptimalStock" Total RBC Deliveries
            SET in Excel worksheet "OptimalStock" Total PLT units' Requests
            IF Simulation Time = Hospital's Routine Order time
                SET in Excel worksheet "OptimalStock" Total Routine RBC Deliveries
            END IF
        END FOR
    END FOR
    Signal= "Orders"
ENF FOR
```

VBA

IF Signal= “Orders”

INITIALIZE Count Non-Routine PLT Orders

CALL the queue size of

Storage area of RBC in the HBB by blood group

Waiting area of Physician RBC Requests in the HBB by blood group

Waiting area of Physician PLT Requests in the HBB by blood group

Waiting area of Physician PLT Requests in the NBS Centre

Storage area of PLT in the NBS Blood Bank

Waiting area of Physician Requests for Rare RBC groups and Irradiated RBC in the HBB

Waiting area of all RBC HBB’s Orders in the NBS Centre

FOR each hospital

Irradiated RBC & Rare Types RBC Orders

IF Waiting area of Physicians’ Requests for Rare RBC groups and Irradiated RBC in HBB is not empty

FOR each Request on descending order

READ Attribute value ("Urgent")

IF Request is Urgent AND Simulation Day is not Sunday AND (Simulation Time is 2 hours OR 1 hour before the NBS Centre’s Routine Delivery time)

SET Attribute value “Delivery Type” to Routine

Move Request to Waiting area of all RBC HBB’s Orders in NBS Centre

ELSE IF Request is Urgent AND Simulation Day is Sunday OR (Request is Urgent AND Simulation Time is not 2 hours OR 1 hour before the NBS Centre’s Routine Delivery time)

SET Attribute value “Delivery Type” to Ad-Hoc

Move Request to Waiting area of all RBC HBB’s Orders in NBS Centre

ELSE IF Request is Non Urgent AND Simulation Time is Hospital’s Routine Order time AND Simulation Day is not Sunday

SET Attribute value “Delivery Type” to Routine

Move Request to Waiting area of all RBC HBB’s Orders in NBS Centre

END IF

END FOR

END IF

PLT Orders

FOR each blood group

READ the value of Total PLT units' Requests from the beginning of the simulation run until now from Excel worksheet "OptimalStock"

IF Total PLT units' Requests from the beginning of the simulation run until now are different from Total Requests of PLT from the beginning of the simulation run until the previous reading of this code

COMPUTE PLT Order = Total PLT units' Requests from the beginning of the simulation run until now - Total Requests of PLT from the beginning of the simulation run until the previous reading of this code

IF PLT Order > queue size of the Waiting area of Physicians' PLT Requests in NBS Centre

PLT Order = queue size of the Waiting area of Physicians' PLT Requests in NBS Centre

END IF

FOR each new Request in the Waiting area of Physicians' PLT Requests in NBS Centre of the size of the Order PLT

READ Attribute value ("Usage") and ("Urgent")

ADD Request to Waiting area of Physicians' PLT Requests in NBS Centre

SET Attribute value "Blood Group" to blood group

SET Attribute value "Product" to PLT

RETURN Attribute value ("Usage") and ("Urgent")

END FOR

UPDATE Total Requests of PLT from the beginning of the simulation run until the previous reading of this code

END IF

END FOR

Move PLT Orders as necessary

CALL queue size of Waiting area of Physicians' PLT Requests in NBS Centre

IF Waiting area of Physicians' PLT Requests in NBS Centre is not empty
FOR each Request on descending order
READ Attribute value ("Urgent")

IF Request is Urgent AND Simulation Day is not Sunday AND (Simulation Time is 2 hours OR 1 hour before the NBS Centre's Routine Delivery time)
SET Attribute value "Delivery Type" to Routine
Move Request to Waiting area of Physicians' PLT Requests in NBS Centre

ELSE IF Request is Urgent AND Simulation Day is Sunday OR (Request is Urgent AND Simulation Time is not 2 hours OR 1 hour before the NBS Centre's Routine Delivery time)
SET Attribute value "Delivery Type" to Ad-Hoc
Move Request to Waiting area of Physicians' PLT Requests in NBS Centre
INCREMENT Count Non-Routine PLT Orders

ELSE IF Request is Non Urgent AND Simulation Time is Hospital's Routine Order time AND Simulation Day is not Sunday
SET Attribute value "Delivery Type" to Routine
Move Request to Waiting area of Physicians' PLT Requests in NBS Centre
END IF
END FOR
END IF

RBC orders

IF Simulation Time is Hospital's Routine Order time AND Simulation Day is not Sunday
FOR each blood group
