Sheffield Hallam University

A Sheffield Hallam University thesis
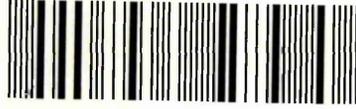
Fines are charged at 50p per hour

ProQuest Number: 10694136

ProQuest 10694136

A Study of Inventory Classification in Healthcare Logistics Using System Dynamics Modelling

Lina Khalil Al-Qatawneh

A thesis submitted in partial fulfilment of the requirements of

Sheffield Hallam University

for the degree of Doctor of Philosophy

May 2006

Abstract

One of the key challenges for a modern day health care provider is to dispense high quality of medical care while limiting or even reducing the health care expenditures. This research work endeavours to meet this challenge through effective management of hospitals logistics systems. The aim of this research work is to provide a structured mechanism for modelling and analysing health care logistics to be able to understand its dynamic behaviour and effectively manage its logistical activities on the basis of the model. In order to achieve the research objectives, this research uses system dynamics as the main medium of analysis, and in particular, employs an integrated system dynamics framework which has been used previously for manufacturing industry supply chain designs and tests the feasibility of the framework for analysing and modelling health care logistics. This is ascertained by developing and incorporating a decision making metrics in the system dynamics model based on item criticality, usage, and value to optimise overall logistics costs.

System Dynamics methodology is employed at first to develop a model for existing inventory control decisions, and subsequently to produce two alternative approaches based on traditional (R, s, S) inventory control approach and Continuous Replenishment Inventory and Order Based Production Control CR(IOBPCS) approach. These approaches are tested for two case hospitals, namely: Children's National Medical Center (CNMC) USA, and Derbyshire Royal Infirmary (DRI) UK. The dynamic analysis for each case revealed problems in terms of multistage inventories and order batching, which could lead to demand amplification causing a detrimental effect on the inventory management throughout the supply chain. Accordingly, the simulations results produced for the two cases are benchmarked using alternative strategies in terms of lower inventory cost, and robustness to meet the unpredictable demand arising from a large number of items.

Overall, this research work has enhanced the understanding of hospitals logistics systems by building qualitative and quantitative models. More specifically, this research work has illustrated the applicability of the integrated system dynamics framework in analysing and modelling hospitals logistics systems and inventory control decisions. One particular contribution of this study is introducing inventory classification based on the criticality of items for patient needs which is more suited for health care situations rather purely cost based policies prevalent in other manufacturing and service chains. Therefore, this work has rigorously tested a multi-criteria based inventory classification method that takes into account the criticality of use, cost, and usage value of items for optimising overall inventory cost while maintaining the required patient care/service level. Future studies may be conducted to further evaluate the trade-offs in between different logistics decision making (such as, inventory control, service level, purchasing, transportation and warehousing) in order to design a set of "best practice" simulation models to optimise the overall dynamic behaviour for health care supply chains.

I

Acknowledgements

In carrying out this study, I have received considerable help from several individuals and organisations to whom I extend my thanks. First, I would like to acknowledge the considerable help, advice and guidance I have received during my study for this degree from my supervisory team: Dr. Khalid Hafeez, Dr. Ian Morrey, Dr. Mike Hubbard, and Dr. Zain Tahboub. A special acknowledgement and thank you to Dr. Khalid Hafeez, whose knowledge, suggestions, guidance and constructive advice have provided much insight.

I would like to thank Mr. Tony Kamillo (Supplies Manager at Derbyshire Royal Infirmary) and Mr. Leland Kuhn (Materials Management Director at Children's National Medical Center) for their help, cooperation and valuable data used in conducting the two case studies in this thesis. Also, I would like to thank all members of Sheffield Hallam University for providing me with the databases, resources and facilities needed to finish this thesis.

My family and friends deserve my uttermost gratitude and appreciation. First, I would like to thank my mother and father for their love and care all these years. Secondly, I would like to thank my mother and father in law as well as my sister in law for their support and taking care of my children when I was away. Finally, and most importantly, my deepest appreciation to my beloved husband Mustafa and my three wonderful sons Yousef, Ahmad and Ibraheem for their continuing love, encouragement, and support in completing this thesis. It is to them that I rightly dedicate this thesis.

Table of Contents

List of Figures

Appendices

List of Tables

Appendices

Chapter One: Introduction

1.1 The Research Issues

This research work investigates the issue of logistics management in health care and how to effectively manage hospitals logistics systems as an attempt to contain cost without sacrificing the quality of health care. This research work argues that an effective management of hospitals logistics systems should be based on a clear understanding of the interconnectivity in between logistical activities in a hospital logistics system and which demands trade-offs considerations between various logistical decisions. This research work argues that this understanding is achieved through modelling hospitals logistics systems and analysing their dynamic behaviour. In addition, this research work argues that an effective management of hospital logistics addresses the conflicting objectives of minimizing logistics-related cost while simultaneously reducing the incidence of stockouts, especially for critical items. Therefore, this research work focuses in the assessment of the dynamic behaviour of health care logistics on two main variables: logistics cost and service level. Furthermore, this research work investigates a number of strategies to improve the dynamic behaviour of hospitals logistics systems in terms of performance and cost. As part of this investigation, this research work assesses the role of inventory classification when incorporated into the redesigning strategies of health care logistics. This research work argues that a distinctive feature of health care logistics is the criticality of items used by hospitals and the life threatening situations that could happen due to the unavailability of these items. Therefore, this research work studies the impact of using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items on logistics cost reduction.

The remaining of this chapter is organised as follows. Section 1.2 presents a brief background concerning the issues that are raised in this research work and the context of this research. Section 1.3 discusses the overall aims and objectives of this research work. The research questions are given in section 1.4. Finally, section 1.5 gives an overview of the structure of this thesis and section 1.6 summarises this chapter.

1.2 The Research Background and Context

Offering health care and developing health services are fundamental national duties. Most of the population in the developed countries are covered against medical cost by one of the following three models: National Health Service (NHS), Social Insurance (SI), and Private Insurance (PI). Irrespective of the economic and health care structure, a major concern with health care is its growing cost. The latest OECD Health data (2005) shows that the highest health care spending as a percent of gross domestic product (GDP) between the thirty OECD countries amounts 15 % in the United States followed by 11.5 % in Switzerland, 11.1 % in Germany, 10.5 % in Iceland, 10.3 % in Norway, and 10.1 % in France. This rise in the health care expenditure may be attributed to factors including population aging, population increase, widening range of treatment available, level of technology used, and intensive labour requirements (Docteur and Oxley, 2003; Mehrotra *et al.*, 2003). Therefore, providing a high quality of medical care at a reduced cost has become a top priority for many governments in the world.

Although personnel, nursing and physician pay is the single largest expense in any hospital, costs related to inventory, logistics, and administration processes are nevertheless significant and are steadily rising. In some cases, it is estimated that approximately 30-40 % of hospital spending is invested in various logistical activities (Sheyer, 1995; Poulin, 2003). Logistic related costs are often ignored whenever governments or other organizations examine the economics of health care service delivery. Rather than introducing efficiencies in logistics and supply processes, health care service providers usually look at cutting suppliers' margins or reducing the price of standard medical products whenever faced with budget cuts.

In recent years, the health care industry began to realise that health care strategies should be directed toward identifying the logistics solutions that will lead to increase in overall customer service levels and reductions in total health care cost. Therefore, more interest should be directed to investigating logistics in health care.

Although, there is an established work in the literature that has provided insights concerning health care logistics, the focus of these studies was directed toward qualitative process improvements. There are few studies that have quantitatively analysed problems associated with logistical activities within the context of health care, and most of which have focused on only one particular logistical activity, mainly inventory control. Therefore, one can argue that considering the effect of the interrelated decisions that are applied for managing the logistics system within the context of health care and understanding the dynamic nature of health care logistics to aid in the whole logistics system design are still to be explored. In this research work, the modelling and analysis of health care logistics are expected to be more useful to this context. Since the health care industry started to realise the important role logistics management can play to contain cost without sacrificing the quality of health care, the assessment of the dynamic behaviour of health care logistics in terms of performance and cost increases the importance of this research work to this context.

Moreover, the distinctive feature of health care logistics concerning the criticality of items and the life threatening situations that could happen due to the unavailability of these items may require different redesigning strategies than those used to improve the dynamic behaviour of other industries logistics systems. Therefore, investigating redesigning strategies that takes into consideration the criticality of items adds to the importance of this research work to this context.

1.3 Aims and Objectives

The overall aim of this research work is to understand the dynamic behaviour of health care logistics systems to effectively manage their logistical activities. Among the objectives of this research work is first to provide a structured mechanism for modelling and analysing health care logistics to be able to understand its dynamic behaviour and effectively manage its logistical activities on the basis of the model. The second objective of this research work is the application of modelling system dynamics for health care logistics that incorporates service and cost dimensions. This research work will focus in the assessment of the dynamic behaviour of health care logistics on two main variables: logistics cost and service level. The third objective is redesigning health care logistics to improve its dynamic behaviour in terms of performance and cost,

taking into consideration the distinctive feature of health care logistics concerning the criticality of items. The attainment of these objectives will enable the achievement of the overall aim of this research work.

1.4 Research Questions

From the literature review, it was apparent that there is a gap in understanding the dynamic nature of health care logistics systems as a comprehensive whole and in considering the effect of the interrelated decisions that are applied for managing logistics systems in health care, which formed the overall aim of this research work and its main question. To enable the achievement of this aim, the following research questions were developed based on a comprehensive and critical review of the available literature:

- Is the integrated system dynamics framework for supply chain design applicable in the health care industry?

- Does the integrated system dynamics framework provide a structured mechanism for analysing and modelling health care logistics systems and their dynamic behaviour?

- Does the analysis and evaluation of the effects of the different logistics decisions on the dynamic behaviour of health care logistics reveal any problematic behaviour?

- How to quantify in terms of cost the relative improvements of redesign strategies in health care logistics?

- What is the role of inventory classification when incorporated into the redesigning strategies of health care logistics?

- What is the impact of using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items on logistics cost reduction?

1.5 Structure of the Thesis

The rest of the thesis is organised in four chapters. The main aim of Chapter Two is to review the available literature to identify existing gaps in the body of knowledge developed during previous work and then to develop, based on these gaps, the research questions that specify exactly what is going to be investigated in this research work.

The main aim of Chapter Three is to explain how to develop conceptual and quantitative models of hospitals logistics systems using System Dynamics methodology. This chapter first explains the development of a general conceptual model of a hospital logistics system. Then, this chapter describes the conceptual model development, simulation model development and dynamic analysis of two specific hospital logistics systems: one using a traditional (R, s, S) inventory control approach and the other using continuous replenishment (CR).

The main aim of Chapter Four is to answer the research questions through conducting two case studies. This chapter begins by discussing the research methods. This is followed by demonstrating the implementation of the various stages of an integrated system dynamics framework proposed to be used for logistics system redesign of two case hospitals: Children's National Medical Center (CNMC) in the United States of America (USA), and Derbyshire Royal Infirmary (DRI) in the United Kingdom (UK). This chapter concludes with a discussion of how, through conducting the two case studies in this chapter, this author answered the research questions that were developed in Chapter Two.

The main aim of Chapter Five is to identify the main contribution of this research work to the body of knowledge. This chapter also evaluates the research methodology and highlights the main limitations of this research work. The chapter ends by giving suggestions for future research.

1.6 Summary

This chapter began by discussing the issues that are raised and investigated in this research work. This was followed by presenting a brief background concerning these issues and the context of this research work. This chapter then provided the overall aim and objectives of this research work as well as the research questions. This chapter concluded by giving an organisation structure for the rest of the thesis.

Chapter Two: Literature Review

2.1 Introduction

This chapter first gives an overview of the relevant literature on logistics and supply chain management and then –more specifically- on health care logistics to identify its main characteristics and features and what is distinctive about it. This chapter then provides a comprehensive and critical review of the available literature on modelling health care logistics to identify existing gaps that will provide an overall aim for this research work. This is followed by a critical review of the different modelling techniques that have been used to analyse problems associated with logistical activities to choose the appropriate approach that is useful for solving the main question of this research work. A brief discussion of the chosen approach is then provided, followed by a critical review of the literature on the role of using this approach in the field of logistics management. The research questions that specify exactly what is going to be investigated in this research work are developed in this chapter based on the identified gaps in the literature.

2.2 Logistics and Supply Chain Management

The term supply chain management (SCM) was originally introduced in the early 1980's (Oliver and Webber, 1992), and since then it has received ever-growing interest both from academics and practitioners. Several definitions of SCM have been offered in the literature. For example, Stevens (1989) describes a supply chain as a system whose constituent parts include material suppliers, production facilities, distribution services, and customers linked together via the feed forward flow of materials and the feedback flow of information as shown in Figure 2.1. According to Stevens (1990) SCM controls the flow of material from suppliers, through the value adding processes and distribution channels, to customers.

Material flow

Information flow
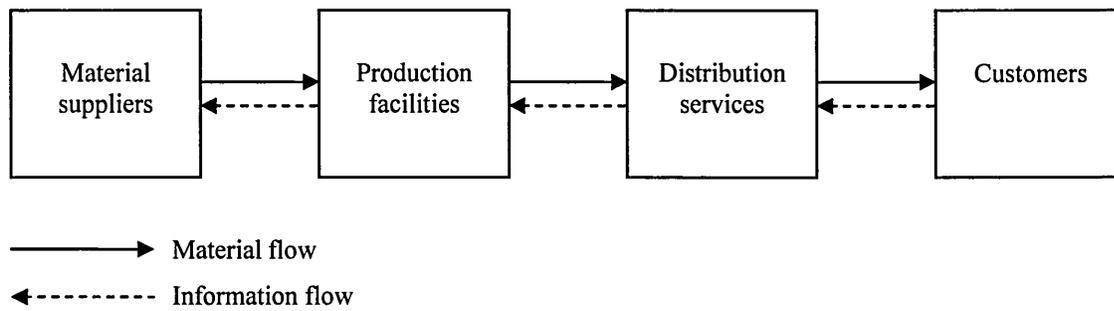
Figure 2.1: A typical supply chain

Over the last two decades, a number of related fields have contributed to the explosion of SCM literature (Chen and Paulraj, 2004) such as purchasing and supply, logistics and transportation, operations management, marketing, organizational theory, management information systems, and strategic management. Bechtel and Jayaram (1997) and Otto and Kotzab (2003) provided an extensive retrospective review of the literature and research on SCM. According to Gunasekaran (2004), there is a gap that exists between practice and theory, which needs to be addressed with a view to enhancing the application of SCM in real life environments and through further theoretical developments in the field. He argues that there are only a limited number of models and application frameworks that are available in the literature to give a comprehensive analysis of an integrated SCM system.

According to Lambert (2004) there is a great deal of confusion regarding exactly what supply chain management involves and that many use supply chain management as a synonym for logistics. In order to develop a common view of the field, the Global Supply Chain Forum was established. The forum is a group of non-competing firms and academic researchers who, working together, developed the following definition of SCM:

> *Supply Chain Management is the integration of key business processes from end user through original suppliers that provides products, services, and information that add value for customers and other stakeholders.*

In October 1998, the Council of Logistics Management (CLM) has announced a modified definition of logistics based on the understanding of SCM that has been re-conceptualised from integrating logistics across the supply chain to integrating and managing key business processes across the supply chain. The CLM defines logistics as:

> *Logistics is that part of the supply chain process that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from the point-of-origin to the point-of-consumption in order to meet customers' requirements.*

This author agrees with the above distinction between logistics and SCM, and considers that SCM embraces all business processes –not just logistics- cutting across all organisations within the supply chain. From that understanding, in this research work, this author will focus on logistics as part of SCM, specifically, on analysing and managing hospitals logistics systems.

Each echelon in the supply chain has its own logistics system. Each logistics system is associated with its own logistics activities. A comprehensive list of these activities is provided by Coyle *et al.* (1996) as shown in Table 2.1. However, each echelon may not place responsibility for all of these activities within their logistics system. For example, this research, with case studies included in the thesis, suggests that hospitals usually do not include production planning in their logistics systems. However, production planning is one of the main logistics activities for product manufacturers.

Table 2.1: Logistics activities

• Traffic and Transportation	• Production planning
• Warehouse and storage	• Purchasing
• Industrial packaging	• Customer service levels
• Materials handling	• Plant and warehouse site location
• Inventory control	• Return goods handling
• Order fulfilment	• Parts and service support
• Demand forecasting	• Salvage and scrap disposal

Source: Coyle *et al.* (1996)

Each of the indicated logistics activities demands some kind of decision making. For example, decisions related to warehousing (Ballou, 1992; Bowersox and Closs, 1996) include: how many warehouses, where to locate the warehouse, what size the warehouse should be, and so on. Such decision making has pros and cons. For example, a faster transport system would permit the holding of lower inventories and use less warehousing space. Also, the interconnectivity in between logistics systems demands that the decision maker evaluates various economic trade-offs. For example, adding a warehouse means adding related fixed and variable costs. However, this may reduce the overall transportation cost.

Logistics also has important relationships with other operational systems such as: manufacturing, marketing, finance, and other key business processes. In the case of marketing, logistics must ensure that the customers requirements as identified by the marketing system are available when and where desired by customers. Similarly, with regards to manufacturing, a long production run means more products, therefore requiring larger warehouse space to maintain a high level of inventory.

In summary, in any supply chain, interrelationships exist between:

- Different echelons within the supply chain.
- Sub-systems in each echelon.
- Different logistics activities.

Therefore, to optimize costs in supply chains, the following optimisation and trade-offs need to be considered:

a) the cost of each logistics activity individually; and/or
b) the trade-off between various logistics activities; and/or
c) the trade-off between sub-systems; and/or
d) the trade-off between different echelons in a supply chain.

In practice, these trade-offs are driven by the overall supply chain as well as business strategy. Therefore, this author would like to define supply chain management (SCM) as follows:

Supply chain management is about managing and coordinating all trade-off relationships that could exist in a supply chain in a way that optimises the overall supply chain cost while maintaining a high customer service level.

2.3 Health Care Logistics

The research in this thesis represents the view that a typical health care supply chain consists of three echelons: health care provider, distributor, and product manufacturer, which are linked together via information, material, and cash flows as shown in Figure 2.2. Information and cash would flow in both directions, whereas, materials would usually flow in one direction –except in the case of reverse logistics[1]. As shown in Figure 2.2, the health care provider orders its supplies –medical and non-medical products- either directly from product manufacturers, or from distributors who in turn order their supplies from product manufacturers.
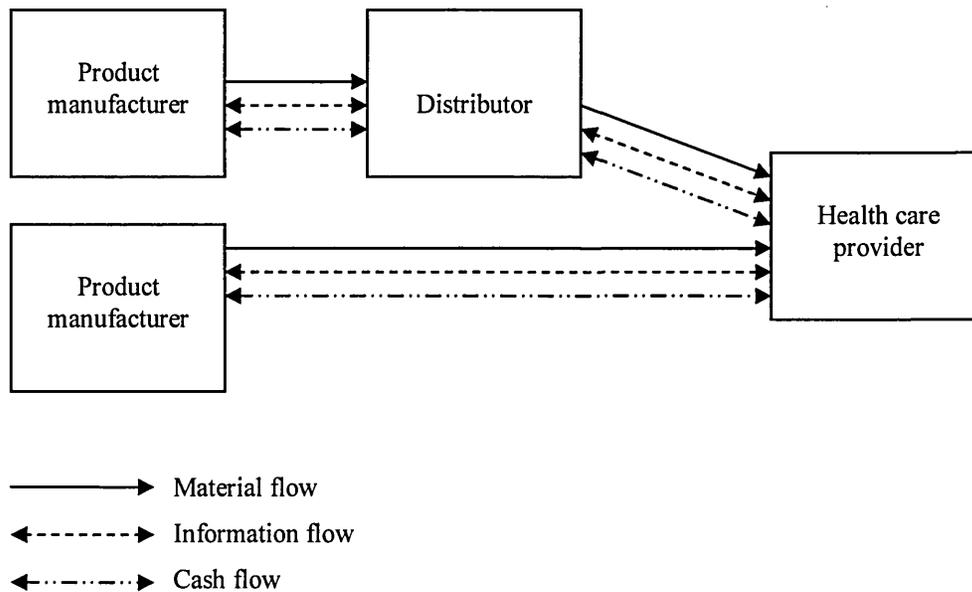
Figure 2.2: A typical health care supply chain

---

[1] The concept of reverse logistics in health care is concerned with the recycling of pharmaceutical stock for later re-use (Ritchie *et al.*, 2000). Reverse logistics will not be included in the scope of this research work.

Based on the literature review of logistics systems that is discussed briefly in section 2.2, a holistic view of a health care supply chain was drawn as illustrated in Figure 2.3, showing interrelationships between different echelons within the supply chain, sub-systems in each echelon, and different logistics activities.

A literature review of health care supply chains revealed that they are complex supply chains due to the wide product range, the criticality of and the perceived need to supply very high level of services for most items, and the high value of products involved (Beier, 1995). The wide variability in product ranges is often the result of too much differentiation among the available products. This usually tends to occur due to the subjective decision making of persons involved (e.g. physicians who have significant technical knowledge of what the products are supposed to do) (Neumann, 2003). In many industries, fluctuations in demand can be linked to specific factors that can be controlled to some extent. However, health care organisations have very little control over the demand for supplies (Smith, 1999). In this author's view, this is due to the fact that the health care industry is unique in terms of the large volume of diverse support services required to deliver the end product which is patient care.

Like its counterparts, the health care industry is beginning to look into effective supply chain management (SCM) as an answer to its quest for reducing costs. Hospitals are taking advantage of the latest tools available on the market including: implementation of the Universal Product Number (UPN) (DeJohn, 1997), bar coding (Moynihan, 1998), automated data capture and electronic data interchange (EDI) (Moynihan, 1997).

There have been some global initiatives to enhance the benefits of SCM, for example, Efficient Healthcare Consumer Response (EHCR). In 1996, the EHCR initiative was launched by a consortium of health care industry associations and health care supply chain participants in response to intensifying pressure to reduce health care costs while enhancing the quality and efficiency of care (CSC, 1996). The goal of EHCR is to streamline the health care products supply chain by improving efficiency and eliminating waste at every step of the chain. EHCR has three foundation strategies that are based upon: efficient product movement, efficient order management and efficient information sharing. The key enablers of these strategies are product identification through bar coding, continuous replenishment, and activity based costing.
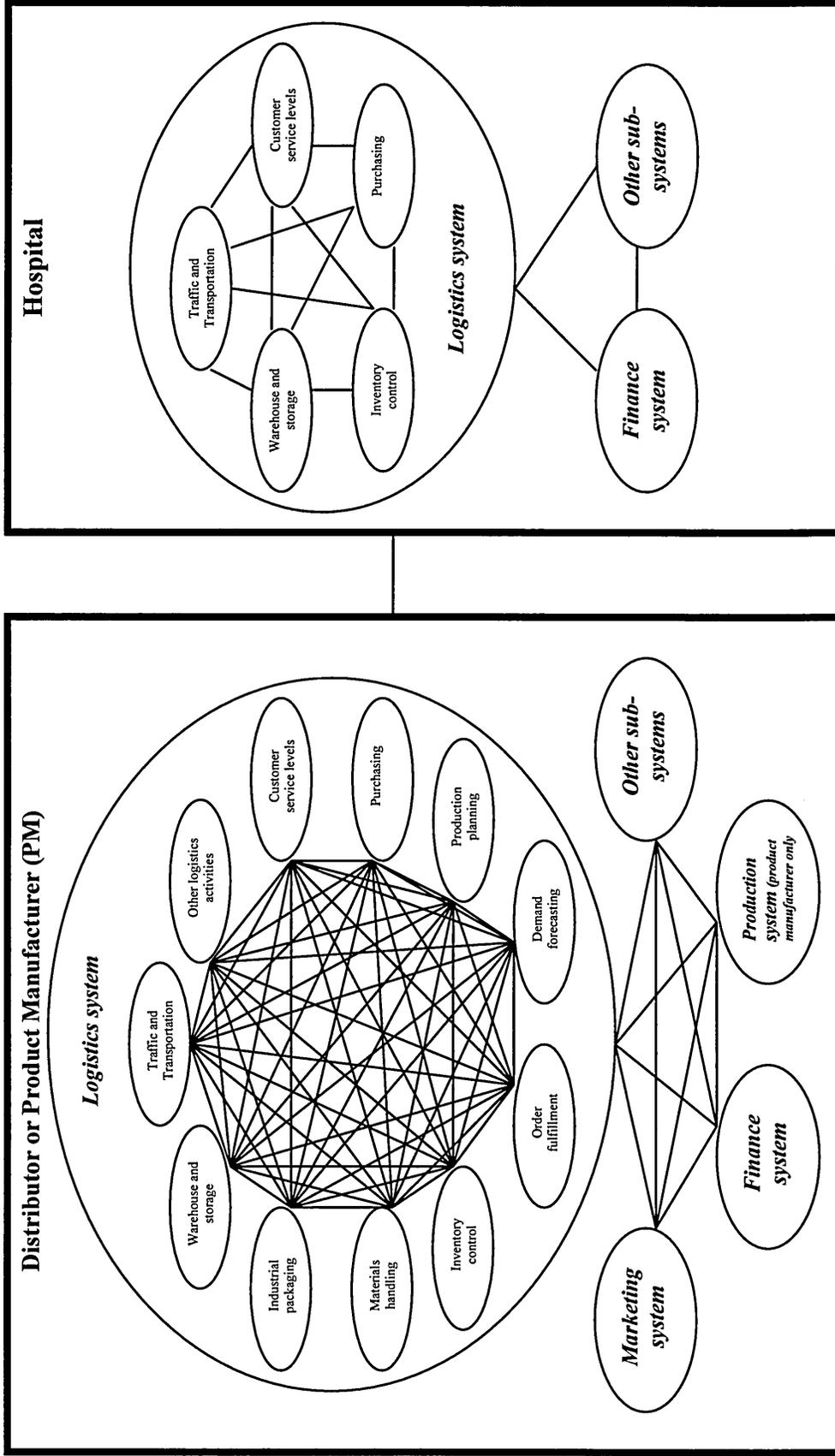
Figure 2.3: The overall interfaces and interrelationships in a health care supply chain

13

In health care, usually the management of logistics activities within hospitals is discussed under the broad heading of materials management. One of the classical definitions of materials management in hospitals comes from Arnold Reisman (1981, p432) who defines it as:

> *A term used to describe the grouping of management functions related to the complete cycle of material flow, from the requisitioning, purchase, and internal control of materials; to the planning and control of work in process; to the warehousing, shipping, distribution, and / or disposal after use of a product.*

The logistics department – also named as the materials management department or the supply department – is the focal point of a hospital's logistics activities. It has direct responsibility for managing the functions of purchasing, inventory control, warehousing, and transportation (Henning, 1986; Scheyer, 1995; Poulin, 2003).

In recent years, health care strategies are directed toward identifying the logistics solutions that will lead to increases in overall customer service levels and reductions in total health care cost. This led to the application of time-based logistics strategies including: just-in-time (JIT) (North, 1994; Heinbuch, 1995; Whitson, 1997), stockless inventory (Wilson *et al.*, 1992; Rivard-Royer *et al.*, 2002), vendor-managed inventory (Haavik, 2000), third-party logistics (Kontzer, 2003), time-phased order points (Spedding, 1998), reverse logistics (Ritchie *et al.*, 2000), and efficient healthcare consumer response (EHCR) (CSC, 1996). All of these time-based logistics strategies which Kotzab (1999) refers to as IT-driven logistics strategies employing EDI, barcode and scanning technology are pursuing the following objectives (La Londe and Masters, 1994; Aptel and Pourjalali, 2001):

a) Reduction of cycle time.
b) Reduction of inventories.
c) Avoiding duplications of logistics costs.
d) Increasing customer service.

In this author's view, in a hospital setting, these objectives lead to conflicts within concerned parties. Health providers (e.g. physicians, nurses, and laboratory technicians) are generally quite intolerant of shortages or stockouts, however, they are relatively less

sensitive to costs. Whereas, hospital administrators are concerned with decreasing the total cost, while increasing hospital service level.

There are a variety of ways by which hospital service level is measured (Morey *et al.*, 1994; Huarng and Lee, 1996; Pina and Torres, 1996; Mittler, 1998). These measures are a reflection of how hospitals insure for each patient the availability of:

a) Excellent medical and nursing staff.
b) High standard medical technology.
c) Short queues and waiting time.
d) High hotel services.
e) Availability of medical and non-medical products.

This research work is concerned exclusively with the availability of medical and non-medical products. However, there are implied benefits of this associated with short queues and waiting time and high hotel services.

Based on the literature review, the following points summarise the main characteristics and features of health care logistics:

I.   Hospitals generally think of their offerings as services rather than products. The core service is inpatient care.

II. Hospitals when providing their main product – inpatient care – need tangible medical and non-medical products.

III. Hospitals maintain a large number of different products. This wide variability of product types is caused by the diverse health services the hospital offers to patients and the role of physicians in choosing these products.

IV. The large diversity of patients' needs, combined with the physicians' preferences of the way to treat their patients makes the demand for products unpredictable and uncontrollable.

V. In hospitals, products are ranged between high-critical to low-critical item. High-critical items are either essential for the work carried out and/or have no immediate alternative. While, medium-critical items are important for the work, but may have acceptable alternatives, or other sizes may be used in the event of stock-out. Low-critical items are unlikely to affect the well being of patients other than causing minor inconvenience.

VI. The unavailability of critical items could lead to life threatening situations.

VII. Although critical items constitute a small number of items, the majority of the total inventory investment is in critical items (around 60%) (Nicholson *et al.*, 2004). This is because critical items are usually extremely expensive, have a short shelf-life, and/or require expensive storage facilities on site.

Other industries logistics systems may have the same above characteristics and features of health care logistics, except for one. The criticality of certain items used by hospitals and the life threatening situations that could happen due to the unavailability of these items is a distinctive feature of health care logistics. This feature is what makes health care logistics distinct and different from other industries logistics systems. Therefore, this feature will be one of the main concerns of this research work when modelling and analysing health care logistics systems.

2.4 Modelling Health Care Logistics

Most of the research in the health care industry has been directed toward qualitative process improvements (Jarrett, 1998). There are only a few examples that quantitatively analyse problems associated with logistical activities in health care. Kapur and Moberg (1987) modified a traditional EOQ model, to manipulate yearly inventory turns and generate optimal space requirements for the stores operations at Georgetown University Hospital. The advantage of the results of their study is that a material management system can be configured for acceptable yearly turns such that space requirements can be reduced.

Beier (1995), applied an economic order quantity (EOQ) analysis to questionnaire data in order to draw a comparison with current inventory management practices in hospital pharmacies. The results of the comparison suggest that the average pharmacy has the potential for savings in inventory related costs. However, Beier assumes too much homogeneity in the inventory items analysed. The application of an EOQ model over a broad spectrum of inventory items can be questioned.

Dellaert and Poel (1996), suggested an inventory control model by extending an EOQ model to a so-called (R,s,c,S) model, in which the values of the control parameters s, c, and S are determined in a very intuitive way. They compared various cost components and service levels through a simulation study. The comparison showed a decrease in the cost in combination with an increase in the service rate for the proposed new rule. They also showed that the performance of the new rule was comparable to that of a rule in which the control parameters were determined in a more sophisticated way.

Banerjea-Brodeur *et al.* (1998) presented an application of a routing model. Their study aimed at improving the linen delivery operations in a hospital by reassessing the quantities of linen to be delivered and by redesigning the delivery schedule using a tabu search heuristic algorithm.

In a more recent study, Nicholson *et al.* (2004) have compared inventory policies, inventory costs, and service levels in an in-house three-echelon distribution network vs. an outsourced two-echelon distribution network for non-critical inventory items. They have found that the recent trend of outsourcing to distribute non-critical medical supplies directly to the hospital departments using the two-echelon network resulted not only in inventory cost savings but also did not compromise the quality of care as reflected in the service levels.

Most of the studies mentioned above focused on only one particular logistical activity - inventory control. They addressed some specific scenarios of inventory policies, but failed to consider explicit interrelations among the hospital logistical activities in an overall supply chain context. Answers to all questions related to the planning and control of all logistical activities in a hospital logistics system can not be provided by inventory control models alone. The interconnectivity in between logistical activities in a hospital logistics system –as explained in section 2.2 and section 2.3 – demands that

the decision maker considers the trade-offs between various logistical activities. Therefore, focusing on only one particular logistical activity is too restrictive to be very useful in understanding the dynamic nature of health care logistics which will help in giving a comprehensive treatment to the entire health care logistics system. The literature review of modelling health care logistics showed that there is a gap in understanding the dynamic nature of health care logistics systems as a comprehensive whole and in considering the effect of the interrelated decisions that are applied for managing logistics systems in health care. This gap has directed the focus of this research work towards analysing and modelling health care logistics to be able to understand its dynamic behaviour and effectively manage its logistical activities on the basis of the model. The main question of this research work is:

How can an understanding of the dynamic behaviour of hospitals logistics systems through modelling and analysis help hospitals to effectively manage their logistical activities?

There is an agreement in the literature that an effective management of hospital logistics addresses the conflicting objectives of minimizing logistics-related cost while simultaneously reducing the incidence of stock-outs, especially for critical items. In health care, as explained in section 2.3, the availability of medical and non-medical products is a measure of hospital service level. Therefore, one of the objectives of this research work is the application of modelling system dynamics for health care logistics that incorporates service and cost dimensions. This research work will focus in the assessment of the dynamic behaviour of health care logistics on two main variables: logistics cost and service level.

2.5 Quantitative Techniques Used to Analyse Problems Associated with Logistical Activities

Logistics – not specifically for health care – and issues associated with logistical activities have received great attention in the literature. The areas of logistics receiving attention by researchers can be classified as warehousing and facility location, inventory control, transportation/routing and scheduling, demand forecasting, production

planning, and logistics systems design. The last of these classifications, which is an organised attempt to consider the previously mentioned classifications as a comprehensive whole, is most relevant to the main objective of this research work. The following is a brief discussion of some examples from the literature for the most popular quantitative techniques that have been used to analyse problems associated with logistical activities, including: optimisation models, queuing models, simulation models, and heuristic models.

- **Optimisation models:** The Concise Oxford Dictionary of Mathematics defines optimisation as:

  "The process of finding the best possible solution to a problem. In mathematics this often consists of maximizing or minimizing the value of a certain function, perhaps subject to given constraints."

The optimisation models in use today incorporate such techniques as mathematical programming (linear, integer, dynamic, mixed-integer linear, etc.), enumeration, sequencing, and the use of calculus (Ballou, 1992). In logistics, optimisation techniques have been applied to problems associated with facility location, inventory control, routing, scheduling, and supplier selection. Some examples from literature are: Ahn *et al.* (1994) formulated a mathematical model to minimize the sum of inventory holding costs at the depot and the inventory and transportation costs in the parts manufacturer on JIT production systems, Speranza and Ukovich (1994) developed some optimisation models for the minimization of transportation and inventory costs on single links of logistics networks, Bertazzi and Speranza (1999) proposed a mixed integer linear programming model to deal with the problem of minimizing the sum of the inventory and transportation costs in the multi-product logistics network with one origin, Leung *et al.* (2002) proposed an optimisation model which can effectively find an optimal transportation strategy in terms of optimal delivery routes and optimal vehicle fleet composition, Hwang (2002) developed a two-step approach of logistics system design which optimises the performance of logistics system subject to required service levels both in the number of warehouses/distribution centres and vehicle routing schedule, and

Fleischmann and Kuik (2003) considered a stochastic inventory model encompassing random item returns.

- **Queuing Models:** Queuing theory is the branch of operations research concerned with waiting line (delay/congestion). In logistics, queuing models have been developed to aid management decisions concerning arrival schedules, speed of service facilities, the number of facilities and their location (Haley and Krishnan, 1995). Some examples from literature are: Kim and Tang (1997) developed a queuing model of a pull-based production control system for a single-stage facility, Elwany and Baddan (1998) modelled the job-shop as a single server queue and provided a procedure for calculating the sensitivity of the production lead time to the average job processing time for a single machine problem under general priority rule using simulation, and Souza *et al.* (2001) modelled a production process for studying the focused factory using multi-class *GI/G/c* queuing models.

- **Simulation models:** A simulation model creates an approximate (mathematical) model of some system and runs it for a simulated length of time in an attempt to predict aspects of the dynamic behaviour of that system. In other words, simulation models are "what if" tools (Ganeshan and Harrison, 1995) that predict how systems might behave in the future under assumed conditions. There are many different simulation techniques, including: stochastic modelling, system dynamics, discrete simulation, and role-playing games (Sterman, 1991). In logistics, simulation techniques have been applied to problems associated with demand and sales planning, inventory planning, distribution and transportation planning, and production planning and scheduling (Terzi and Cavalieri, 2004), as well as in logistics systems design (Mentzer and Schuster, 1982). Some examples from literature are: Alstrom and Madsen (1992) developed a simulation model to simulate a number of different inventory control systems under different assumptions, Ruiz-Torres and Tyworth (1997) studied basic scheduling rules and existing routing/transportation alternatives using a simulation model, Perea *et al.* (2000) proposed a framework to model the flow of information and material within the supply chain and uses them to capture its dynamic behaviour, Persson and Olhager (2002) evaluated alternative supply chain designs by developing a simulation model using discrete event simulation techniques, Chen *et al.* (2002) described an

application of discrete-event simulation to study logistics activities in a chemical plant, Lai *et al.* (2003) built an integrated framework model of JIT and Kanban using a system dynamics tool.

- **Heuristic models:** A heuristic model usually do not have a precise mathematical form but can be a rule of thumb or an educated guess that reduces or limits the search for solutions in domains that are difficult and poorly understood (Ballou, 1989). In logistics, problems associated with distribution and logistics network design have been approached by a variety of heuristic methods. The grid technique is a well-known heuristic approach used to determine a least-cost facility location for companies with multiple markets and multiple supply points (Coyle *et al.*, 1996). Some examples from literature are: Kim (1995) developed a heuristic inventory model for determining the ordering schedule in which the demand rate is changing linearly with time and the decay is assumed to be a constant rate of the on-hand inventory, Randhawa and Rai (1995) developed a linear programming optimisation model to determine production goals in glass fibre manufacturing industry and then used the output of that model in a heuristic model to incorporated system-specific constraints in developing processing sequences, Chiu (1995) constructed a heuristic (R,T) model to deal with the problem of determining a best order-up-to-level and review interval policy for a fixed-life perishable product under the assumption that the lead time is positive, Korupolu *et al.* (2000) performed an analysis of a local search heuristic for several NP-hard facility locations problems, and Levin and Ben-Israel (2004) presented a heuristic method for solving large-scale multi-facility location problems.

Model-based analysis of logistics systems ranges from specific problem types to overall system design. According to Slats *et al.* (1995), most of the logistics models in use are based on optimisation and simulation. Each of the following authors addresses a particular approach to logistics modelling and discusses its advantages, disadvantages, and appropriate applications: Powers (1989) addresses the optimisation modelling technique, Ballou (1989) addresses the heuristic modelling technique, and Bowersox and Closs (1989) addresses the simulation modelling technique. Each article is a strong advocate for that particular approach and compares the three approaches from that perspective. Also, Sterman (1991) in his article "*A skeptic's guide to computer models*"

provides a comprehensive study of the distinction between optimisation and simulation models in terms of the characteristics and capabilities of the two types of models, their fundamental assumptions, their advantages and disadvantages, and uses and misuses. The following limitations of optimisation models and simulation models are summarised from Sterman's comparison.

The problems and limitations that many of the optimisation models have can be summarised as follows:

1. One of the difficulties with optimisation models is the problem of specifying the objective function; the goal that the model user is trying to reach.

2. Linearity is one of the problems that can seriously undermine the verisimilitude of optimisation models. One of the simplifications that modellers commonly introduce into their optimisation models is that the relationships in the system are linear. However, there are techniques available for solving certain non-linear optimisation problems.

3. Another problem in optimisation models is lack of feedback. Some models do not reflect the fact that complex systems in the real world are highly interconnected, and having a high degree of feedback among sectors. In theory, feedback can be incorporated into optimisation models, but the resulting complexity and non-linearity usually render the problem insoluble.

4. Another problem is lack of dynamics. Many optimisation models are static. They determine the optimal solution for a particular moment in time without regard for how the optimal state is reached or how the system will evolve in the future. Moreover, delays are a crucial component of the dynamic behaviour of systems. But – like non-linearity – they are difficult to incorporate into optimisation models.

The weak points of simulation models can be summarised as follows:

1. The description of the decision rules is one potential trouble spot in a simulation model. The model must accurately represent how the actors in the system make

their decisions, even if these decision rules are less than optimal. Discovering rules is often difficult and cannot be determined from aggregate statistical data, but must be investigated first hand.

2. The majority of data are soft variables that are descriptive, qualitative, difficult to quantify, and has never been recorded. Such information is crucial for understanding and modelling complex systems.

3. The definition of a reasonable model boundary, choosing which factors to be exogenous and which to be endogenous, and choosing which feedbacks to be incorporated into the model are another challenges for the builders of simulation models.

Each model type -optimisation and simulation- has its positive aspects as well as limitations, which can make them appropriate to analyse a specific problem and not another. What is important in modelling is that the model should be built and designed for specific purpose, and that purpose should be to solve a particular problem. A clear purpose allows system-analysts to choose the appropriate type of model that is useful for solving the problem under construction. Therefore, based on the analysis of the literature review of the modelling techniques that have been used to analyse problems associated with logistical activities, this author found that simulation modelling is the most appropriate approach for the purpose of understanding the dynamic behaviour of logistics systems to aid in the whole logistics system design.

To achieve the overall aim of this research work, it is proposed to develop simulation models of hospitals logistics systems using System Dynamics methodology. This is because system dynamics deals with the broad behaviour of the system and how it influences its own evolution into the future which facilitates decision making. System dynamics can accept the complexity, nonlinearity, and feedback loop structures that are inherent in systems, and can then interpret the real world into a description that can be used in subsequent stages as follows: description leads to equations of a model, simulation to understand dynamic behaviour, evaluation of alternative policies, education and choice of a better policy, and implementation (Forrester, 1994). The next section provides information about system dynamics, its definition, and its modelling process.

2.6 System Dynamics Methodology

System dynamics is a methodology for studying and managing complex feedback systems. The methodology of system dynamics was developed in the late 1950s and early 1960s by Jay Forrester at the Massachusetts Institute of technology's Sloan School of Management. It was originally rooted in the management and engineering sciences, but the span of its application has now grown extensively to encompass other fields. The System Dynamics Society (2004) – an international, non profit organisation devoted to encouraging the development and use of systems thinking and system dynamics around the world – gives a list of fields in which system dynamics has been applied, including:

- Corporate planning and policy design.
- Public management and policy.
- Biological and medical modelling.
- Energy and the environment.
- Theory development in the natural and social sciences.
- Dynamic decision making.
- Complex non-linear dynamics.

System dynamics has been used in modelling health care issues. For example Coyle (1984) has considered the problem of short-stay psychiatric patients using system dynamics. Gonzalez-Busto and Garcia (1999) and Van Ackere and Smith (1999) have modelled patients waiting lists. Dangerfield and Roberts (1999) have used system dynamics to model the epidemiology of AIDS. Wolstenholme *et al.* (2004) have developed a model of total patient flow through the UK National Health Service and used it to test alternative major new structural initiatives for relieving pressure on health services. To the best of our knowledge, modelling health care logistics using system dynamics has not previously been done.

Forrester (1961, p13), in his seminal book *"Industries Dynamics"*, defines system dynamics as:

...the investigation of the information-feedback characteristics of systems and the use of models for the design of improved organisational form and guiding policy.

While, Wolstenholme (1990, p3) defines system dynamics as:

A rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organisational boundaries and strategies; which facilitates quantitative simulation modelling and analysis for the design of system structure and behaviour.

Whereas, Coyle (1996) tries to offer a more complete definition of system dynamics, as he argues that Forrester does not say what type of models are involved and neither Forrester's nor Wolstenholme's definitions refer to time. Coyle (1996) defines system dynamics as:

System dynamics deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation.

This research work depended on two main sources in learning the basic concepts behind the study of complex systems using system dynamics. The two sources are:

1. *"Road Maps, A Guide to Learning System Dynamics"*: It is a self-study guide to learning system dynamics. It is organised as a series of chapters, and is being developed by the System Dynamics in Education Project at MIT under the direction of Professor Jay Forrester.

2. *"Introduction to System Dynamics"*: It is an online book prepared for the Department of Energy by Michael J. Radzicki, PhD. Of Sustainable Solutions, Inc. While the examples are directed to energy policy, anyone interested in learning system dynamics will find it valuable.

Both sources above can be found on the System Dynamics Society website <<
http://www.systemdynamics.org/ >>. However, this research work used other sources
and references to reinforce the knowledge of these concepts. **Appendix A** provides a
brief discussion of the main concepts of system dynamics. Learning these concepts are
fundamental requirements for the system dynamics modeller before going into the
modelling process. Meadows (1989, p68) summarises these concepts of system
dynamics in one statement as follows:

> *(System Dynamics) assume that things are interconnected in complex patterns,*
> *that the world is made up of rates, levels and feedback loops, that information*
> *flows are intrinsically different from physical flows, that non-linearities and*
> *delays are important elements in systems, (and) that behaviour arises out of*
> *system structure.*

Forrester (1961) gives a clear, step-by-step definition of the process to be followed in
modelling dynamic systems using the system dynamics methodology. However, over
the years different approaches and frameworks for the process of system dynamics
modelling have been proposed in the literature such as those proposed by Richardson
and Pugh (1981), Wolstenholme (1990), Forrester (1994), Coyle (1996), Albin (1997),
Lane and Oliva (1998), and Sterman (2000). Yet, all of these proposed approaches rely
on the basic concepts of system dynamics that were explained above. In most of these
approaches, the system dynamics modelling process involves the identification,
mapping-out, and simulation of a system's stocks, flows, feedback loops, and non-
linearities.

A review of the system dynamics literature showed that there has been an attempt to
establish a structured approach that can be used to analyse the dynamic behaviour of
supply chains and guide a supply chain redesign. An integrated system dynamics
framework for supply chain design as described by Hafeez *et al.* (1996) (shown in
Figure 2.4) has been established in which system dynamics modelling, analysis and
simulation aids in the decision making process for logistical control systems. The
framework has been successfully used for modelling and analysing a number of supply
chains, for example in the steel industry by Hafeez *et al.* (1996), in the electronic
industry by Berry and Naim (1996), and in the medical supplies industry by Evans *et al.*

(1998). This author has already conducted some elementary study to determine the applicability of the framework in the health care industry as her master's dissertation (Al-Qatawneh, 1998).

In this research work, the modelling and simulation of the dynamic behaviour of health care logistics is proposed to be conducted by adopting the integrated system dynamics framework for supply chain design (shown in Figure 2.4). Accordingly, the following two research questions were proposed:

- Is the integrated system dynamics framework for supply chain design applicable in the health care industry?

- Does the integrated system dynamics framework provide a structured mechanism for analysing and modelling health care logistics systems and their dynamic behaviour?

2.7 The Role of System Dynamics in Improving Logistics Chain Dynamics

The fundaments of the research on supply chain behaviour and characteristics were laid by Forrester (1961) in his seminal work on industrial dynamics. Forrester (1961) first demonstrated the potentially devastating phenomenon of demand amplification along the supply chain. He showed, via simulation, that when final customer demand changes upstream the logistics chain, orders amplify as they are transferred from one echelon to another, resulting in large demand fluctuations at the beginning of the logistics chain. Forrester (1961) explains that demand amplification is caused by system structure, and the delays in decision making concerning information and material flows. His explanation is known as the Forrester effect.

Forrester's work was then complemented by John Burbidge (1983) who coined the "Law of Industrial Dynamics" which states (Towill and Del Vecchio, 1994, p83):

If demand for products is transmitted along a series of inventories using stock control ordering, then the demand variation will increase with each transfer.
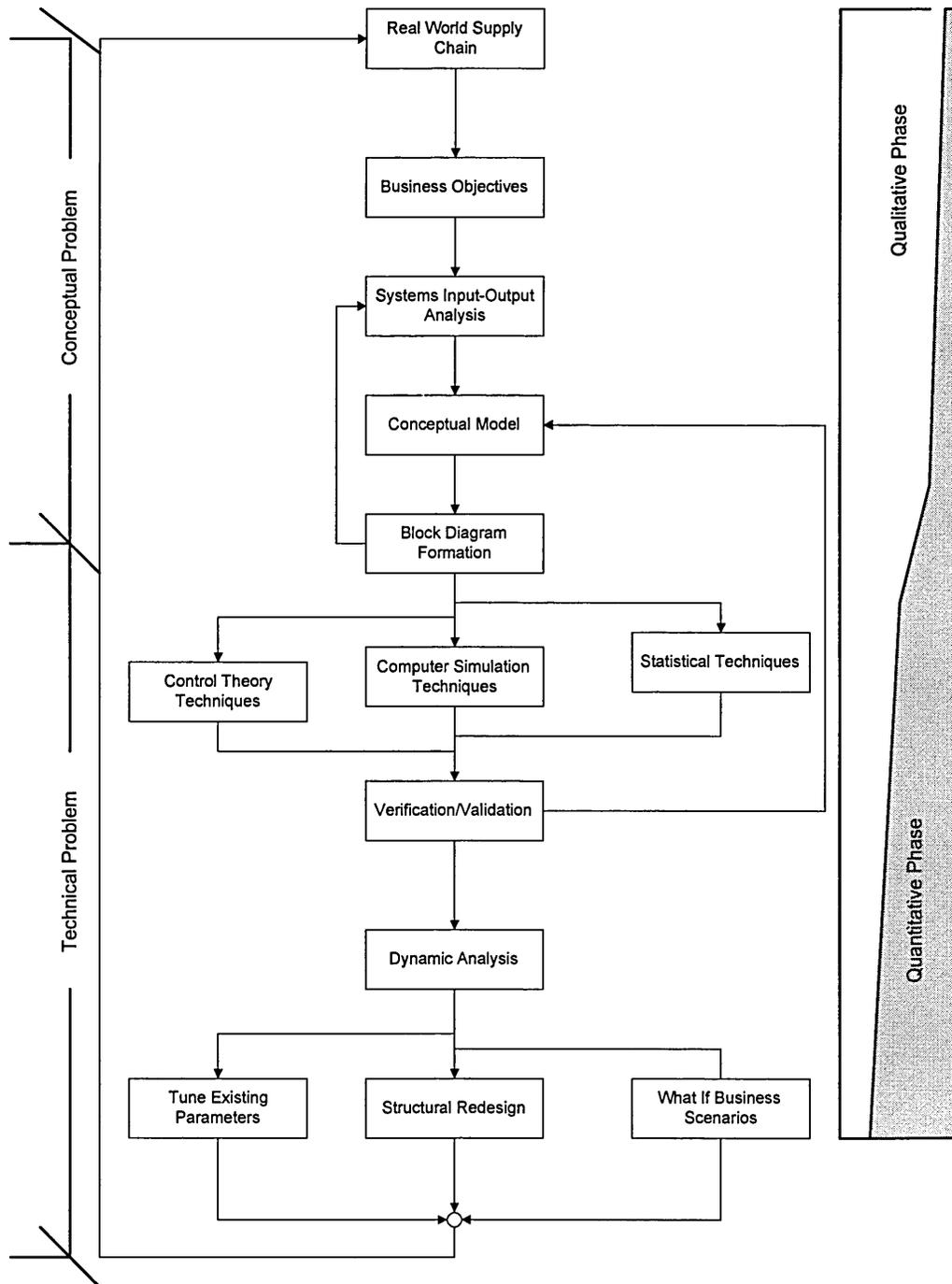
Source: Hafeez *et al.* (1996)

Figure 2.4: An integrated system dynamics framework for supply chain design

Burbidge (1983) explains that demand amplification is caused by the poor practice of placing orders up the logistics chain in batches. His explanation is known as the Burbidge effect or order batching. Later on, other researchers such as Houlihan (1987), Towill (1991), Lee *et al.* (1997), and Mason-Jones *et al.* (1997) have further developed the theory of industrial dynamics.

Demand amplification is considered a main problem of logistics chain dynamics that may lead to inefficient capacity utilisation, poor product availability, and high stock levels (Forrester, 1961; Houlihan, 1987; Towill *et al.*, 1992). A review of the available literature shows that no research has been done to study if demand amplification phenomenon is present in the health care industry. Based on the identified gap in the literature, the following research question was formulated:

- Does the analysis and evaluation of the effects of the different logistics decisions on the dynamic behaviour of health care logistics reveal any problematic behaviour?

In the literature there are several studies on how best to improve logistics chain dynamics. Forrester (1961) himself demonstrated how demand amplification could be reduced by removing the distributor echelon in the simulation. Burbidge (1983) also suggested some simple strategies for reducing demand amplification including frequent deliveries and ordering in smaller batch sizes from suppliers (i.e. ordering policies adjustments). Wikner *et al.* (1991) show that there are a number of business strategies for improving logistics chain dynamics, which includes: tuning policy parameters, reducing time delays, removing a distributor echelon, and integrating information flows along the supply chain. Although the above guidelines provide guidance for improving logistics chain dynamics in a given situation, they rarely quantify these improvements in terms of cost. Therefore, the following research question is proposed to help bridge this gap:

- How to quantify in terms of cost the relative improvements of redesign strategies in health care logistics?

In the literature, most of the redesign strategies suggested to improve logistics chain dynamics have direct impact on the logistics management objectives of providing good customer service level (i.e. reducing the incidence of stock-outs to minimum) while maintaining minimum stock holding requirements. However, in practice, the acceptable level of customer service in a given situation (measured for example by the number of stock-out incidents) may differ from item to item. This is especially true in health care logistics which maintain a large number of different products that are ranged between high-critical to low-critical items. It is acceptable for low-critical items to encounter stock-out situations to a certain degree. Whereas, it is not acceptable at all to encounter stock-out situations for high-critical items since the unavailability of these items could lead to life threatening situations. Again, the issue of criticality of items used by hospitals and the life threatening situations that could happen due to the unavailability of these items is very important to focus on in this research work because this is what makes health care logistics distinct and different from other industries logistics systems.

Inventory classification has been used for a long time (Coyle *et al.*, 1996) as a simple yet very effective technique for stratifying individual items into logical groupings for management where "generic" control policies are set for each group. The analysis of the literature showed that most of the studies on improving logistics chain dynamics assumed that a standardised product unit exists, and that there is gap in considering inventory classification in the redesigning strategies. Therefore, it is proposed in this research work to incorporate inventory classification into the redesigning strategies of health care logistics. Accordingly, the following research question is proposed:

- What is the role of inventory classification when incorporated into the redesigning strategies of health care logistics?

Inventory classification is discussed in more detail in the next section.

2.8 Inventory classification

Inventory Classification is usually a first step toward efficient inventory management. The ABC inventory classification method, which groups items based on annual dollar

usage, is the most frequently used method for item aggregation (Cohen and Ernst, 1988). The ABC approach is based on the fact that a small fraction of items account for a high percentage of total dollar use, and that these items are classified as Class A and are given greater management attention (Pinkerton, 1987), whereas, the rest of the items are classified as Class B and Class C and are given moderate to low attention respectively.