IF Storage area of RBC in HBB is less than the Routine re-ordering point
READ value of Total RBC Deliveries from the beginning of the simulation run until now from Excel worksheet "OptimalStock"

IF Hospital's Routine Order time is after Routine Delivery time
RBC Stock Order = Optimal stock – stock in Storage area of RBC in HBB – (Total RBC Stock Order from the beginning of the simulation run until now - Total RBC Deliveries from the beginning of the simulation run until now)

ELSE IF Hospital's Routine Order time is before Routine Delivery time and morning Routine Orders are delivered with the next day's Scheduled Delivery

IF Last Order was made the day before OR on Saturday and now is Monday

RBC Stock Order = Optimal stock – stock in Storage area of RBC in HBB – (Total RBC Stock Order from the beginning of the simulation run until now – Last Order - Total RBC Deliveries from the beginning of the simulation run until now)

ELSE

RBC Stock Order = Optimal stock – stock in Storage area of RBC in HBB – (Total RBC Stock Order from the beginning of the simulation run until now - Total RBC Deliveries from the beginning of the simulation run until now)

END IF

END IF

ELSE IF Simulation Time is different from Hospital's Routine Order time OR Simulation Day is Sunday

FOR each blood group

IF Storage area of RBC in HBB is less than the Ad-Hoc re-ordering point

READ value of Time of Previous Non-Routine Order

IF Simulation Time Now is different from the Routine Delivery Time OR an hour before this AND is not an hour OR two after the Previous Time of placing a Non-Routine Order for this blood group

READ value of Total RBC Deliveries from the beginning of the simulation run until now from Excel worksheet "OptimalStock"

RBC Stock Order = Optimal stock – stock in Storage area of RBC in HBB – (Total RBC Stock Order from the beginning of the simulation run until now - Total RBC Deliveries from the beginning of the simulation run until now)

Shortages

END IF

END IF

END FOR

For 2 or less Non-Routine RBC Stock Orders alone avoid placing an order

SUM RBC Stock Order of all blood groups

IF there are RBC Stock Order which are less than 3 blood units AND there are no Irradiated OR Rare group RBC Stock Order AND no Non-Routine PLT Orders

SET RBC Stock Order to zero

UPDATE Total Non-Routine RBC Stock Orders from the beginning of the simulation run until now subtracting the last Order

END IF

Order more than Optimal Stock if there are unfulfilled Physician's Requests

FOR each blood group

IF Optimal Stock >0 AND RBC Stock Order > 0 AND there are no Physicians' Requests waiting to be fulfilled

ADD as many blood units' Requests in the Waiting area of all RBC HBB's Orders in NBS Centre as the RBC Stock Order

CALL Labels

ELSEIF Optimal Stock >0 AND RBC Stock Order > 0 AND there are Physicians' Requests waiting to be fulfilled

ADD as many blood units' Requests in the Waiting area of all RBC HBB's Orders in NBS Centre as the RBC Stock Order + the number of Physicians' Requests waiting to be fulfilled

CALL RBC Orders' Labels

IF Simulation Time is different from the Routine Delivery Time OR Simulation Day is Sunday

UPDATE Total Routine RBC Stock Order from the beginning of the simulation run until now with the additional Physicians' Requests waiting to be fulfilled

ELSE

UPDATE Total Non-Routine RBC Stock Orders from the beginning of the simulation run until now with the additional Physicians' Requests waiting to be fulfilled

END IF

END IF

END FOR

SUB RBC Orders' Labels

SET Attribute value "Blood Group" to blood group

SET Attribute value "Product" to RBC

SET Attribute value ""Where to go"," to Bank for storage

IF Simulation Time = Routine Delivery Time AND Simulation Day is not Sunday

SET Attribute value "Delivery Type" to Routine

ELSE IF stock in Storage area of RBC in HBB by blood group is less than 15% of the Optimal Stock

SET Attribute value "Delivery Type" to Emergency

ELSE

SET Attribute value "Delivery Type" to Ad-Hoc

END IF

END SUB

Report Shortages If time > warm-up period (18 days)

FOR each blood group

IF Total RBC Stock Order from the beginning of the simulation run until now are more than the Total RBC Deliveries from the beginning of the simulation run until now

IF day is Monday

PRINT Monday in the 1rst Column "Day" of Excel worksheet "Short H#"

END IF