The ABC inventory classification method has been specifically proposed by researchers (Reid, 1986; Fernandez, 1987; Reid, 1987) to help hospitals logistics managers to categorize inventory items so that effective managerial policies and procedures can be implemented. However, there is one problem in applying this method in hospitals. The main limitation is that some critical items that may demonstrate low usage value will not receive priority attention under this method. To overcome this limitation, it is proposed in this research work to use a multi-criteria approach for classification purposes that takes into account the criticality, cost, and usage value of the items. Accordingly, the following research question is formulated:

- What is the impact of using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items on logistics cost reduction?

2.9 Summary

The main aim of this chapter is to review the available literature to identify existing gaps in the body of knowledge developed during previous work and then to develop, based on these gaps, the research questions that specify exactly what is going to be investigated in this research work. This chapter first gave an overview of the relevant literature on logistics and supply chain management and then –more specifically– on health care logistics. The analysis of the literature review of health care logistics revealed some of the main characteristics and features of health care logistics and more importantly its distinctive feature. The criticality of items used by hospitals and the life threatening situations that could happen due to the unavailability of these items is what makes health care logistics distinct and different from other industries logistics systems.

Therefore, this feature will be one of the main concerns of this research work when modelling and analysing health care logistics systems.

This chapter then provided a comprehensive and critical review of the available literature on modelling health care logistics which has shown that there is a gap in understanding the dynamic nature of health care logistics systems as a comprehensive whole and in considering the effect of the interrelated decisions that are applied for managing logistics systems in health care. This gap has directed the focus of this research work towards analysing and modelling health care logistics to be able to understand its dynamic behaviour and effectively manage its logistical activities on the basis of the model. Moreover, this research work will focus in the assessment of the dynamic behaviour of health care logistics on two main variables: logistics cost and service level.

This was followed by a critical review of the different modelling techniques that have been used to analyse problems associated with logistical activities, including: optimisation models, queuing models, simulation models, and heuristic models. Based on this critical review, it was found that simulation modelling is the most appropriate approach for the purpose of understanding the dynamic behaviour of logistics systems to aid in the whole logistics system design. To achieve the overall aim of this research work, it is proposed to develop simulation models of hospitals logistics systems using System Dynamics methodology.

A brief discussion of system dynamics, its definition, and its modelling process was then provided, followed by a critical review of the literature on the role of system dynamics in improving logistics chain dynamics. Several gaps in the literature were identified upon which several research questions were proposed. First, it was proposed to study the presence of any problematic behaviour in health care logistics dynamics since a review of the available literature showed that no research has been done to study that in the health care industry. Second, it was proposed to quantify in terms of cost the relative improvements of redesign strategies in health care logistics since most of the guidelines that have been provided in the literature for improving logistics chain dynamics in a given situation rarely quantified these improvements in terms of cost. Third, it was proposed to incorporate inventory classification into the redesigning strategies of health care logistics since the analysis of the literature showed that most of

the studies on improving logistics chain dynamics assumed that a standardised product unit exists, and that there is gap in considering inventory classification in the redesigning strategies.

This chapter ended by a critical review of the ABC inventory classification method which is the most frequently used method for item aggregation. The critical review revealed a main limitation of using this method in health care which is that some critical items that may demonstrate low usage value will not receive priority attention under this method. Since the criticality of items used by hospitals (a distinctive feature of health care logistics) is the main concern of this research work, it is proposed to use a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items and study the impact of its use on logistics cost reduction.

The next chapter explains how to develop conceptual and quantitative models of hospitals logistics systems using System Dynamics methodology.

Chapter Three: Modelling Health Care Logistics Using System Dynamics

3.1 Introduction

This chapter first explains the development of a general conceptual model of a hospital logistics system. Then, this chapter explains how to develop quantitative models of health care logistics by developing simulation models of two specific hospital logistics systems: one using a traditional (R, s, S) inventory control approach and the other using continuous replenishment (CR). The computer simulation models are then subjected to dynamic analysis to represent the relative time behaviour in order to evaluate the impact of the inventory control decisions and service level decisions.

3.2 Conceptual Modelling of a Hospital Logistics System

Through the understanding of the literature review of health care logistics in section 2.3, as well as the understanding of the main concepts of system dynamics explained in **Appendix A,** a high level stock-flow diagram for a three-echelon health care supply chain is developed as shown in Figure 3.1. In system dynamics, stock-flow diagrams are used as mediums of conceptualization. The stock-flow diagram in Figure 3.1 is drawn using the *ithink* Analyst Software (one of the industry standard system dynamics software). See **Appendix B** for more information about the *ithink* Analyst Software – specially the purpose of the Map/Model level building blocks which are used in building all stock-flow diagrams in this thesis.

As shown in Figure 3.1, inventories are the "glue" for the individual logistics systems in the supply chain. The dynamic behaviour of inventories is altered by inflows and outflows of material. These inflow and outflow rates are controlled via the decision making at different logistics activities. The trade-off between various logistics decisions are determined by the overall business strategy for each echelon.
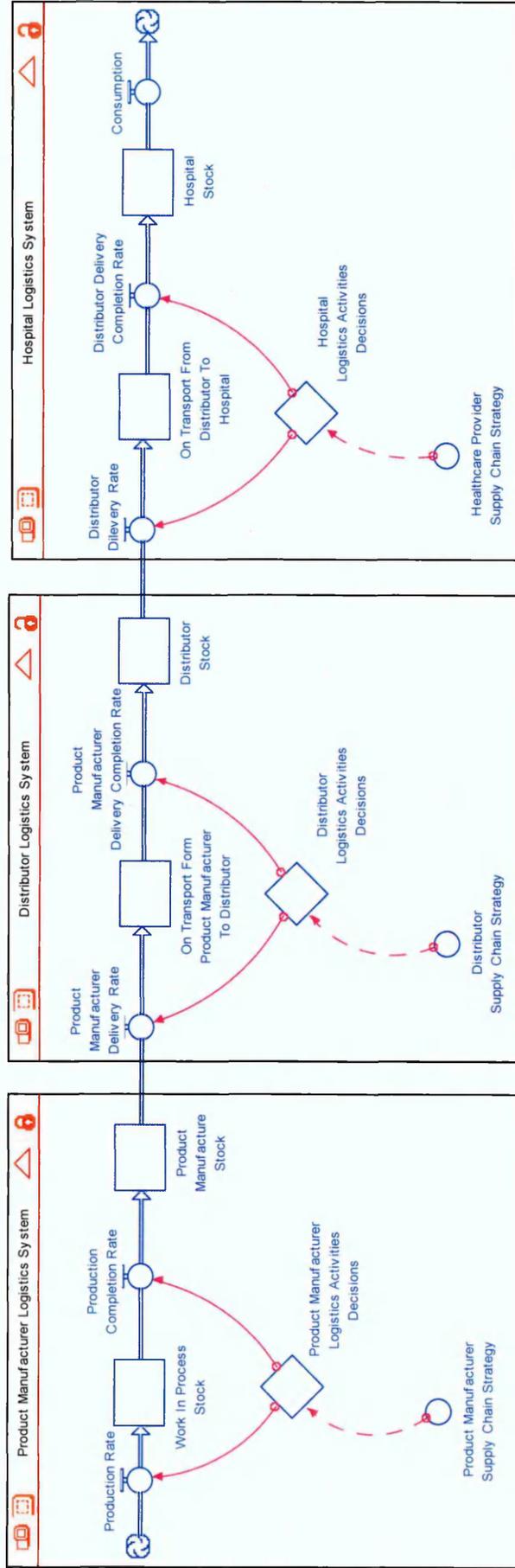
Figure 3.1: A high level stock-flow diagram for three-echelon health care supply chain

35

Hospitals logistics systems usually have responsibility for the following logistics activities: inventory control, transportation, warehousing, purchasing, and service level (Henning, 1986; Scheyer, 1995; Poulin, 2003). A general stock-flow diagram for a hospital logistics system, developed by this author, is shown in Figure 3.2, which shows the stocks, material flows, information flows and logistics decisions. This stock-flow representation is a reflection of the data gathering and the conceptual knowledge acquired through the literature review and the two conducted case studies that are explained in Chapter Four.
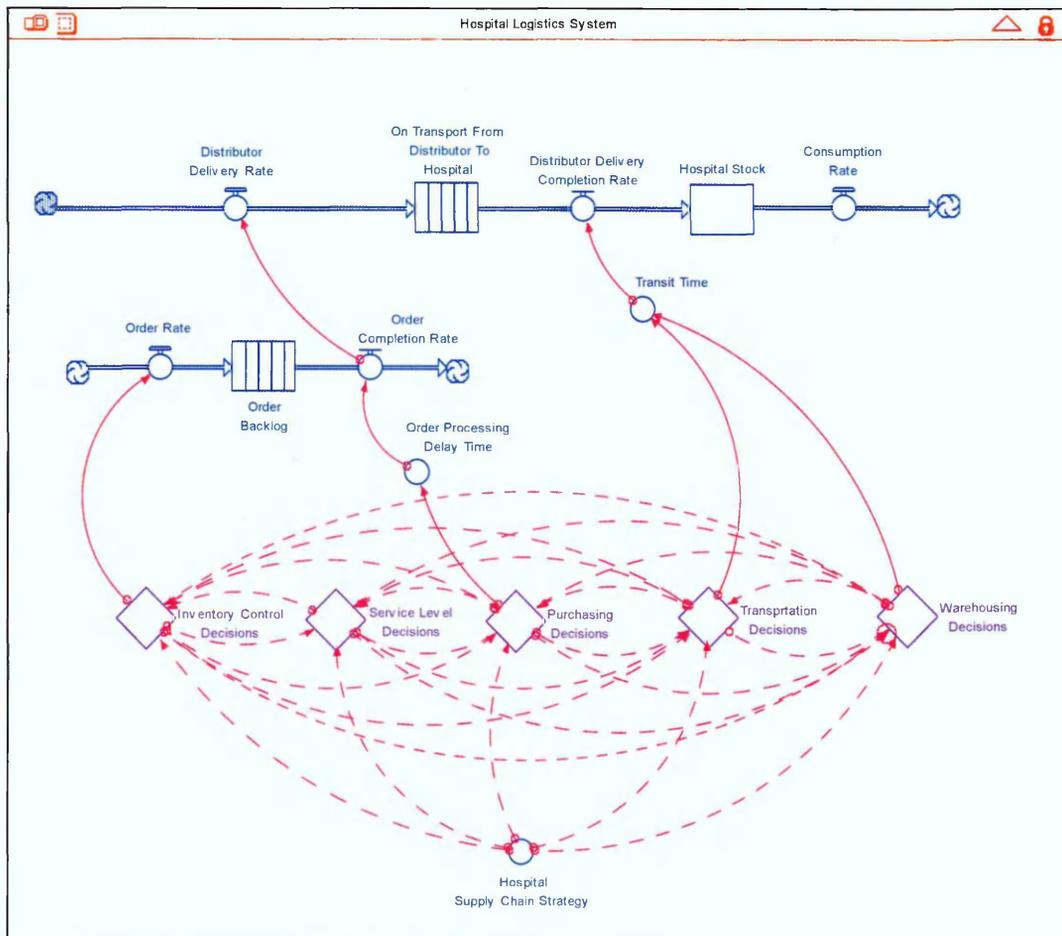
Figure 3.2: Stock-flow diagram of a hospital logistics system

The salient features of Figure 3.2 are explained as follows[1]:

Consumption of all hospital wards and departments are represented as *Consumption Rate*, and all deliveries from distributors are represented as *Distributor Delivery Rate*. The *Hospital Stock* depletes due to *Consumption Rate* and experiences an increase due to *Distributor Delivery Completion Rate*. Delivering materials from distributor stock to *Hospital Stock* takes *Transit Time*. All materials from distributor to *Hospital Stock* experience a delay. This pipeline effect is represented by the stock *On Transport from Distributor to Hospital* (i.e. the materials that have been out of distributor stock but not yet received by *Hospital Stock*). *Transit Time* is driven by a combination of *Transport Decisions* and *Warehousing Decisions*.

The hospital *Inventory Control Decisions* determine how much material the hospital should order, which in turn determines how much material the distributor should deliver to *Hospital Stock*. The ordering process takes *Order Processing Delay Time*. There is an information delay between the moment when the need for materials is realised by the hospital and the moment when this information is received by the distributor in the form of an order. This is represented by the stock *Order Backlog* which is increased by *Order Rate* and decreased by *Order Completion Rate*. *Order Processing Delay Time* depends on *Purchasing Decisions*.

As shown, *Inventory Control Decisions*, *Transportation Decisions*, *Warehousing Decisions*, *Purchasing Decisions*, and *Service Level Decisions* are interdependent. The trade-off between these logistics decisions is determined by the *Hospital Supply Chain Strategy*.

The overall hospital logistics system cost equals the sum of purchasing cost plus transportation cost plus inventory control cost plus warehousing cost (Rivard-Royer *et al.*, 2002). *Hospital Supply Chain Strategy* should allow for trade-offs between

---

[1] Throughout this thesis, the names of all variables within stock-flow diagrams –although written in these diagrams as non-italic- will be written within the text in italic format, so the reader can recognize them easily.

inventory control, transportation, warehousing and purchasing with a view to optimising the overall hospital logistics system cost while maintaining the required service level.

In Figure 3.2, the complete logic of the *Inventory Control Decisions*, *Transportation Decisions*, *Warehousing Decisions*, *Purchasing Decisions*, and *Service Level Decisions* is not visible as it is embedded within the space-compressed decision-process diamond (DPD) (see **Appendix B** for more information about DPD in the *ithink* Software). Given the situation, a specific and detailed logic of the logistics decisions can be constructed according to the operating practices. Such logic can be subsequently converted into a quantitative model that can be used to study the dynamic behaviour of the system. The following two sections discuss the common practices in health care for *Service Level Decisions and Inventory Control Decisions*.

3.2.1 Hospital service level decisions

As explained in Chapter Two, this research work is concerned with the availability of medical and non-medical products needed to offer health services for patients. For hospitals, *Service Level Decisions* usually entails the following questions:

a) What is the desired service level?
b) How much safety stock is to be kept for each item to maintain the desired service level?

There are indications that the usual managerial practice, in terms of desired service level is to treat all items the same. Beier (1995) summarizes the practices that are used in hospitals to calculate safety stock as follows:

- No policy for determining safety stock.
- Carry safety stock for average usage.
- Carry safety stock for maximum usage.
- Safety stock is a function of vendor deals.
- Safety stock is determined by personal judgment. (Beier (1995) shows in his study that this practice is the most common one used by hospitals).

3.2.2 Hospital inventory control decisions

In hospitals, the main *Inventory Control Decision* involves three fundamental questions (Reisman, 1981; Scheyer, 1995):

a) How often to review? (the inventory status)
b) When to order?
c) How much to order?

The answers for the above questions are determined by the inventory control approach used. There are two inventory control approaches that are usually used by hospitals:

1. Traditional (R, S) and (R, s, S) approaches (Reisman, 1981; Cox and Gibson, 1986; Scheyer, 1995).
2. Continuous replenishment (CR) (CSC, 1996) and (Haavik, 2000).

The decision as to which inventory control approach to use depends on the supply chain strategy (for example, continuous replenishment (CR) should be used with time-based logistics strategies such EHCR).

3.3 Quantitative Modelling of a Hospital Logistics System

Although qualitative modelling (as explained in section 3.2) is a valuable device in its own right for describing and understanding hospitals logistics systems and their interrelated logistics decisions, yet qualitative modelling lacks the ability to quantify the effect of the different logistics decisions in terms of time dependent changes in the related outputs. Therefore, qualitative modelling is followed by quantitative modelling which adds significant value by enabling comprehensive and more rigorous dynamic analysis. The qualitative model is usually converted into a quantitative model by developing relevant mathematical equations. To show how this is done, the rest of Chapter Three is devoted to developing and analysing quantitative models of two specific hospital logistics systems: one using a traditional (R, s, S) inventory control approach and the other using continuous replenishment (CR). The reason for choosing

to study the effect of using these two specific inventory control approaches on hospital logistics dynamics is that these two approaches will be used later on in the redesigning strategies for the two case hospitals in Chapter Four.

3.4 Modelling a Hospital Logistics System that is Using a Traditional (*R*, *s*, *S*) Inventory Control Approach

The (*R*, *s*, *S*) inventory control approach is one of the most common traditional approaches that are used by hospitals (Reisman, 1981; Cox and Gibson, 1986; Scheyer, 1995). The subsequent sections describe the conceptual model development, simulation model development and dynamic analysis of a hospital logistics system that is using this approach.

3.4.1 Conceptual model of a hospital logistics system that is using a traditional (*R*, *s*, *S*) inventory control approach

The stock-flow diagram of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach developed by this author is illustrated in Figure 3.3. The abbreviations *R*, *s*, and *S* in this approach are defined as follows (Blumenfeld, 2001):

- *R* : review period (time interval between reviews)
- *s* : reorder level
- *S* : order-up-to level

Usually, hospitals use par level in lieu of order-up-to level and accordingly name this approach as periodic review par level system (Nicholson *et al.*, 2004). One of the major issues in setting par levels for various items in hospitals is that these levels usually tend to reflect the desired inventory levels of the patient caregivers rather than the actual inventory levels needed in a department over a certain period (i.e. par levels are experience-based and politically driven, rather than data-driven) (Prashant, 1991).
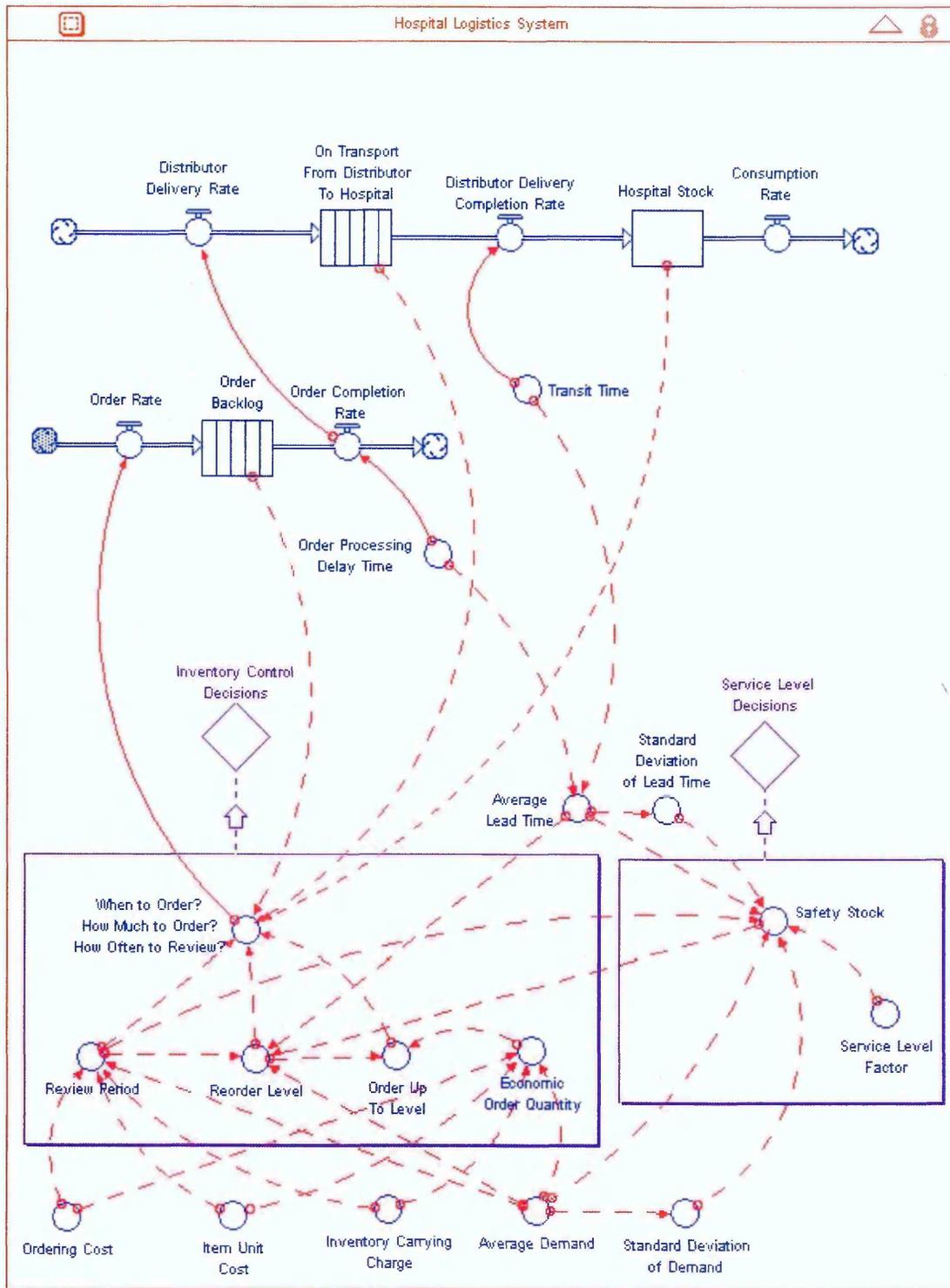
Figure 3.3: Stock-flow diagram of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach

However, in Figure 3.3 the values of R, s, and S are determined algorithmically. Table 3.1 gives a description of the (R, s, S) inventory control approach, describes how the *Inventory Control Decision* of (*How Often to Review?*, *When to Order?*, and *How Much to Order?*) is determined, and lists all variables that are used to determine this decision. **Appendix C** provides a full explanation of how the stock-flow diagram (shown in Figure 3.3) is developed.

The main concept of traditional inventory control approaches is to give optimum answers for the *Inventory Control Decision* (*How Often to Review?*, *When to Order?*, and *How Much to Order?*) based on a trade-off between inventory carrying cost and ordering cost (Coyle *et al.*, 1996). However, in the case of the (R, s, S) inventory control approach, joint optimization of the three parameters R, s, and S leads to complicated mathematics (Silver and Peterson, 1985). Therefore, the equations in Table 3.1 that are given by Blumenfeld (2001) were developed using a simple heuristic approximation. These equations give approximate optimum values for the three parameters R, s, and S.

Table 3.1: An explanation of the (R, s, S) inventory control approach

Inventory control approach	(R, s, S)
Description of the approach	Inventory position (items on hand plus items on order) is reviewed at regular instants, spaced at time intervals R. At each review, if inventory position is at level s or below, an order of sufficient quantity is placed to bring the inventory to a given level S.
Inventory control decision: • *How Often to Review?*	Inventory status is reviewed at regular instants, spaced at time intervals R, where $$R = \sqrt{\frac{2A}{DH}}$$
• *When to Order?*	An order is placed: If (inventory position) $\leq s$, where $$s = D(L+R) \;+\; k \;\sqrt{(L+R)\sigma_D^2 \;+\; D^2\sigma_L^2}$$ where, the value of $$(\quad k \;\sqrt{(L+R)\sigma_D^2 \;+\; D^2\sigma_L^2} \;)$$ is usually referred to as safety stock.

Table 3.1: An explanation of the (R, s, S) inventory control approach (continued)

• *How Much to Order?*	Order quantity = $(S -$ inventory position), where $$S = s \; + \; EOQ$$ $$EOQ = \sqrt{\frac{2AD}{H}}$$ The economic order quantity (EOQ) is the optimal quantity to order –under the condition of certainty–needed to replenish inventory based on a trade-off between inventory carrying cost and ordering cost.
Variables used in the decision rule	• D = average demand (number of items per unit time) • σ_D = standard deviation of demand (item per unit time) • σ_D^2 = variance of demand (items^2 per unit time) • L = average lead time (units of time) • σ_L = standard deviation of lead time (unit time) • σ_L^2 = variance of lead time (units of time^2) • A = ordering cost ($ per order) • c = cost of an item ($ per item) • r = inventory carrying charge (fraction per unit time) • $H = cr$ = holding cost of an item ($ per item per unit time) • k = service level factor

Sources: (Silver and Peterson, 1985; Blumenfeld, 2001)

3.4.2 Simulation model and dynamic analysis of a hospital logistics system that is using a traditional (R, s, S) inventory control approach

A simulation model of a hospital logistics system that is using the (R, s, S) inventory control approach is developed by this author using the stock-flow diagram shown in Figure 3.3. **Appendix C** provides all the equations that make up the simulation model.

In developing the simulation model it was observed that the model formulation is robust by ensuring:

1. Inflows remain non-negative no matter how large the surplus of their stocks may be.

2. All stocks (conveyors and reservoirs) never fall below zero no matter how large their outflows maybe.

3. Outflows approach zero when their stocks are depleted.

4. "Real data" that is available to the decision makers is used in the model.

Figure 3.4 shows the dynamic behaviour of a hospital logistics system that is using the (*R, s, S*) inventory control approach for an example item. The variables that are used in the simulation model for the example item are defined in Table 3.2. Figure 3.4 shows *Hospital Stock, Order Up To Level, Reorder Level, Consumption Rate, Order Rate,* and *Distributor Delivery Completion Rate.*

Table 3.2: Definition of the variables used in the simulation model of the (*R, s, S*) inventory control approach for the example item

Variables used in the simulation model	Value
Average Demand	100 item/day
Item Unit Cost	1 $
Order Processing Delay Time	1 day
Transit Time	3 days
Standard Deviation of Lead Time	(1/30) * *Average Lead Time*
Ordering Cost	15 $
Inventory Carrying Charge	0.3 /unit time
Standard Deviation of Demand	(1/3) * *Average Demand*
Consumption Rate	Normal[2] (100,0.3)
Service Level Factor	3
Length of simulation	50 days
Dt	0.0625 day

---

[2] The NORMAL function generates a series of normally distributed random numbers with a specified *mean* and *standard deviation* (The *ithink* and STELLA Technical Documentation, 2002).
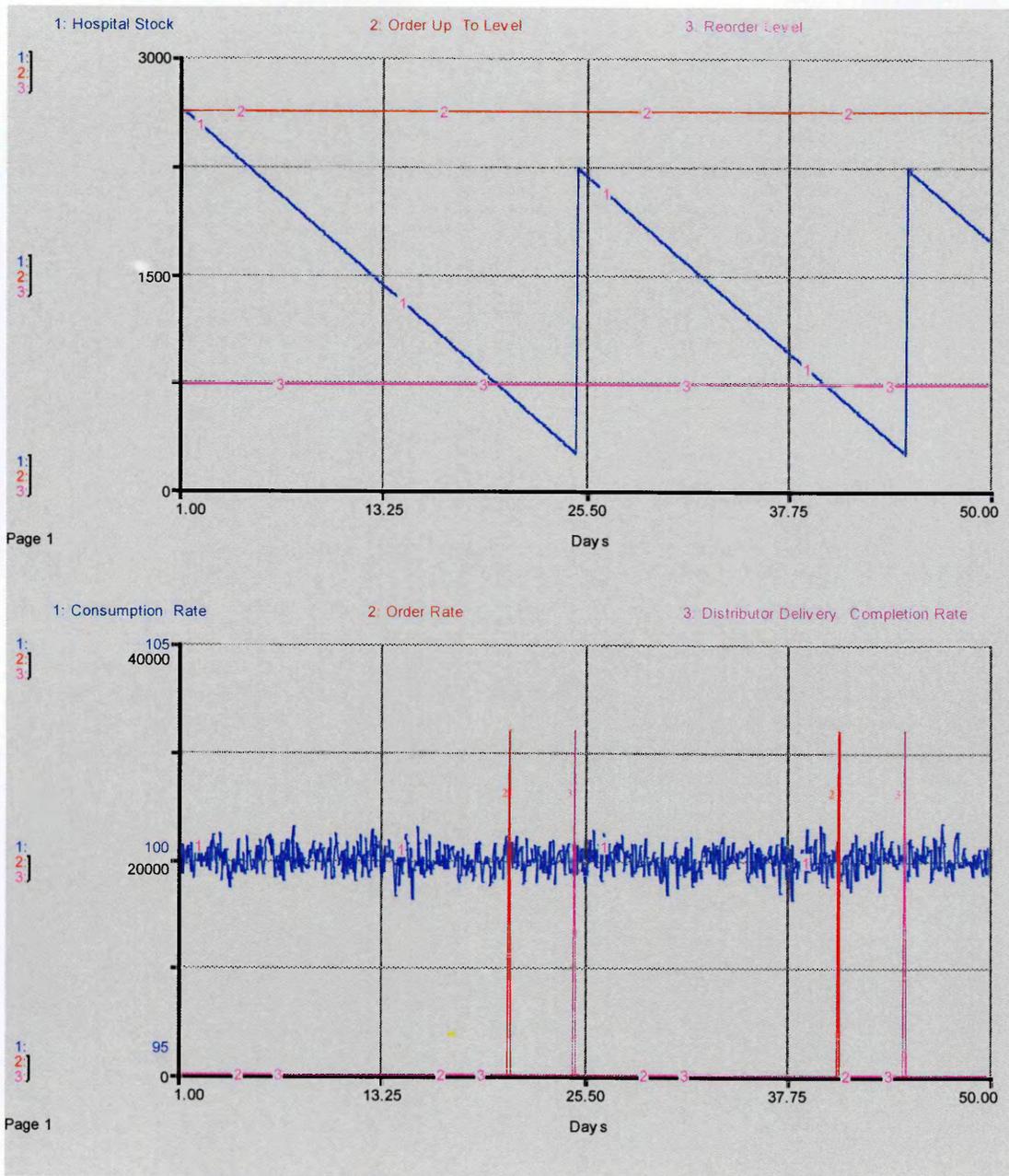
Figure 3.4: Dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for the example item defined in Table 3.2

As shown in Figure 3.4, *Hospital Stock* depletes gradually till it reaches *Reorder Level*. At the first *Review Time* that follows this condition, an order is generated. Therefore, in the simulation model, *Order Rate* is a pulse function[4] of height equals (Q/dt), where Q is the ordered quantity which is calculated according to the equation in Table 3.1.