PRINT number of Simulation Day in the 2nd Column "Day" of Excel worksheet "Short H#"

PRINT Hour of the Day in the 3rd Column "Time" of Excel worksheet "Short H#"

PRINT blood group in the 4th Column "Group" of Excel worksheet "Short H#"

PRINT Total RBC Stock Order from the beginning of the simulation run until now in the 5th Column of "Ordered H#" Excel worksheet "Short H#"

PRINT Total RBC Deliveries from the beginning of the simulation run until now in the 6th Column "Delivered H#" of Excel worksheet "Short H#"

INCREMENT row

END IF

UPDATE Previous Time of placing a Non-Routine Order for this blood group to Simulation Time Now

UPDATE Total Non-Routine RBC Stock Orders from the beginning of the simulation run until now including the new RBC Order

END FOR

END IF

Excel worksheet "Short H#"

FOR each row

COMPUTE the non returned blood units which is the difference between Total RBC Stock Order (5th Column) and Total RBC Deliveries (6th Column) in the 7th Column "Non Return" of Excel worksheet "Short H#"

COMPUTE the following in the 8th Column "Logic" of Excel worksheet "Short H#"

IF (blood groups (4th Column) between this and the previous time check (previous row) are the same AND Non Return units (7th Column) of this time check are the same or less than the previous time check AND Ordered units (5th Column) between this and the previous time check are the same) OR *(blood groups (4th Column) between this and 2 time checks before (2 rows before) are the same AND Non Return units (7th Column) of this time check are the same or less than 2 time checks before AND Ordered units (5th Column) between this and 2 time checks before are the same)

PRINT True

ELSE

PRINT False

END IF

* This extra precaution is taken in case there is a repeated pattern of Non-Routine time checks with the same Non Retuned units but there are interrupted by a Routine time check.

COMPUTE the following in the 9th Column "Shortage" of Excel worksheet "Short H#"

IF Logic (8th Column) = True

PRINT 0

ELSE

IF Logic (8th Column) = False AND blood groups (4th Column) AND Delivered units (6th Column) between this and the previous time check (previous row) are the same

PRINT the difference between the Non Returned units (7^{th} Column) of this and the previous time check

ELSE

PRINT the difference between the Non Returned units (7^{th} Column) of this time check

END IF

END FOR

After shortages (9^{th} Column) have been sorted according to blood group and time

Total shortages of H# for this simulation run = SUM "shortages" (9^{th} Column)

Report Orders If time > warm-up period (18 days)

CALL number of contents in the

Waiting area of all RBC HBB's Orders in NBS Centre

Waiting area of Physicians' PLT Requests in NBS Centre

IF there are Orders placed in the Waiting area of all RBC HBB's Orders in NBS Centre at this Simulation Time

FOR each current content in the Waiting area of all RBC HBB's Orders in NBS Centre

CALL Report Labels in Excel

END FOR

END IF

IF there are Orders placed in the Waiting area of Physicians' PLT Requests in NBS Centre at this Simulation Time

FOR each current content in the Waiting area of Physicians' PLT Requests in NBS Centre

CALL Report Labels in Excel

END FOR

END IF

SUB Report Labels in Excel

READ labels of each content

IF day is Monday

PRINT Monday in the 1rst Column of Excel worksheet "Order H#"

END IF

PRINT number of Simulation Day in the 2nd Column of Excel worksheet "Order H#"

PRINT Hour of the Day in the 3rd Column of Excel worksheet "Order H#"

PRINT Product in the 4th Column of Excel worksheet "Order H#"

PRINT "Blood group" in the 5th Column of Excel worksheet "Order H#"

PRINT "Delivery Type" in the 6th Column of Excel worksheet "Order H#"

PRINT "Urgency" in the 7th Column of Excel worksheet "Order H#"

PRINT "Where to go" in the 8th Column of Excel worksheet "Order H#"

PRINT "Usage" in the 9th Column of Excel worksheet "Order H#"

INCREMENT row

END SUB

END FOR

<u>Excel worksheet "Order H#"</u>

FOR each row

COMPUTE the following in the 10th Column "Logic" of Excel worksheet "Order H#"

IF Delivery type (6th Column) between this and the previous time check (previous row) are not the same OR Hour (3rd Column) between this and the previous time check are not the same OR Day (2rd Column) between this and the previous time check are not the same