After a time (equal to *Average Lead Time*), *Distributor Delivery Completion Rate* exhibits a pulse function of height equals (Q/dt) which causes *Hospital Stock* to increase its level by Q. However, because *Consumption Rate* is a continuous function, that means that when the ordered quantity entered the *Hospital Stock*, also a quantity (equal to *Consumption Rate**dt) was taken out of the Hospital Stock. Therefore, *Hospital Stock* does not reach *Order Up To Level*.

The dynamic behaviour generated by the simulation model is representative of the typical sawtooth pattern (Silver and Peterson, 1985; Blumenfeld, 2001) that is expected to be generated from the traditional (*R*, *s*, *S*) inventory control approach.

The validated simulation model is subsequently used to study the dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for various other items. Figure 3.5, Figure 3.6, and Figure 3.7 illustrate the dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for three different scenarios as summarised in Table 3.3, respectively. Each Figure shows *Hospital Stock, Order Up To Level, Reorder Level, Consumption Rate, Order Rate,* and *Distributor Delivery Completion Rate.*

---

[4] The pulse function has an area of unity; thus an arbitrary pulse input of Q units at time T is approximated in simulation models by a rectangular pulse with duration equal to simulation time step DT and a height of Q/DT (Sterman, 2000).

Table 3.3: Definition of the variables used in the simulation model of the (R, s, S) inventory control approach for the three test scenarios

Variables used in the simulation model	Scenario 1	Scenario 2	Scenario 3
Average Demand (item/day)	1	100	50
Item Unit Cost ($)	1	30	2
Order Processing Delay Time (day)	1	1	0.5
Transit Time (day)	2	1	4
Standard Deviation of Lead Time(day)	(1/30) * *Average Lead Time*	(1/30) * *Average Lead Time*	(1/3) * *Average Lead Time*
Ordering Cost ($)	15	12	15
Inventory Carrying Charge (fraction/unit time)	0.3	0.25	0.35
Standard Deviation of Demand (item/unit time)	(1/30) * *Average Demand*	(1/3) * *Average Demand*	(1/3) * *Average Demand*
Consumption Rate (item/day)	1	100+STEP[5](20,25)	Normal(50,16.7)
Service Level Factor	3	3	3
Length of simulation (day)	365	50	365
Dt (day)	0.0625	0.0625	0.0625

---

[5] The STEP function (i.e. STEP(<height>,<time>)) generates a one-time step change of specified height, which occurs at a specified time (The *ithink* and STELLA Technical Documentation, 2002). Height and time can be either variable or constant.
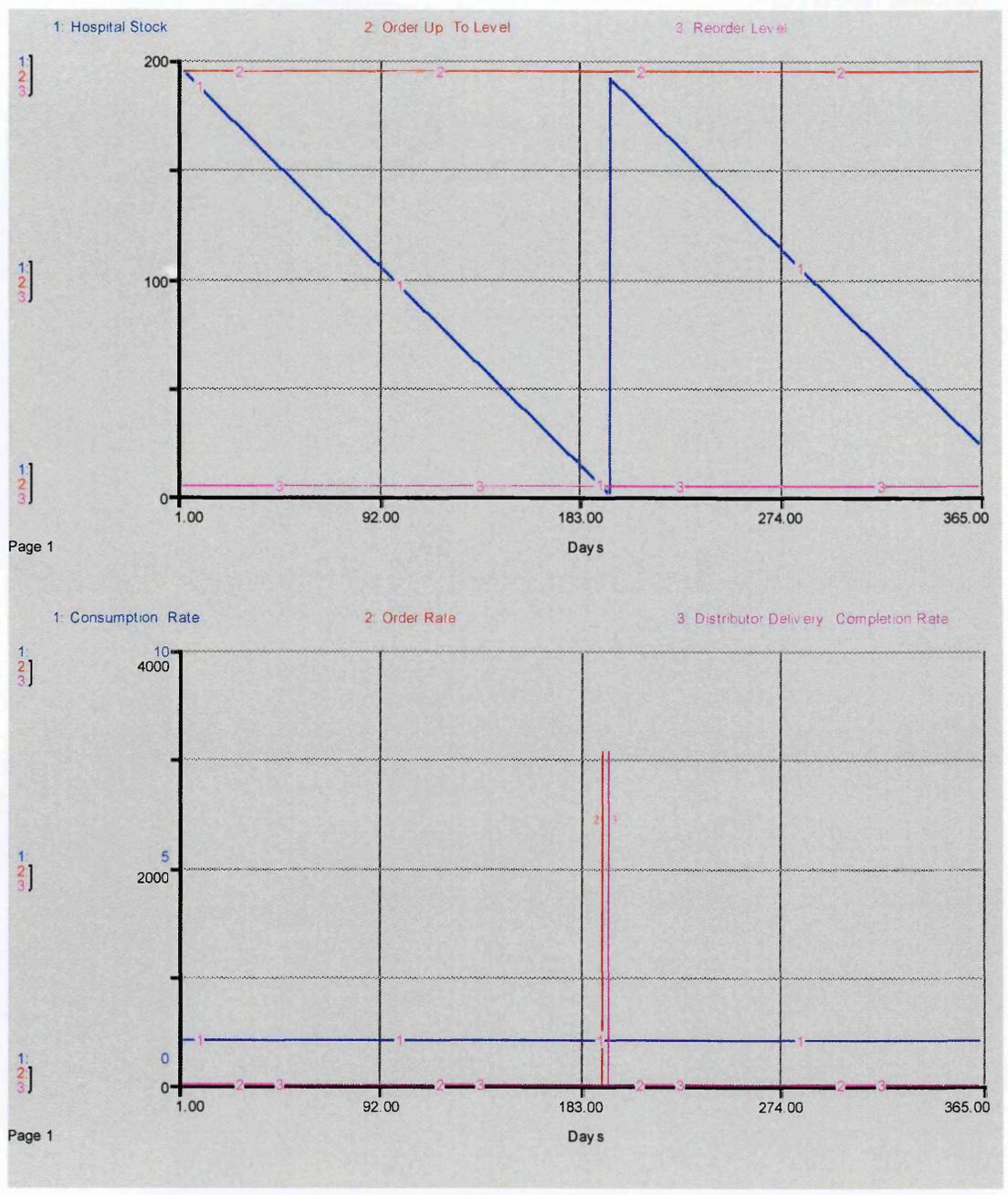
Figure 3.5: Dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for the item of scenario 1 defined in Table 3.3
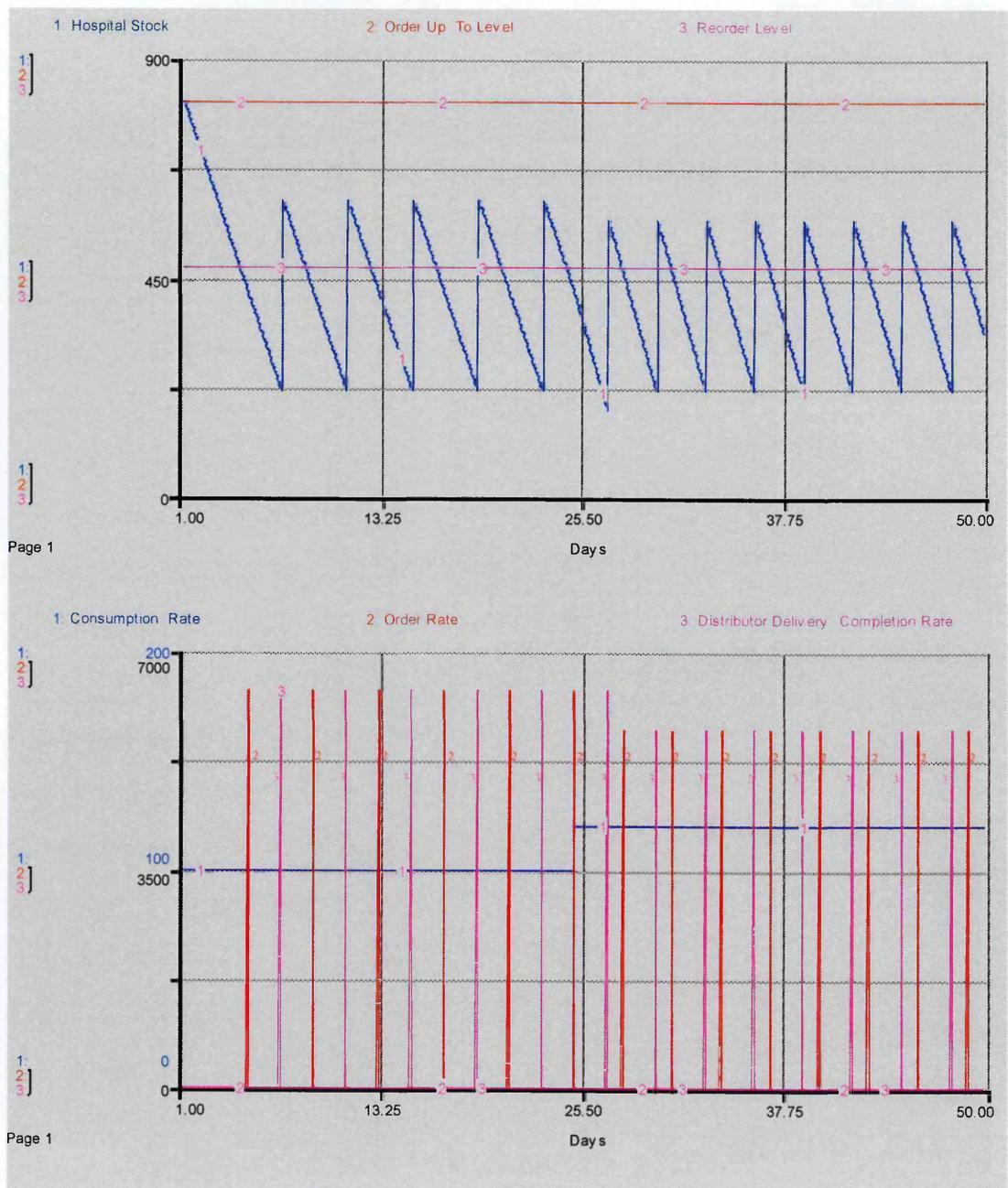
Figure 3.6: Dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for the item of scenario 2 defined in Table 3.3
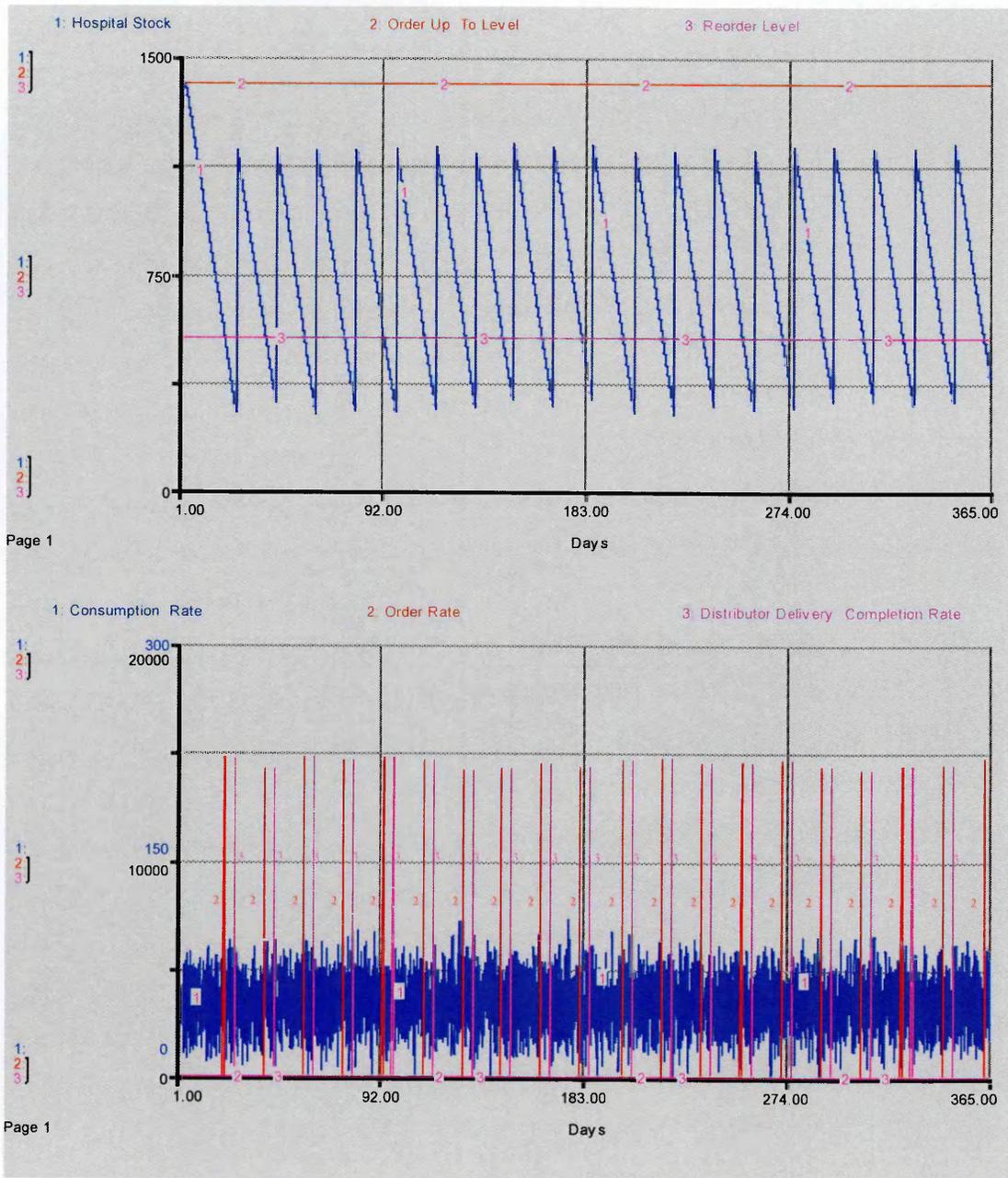
Figure 3.7: Dynamic behaviour of a hospital logistics system that is using the (*R*, *s*, *S*) inventory control approach for the item of scenario 3 defined in Table 3.3

By analysing the dynamic behaviour of the hospital logistics system shown in Figure 3.4 to Figure 3.7, this author concludes that when using the (*R, s, S*) inventory control approach the *Inventory Control Decisions* are non-linear, generating a sequence of order impulses rather than continuous-time order flows. This non-linearity –as this author explains- is caused by the conditional statement IF…THEN…ELSE present in the *Inventory Control Decisions*.

Moreover, the analysis shows that *Order Rate* is controlled by what has been consumed (pull) plus safety stock (push), which confirms that the (*R, s, S*) inventory control approach is a hybrid approach that includes elements of pull- and push-based strategies (Coyle *et al.*, 1996).

The time-based behaviour as illustrated in Figure 3.4 to Figure 3.7 also reveals how the continuous demand for products (i.e. *Consumption Rate*) is transmitted to the distributor (i.e. next echelon in the supply chain) as order pulses known as order batching (Disney and Towill, 2003). It was Burbidge (1983) who first studied how order batching causes the problem of demand amplification (i.e. *Order Rate* has a larger fluctuation than *Consumption Rate*) later known as the Burbidge Effect (explained in section 2.7).

Burbidge (1983) suggested some simple strategies for reducing these fluctuations including frequent deliveries and ordering in smaller batch sizes from suppliers. These suggestions -as this author proves- are more vividly reproduced using continuous replenishment (CR) which is discussed in section 3.5.

Although modelling non-linear systems using control theory usually leads to complicated mathematical models (Edghill and Towill, 1989), Grubbstrom and Wikner (1996) were able to model non-linear inventory control decisions by developing differential equations involving Heaviside and Dirac impulse functions. They have shown that these equations correspond to order policies generating the typical sawtooth patterns of traditional inventory control approaches. However the system that they have modelled was limited to one product system only. Also, in their model, they have assumed that the supply lead time is zero.

In this research, the computer simulation model of a hospital logistics system that is using the (R, s, S) inventory control approach developed by this author overcomes the above shortcomings by having the following added advantages:

- The model is relatively easy to use and understand by end users who are unfamiliar with mathematical difference and differential equations.
- It is relatively easy to change values of variables in this model.
- The model can be easily modified later to include any linear and non-linear decisions without worrying about how sophisticated the equations will be.

3.5 Modelling a Hospital Logistics System that is Using Continuous Replenishment (CR) Approach

Continuous replenishment (CR) is a vital tool in the implementation of Efficient Healthcare Consumer Response (EHCR) strategy (CSC, 1996). It has been defined as (Vergin and Barr, 1999, p146):

> *the practice of partnering between distributor channel members that changes the traditional replenishment process from distributor-generated purchase orders, based on economic order quantities, to the replenishment of products based on actual and forecasted product demand.*

The main concept of CR –as its name implies- is that order rate is adjusted continuously based on actual or forecasted demand. However, in practice, the decision rule of CR took different forms –although based on the same main concept- depending on the industry. In literature, several studies –most of which are quite recent- have looked into some of these decision rules of CR in an attempt to develop analytical models of them, for example by Cachon (1997), Cetinkaya and Lee (2000), Axsäter (2001), Fry *et al.* (2001), Raghunathan and Yeh (2001), Dejonckheere *et al.* (2003).

This research work proposes to study one specific decision rule of CR, which is based on the well-studied inventory and order based production control system (IOBPCS).

The term IOBPCS was coined by Coyle (1977) to represent much of the industrial practice associated with manual production control systems. Although the IOBPCS model was developed initially in terms of smoothing factory orders, it can be readily modified to represent other links in the supply chain (Towill and Del Vecchio, 1994). In the IOBPCS model, the ordering rule is based upon forecast demand and the difference between a fixed target level of inventory and the actual level (Towill, 1982).

The CR model that is based on IOBPCS is called throughout this research as CR(IOBPCS). The following sections describe the conceptual model development, simulation model development and dynamic analysis of a hospital logistics system which uses CR(IOBPCS) inventory control approach.

3.5.1 Conceptual model of a hospital logistics system that is using CR(IOBPCS) inventory control approach

The stock-flow diagram of a hospital logistics system that is using a CR(IOBPCS) inventory control approach, developed by this author, is illustrated in Figure 3.8. Table 3.4 gives a description of the CR(IOBPCS) inventory control approach, describes how the *Inventory Control Decision* of (*How Often to Review?*, *When to Order?*, and *How Much to Order?*) is determined, and lists all variables that are used to determine this decision. **Appendix D** provides a full explanation of how the stock-flow diagram (shown in Figure 3.8) is developed.

However, there is a difference between the CR(IOBPCS) model (in Figure 3.8) and the IOBPCS model developed by Towill (1982), which is how the delay in the system is represented. Towill (1982) represents the production delay as a first order delay. Yet, in the CR(IOBPCS) model in Figure 3.8, this author suggests that transportation/delivery delay is better represented as a pipeline delay. The reason is that pipeline delays preserve the order of entry to a delay so the output is exactly the same as the input, but shifted by the time delay, and also assume no mixing of the contents of the stock in transit at all (Sterman, 2000).

Figure 3.8: The stock-flow diagram of a hospital logistics system that is using CR(IOBPCS) inventory control approach

Table 3.4: An explanation of the CR(IOBPCS) inventory control approach

Inventory control approach	CR(IOBPCS)
Description of the approach	Order rate is adjusted continuously at each period *t* and is equal to the sum of forecasted demand and a fraction (1/T_i) of the stock discrepancy.
Inventory control decision: • *How Often to Review?* • *When to Order?* • *How Much to Order?*	At each period *t* At each period *t* Order quantity at time *t* = O_t, where $O_t = \text{AVCON}_t^{T_a} + \dfrac{1}{T_i}(\text{TL} - \text{AL}_t)$ TL = kD (T_a / T_p) *and* (T_i / T_p) are design parameters which are chosen to give acceptable system performance.
Variables used in the decision rule	• $\text{AVCON}_t^{T_a}$: average consumption at time *t* which is the demand forecast using simple exponential smoothing with parameter T_a (items per unit time) • T_a : demand averaging time constant. • TL : target level (items) (which is considered as safety stock) • D : average demand (number of items per unit time) • k = service level factor • AL_t : actual level at time *t* (items) • T_i: inverse of inventory based production control law gain. • T_p: average lead time (units of time)

Source: (Towill, 1982)

The main concept of the CR(IOBPCS) inventory control approach is to optimise the *Inventory Control Decision* (*How Often to Review?*, *When to Order?*, and *How Much to Order?*) by choosing the appropriate values for the design parameters (T_a / T_p) and (T_i / T_p) based on a trade-off between stock fluctuation and order rate variations (i.e. generating smooth ordering patterns while minimising inventory deviations from target level). The design parameters T_a, T_i and T_p are defined as follows:

- T_a : time to average consumption
- T_i : time to adjust inventory
- T_p : actual pipeline lead-time

By using classical control theory techniques, Towill (1982) and (1984) has highlighted that (T_a / T_p) =2 and (T_i / T_p) = 1 are good design parameters for the IOBPCS model (with first order production delay). However, this author has found that (T_a / T_p) =1 and (T_i / T_p) = 3 are good design parameters for the CR(IOBPCS) model in Figure 3.8 (with pipeline delays). **Appendix E** explains the criterion employed to come up with the optimum values for (T_a / T_p) and (T_i / T_p).

In order to quantify system behaviour in the CR(IOBPCS) model in terms of money, stock fluctuation is interpreted as inventory carrying cost and shortage cost (Dejonckheere *et al.*, 2003), while order rate variation is interpreted as transportation cost (Disney *et al.*, 2003). Therefore, in the CR(IOBPCS) model, a trade-off is made between minimising inventory carrying cost and shortage cost on the one hand and transportation costs on the other.

3.5.2 Simulation model and dynamic analysis of a hospital logistics system that is using CR(IOBPCS) inventory control approach

A simulation model of a hospital logistics system that is using the CR(IOBPCS) inventory control approach is developed by this author using the stock-flow diagram shown in Figure 3.8 (where (T_a / T_p) =1 and (T_i / T_p) = 3)). **Appendix D** provides all the equations that make up the simulation model. As with the (*R*, *s*, *S*) inventory control approach (section 3.4.2), it was observed that the model formulation is robust by ensuring:

1. Inflows remain non-negative no matter how large the surplus of their stocks may be.

2. All stocks (conveyors and reservoirs) never fall below zero no matter how large their outflows may be.

3. Outflows approach zero when their stocks are depleted.

4. "Real data" that is available to the decision makers is used in the model.

The simulation model is subsequently subjected to detailed dynamic analysis for different items and scenarios (see Table 3.5). Figure 3.9, Figure 3.10, and Figure 3.11 show the dynamic behaviour of a hospital logistics system that is using the CR(IOBPCS) inventory control approach for the three scenarios as summarised in Table 3.5. Each Figure shows *Hospital Stock, Target Level, Consumption Rate, Order Rate,* and *Distributor Delivery Completion Rate.*

Table 3.5: Definition of the variables used in the simulation model of the CR(IOBPCS) inventory control approach for the three test scenarios

Variable	Scenario 1	Scenario 2	Scenario 3
Consumption Rate (item/day)	1	100+STEP(20,25)	NORMAL(50,1.67)
Average Demand (items)	1	100	50
Transit Time (days)	2	1	4
Service Level Factor	1	1	1
(T_a / T_p)	1	1	1
(T_i / T_p)	3	3	3
Length of simulation (days)	365	50	365
Dt (day)	1	1	1
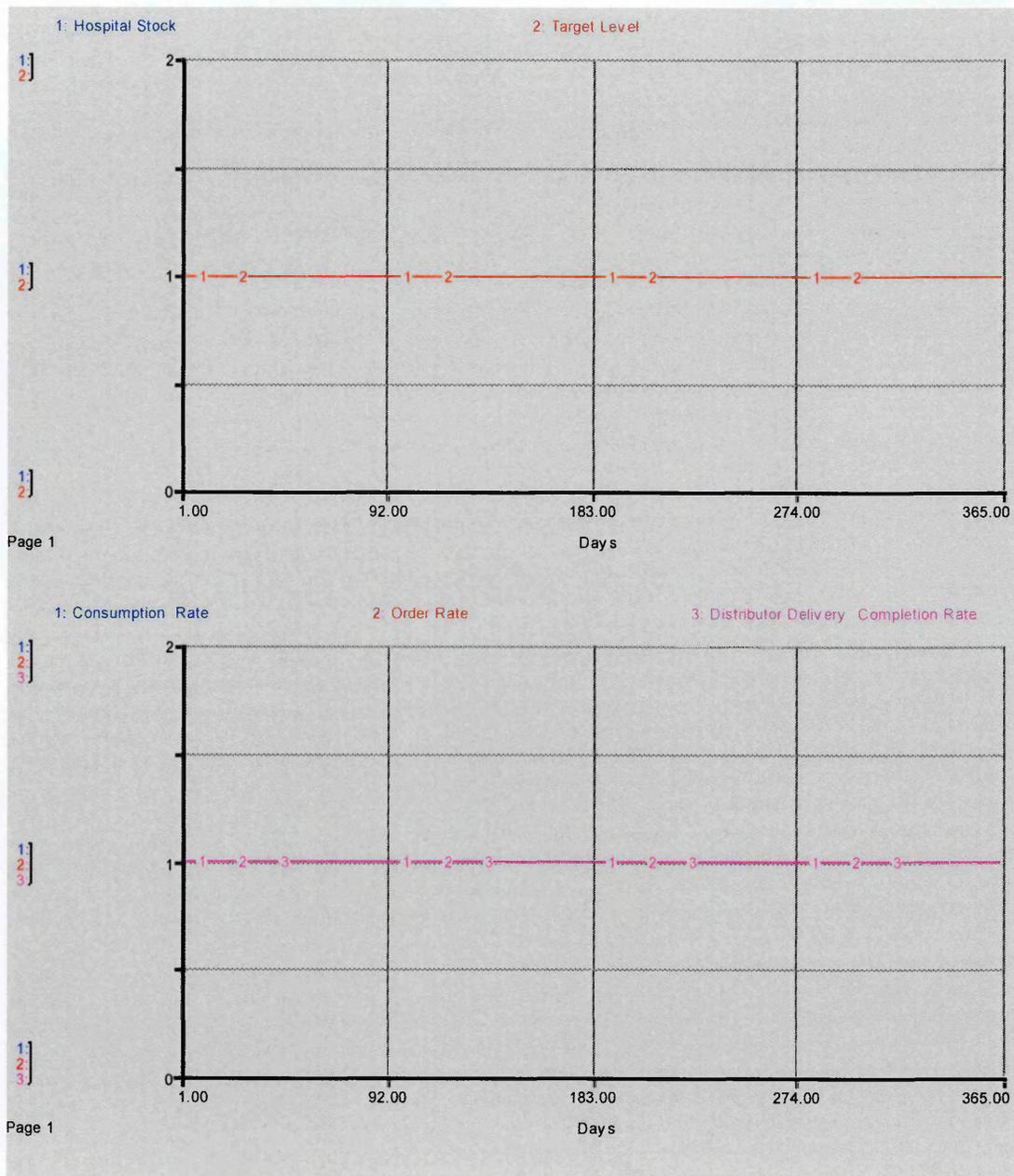
Figure 3.9: Dynamic behaviour of a hospital logistics system that is using the CR(IOBPCS) inventory control approach for the item of scenario 1 defined in Table 3.5
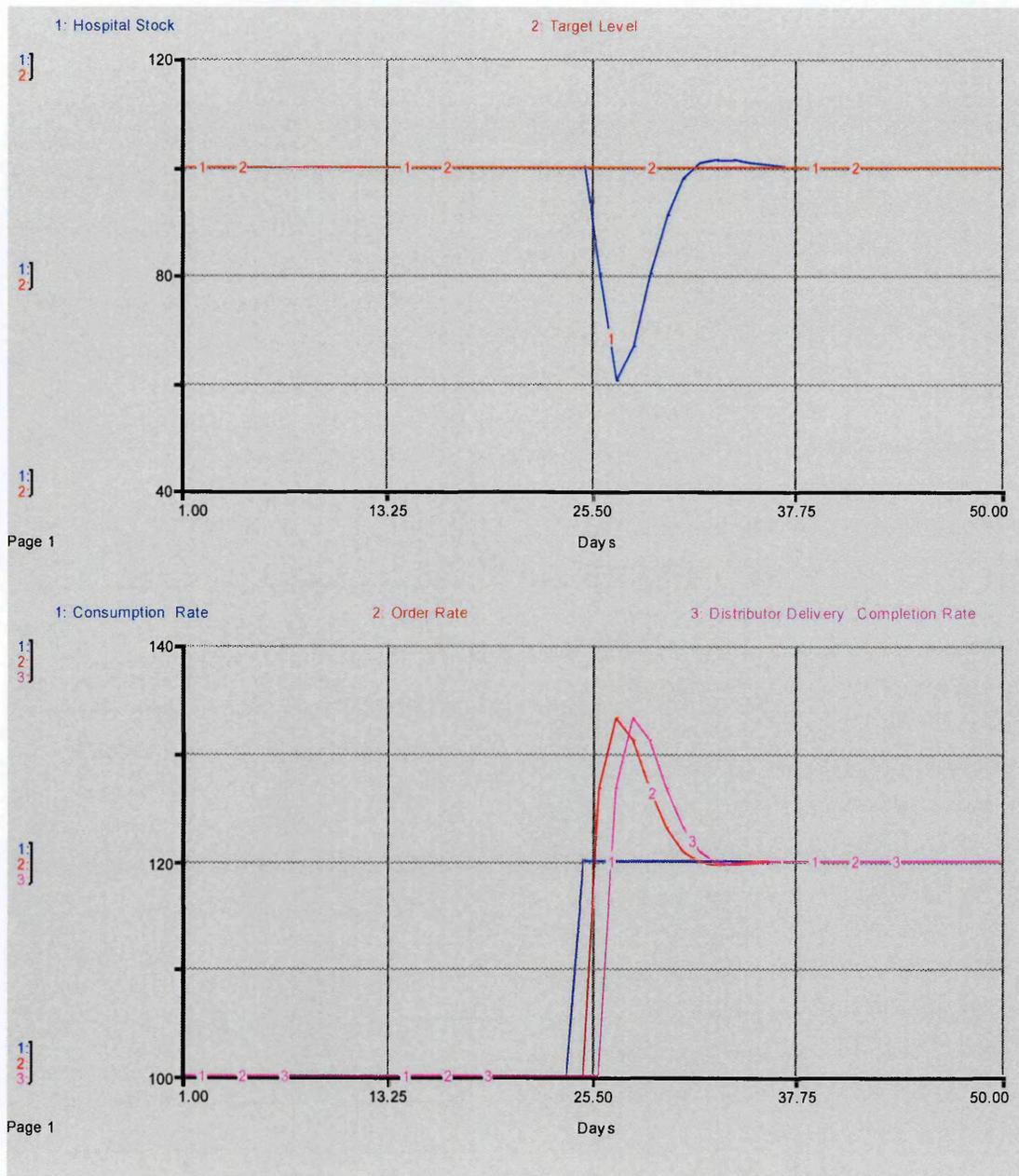
Figure 3.10: Dynamic behaviour of a hospital logistics system that is using the CR(IOBPCS) inventory control approach for the item of scenario 2 defined in Table 3.5
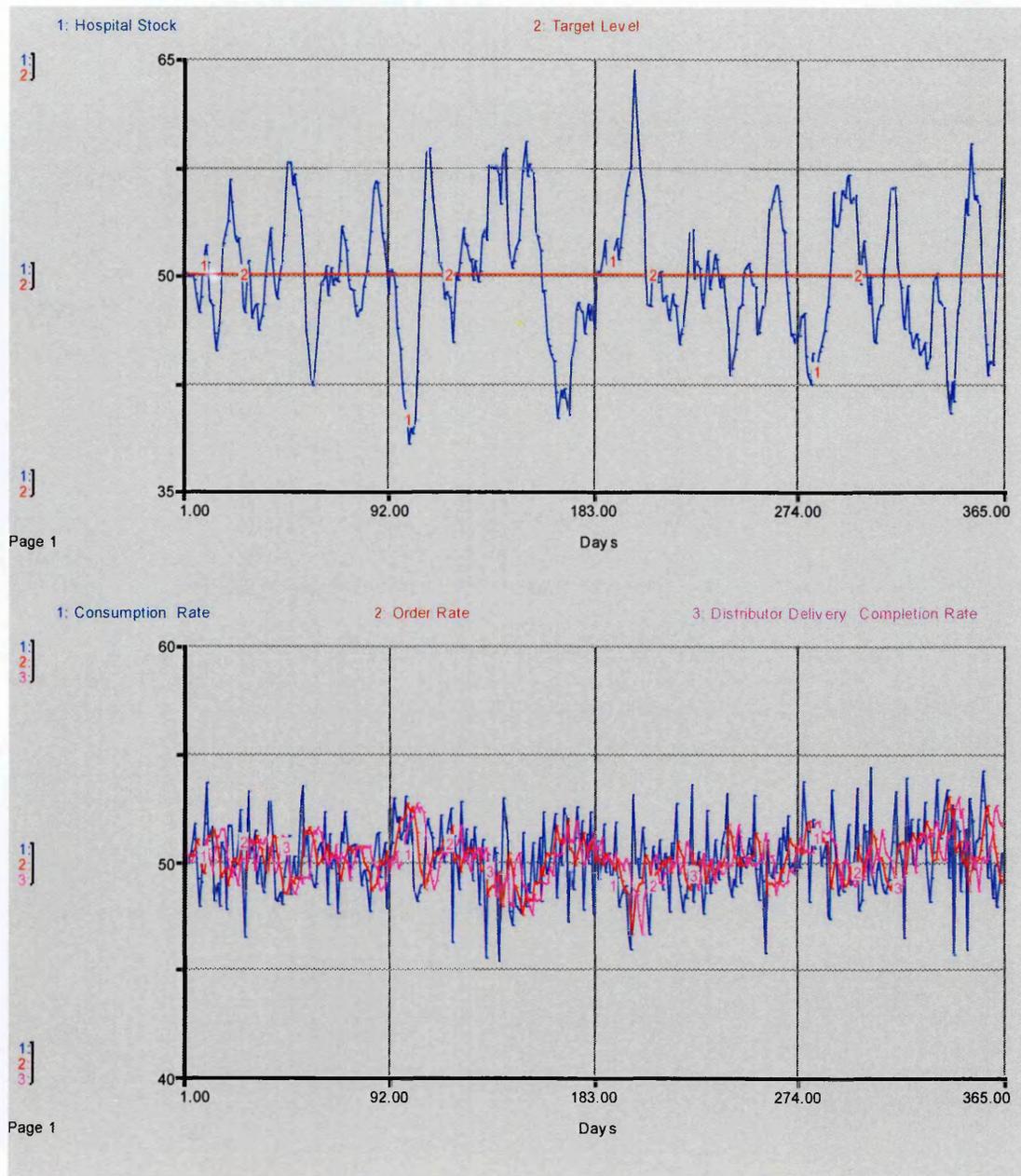
Figure 3.11: Dynamic behaviour of a hospital logistics system that is using the CR(IOBPCS) inventory control approach for the item of scenario 3 defined in Table 3.5

For scenario 1, when *Consumption Rate* is a constant value, Figure 3.9 shows that *Hospital Stock* stays on the *Target Level* as expected, since *Order Rate* is equal to *Consumption Rate*. This also confirms that the CR(IOBPCS) inventory control approach is a "pull" control concept (i.e. what is ordered is controlled by what is consumed and forecasted to be consumed (Coyle *et al.*, 1996)).

In scenario 2, there is a one time abrupt change in the *Consumption Rate* (using 20% STEP function). Figure 3.10 shows that at first there is a drop in *Hospital Stock* to satisfy the initial increase in *Consumption Rate*, followed by a recovery which is facilitated by the increased *Order Rate*. As shown, *Order Rate* not only changes its value to match the new *Consumption Rate*, but at first it overshoots *Consumption Rate* to make up the deficit in *Hospital Stock*. How fast the recovery in *Hospital Stock* and how much *Order Rate* overshoots *Consumption Rate* is determined by the ratios of (T_a / T_p) and (T_i / T_p). **Appendix E** explains in detail how the ratios $(T_a / T_p) = 1$ and $(T_i / T_p) = 3$ are chosen based on a trade off between *Hospital Stock* response and *Order Rate* response.

In scenario 3, *Consumption Rate* is represented, more realistically, as a Normal Distributed function, which can be thought of as a sequence of STEP increase and STEP decrease functions. As shown in Figure 3.11, *Hospital Stock* fluctuates around the *Target Level*. It also shows that when using the CR(IOBPCS) inventory control approach the *Inventory Control Decisions* are linear, generating a smooth continuous-time *Order Rate* based on *Consumption Rate* (feedforward) as well as *Hospital Stock* (feedback).

It is important to note that IOBPCS forms the basis of a generic family of dynamic manufacturing ordering and control models (Ferris and Towill, 1993). Since the manufacturing ordering and control decisions for this generic family are linear, they have been largely analysed by control theory techniques; using signal flow diagrams, block diagrams, *s/z* transforms, "hard system" control laws, frequency response plots and simulation, for example by Towill (1982), Ferris and Towill (1993), John *et al.* (1994), Towill and Del Vecchio (1994), Disney and Towill (2002), and Dejonckheere *et al.* (2003). Since most of the models in the IOBPCS generic family usually contain no more than three design parameters, control theory techniques were found useful to optimise the values of these parameters based on different performance characteristics.

However, since the CR(IOBPCS) model in this research contains only two design ratios (i.e. (T_a / T_p) and (T_i / T_p)), this author used an easy and straightforward way to find the optimum values of these parameters by quantifying some basic performance characteristics (as explained in **Appendix E**) directly from the generated dynamic behaviour of the system.

3.6 Comparison Between (*R*, *s*, *S*) and CR(IOBPCS) Inventory Control Approaches

Table 3.6 illustrates the main observations made by this author between the (*R*, *s*, *S*) and CR(IOBPCS) inventory control approaches based on the results of the dynamic analysis explained in section 3.4.2 and section 3.5.2.

Table 3.6: Comparison between (*R*, *s*, *S*) and CR(IOBPCS) inventory control approaches

Key measures	(*R*, *s*, *S*) inventory control approach	CR(IOBPCS) inventory control approach
Order Rate generated by the *Inventory Control Decision*	Triggered	Continuous
Linearity of the *Inventory Control Decision*	Non-linear; generating a sequence of order impulses.	Linear; generating continuous-time order flows.
Optimality of the *Inventory Control Decision*	Based on a trade off between inventory carrying cost and ordering cost	Based on a trade-off between stock fluctuation (i.e. inventory carrying cost and shortage cost) and order rate variations (i.e. transportation cost).
Pull versus push	Includes elements of pull- and push-based strategies	Pull-based strategy

Moreover, based on the results explained in sections 3.4.2 and 3.5.2, this author concludes that the dynamic behaviour of hospitals logistics systems is smoother when using the CR(IOBPCS) inventory control approach than (*R*, *s*, *S*) inventory control

approach. Specifically, with regard to the problem of order batching and the problem of demand amplification encountered when using the (*R*, *s*, *S*) inventory control approach, the CR(IOBPCS) inventory control approach has shown much improved performance.

3.7 Summary

This chapter first explained the development of a general conceptual model of a hospital logistics system, which shows the stocks, material and information flows, and logistics decisions. The dynamic behaviour of inventories in a hospital logistics system, as shown in the conceptual model, is altered by inflows and outflows of material. These inflow and outflow rates are controlled via the decision making at different logistics activities including: inventory control decisions, service level decisions, purchasing decisions, transportation decisions, and warehousing decisions.. The trade-off between various logistics decisions are determined by the overall business strategy for each echelon.

This chapter then explained how to develop quantitative models of health care logistics by developing simulation models of two specific hospital logistics systems: one using a traditional (*R*, *s*, *S*) inventory control approach and the other using continuous replenishment (CR). The computer simulation models were then subjected to dynamic analysis to represent the relative time behaviour in order to evaluate the impact of the inventory control decisions and service level decisions.

Based on the results of the dynamic analysis, this author concludes that when using the (*R*, *s*, *S*) inventory control approach the *Inventory Control Decisions* are non-linear; generating a sequence of order impulses which is known as order batching that can lead to demand amplification in the overall supply chain.

However, the results illustrate that when using the CR(IOBPCS) inventory control approach the *Inventory Control Decisions* are linear, generating continuous-time order flows. Therefore, this author concludes that the dynamic behaviour of a hospital logistics system improves when using the CR(IOBPCS) inventory control approach, specifically with regard to the problem of order batching.

The next chapter provides a step by step implementation of an integrated system dynamics framework proposed to be used for logistics system redesign of two case hospitals: Children's National Medical Center (CNMC) in the United States of America (USA), and Derbyshire Royal Infirmary (DRI) in the United Kingdom (UK).

Chapter Four: Logistics System Redesign of Two Case Hospitals Using an Integrated System Dynamics Framework

4.1 Introduction

The main aim of this chapter is to answer the research questions through conducting two case studies. This chapter begins by discussing the research methods, the adopted approach in choosing the sites and sectors as well as in collecting the data and analysing them. This is followed by a detailed description of the adopted integrated system dynamics framework and how it was applied in the two case studies.

The rest of the chapter demonstrates the implementation of the various stages of the adopted integrated system dynamics framework for supply chain design using the two case hospitals: Children's National Medical Center (CNMC) in the United States of America (USA), and Derbyshire Royal Infirmary (DRI) in the United Kingdom (UK). This chapter illustrates the qualitative and quantitative analysis of the two case hospitals logistics systems, their dynamic behaviour, and the effect of different logistics decisions –specifically inventory control decisions and service level decisions- on their dynamic behaviour. Several operating strategies are then proposed for redesigning the two case hospitals logistics systems. The computer simulation outputs are used to quantify the effect of the different logistics decisions on inventory cost for each operating strategy and thus provide quantitative evidence to support favourable decisions.

This chapter also answers, through conducting the two case studies, one of the main research questions concerning the role of inventory classification when incorporated into the redesigning strategies of health care logistics. This chapter studies the impact of using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items on logistics cost reduction.

4.2 Research Methods

This chapter will answer the research questions which were developed in Chapter Two through modelling, analysing and redesigning the logistics system of two case hospitals using the System Dynamics Methodology. More specifically, the modelling and redesigning of the logistics system of the two case hospitals are proposed to be conducted by adopting the integrated system dynamics framework for supply chain design (shown in Figure 2.4 in Chapter Two). The framework is in itself a holistic structured approach that is consisting of a number of distinct stages that utilises a range of "soft" and "hard" system analysis techniques originating from a variety of disciplines, such as structured interviews, input-output analysis, process flow charts, information flow analysis, influence and block diagrams, control theory and computer simulation. The following sections discuss the adopted approach in choosing the sites and sectors as well as in collecting the data and analysing them. This is followed by a detailed description of the adopted integrated system dynamics framework and how it was applied in the two case studies.

4.2.1 The research sites

The two case hospitals in this research are: Children's National Medical Center (CNMC) in the United States of America (USA), and Derbyshire Royal Infirmary (DRI) in the United Kingdom (UK). The choice of the DRI to be one of the two case hospitals in this research work was made because an earlier elementary study to determine the applicability of the framework in the health care industry has been conducted on this specific hospital by this author as her master's dissertation (Al-Qatawneh, 1998). Therefore, part of the data needed to conduct the DRI case study in this research work was already available. However, to confirm the applicability of the proposed framework in analysing and modelling health care logistics in practice, it was necessary to broaden the scope of this research work to study different operating practices in managing logistics activities. Therefore, it was necessary to conduct another case study and choose another hospital that operates its logistics system in a different way compared to the DRI.

Several comparative studies in the literature (Jost *et al.*, 1995; Savage and Michael, 1995; Rodwin, 1999) that examined the developments in the health care systems of the UK and the USA concluded that both systems represent a study in contrasts. The National Health Service (NHS) in the UK has provided, since 1948, centrally funded and managed and publicly provided medical care, whereas the health care system in the USA is a privately financed and privately organized system with multiple payers. The high level of organization that traditionally existed in the NHS continues to persist even after the reforms, whereas the American health care system historically has been remarkably uncoordinated. Therefore, the decision was made to choose the second case hospital from the USA. Accordingly, this study was set in a comparative context to analyse a private sector health care provider from the USA (Children's National Medical Center (CNMC)) and a public sector trust in the UK (Derbyshire Royal Infirmary (DRI)) with a view to tracing out the differences in the operating practices in terms of managing logistics activities.

4.2.2 Data collection and analysis

Two types of data are needed to be collected during conducting the two case studies at different stages of the adopted integrated system dynamics framework. The first type of data is needed to be collected at the qualitative phase of the framework (discussed in section 4.2.3.1) to acquire sufficient knowledge and understanding of the structure and operation of the two case hospitals logistics systems. The study addressed this research objective by gathering qualitative data from interviews with the Materials Management Director of the CNMC and the Supplies Manager of the DRI. There was no need to interview other people in the two case hospitals since both the Materials Management Director of the CNMC and the Supplies Manager of the DRI are considered the key individual responsible for managing the logistics system in their hospital. Therefore, they have the complete picture of the structure and operation of their logistics system. Moreover, in addition to interviewing the key member responsible for the logistics system, data collection included site visits and review of hospital documents (e.g. hospital brochures, hospital website documents, in-house reports, etc.). All the interviews were transcribed verbatim and memos were written to summarise information from selected hospital documents. The transcribed interviews and the summary memos constituted the data set used for analysis.

The second type of data is needed to be collected for several sample items to test and validate the computer simulation model developed at the quantitative phase of the framework (discussed in section 4.2.3.2). These sample items were selected to be representative of the overall demand pattern as experienced by the system. Accordingly, the variables that are used in the simulation process (e.g. average demand, transit time, unit cost, etc.) for the example items were collected from the respective hospital. The output data calculated from all simulation runs were summarised in spreadsheets using Microsoft Excel Software. The spreadsheet data were then used to construct graphs of average stock, number of orders, and inventory cost.

4.2.3 An integrated system dynamics framework for supply chain design

Figure 2.4 in Chapter Two illustrates the salient features of the integrated system dynamics framework for supply chain design. The framework consists of several steps, which go under two overlapping phases: qualitative phase, and quantitative phase. Although various stages involved are shown as sequential activities, the method is an iterative procedure, which is represented by the feedback loops in Figure 2.4.

Essentially, the framework decomposes the design problem into two parts: conceptual problem and technical problem, and thereby recommends using qualitative and quantitative phases to negotiate the respective problems.

4.2.3.1 The qualitative phase

The qualitative phase is related to acquiring sufficient intuitive and conceptual knowledge to understand the structure and operation of the supply chain (Hafeez *et al.*, 1996), which in turn can help in recognising and defining the conceptual problem. The main steps involved in this phase are system input-output analysis (IOA), conceptual modelling, and block diagram formulation. IOA helps to identify major systems and the balancing of input and output flows between them (Mason-Jones *et al.*, 1998). In the present research work, the author used content analysis, interviews, Pareto analysis, and information flow analysis to conduct case studies.

Conceptualisation is an important step in the methodology, since the mental model of the system developed during the system analysis stage is made explicit by creating special diagrams (Wolstenholme, 1990). In developing the conceptual model, the main variables that have a dominant impact on the functioning and performance of the system are sought, and relative cause and effect relationships and other interactions are mapped into information-feedback loops. The feedback loops in the model are commonly diagrammed using either sock-flow diagrams or causal-loop diagrams (Albin, 1997). These diagrams are alternatively known as pipe diagrams and influence diagrams respectively (Wolstenholme, 1990). In this research work, both causal-loop diagrams and stock-flow diagrams were used as mediums of conceptualization. Stock-flow diagrams were drawn using the *ithink* Analyst Software - one of the industry standard system dynamics software.

The first step toward the move into the quantitative phase is to transform the conceptual model into a block diagram. The block diagram will be used to construct the exact relationships between various interacting variables in the conceptual model by including mathematical notation that, for example, may represent delays (Naim and Towill, 1994). The conceptual model and the block diagram are then verified by the concerned people. In this research work, block diagrams were not used because the *ithink* Analyst Software allows the creation of stock-flow diagrams directly on the computer screen as icons and constructs appropriate mathematical relationships between key variables automatically (Wolstenholme, 1999; Richmond, 2001).

4.2.3.2   The quantitative phase

The conceptual understanding sets the scene to solve the associated technical problem. The quantitative phase concerns the development and analysis of mathematical and simulation models. There are three possible techniques for developing the quantitative model, which include: control theory, computer simulation, and statistical analysis. Naim and Towill (1994) explained the difference between these techniques. In this research work, computer simulation models were developed using the *ithink* Analyst Software. In this software, the equation structure underlying the model diagram is of vital importance. The equations created behind the scenes when stocks and flows are

hooked together are known as "Finite Difference Equations" (See Appendix B to learn about the *ithink* Analyst Software simulation algorithm).

Whichever technique is chosen, the quantitative model should be subsequently verified by the concerned people and then validated against field data to see whether it can accurately reproduce past statistical data as observed in the real system. However, Wolstenholme (1990) argues that in system dynamics models, validity is seen as a more complex concept that centres on users' confidence in the model, its general behaviour characteristics and its ability to generate accepted responses to policy changes. Once the model has satisfied basic validity tests, it can be subjected to extensive dynamic analysis to represent the time behaviour of the system, and then suggest improving strategies by fine tuning its existing parameters, or redesigning its structure, or exploring different what-if scenarios. Subsequently, the developed model –as best described by Hafeez *et al.* (1996) - may be viewed as a "Management Information System" to investigate various business strategies.

The following sections demonstrate the implementation of the various stages of the adopted integrated system dynamics framework for supply chain design using the two case hospitals: Children's National Medical Center (CNMC) in the United States of America (USA), and Derbyshire Royal Infirmary (DRI) in the United Kingdom (UK).

4.3 Case Study One: Children's National Medical Center

Purchasing in the USA health sector is a relatively mature area. Usually, small or medium size hospitals increase their buying power by forming a group purchasing organization (GPO). A GPO charges its member hospitals a one-time, up-front fee (Brock, 2003). In return, a GPO provides three essential functions for its member hospitals (Kaldor *et al.*, 2003):

i) Aggregate buying power in order to obtain discounts from manufacturers and distributors

ii) Facilitate and enhance comprehensive product comparison analysis.

iii) Streamline and standardise the purchasing process.

Children's National Medical Center (CNMC) is a member of Premier –one of the biggest GPOs and a leading healthcare alliance enterprise owned by more than 200 independent hospitals and health systems in the USA. This organisation operates or is affiliated with approximately 1,500 local hospitals and other healthcare sites (Norling, 2002). Figure 4.1 shows the CNMC supply chain which includes: product manufacturers, primary and secondary distributors, and the CNMC. As illustrated in Figure 4.1, the CNMC orders its supplies from:

- Primary and secondary distributors: the CNMC orders most of its supplies from one primary distributor and three secondary distributors (see Figure 4.2 for percentage shares of the overall CNMC supplies). In turn, these distributors order their supplies from product manufacturers.

- Product manufacturers: sometimes the CNMC orders its supplies directly from product manufacturers (about 6000 manufacturers) (see Figure 4.2 for percentage shares of the overall CNMC supplies).