PRINT True

ELSE

PRINT False

END IF

COMPUTE the following in the 11th Column "No. of Deliveries" of Excel worksheet "Order H#"

IF Logic (10th Column) = False

PRINT 0

ELSE

PRINT 1

END IF

COMPUTE the following in the 12th Column "Type" of Excel worksheet "Order H#"

IF No. of Deliveries (11th Column) = 0

PRINT 0

ELSE

PRINT Delivery type (6th Column)

END IF

COMPUTE the following in the 13th Column "No. of Routines" of Excel worksheet "Order H#"

IF Type (12th Column) = 1

PRINT 1

ELSE

PRINT 0

END IF

COMPUTE the following in the 14th Column "No. of Emergency" of Excel worksheet "Order H#"

IF Type (12th Column) = 3

PRINT 1

ELSE

PRINT 0

END IF

COMPUTE the following in the 15th Column "PLT" of Excel worksheet "Order H#"

IF Product (4th Column) = 1

PRINT 1

ELSE

PRINT 0

END IF

COMPUTE the following in the 16th Column "Irrad" of Excel worksheet "Order H#"

IF Product (12th Column) = 3

PRINT 1

ELSE

PRINT 0

END IF

END FOR

Total No. of Deliveries of H# for this simulation run = SUM "No. of Deliveries" (11^{th} Column)

Total No. of Routine Deliveries of H# for this simulation run = SUM "No. of Routines" (13^{th} Column)

Total No. of Routine Deliveries of H# for this simulation run = SUM "No. of Emergency" (14^{th} Column)

Total No. of Ad-Hoc Deliveries of H# for this simulation run = SUM "No. of Deliveries"- SUM "No. of Routines"- SUM "No. of Emergency"

Total No. of PLT units of H# for this simulation run = SUM "No. of PLT units" (15^{th} Column)

Total No. of Irrad RBC units of H# for this simulation run = SUM "No. of Irrad RBC units" (16^{th} Column)

DISTRIBUTED MODEL

Differences in Coding

PLT Orders are placed also in the Waiting area of all RBC HBB's Orders in NBS Centre instead of Waiting area of Physicians' PLT Requests in NBS Centre.

So there are two different arrangements:

1) For the piece of code ***Move PLT Orders as necessary***

Replace

Move Request to Waiting area of Physicians' PLT Requests in NBS

with

Move Request to Waiting area of all RBC HBB's Orders in NBS Centre

2) For the ***Report Orders***

Erase the second if

The separation comes in the crossmatching phase.

Mismatching of compatible alternatives

Simul8 – Object – workstation - Mismatch H1

FOR each Hospital

```
    FOR every entity it comes out of this Simulation workstation
        In Routing Out – On Work Complete Logic
         Signal VBA    "Mismatch H#"
    END FOR
END FOR
```

<u>VBA</u>

```
FOR each Hospital
IF Signal= "Mismatch H#"
CALL number of contents in the Storage area of RBC in HBB by blood group

    IF Attribute value “Blood Group” = Apos
        FOR the compatible to Apos blood groups of A negative, Opos AND Oneg
            IF there is stock in the Storage area of RBC in HBB
                READ Attribute value “Expiring after” of the oldest unit/first in the queue
            END IF
        END FOR
        IF Aneg is the oldest of the other compatible groups and there are more than 4
blood units of Aneg in the storage area of RCB in HBB
           ASSIGN the Apos Request to the oldest Aneg blood unit
       ELSE IF Opos is the oldest of the other compatible groups and there are more than 4
blood units of Aneg in the storage area of RCB in HBB
           ASSIGN the Apos Request to the oldest Opos blood unit
        ELSE
            ASSIGN the Apos Request to the oldest Oneg blood unit
        END IF

    ELSE IF Attribute value “Blood Group” = Aneg
        FOR the compatible to Bpos blood groups of Apos, Opos AND Oneg
            IF there is stock in the Storage area of RBC in HBB
                READ Attribute value “Expiring after” of the oldest unit/first in the queue
            END IF
        END FOR
        IF Oneg is the oldest of the other compatible groups and there are more than 4
blood units of Bneg in the storage area of RCB in HBB
           ASSIGN the Aneg Request to the oldest Oneg blood unit
```

ELSE IF Apos is the oldest of the other compatible groups and there are more than 4 blood units of Aneg in the storage area of RCB in HBB

ASSIGN the Aneg Request to the oldest Apos blood unit

ELSE

ASSIGN the Aneg Request to the oldest Opos blood unit

END IF

……………………………………..

Repeat process for the rest blood groups. Compatible blood groups are reported in the IF statements according to the popularity of the choice.

END IF

Report Mismatches in Excel worksheet "Shortages" If time > warm-up period (18 days)

PRINT Mismatched Request's blood group on Excel worksheet "Shortages"

INCREMENT Column

PRINT Compatible group given on Excel worksheet "Shortages"

INCREMENT row

END FOR

INCREMENT Column by 3 times the number of hospital -1

Age of blood on arrival in HBB. Report in Excel worksheet "Age" If time > warm-up period (18 days)

Simul8 – Object – workstation - Mismatch H1

FOR each Hospital

FOR every entity it comes out of the workstation "Triage" entering the HBB

In Routing Out – On Work Complete Logic

Signal VBA "Age H#"

END FOR

END FOR

VBA

FOR each Hospital

IF Signal= "Age H#"

SELECT 10% of these blood units randomly

READ Attribute value “Blood Group”

Move cursor to the blood group’s Column

PRINT Attribute value “Expiring after” in days

INCREMENT row

END IF

END FOR

INCREMENT Column by 9 times the number of hospital -1

Retaining basic information from Excel spreadsheets in cases of multiple runs. PRINTing main results from every consecutive run in the VBA intermediate window. Results can be READ after the end of all runs.

IF Simulation Time = End of Results Collection Period

FOR each hospital

In worksheet “Short H#” Select the first 8 Columns

Sort them by Blood group and then by date on ascending order

PRINT Sum of Shortages on VB Immediate Window

FOR each blood unit in Simul8 objects: “Transfuse”, “Expired”, “Transfuse PLT” and “Expired PLT”

READ Blood group

PRINT Blood group in odd number columns for each Simul8 object respectively on Excel worksheet “Returns H#”

READ Number of Crossmatches from Label “Returns

PRINT Number of Crossmatches in even number columns for each Simul8 object respectively on Excel worksheet “Returns H#”

INCREMENT Row

END FOR

END FOR

READ value of Total Deliveries from Worksheets “Order H#”

PRINT value of Total Deliveries on VB Immediate Window

READ value of Total Deliveries from Worksheets “Order H#”

PRINT Total Deliveries on VB Immediate Window

READ value of Non-Routine Deliveries from Worksheets “Order H#”

PRINT value of Non-Routine Deliveries on VB Immediate Window

READ value of Routine Deliveries from Worksheets "Order H#"
PRINT value of Routine Deliveries on VB Immediate Window

READ Average No. of Crossmatches per transfused RBC from Worksheets "Returns H#"
PRINT value of of Crossmatches per transfused RBC on VB Immediate Window

READ Average No. of Crossmatches per transfused RBC from Worksheets "Returns H#"
PRINT value of Crossmatches per expired RBC on VB Immediate Window

READ Average No. of Crossmatches per transfused PLT from Worksheets "Returns H#"
PRINT value of Crossmatches per transfused PLT on VB Immediate Window

READ Average No. of Crossmatches per expired PLT from Worksheets "Returns H#"
PRINT value of Crossmatches per transfused PLT on VB Immediate Window

READ value of increment row of Orders from VBA
PRINT value of increment row of Orders (number of ordered units) on VB Immediate Window
END IF

<u>Excel</u>

<u>Excel worksheet "Returns H#"</u>

Average No. of Crossmatches per transfused RBC = AVERAGE "Transfuse" (2nd Column)

Average No. of Crossmatches per expired RBC = AVERAGE "Expire" (4th Column)

Average No. of Crossmatches per transfused PLT = AVERAGE "Transfuse PLT" (8th Column)

Average No. of Crossmatches per expired PLT = AVERAGE "Expire PLT" (12th Column)

C: INPUTS OF SIMULATION MODELS

C.1 Simul8 Inputs for Validated Model

Parameters of the model which were used to imitate practices of an existing blood centre serving a real hospital. This model was used for validating the model against real data as presented in section 5.5

Table B.1 Distribution parameters of inputs which stay the same among all the simulation models

Parameters which stay the same in all hospitals and models	
Blood Groups Rates for Collections and RBC Requests	35% A+, 7% A-, 3% AB+, 1% AB-, 8% B+, 2% B-, 37% O+, 7% O-
Blood Groups Rates for Platelet Requests	38% A+, 6% A-, 0% AB+, 0% AB-, 4% B+, 1% B-, 41% O+, 10% O-
RBC Usage Rates	10% All units used, 10% Cancelled transfusions, 80% Over-ordering
Platelet Usage Rates	70% transfused, 29.2% returned, 0.8% out of hours
Urgency Rate of NOT in stock units	60% Non-Urgent, 40% Urgent
Platelets Reservation period	Before transfusion LogNormal (360, 120), Transfusion Normal (120, 30), After Transfusion difference between transfusion time and returns at 10.00 in the morning)

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	Working Hours (60,10)		LogNormal	4.1, 1.15
	Normal	Out of Hours (275,30)			
	Exponential	Sunday (540)			
Emergency RBC	Exponential	26000		LogNormal	10, 4
Irradiated RBC	Exponential	15000		LogNormal	4.1, 1.15
Rare RBC Groups	Exponential	18720		LogNormal	4.1, 1.15
Platelets	Exponential	1800		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	22
Industrial	Exponential	39
On site	Exponential	230

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	40	10	4	4	10	0	40	10	118

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	41	11	3	1	7	2	46	13	124
Maximum	64	17	4	2	11	3	72	20	193

Hospital order of RBC Issues	FIFO for arrivals & returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	55% Transfuse, 44.2% Return, 0.8% Out of Hours
RBCs Reservation period	Before transfusion LogNormal (1260, 720), Transfusion Normal~(120,30), After Transfusion LogNormal(720, 120) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelet Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 50% and 10% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(120,30), Ad-hoc/Emerg. LogNormal(40, 10)

C.2 Simul8 Inputs for Medium-sized Hospital Model

This appendix presents the parameters of the model which were used to imitate practices of a blood centre and a medium hypothetical hospital as illustrated in section 6.2.