4.3.1 Qualitative analysis of the CNMC logistics system

Several meetings were conducted with the Materials Management Director of the CNMC to gain sufficient knowledge and understanding of the structure and operation of their logistics system. The following subsections summarise the analysis and information processing that were performed and the information gathered in these meetings, mainly:

- Input-output analysis (IOA).
- Classification of items.
- Material, information, and cash flows for stock items.
- Material, information, and cash flows for non-stock items.
- Purchasing, warehousing, and transportation decisions.
- Inventory control and service level decisions.
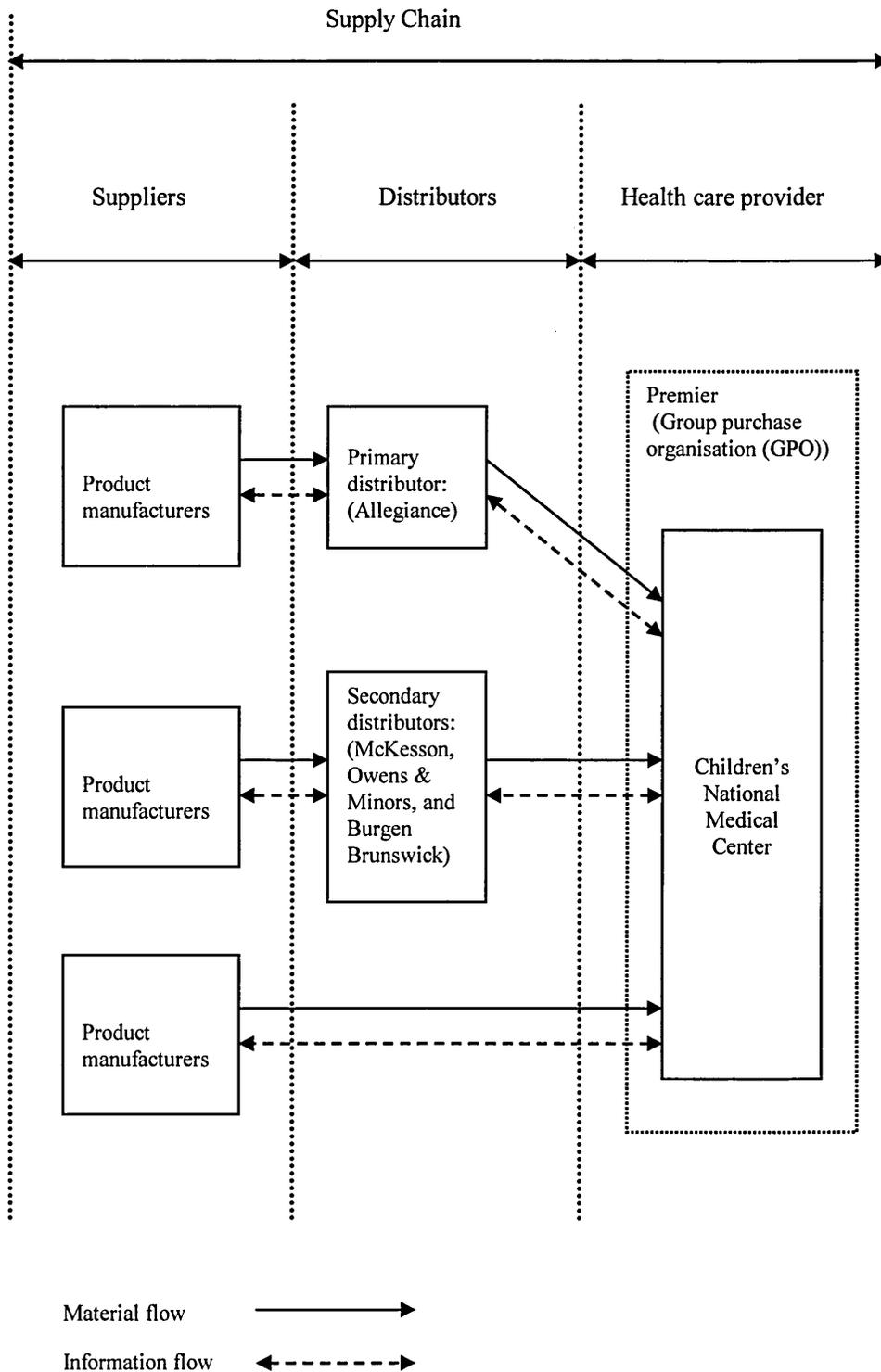
Figure 4.1: The overall material and information flow in the CNMC supply chain
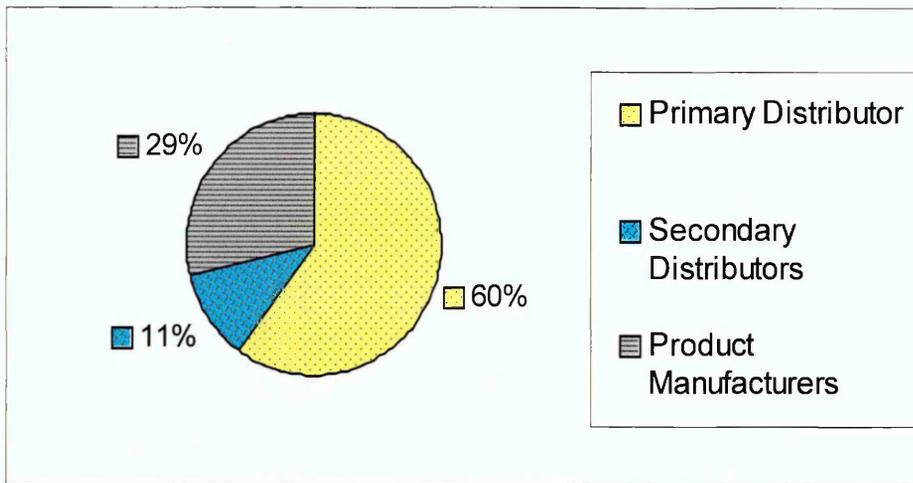
Figure 4.2: Percentage breakdown of suppliers shares for the CNMC

4.3.1.1 Input-output analysis (IOA)

IOA was conducted to identify the major CNMC departments that are involved with the logistics activities and then identify for each department all kinds of input and output flows associated with the logistics activities. As examples, the IOA for the central supply and main warehouse of the CNMC are illustrated, respectively, in Figure 4.3 and Figure 4.4. Subsequently, individual IOA diagrams were then linked together to develop an overall picture of the material, information, and cash flows through the system as described in section 4.3.1.3 and section 4.3.1.4.
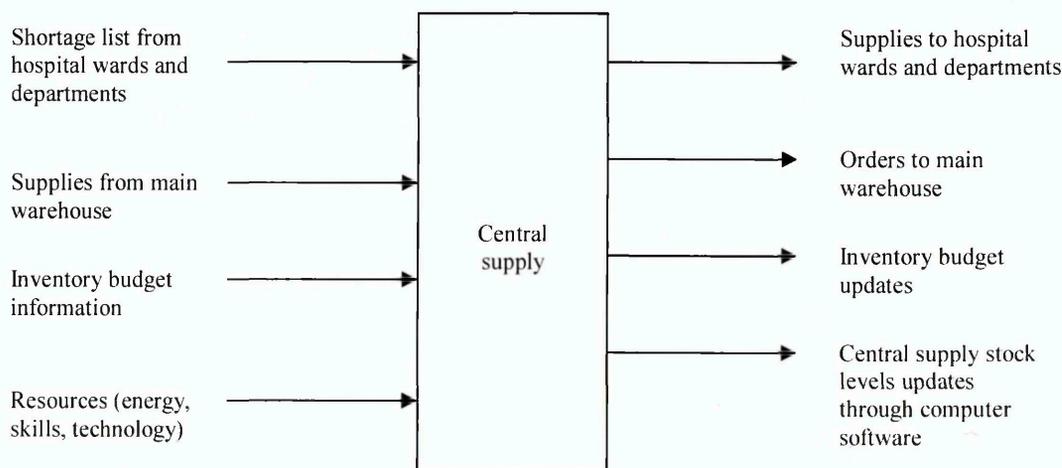
Figure 4.3: Input-output analysis of the central supply at the CNMC

Orders from central supply → Main warehouse → Supplies to central supply

Supplies from suppliers → → Orders to purchase office

Inventory budget information → → Inventory budget updates

Transport information → → Main warehouse stock levels updates through computer software

Resources (energy, skills, technology) → → Transport requirements
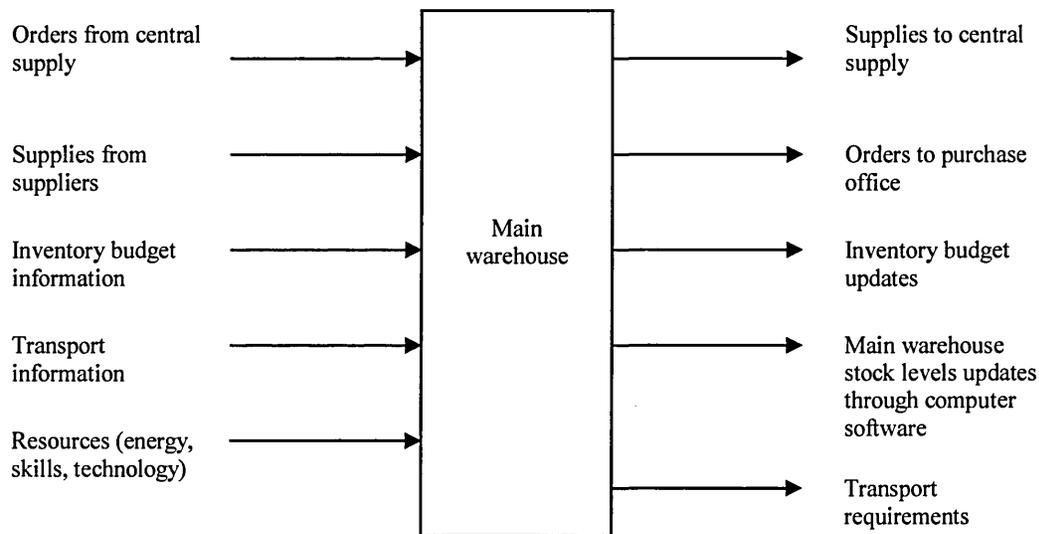
Figure 4.4: Input-output analysis of the main warehouse at the CNMC

4.3.1.2 Classification of items

The items ordered by the materials management department are classified into three types: stock items, non-stock items and special items.

- Stock items (fast moving items): these items are stocked at the main warehouse and represent 98% of all items.

- Non-stock items[1] (slow moving items): these items are delivered directly to the different hospital wards and departments through the hospital receiving dock and they are not stocked at the main warehouse. These items represent about 2% of all items.

- Special items: these are one-time order items.

---

[1] A travelling purchase requisition (TPR) card is issued for non-stock items. This card has all the requisitioning information (quantity, requisition date, supplier ...etc.). One of the purposes of this card is to count how many times it is requested by different wards and departments, and therefore to see if it has to be considered as a stock item or not.

The classification above is based upon the following criteria:

- If an item is used by the hospital 12 times/year, this is to be stocked at the main warehouse.

- If an item –after being considered as a stock item- is used less than 3 times/year in the following year, it will not be stocked at the main warehouse and will be considered as a non-stock item.

4.3.1.3 Material, information, and cash flows for stock items

Figure 4.5 illustrates the material, information, and cash flows for stock items. Different wards and departments consume supplies when conducting services to patients. This causes a decrease in the wards' and departments' stocks. The central supply checks the wards' and departments' stock levels every 24 hours. They simply count manually what is on shelves, and fill in a prewritten list of all items in stocks. Then they top up these stocks daily to a predetermined level from the central-supply-storage area. The central supply works as an internal distribution system.

The central supply uses special computer software to determine its stocks' levels. When these levels fall below a predetermined level, an order is filled and sent to the main warehouse, which is located one mile away from the hospital. The main warehouse then meets the central-supply demand and checks its stocks' levels on the software system. When the main warehouse levels fall below a predetermined limit, an order is filled and sent to the hospital purchase office. In response, the purchase office sends a purchase order to suppliers (primary distributor, secondary distributors, or product manufacturers), and an electronic copy of the purchase order to the accounts payable office (under the finance department).

Suppliers deliver supplies to the main warehouse receiving dock and send an invoice to the accounts payable office. When the receiving dock at the main warehouse receives supplies from suppliers, they fill a receiving note and send it electronically to the accounts payable office. Thereupon, supplies are delivered to the main warehouse.
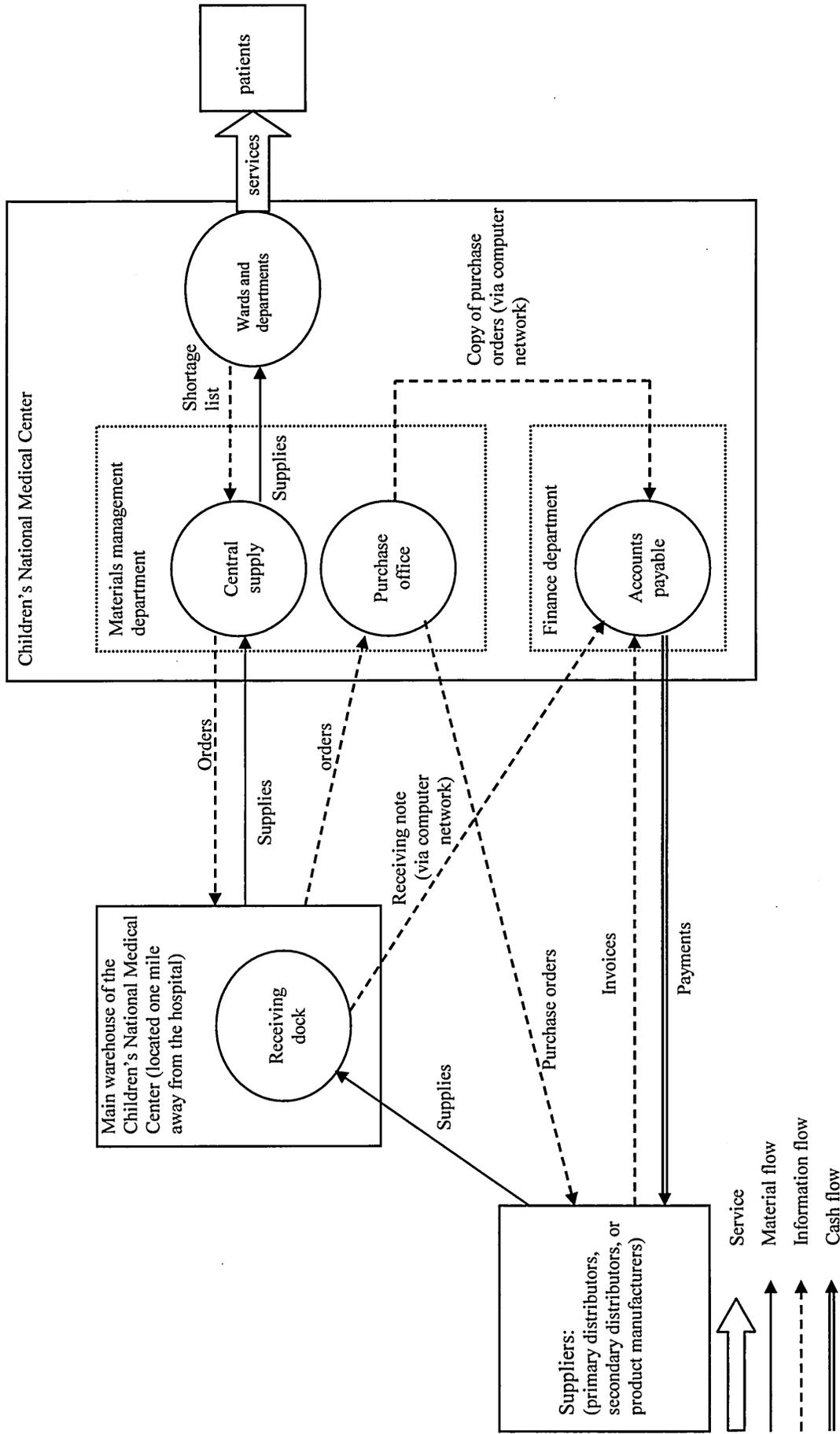
Figure 4.5: Material, information, and cash flows for stock items (CNMC case study)

76

The accounts payable office compares and matches the receiving notes and invoices with the copy of the purchase orders and sends payments to suppliers. Payments are usually sent 30 days after receiving the invoice from suppliers.

4.3.1.4 Material, information, and cash flows for non-stock items

Figure 4.6 illustrates material, information, and cash flows for non-stock items. When wards or departments need a non-stock item, they send a requisition directly to the hospital purchase office. In turn, the purchase office sends a purchase order to suppliers and a copy of that order electronically to the accounts payable office. Suppliers then deliver the items to the hospital's receiving dock and send an invoice to the accounts payable office.

The hospital's receiving dock delivers the item directly to the ward or department that requested that item and sends electronically a receiving note to the accounts payable office. In turn, the accounts payable office matches the receiving note and invoice with the purchase order and sends payments to suppliers after 30 days of receiving the invoice from them.

4.3.1.5 Purchasing, warehousing, and transportation decisions

The purchasing activity is the interface between the CNMC and its suppliers. The interaction of the purchase office with other parts of the logistics system has already been illustrated (see Figure 4.5 and Figure 4.6). Information flow is the only flow that comes in and out of the purchase office from and to the other parts. As shown in Figure 4.5 and Figure 4.6, purchasing is grouped along with other materiel-oriented functions within a single materials management department. The purpose of this strategy is that by combining material procurement with control, many communications lines (i.e. information flows) are shortened.
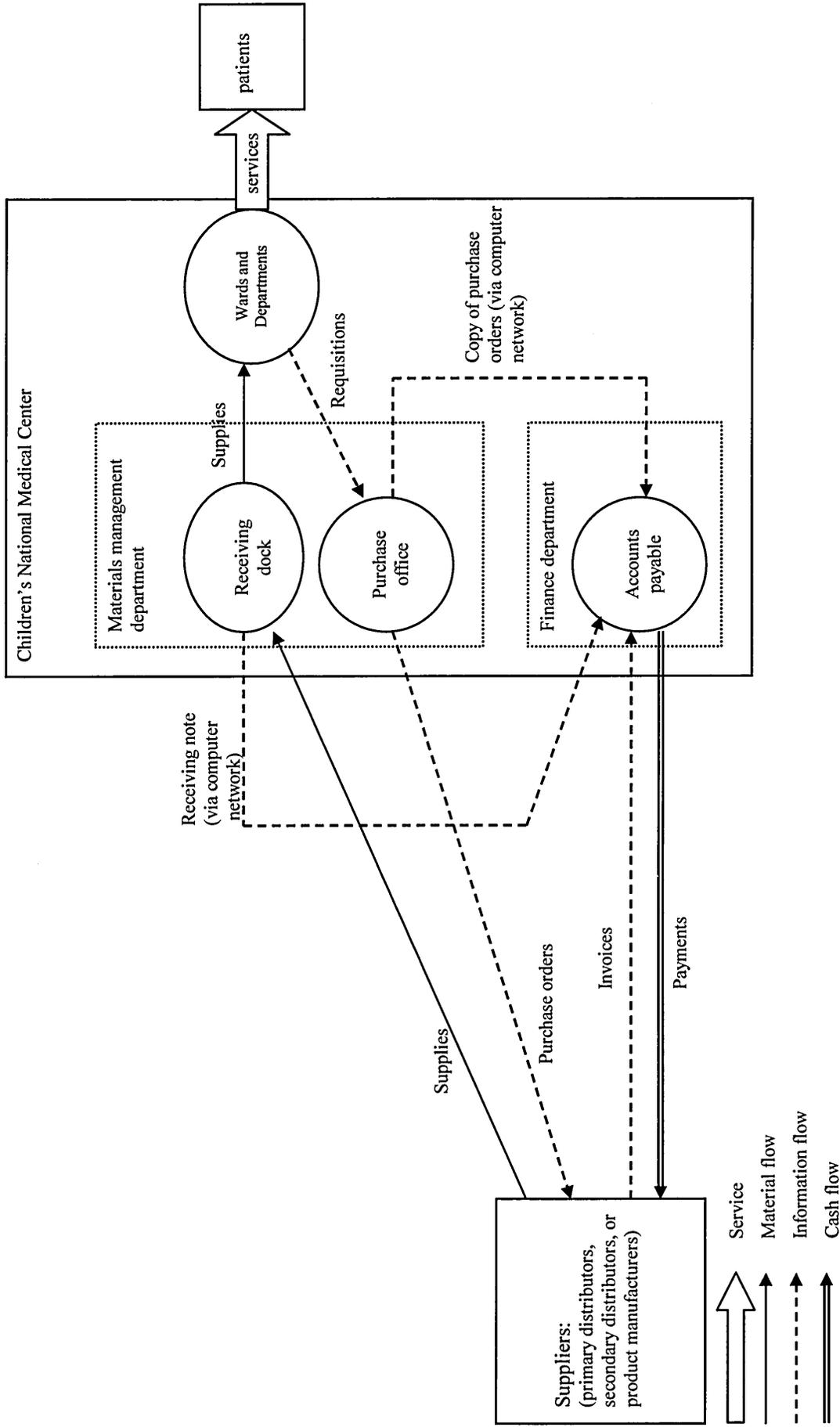
Figure 4.6: Material, information, and cash flows for non-stock items (CNMC case study)

78

At the CNMC there are three different storage areas for stock items: wards and departments stocks, central supply, and main warehouse. Wards and departments stocks are used for stocking items that are used frequently when conducting services to patients. The central supply –located at the hospital site- works as an internal distribution system to replenish the deficiencies in the wards and departments stocks. The main warehouse –located one mile away from the hospital- is used to replenish the deficiencies in the central supply stocks.

The transport used at the hospital and at the main warehouse either belongs to the distributor/product manufacturer or to a third party. However, the transportation within the hospital boundary is owned by the hospital itself. Delivery of supplies between distributors/product manufacturers and the CNMC is conducted daily.

4.3.1.6   Inventory control and service level decisions

The following describe the inventory control and service level decisions for wards and departments stocks, central supply (CS), and main warehouse (MWH).

Wards and departments stocks:

Wards and departments at the CNMC use an (R, S) inventory control approach; where:

- R: review period (time interval between reviews)
- S: order-up-to level

The values of R and S are usually selected based on experience and not algorithmically optimised. Table 4.1 summarises the inventory control and service level decisions for the CNMC wards and departments stocks.

Table 4.1: CNMC inventory control and service level decisions for wards and departments stocks

Inventory control approach	(R, S) (non-optimised)
Description of the approach	Stock level (items on hand) is reviewed at regular instants, spaced at time interval R. At each review an order is placed to bring the inventory to a given level S.
Inventory control decision: • *How Often to Review?* • *When to Order?* • *How Much to Order?*	Inventory status is reviewed at regular instants, spaced at time interval R, where $R = 24$ hours At each review time (i.e. every 24 hours) Order quantity = $(S -$ stock level), where $S = (3\ D)$
Variables used in the decision rule	• D = average demand (number of items per unit time), based on 30 days worth of data

Central supply and main warehouse stocks:

The CNMC central supply and main warehouse use an (R,s,S) inventory control approach; where:

- R: review period (time interval between reviews)
- s: reorder level
- S: order-up-to level

The values of R, s, and S are also usually selected based on experience and not algorithmically optimised. Table 4.2 summarises the inventory control and service level decisions for the CNMC central supply and main warehouse stocks.

Table 4.2: CNMC inventory control and service level decisions for central supply and main warehouse stocks

Inventory control approach	(R, s, S) (non-optimised)
Description of the approach	Inventory position (items on hand plus items on order) is reviewed at regular instants, spaced at time interval R. At each review, if the inventory position is at level s or below, an order of sufficient quantity is placed to bring the inventory to a given level S.
Inventory control decision: • *How Often to Review?* • *When to Order?* • *How Much to Order?*	Inventory status is reviewed at regular instants, spaced at time interval R, where $R = 24$ hours An order is placed: If (inventory position) $\leq s$, where $s = D(L+R) +$ Safety stock Safety stock $= (14\ D)$ Order quantity $= (S -$ inventory position), where $S = s\ +\ EOQ$ $EOQ = \sqrt{\dfrac{2AD}{H}}$ The economic order quantity (EOQ) is the optimal quantity –under the condition of certainty- needed to replenish inventory based on a trade-off between inventory carrying cost and ordering cost.
Variables used in the decision rule	• D = average demand (number of items per unit time) • L = average lead time (units of time) • A = ordering cost (\$ per order) • c = cost of an item (\$ per item) • r = inventory carrying charge (fraction per unit time) • $H = cr$ = holding cost of an item (\$ per item per unit time)

4.3.2 Conceptual model[2] of the CNMC logistics system

As mentioned earlier, in this case study, both causal-loop diagrams and stock-flow diagrams were used as a medium of conceptualisation. Figure 4.7 shows a causal-loop diagram of the CNMC logistics system for stock items. The causal-loop diagram, being simple to understand, was used as a tool to communicate with the Materials Management Director. A stock-flow diagram of the CNMC logistics system for stock items, shown in Figure 4.8, was developed using the *ithink* Analyst Software to develop the simulation model. Both the causal-loop diagram and the stock-flow diagram were verified by the Materials Management Director who confirms that both models are representative of the decision rules related to the different logistics activities as adopted by the materials management department.

The author would like to point out that in the causal-loop diagram (shown in Figure 4.7) there are four stocks: wards and departments stocks, Central Supply (CS) stock, Main Warehouse (MWH) stock, and suppliers stock. However, in the stock-flow diagram (shown in Figure 4.8) there are two stocks: *CS Stock* and *MWH Stock*; consumption of all wards and departments is represented as *Consumption Rate* and delivery from suppliers is represented as *Suppliers Delivery Rate*.

4.3.3 Computer simulation model of the CNMC logistics system

A computer simulation model of the CNMC logistics system (for stock items) was developed using the verified stock-flow diagram shown in Figure 4.8. The simulation model was developed using the *ithink* Analyst Software. **Appendix F** provides all the equations that make up the simulation model. The main variables in the computer simulation model are: *Consumption Rate, Average Demand, MWH To CS Average Transit Time, CS Average Order Processing Delay Time, Ordering Cost, Item Unit Cost, Inventory Carrying Charge, Suppliers To MWH Average Transit Time*, and *MWH Average Order Processing Delay Time*. The verified model was subjected to extensive dynamic analysis as explained in the subsequent subsections.