Baseline Scenario for a Medium-sized Hospital

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	Working Hours (60,10)		LogNormal	4.2, 1.3
	Normal	Out of Hours (275,30)			
	Exponential	Sunday (540)			
Emergency RBC	Exponential	26000		LogNormal	10, 4
Irradiated RBC	Exponential	15000		LogNormal	4.2, 1.3
Rare RBC Groups	Exponential	18720		LogNormal	4.2, 1.3
Platelets	Exponential	1800		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	22
Industrial	Exponential	39
On site	Exponential	215

Hospital	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Stock	50	12	4	4	10	0	55	15	150

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	41	11	3	1	7	2	46	13	124
Maximum	64	17	4	2	11	3	72	20	193

Hospital order of RBC Issues	FIFO for arrivals & returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	50% Transfuse, 49.2% Return, 0.8% Out of Hours
RBCs Reservation period	Before transfusion LogNormal (1260, 720), Transfusion Normal(120,30), After Transfusion Fixed (900) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelet Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 50% and 15% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)

Best Scenario for a Medium-sized hospital

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	Working Hours (60,10)		LogNormal	3, 0.5
	Normal	Out of Hours (275,30)			
	Exponential	Sunday (540)			
Emergency RBC	Exponential	26000		LogNormal	10, 4
Irradiated RBC	Exponential	15000		LogNormal	3, 0.5
Rare RBC Groups	Exponential	18720		LogNormal	3, 0.5
Platelets	Exponential	1800		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	23.5
Industrial	Exponential	42
On site	Exponential	220

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	40	8	4	4	8	4	40	10	118

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	41	11	3	1	7	2	46	13	124
Maximum	64	17	4	2	11	3	72	20	193

Hospital order of RBC Issues	FIFO for arrivals & LIFO for returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	70% Transfuse, 29.2% Return, 0.8% Out of Hours
RBCs Reservation period	Before transfusion LogNormal (720, 360), Transfusion Normal(120,30), After Transfusion Fixed (600) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelets Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 30% and 10% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)
Routine Orders/Deliveries	Routine Order at 9.00 Scheduled delivery sets off at 14.00, Routine Order at 17.00 Scheduled Delivery sets off at 10.00 next day.

C.3 Simul8 Inputs for Small Hospital Model

This appendix presents the parameters of the model which were used to imitate practices of a blood centre and a small hypothetical hospital as illustrated in section 6.2.

<u>Baseline Scenario for a Small Hospital</u>

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	Exponential	490		LogNormal	4.2, 1.3
Emergency RBC	Exponential	50000		LogNormal	10, 4
Irradiated RBC	Exponential	45000		LogNormal	4.2, 1.3
Rare RBC Groups	Exponential	43200		LogNormal	4.2, 1.3
Platelets	Exponential	5600		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	70
Industrial	Exponential	100
On site	Exponential	500

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	18	5	0	0	4	0	20	5	52

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	16	4	1	0	3	1	18	5	48
Maximum	25	6	1	1	4	1	28	8	74

Hospital order of RBC Issues	FIFO for arrivals & returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	50% Transfuse, 49.2% Return, 0.8% Out of Hours
RBCs Reservation period	Before transfusion LogNormal (1260, 720), Transfusion Normal(120,30), After Transfusion Fixed (900) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelets Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 50% and 15% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)

Best Scenario for a Small Hospital

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	490		LogNormal	3, 0.5
	Normal				
	Exponential				
Emergency RBC	Exponential	50000		LogNormal	10, 4
Irradiated RBC	Exponential	45000		LogNormal	3, 0.5
Rare RBC Groups	Exponential	43200		LogNormal	3, 0.5
Platelets	Exponential	5600		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	70
Industrial	Exponential	100
On site	Exponential	500

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	15	4	4	4	4	4	15	5	55

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	41	11	3	1	7	2	46	13	124
Maximum	64	17	4	2	11	3	72	20	193

Hospital order of RBC Issues	FIFO for arrivals & LIFO for returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-	70% Transfuse, 29.2% Return, 0.8% Out of Hours

ordering Usage rate	
RBCs Reservation period	Before transfusion LogNormal (720, 360), Transfusion Normal(120,30), After Transfusion Fixed (600) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelets Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 30% and 10% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)

C.4 Simul8 Inputs for Big Hospital Model

This appendix presents the parameters of the model which were used to imitate practices of a blood centre and a big hypothetical hospital as illustrated in section 6.4.

Baseline Scenario for a Big Hospital

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	Working Hours (32,5)		LogNormal	4.2, 1.3
	Normal	Out of Hours (150, 20)			
	Exponential	Sunday (540)			
Emergency RBC	Exponential	18720		LogNormal	10, 4
Irradiated RBC	Exponential	8500		LogNormal	4.2, 1.3
Rare RBC Groups	Exponential	18720		LogNormal	4.2, 1.3
Platelets	Exponential	1000		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	12
Industrial	Exponential	22
On site	Exponential	120

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	95	20	8	8	18	4	105	30	284

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	95	25	8	8	15	4	100	30	285
Maximum	147	38	9	4	26	8	165	46	441

Hospital order of RBC Issues	FIFO for arrivals & returning units

Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	50% Transfuse, 49.2% Return, 0.8% Out of Hours
RBCs Reservation period	Before transfusion LogNormal (1260, 720), Transfusion Normal(120,30), After Transfusion Fixed (900) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelets Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 50% and 15% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)

Best Scenario for a Big Hospital

Requests	Request per patient Distribution	Parameters (Inter-arrival time in minutes)		Request's Size Distribution	Parameters (in blood units)
Normal RBC	LogNormal	Working Hours (32,5)		LogNormal	3, 0.5
	Normal	Out of Hours (150, 20)			
	Exponential	Sunday (540)			
Emergency RBC	Exponential	18720		LogNormal	10, 4
Irradiated RBC	Exponential	8500		LogNormal	3, 0.5
Rare RBC Groups	Exponential	18720		LogNormal	3, 0.5
Platelets	Exponential	1000		LogNormal	1.3, 0.5

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	12
Industrial	Exponential	22
On site	Exponential	120

Hospital Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
	95	18	8	4	15	4	105	20	269

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	95	25	8	8	15	4	100	30	285
Maximum	147	38	9	4	26	8	165	46	441

Hospital order of RBC Issues	FIFO for arrivals & LIFO for returning units
Hospital order of Platelet Issues	FIFO for arrivals & LIFO for returning units
Over-ordering Usage rate	70% Transfuse, 29.2% Return, 0.8% Out of Hours

RBCs Reservation period	Before transfusion LogNormal (720, 360), Transfusion Normal(120,30), After Transfusion Fixed (600) plus the difference between the end of this period and the returns at 10.00 in the morning)
Platelets Reservation period	Before transfusion LogNormal (720, 260), Transfusion Normal(120,30), After Transfusion Fixed (500)
Re-ordering stock point	80%, 30% and 10% of ideal RBC stock for routine, ad-hoc and emergency orders respectively
Distribution Time	Routine LogNormal(130,30), Ad-hoc/Emerg. LogNormal(60, 10)
Routine Orders/Deliveries	Routine Order at 9.00 Scheduled divery at sets off at 14.00, Routine Order at 17.00 Scheduled Delivery sets off at 10.00 next day.

C.5 Simul8 Inputs for Three Hospitals Model

This appendix presents the parameters of the model which were used to imitate practices of a blood centre and three hypothetical hospitals the first of medium size, the second of big-volume blood usage and the third of small-volume. The inputs which are not presented here are the same as shown in appendices B2, B3 and B4 for the corresponding size of hospital.