---

[2] In this case study, conceptual modelling and computer simulation modelling were conducted for stock items only, as they represent 98% of all items.
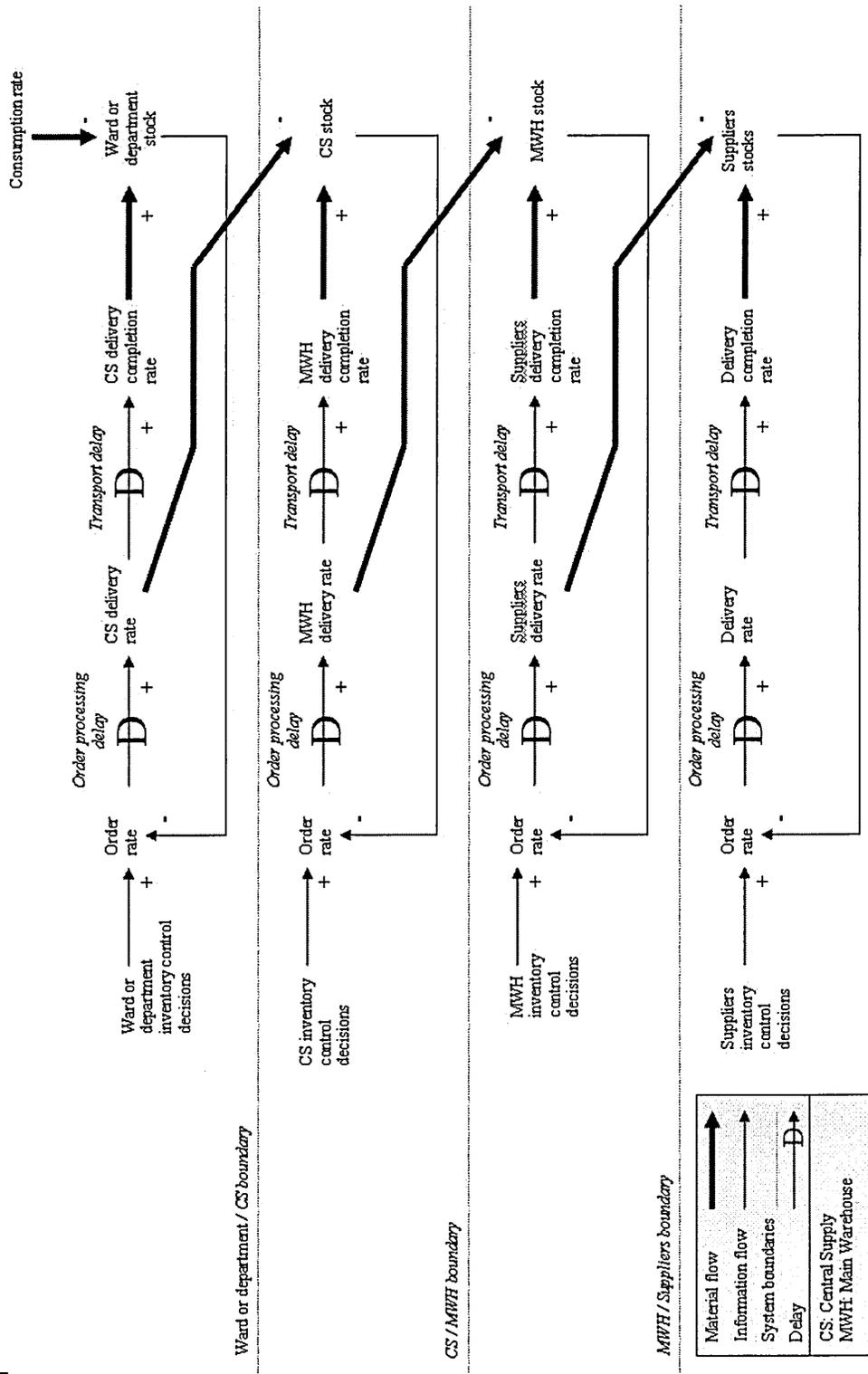

Figure 4.7: Causal-loop diagram of the CNMC logistics system for stock items

83
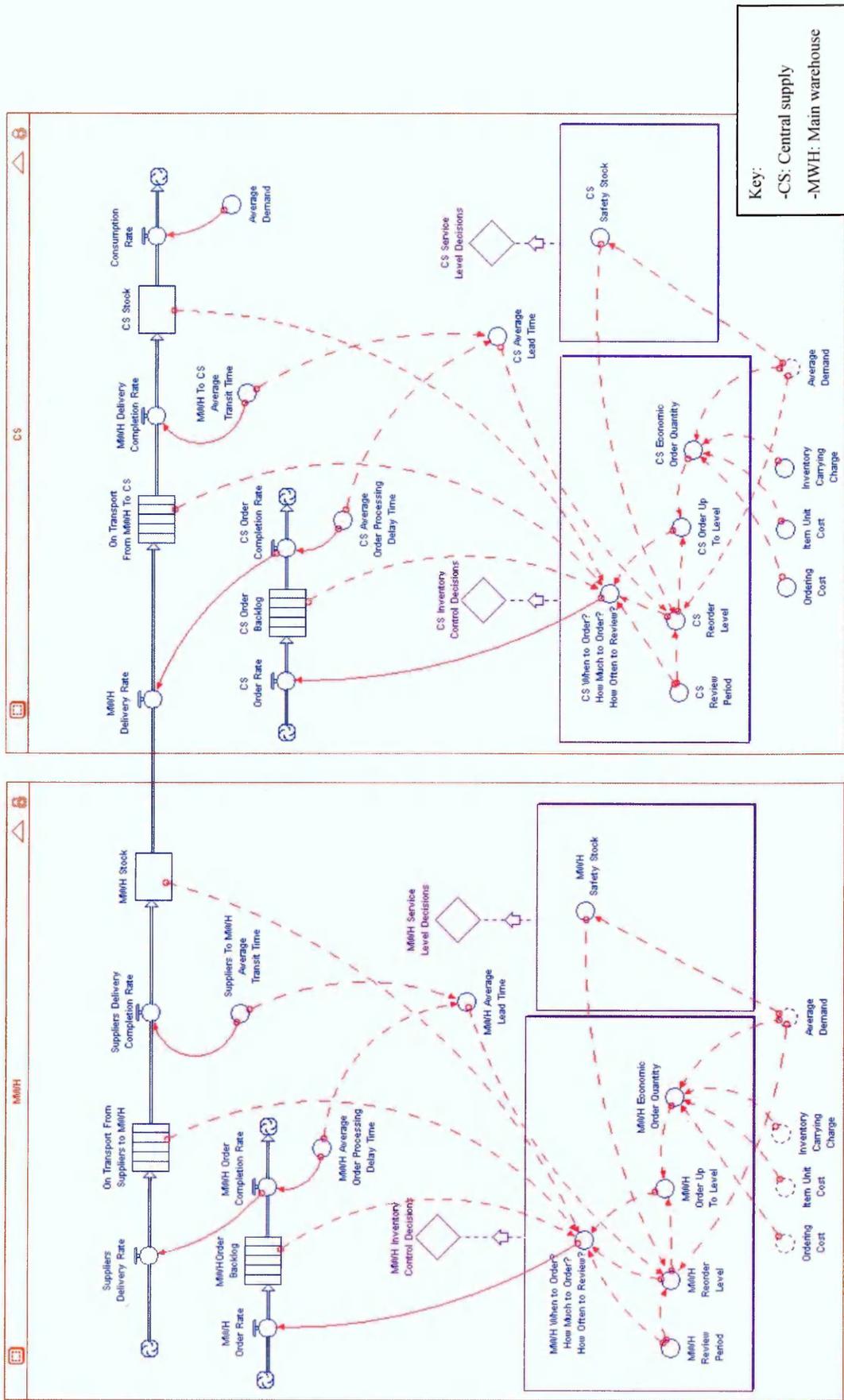
Figure 4.8: The stock-flow diagram of the CNMC logistics system for stock items

84

4.3.4 Dynamic analysis

The computer simulation model of the CNMC logistics system was tested for four stock items, namely, scalpel sterile disposable (low value and low demand), container specimen sterile (low value and high demand), oxygenator membrane (high value and low demand), and bottle aerobic fan (moderate value and high demand). These items were selected to be representative of the overall demand pattern as experienced by the system. The variables that are used in the simulation process for the example items are defined in Table 4.3. The demand data used is for one month and daily averages are found.

Figure 4.9 to Figure 4.12 show the dynamic behaviour of the CNMC logistics system for the four example items, respectively: scalpel sterile disposable, container specimen sterile, oxygenator membrane, and bottle aerobic fan. Each figure shows *CS Stock, CS Order Up To Level, CS Reorder Level, Consumption Rate, CS Order Rate, MWH Delivery Completion Rate, MWH Stock, MWH Order Up To Level, MWH Reorder Level, MWH Order Rate*, and *Suppliers Delivery Completion Rate*.

As shown in Figure 4.9 to Figure 4.12, *CS Stock* depletes gradually till it reaches *CS Reorder Level*. At the first *Review Time* that follows this condition, an order is generated. Therefore, at this *Review Time*, *CS Order Rate* is a pulse of height (Q/dt), where Q is the ordered quantity given by equation in Table 4.2. After a time (equal to *CS Average Lead Time*), *MWH Delivery Completion Rate* is a pulse of height (Q/dt) which causes *CS Stock* to increase its level by a value of Q. As a result, the dynamic behaviour of *CS Stock* resembles a sawtooth pattern. Out of the four items analysed, the oxygenator membrane seems to be more difficult to manage due to its variation in demand and consequent irregular CS Stock pattern (Figure 4.11).

Since *CS Inventory Control Decisions* generates a sequence of order pulses rather than continuous-time order flows, *MWH Stock decreases* abruptly in an amount equal to Q at each pulse of *CS Order Rate*. For this reason, the dynamic behaviour of MWH Stock resembles a square wave rather than a typical sawtooth pattern.

Table 4.3: The variables that are used in the simulation process for the example stock items

| Month/Year	Scalpel sterile disposable		Container specimen sterile		Oxygenator membrane		Bottle aerobic fan	
	Total consumption (items)	Average daily consumption (item/day)	Total consumption (items)	Average daily consumption (item/day)	Total consumption (items)	Average daily consumption (item/day)	Total consumption (items)	Average daily consumption (item/day)
6/98	80	2.7	1031	34.4	8	0.27	911	30.4
7/98	166	5.5	1313	43.8	1	0.03	932	31.1
8/98	307	10.2	1063	35.4	2	0.07	976	32.5
9/98	95	3.2	1466	48.9	8	0.27	858	28.6
10/98	72	2.4	723	24.1	4	0.13	1445	48.2
11/98	129	4.3	1640	54.7	6	0.2	1232	41.1
12/98	79	2.6	1739	58	17	0.57	1350	45
1/99	73	2.4	1407	46.9	12	0.4	1375	45.8
2/99	52	1.7	1455	48.5	2	0.07	1300	43.3
3/99	106	3.5	1504	50.1	10	0.33	2075	69.2
4/99	280	9.3	1320	44	7	0.23	1700	56.7
5/99	133	4.4	1216	40.5	9	0.3	2193	73.1
Average Demand (item/day)	4.4		44.1		0.24		45.4	
MWH To CS Average Transit Time (hours)	4		4		4		4	
CS Average Order Processing Delay Time (hours)	2		2		2		2	
Suppliers To MWH Average Transit Time (hours)	36		36		36		36	
MWH Average Order Processing Delay Time (hours)	12		12		12		12	
Item Unit Cost ($)	0.72		0.16		599		2.95	
Ordering Cost ($)	15		15		15		15	
Inventory Carrying Charge ($/item/day)	30 %		30 %		30 %		30 %	
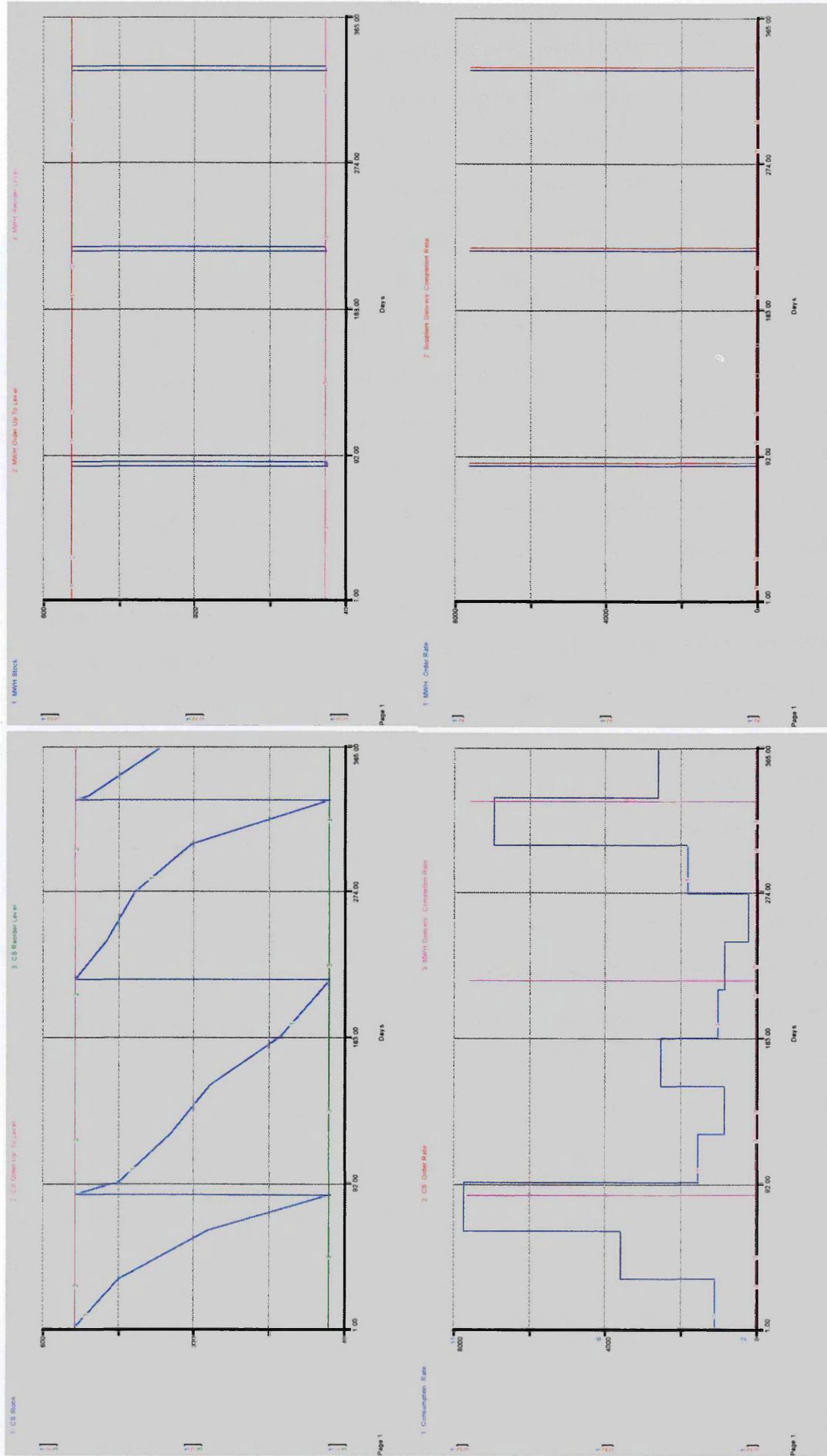
Figure 4.9: The dynamic behaviour of the CNMC logistics system for the example item: scalpel sterile disposable (see Table 4.3)

87
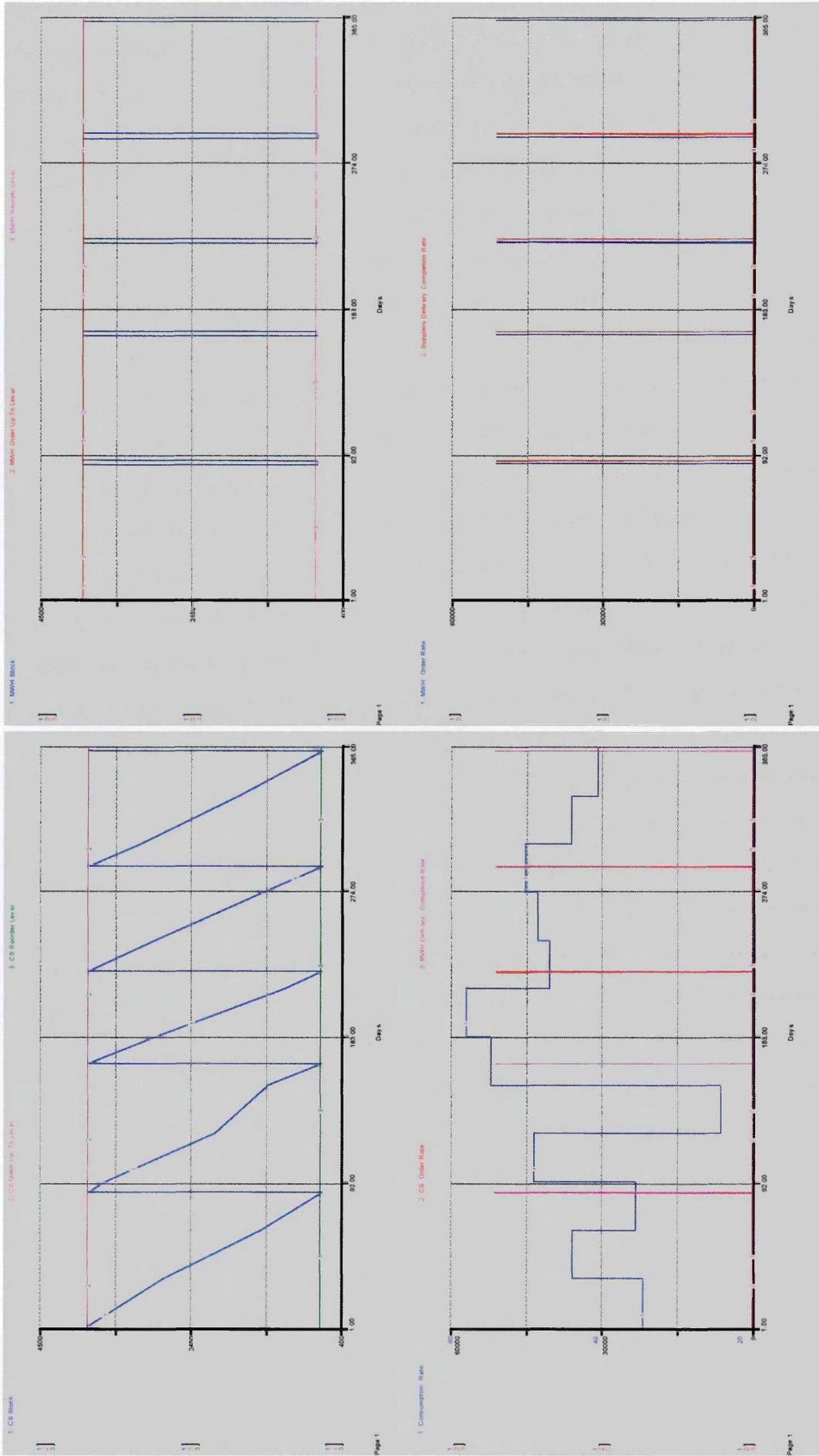
Figure 4.10: The dynamic behaviour of the CNMC logistics system for the example item: container specimen sterile (see Table 4.3)

88
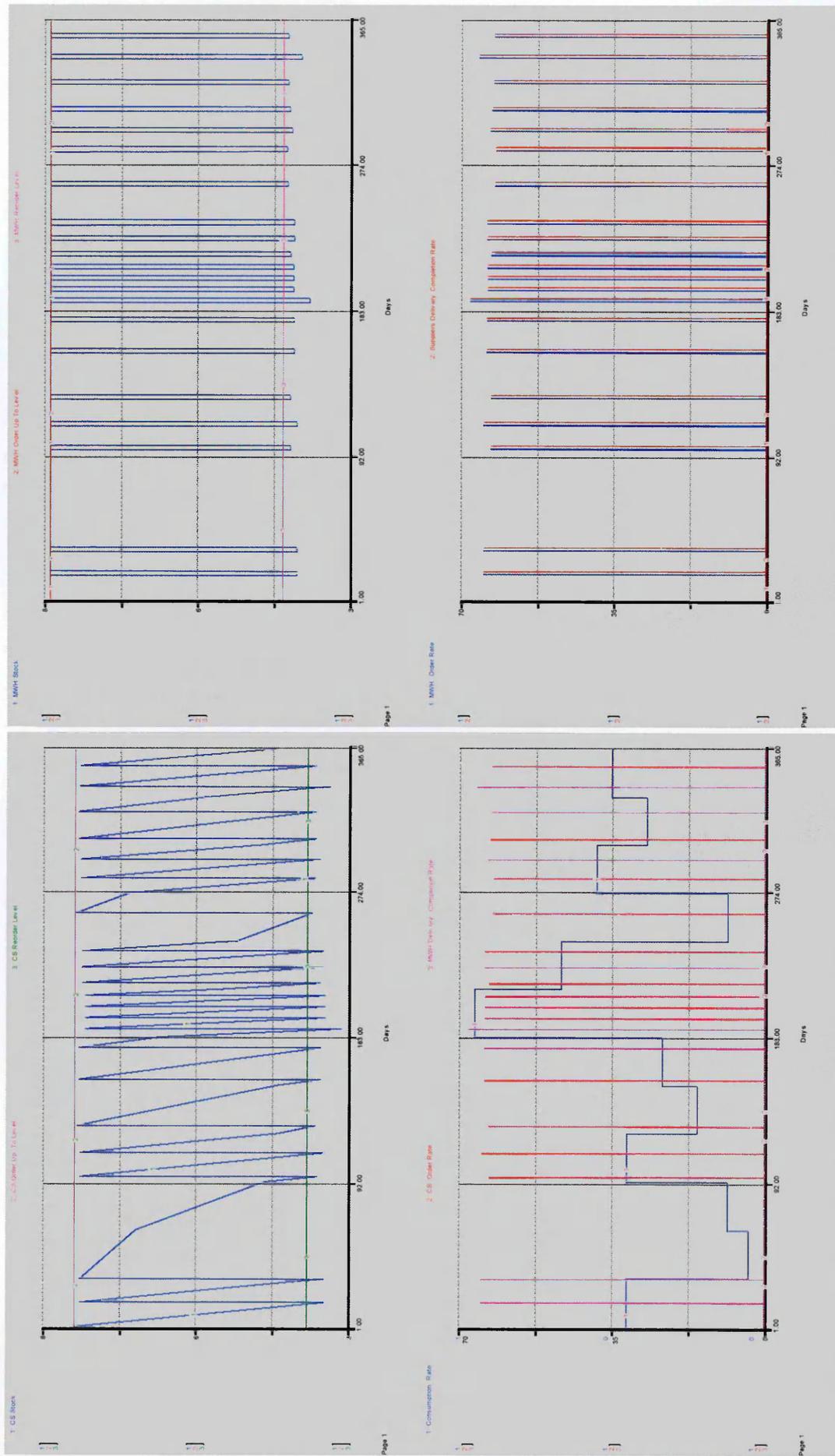
Figure 4.11: The dynamic behaviour of the CNMC logistics system for the example item: oxygenator membrane (see Table 4.3)

89
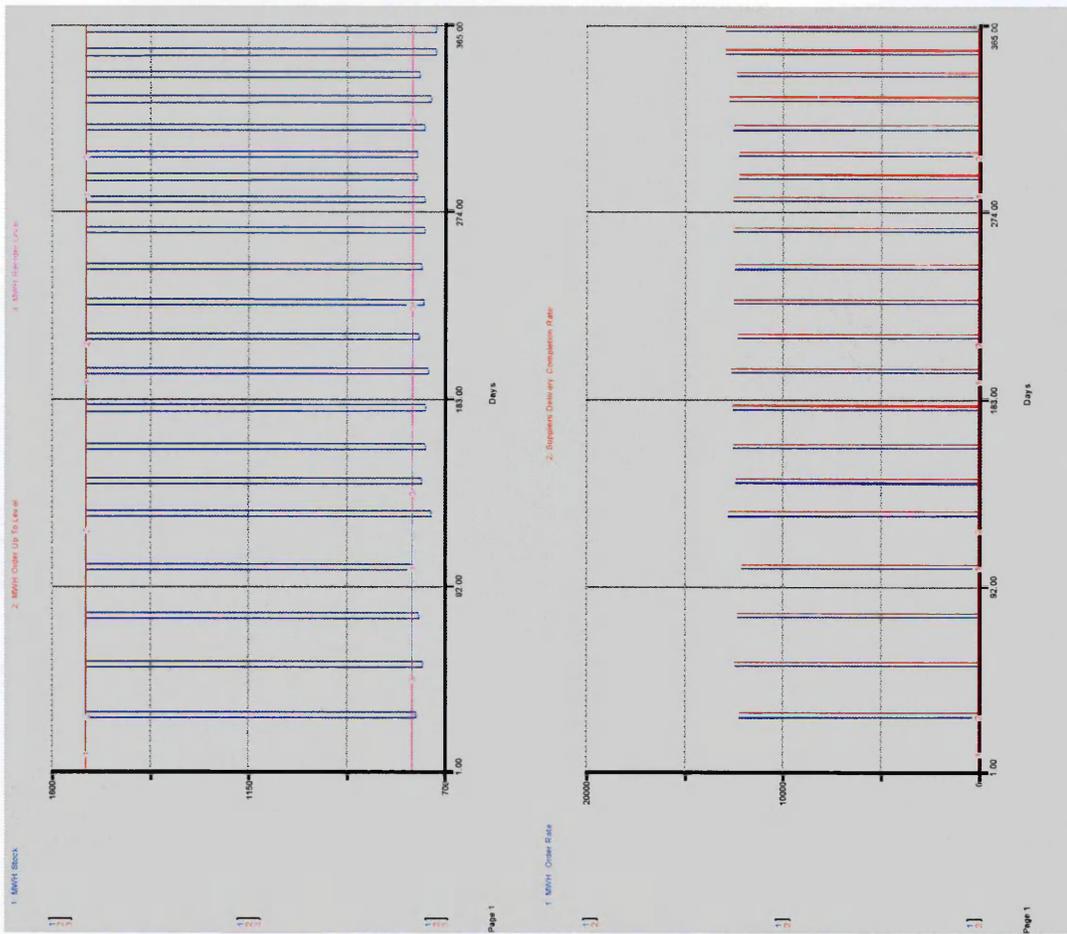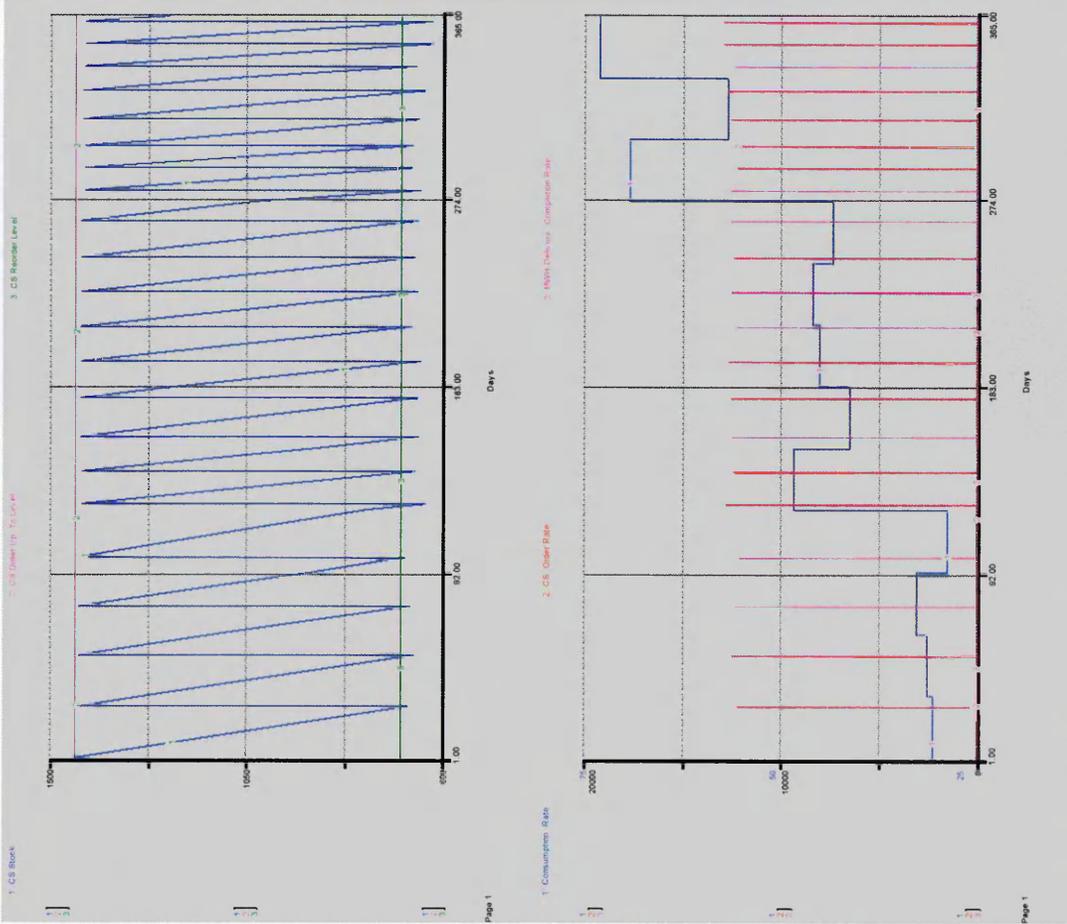
Figure 4.12: The dynamic behaviour of the CNMC logistics system for the example item: bottle aerobic fan (see Table 4.3)

90

Note that the dynamic behaviour of the CNMC logistics system, when CS and MWH use a non-optimised (R, s, S) inventory control approach, behaves similarly to using an optimised (R, s, S) inventory control approach (see section 3.4). Specifically, the occurrence of order batching (i.e. the continuous demand for products has been transmitted to the MWH and then to the distributor as order pulses), which is the main cause of the Burbidge Effect problem.

Moreover, since the (R, s, S) inventory control approach used by CS and MWH is non-optimised, both CS and MWH hold very high stock levels, which was also emphasised by the CNMC Materials Management Director to be one of the drawbacks of their inventory control decisions.

4.3.5 Redesigning the CNMC logistics system

In this section, several operating strategies for the CNMC logistics system are proposed to improve its dynamic behaviour. The aim is to identify the most successful proposed operating strategy in terms of lower inventory cost and which deals with unpredictable demand of a large number of different items. This author would like to point out that the comparison between the current operating strategy of the CNMC logistics system and the proposed strategies is exclusively done for the inventory cost and not in terms of total logistics cost which is equal to (inventory cost + purchasing cost + transportation cost + warehousing cost (Coyle *et al.*, 1996)). This allows the author to focus on evaluating inventory control decisions, which is the main area of concern for this research. However, to make a fair comparison, other costs are fixed, for example transportation costs are fixed by considering daily deliveries for all the compared operating strategies.