Baseline Scenario for three Hospitals

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	6.1
Industrial	Exponential	11
On site	Exponential	75

Centre Stock	Apos	Aneg	ABpos	ABneg	Bpos	Bneg	Opos	Oneg	Total
Normal	148	38	9	4	26	8	166	46	444
Maximum	229	60	14	6	40	12	258	72	689

Delivery Type	Distribution Times
Routine	On the way to hospitals: LogNormal(40,10), Returning from hospital: LogNormal(60, 10) Mid-day collections pick-ups: Triangular Distribution(15, 170, 50)
Ad-hoc/Emergency	On the way to hospital: LogNormal(60, 10), Returning from hospital: LogNormal(50, 10)

Best Scenario for three Hospitals

Collections	Distribution	Parameters (Inter-arrival time in minutes)
Public	Exponential	6.7
Industrial	Exponential	13
On site	Exponential	80

D: INTERFACE OF SIMULATION MODELS

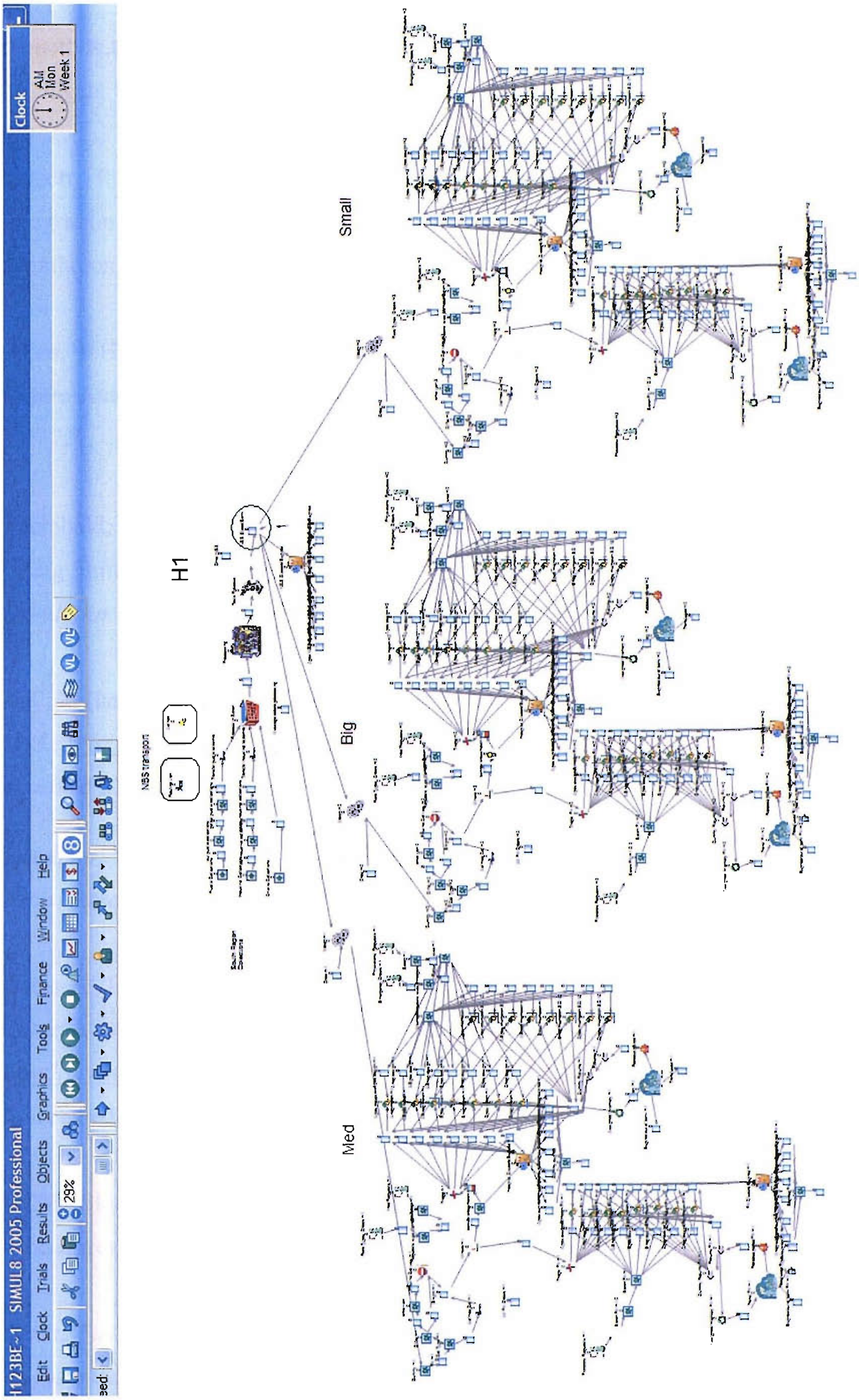

Figure D.1 A snapshot of the simulation model with one centre – three hospitals

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