An operating strategy contains several decisions: inventory control decisions, service level decisions, purchasing decisions, transportation decisions, and warehousing decisions. The current operating strategy of the CNMC logistics system and the proposed strategies are explained in Table 4.4. Figure 4.13 to Figure 4.17 show the stock-flow diagram of the CNMC logistics system, respectively, for the following operating strategies: "current situation", (R,s,S), (R,s,S)(eliminate), CR(IOBPCS), and CR(IOBPCS) (eliminate).

Table 4.4: Summary of the current operating strategy of the CNMC logistics system and the proposed operating strategies for redesigning the CNMC logistics system

Name of operating strategy	Inventory control decisions	Service level decisions	Purchasing decisions	Transportation decisions	Warehousing decisions
1- "current situation":	Non-optimised (R,s,S) inventory control approach. Stock level is checked manually.	100 % service level for all items. Safety stock is equal to two weeks worth of stock.	Paper/Fax-based requisitioning and ordering.	Daily deliveries.	Having two main stocks: central supply and main warehouse.
2- (R,s,S):	(R,s,S) inventory control approach. Stock level is checked manually.	100 % service level for all items. Service level factor (k) =3 (see Table 2.1)	Paper/Fax-based requisitioning and ordering.	Daily deliveries.	Having two main stocks: central supply and main warehouse.
3- (R,s,S)(eliminate):	(R,s,S) inventory control approach. Stock level is checked manually.	100 % service level for all items. Service level factor (k) =3 (see Table 2.1)	Paper/Fax-based requisitioning and ordering.	Daily deliveries.	Having one main stock: central supply (i.e. main eliminating warehouse).
4- CR(IOBPCS):	CR(IOBPCS) inventory control approach. Stock level is checked using electronic POU*.	100 % service level for all items. Service level factor (k) =1 (see Table 2.4)	Electronic requisitioning, primarily EDI ordering.	Daily deliveries.	Having two main stocks: central supply and main warehouse.
5- CR(IOBPCS) (eliminate):	CR(IOBPCS) inventory control approach. Stock level is checked using electronic POU*.	100 % service level for all items. Service level factor (k) =1 (see Table 2.4)	Electronic requisitioning, primarily EDI ordering.	Daily deliveries.	Having one main stock: central supply (i.e. main eliminating warehouse).

* POU: Point of use (POU) equipment is an automatic dispensing system that provides secured storage of supplies close to where the supplies are used.
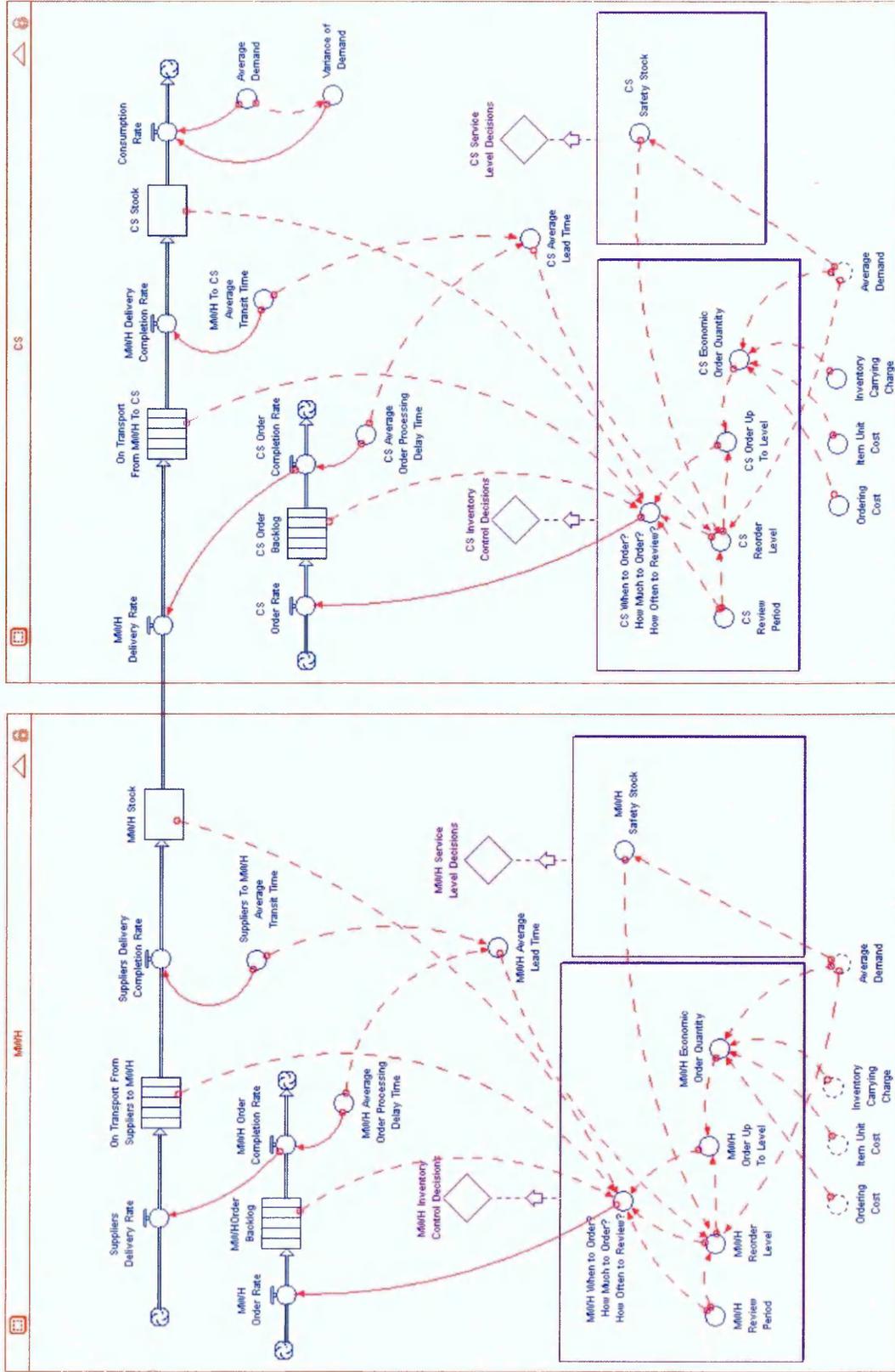
Figure 4.13: The stock-flow diagram of the CNMC logistics system for the "current situation" operating strategy (see Table 4.4)
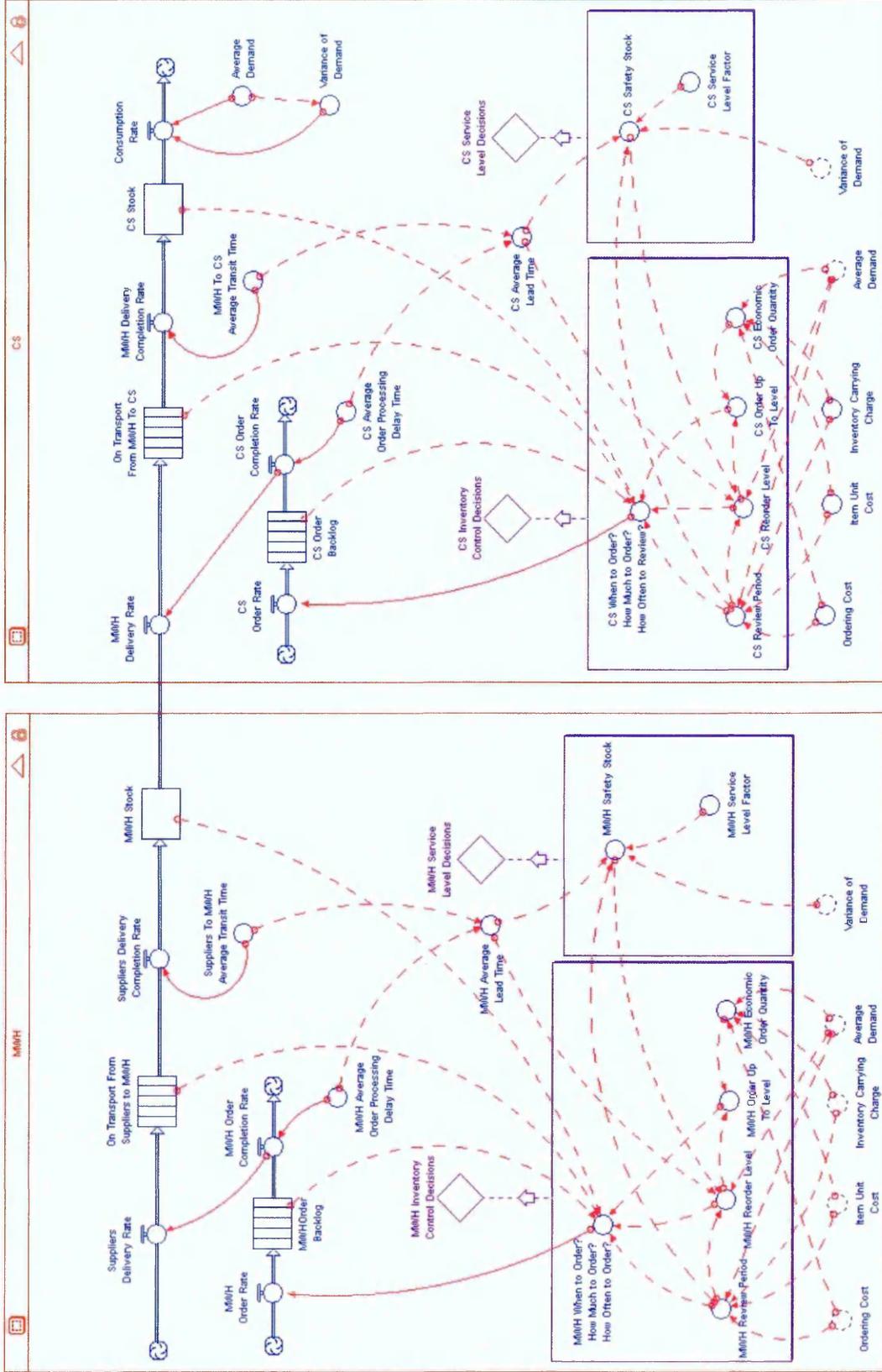
Figure 4.14: The stock-flow diagram of the CNMC logistics system for the (R,s,S) operating strategy (see Table 4.4)
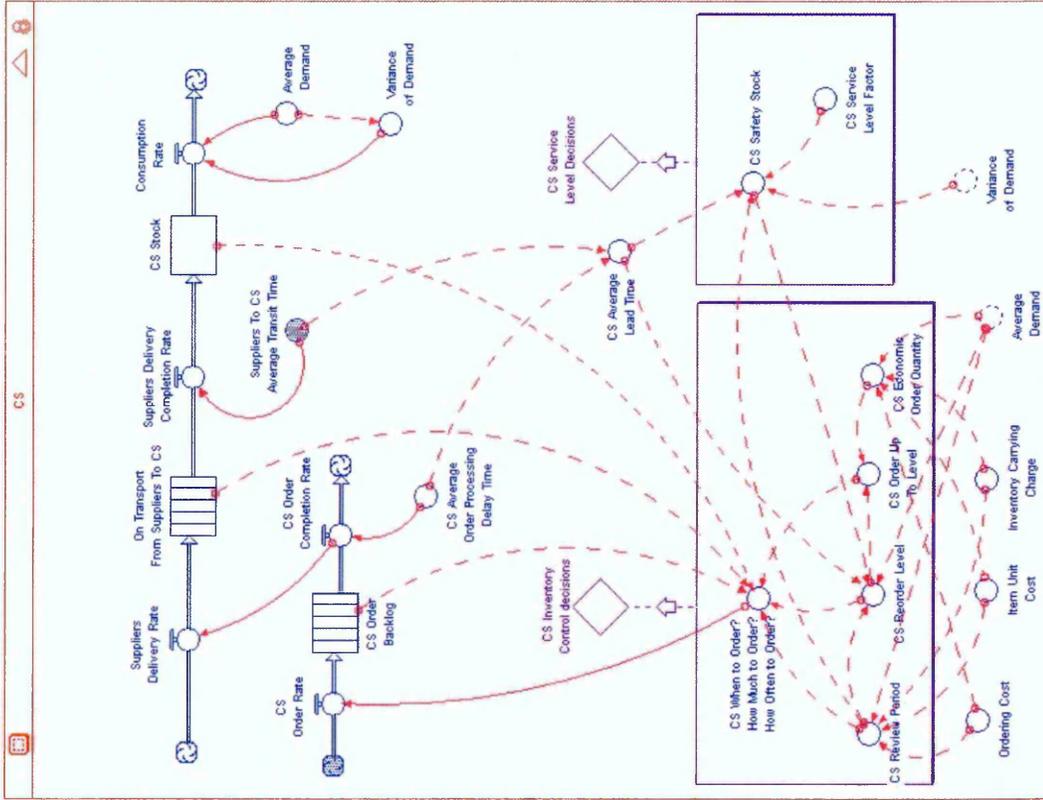
Figure 4.15: The stock-flow diagram of the CNMC logistics system for the (*R*,*s*,*S*)(eliminate) operating strategy (see Table 4.4)
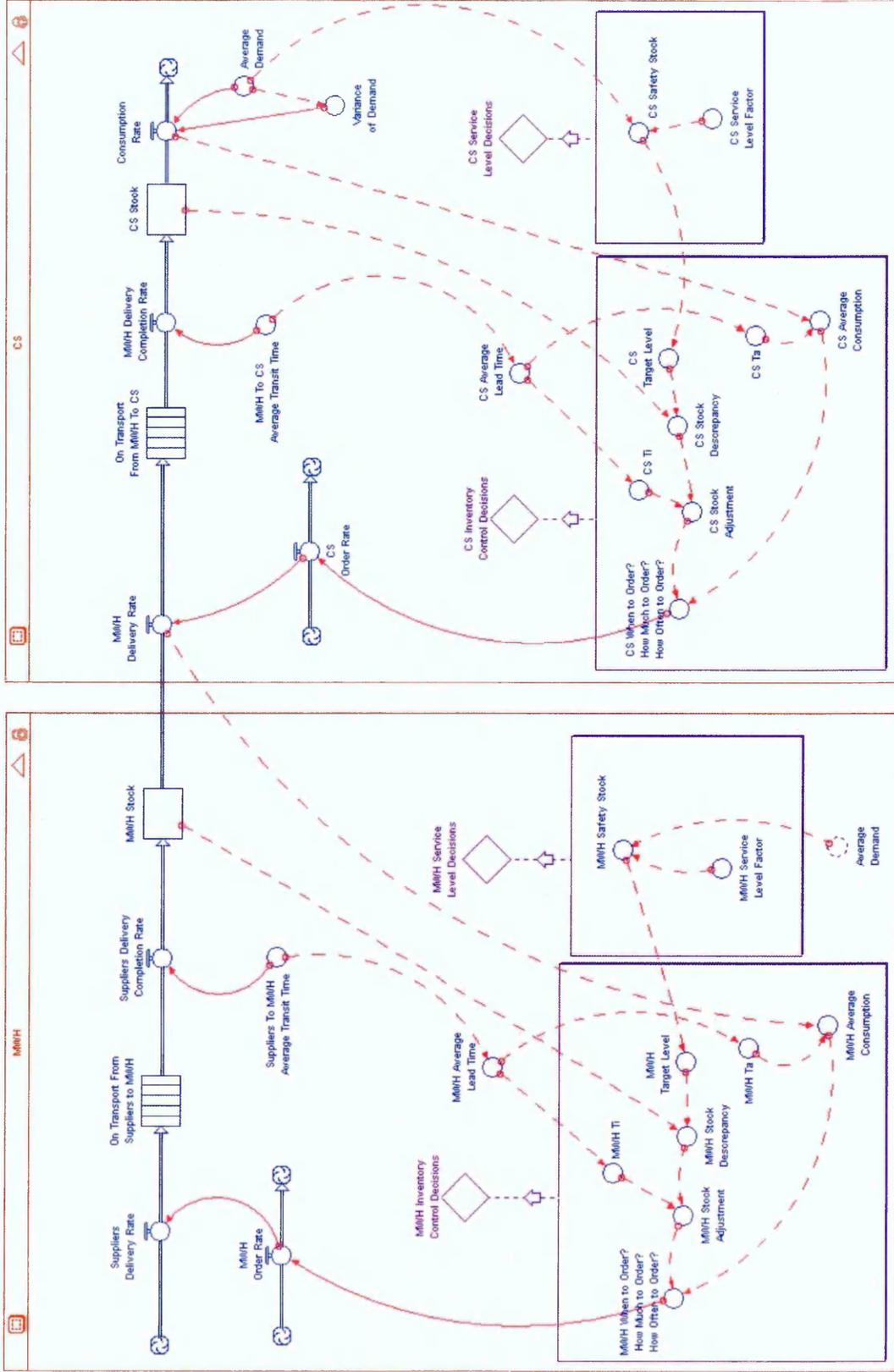
Figure 4.16: The stock-flow diagram of the CNMC logistics system for the CR(IOBPCS) operating strategy (see Table 4.4)

96
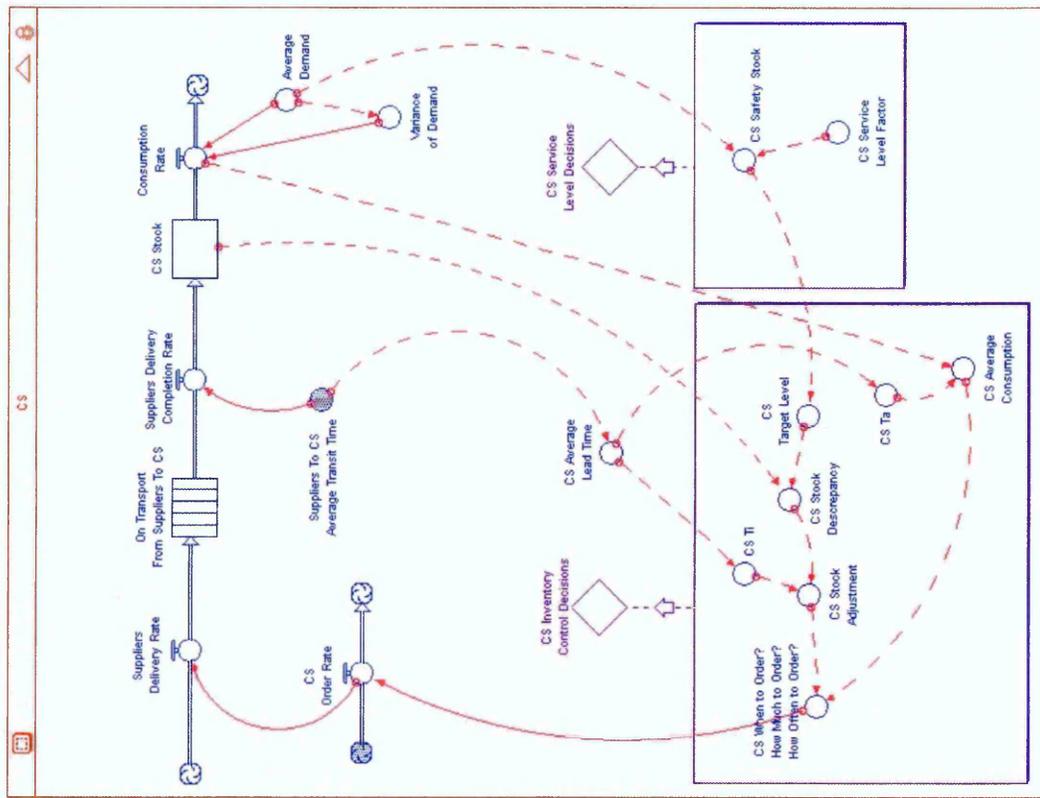
Figure 4.17: The stock-flow diagram of the CNMC logistics system for the CR(IOBPCS) (eliminate) operating strategy (see Table 4.4)

The computer simulation models developed using the stock-flow diagrams shown in Figure 4.13 to Figure 4.17 were run for all items shown in the matrix illustrated in Figure 4.18. This author conducted 242 simulation runs for each model. The matrix shows different combinations of *Item Unit Cost*, *Average Demand*, and *Standard Deviation of Demand* to represent a wide range of different items used by the hospital.

For all simulation runs *Consumption rate* was set as NORMAL[3](Average Demand, Standard Deviation of Demand,5). The author set the seed for the NORMAL function to be equal 5 for all simulation runs so a fair comparison between simulation outputs is achieved.

For each simulation run, performance indices were recorded:

1. Average stock[4] (items/year), which is the annual average amount of items held in stock.
2. Number of orders[5] (orders/year), which is the annual total number of orders issued.

The value of average stock is then used to calculate -for each simulation run- the inventory carrying cost according to the following equation:

Inventory carrying cost = (Inventory carrying charge)(Item unit cost)(Average stock)

Where, inventory carrying charge is fixed for all simulation runs and is equal to (0.3/year).

---

[3] NORMAL(<mean>,<std>[,<seed>]): the NORMAL function generates a series of normally distributed random numbers with a specified *mean* and *standard deviation*. NORMAL samples a new random number in each iteration of a simulation. If you wish to replicate the stream of random numbers, specify *seed* as an integer between 1 and 32767.

[4] Average stock is equal to CS average stock plus MWH average stock. However, in the cases of eliminating MWH, average stock is equal to CS average stock.

[5] Number of orders is equal to CS number of orders plus MWH number of orders. However, in the cases of eliminating MWH, number of orders is equal to CS number of orders.

Item Unit Cost ($)	Standard Deviation of Demand(σ_D) = (1/3)(Average Demand)											Standard Deviation of Demand(σ_D) = (1/30)(Average Demand)										
	Average Demand											Average Demand										
	1	10	20	30	40	50	60	70	80	90	100	1	10	20	30	40	50	60	70	80	90	100
1																						
100																						
200																						
300																						
400																						
500																						
600																						
700																						
800																						
900																						
1000																						

Figure 4.18: Matrix of different combinations of *Item Unit Cost, Average Demand*, and *Standard Deviation of Demand* to represent a wide range of different items used by the CNMC

99

The value of number of orders is then used to calculate -for each simulation run- the order processing cost according to the following equation:

Order processing cost = (Ordering cost)(Number of orders)

where ordering cost is the cost of placing an order such that:

- It is equal ($ 15) when using Paper/Fax-based requisitioning and ordering.
- It is equal ($ 0.43)[6] when using electronic requisitioning, primarily EDI ordering.

Finally, for each simulation run, the inventory cost was calculated according to the following equation:

Inventory cost = Inventory carrying cost + Order processing cost

This author summarised the data calculated for all simulation runs in spreadsheets using Microsoft Excel Software. The spreadsheet data were then used to construct graphs of average stock, number of orders, and inventory cost for the following purposes:

- To investigate how average stock, number of orders, and inventory cost change when changing *Average Demand* and *Item Unit Cost* for each operating strategy.

- To compare all operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for each *Average Demand*.

- To calculate the % changes in average stock, number of orders, and inventory cost when changing from "current situation" operating strategy to the most successful operating strategy.

---

[6] This number is assumed based on the Derby Royal Infirmary case study –in Chapter Four- where the hospital uses EDI ordering.

4.3.5.1 Average stock, number of orders, and inventory cost for each operating strategy

In **Appendix G** (section G.1), Figure G.1 to Figure G.5 illustrate how average stock, number of orders, and inventory cost vary when changing *Average Demand* and *Item Unit Cost* as given in Figure 4.18 for the following operating strategies: "current situation", (*R,s,S*), (*R,s,S*)(eliminate), CR(IOBPCS), and CR(IOBPCS) (eliminate). A cumulative and comparative impact of these behaviours is fully discussed in **Appendix G** (section G.1). However, Table 4.5 gives an overall summary of the effects of changing *Average Demand* and *Item Unit Cost* on average stock, number of orders, and inventory cost for the five operating strategies.

Table 4.5: Overall dynamic behaviour for the five operating strategies

Operating strategy	Variable under investigation	Effect of increasing *Average Demand*	Effect of increasing *Item Unit Cost*
"current situation"	Average stock	increases as S-shaped curve	decreases as a goal-seeking exponential decay
	Number of orders	increases as S-shaped curve	increases as S-shaped curve
	Inventory cost	increases linearly	increases linearly
(*R,s,S*)	Average stock	increases as S-shaped curve	decreases as a goal-seeking exponential decay
	Number of orders	increases as S-shaped curve	increases as S-shaped curve
	Inventory cost	increases linearly	increases linearly
(*R,s,S*) (eliminate)	Average stock	increases as S-shaped curve	decreases as a goal-seeking exponential decay
	Number of orders	increases as S-shaped curve	increases as S-shaped curve
	Inventory cost	increases linearly	increases linearly
CR(IOBPCS)	Average stock	increases linearly	stay constant
	Number of orders	stay constant	stay constant
	Inventory cost	increases linearly	increases linearly
CR(IOBPCS) (eliminate)	Average stock	increases linearly	stay constant
	Number of orders	stay constant	stay constant
	Inventory cost	increases linearly	increases linearly

Although the effects of changing *Average Demand* and *Item Unit Cost* on average stock, number of orders, and inventory cost are the same for "current situation" operating strategy, (*R,s,S*) operating strategy, and (*R,s,S*)(eliminate) operating strategy, and also the same for CR(IOBPCS) operating strategy, and CR(IOBPCS) (eliminate) operating strategy. Yet the values of average stock, number of orders, and inventory cost for any combination of *Average Demand* and *Item Unit Cost* differ in these operating strategies. Therefore, in the next section, this author compares the five operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for each *Average Demand*.

4.3.5.2 Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost

In **Appendix G** (section G.2), Figure G.6 to Figure G.16 compare the five operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for the following values of *Average Demand*, respectively: 1 item/day, 10 items/day, 20 items/day, 30 items/day, 40 items/day, 50 items/day, 60 items/day, 70 items/day, 80 items/day, 90 items/day, and 100 items/day. A full discussion of the comparison presented in Figure G.6 to Figure G.16 is provided in **Appendix G** (section G.2).

By analysing the overall results discussed in **Appendix G** (section G.2), in this author's view, among the proposed operating strategies in Table 4.4 the CR(IOBPCS) (eliminate) operating strategy is the most successful one –in terms of lower inventory cost- for a wide range of different items used by the CNMC. In Chapter Three, this author concluded that the dynamic behaviour of hospitals logistics systems improves when using the CR(IOBPCS) inventory control approach, specifically with regard to the problem of order batching and the problem of demand amplification that are encountered when using the (*R, s, S*) inventory control approach or when using the current non-optimised (*R, s, S*) inventory control approach. Therefore, this author would recommend that the CNMC should adopt the CR(IOBPCS) (eliminate) operating strategy.

It is worth noting that (as shown in the Figures G.6 to G.16 in **Appendix G**) the CR(IOBPCS) (eliminate) operating strategy has the lowest average stock. But at the same time it requires a relatively high number of order processing compared to the (R,s,S)(eliminate) operating strategy. Therefore, in this author's view, electronic requisitioning using EDI (i.e. very low ordering cost) would ensure that the CR(IOBPCS) (eliminate) operating strategy has the lowest inventory cost. In addition, the use of EDI would provide greater accuracy and control with the capability for frequent order cycles (i.e. continuous replenishment).

Another important conclusion from the above results is that eliminating one level of stocks from the logistics system gives better results, not just in reducing market-demand amplification (Forrester, 1961) and smoothing supply chain dynamics (Wikner et al., 1991), but also in reducing inventory cost by reducing average stock in the system and reducing number of orders. As shown in the Figures G.6 to G.16 in **Appendix G**, average stock, number of orders, and inventory cost for the (R,s,S)(eliminate) operating strategy are less than for the (R,s,S) operating strategy. Also, average stock, number of orders, and inventory cost for the CR(IOBPCS) (eliminate) operating strategy are less than for the CR(IOBPCS) operating strategy.

4.3.5.3 The % changes in average stock, number of orders, and inventory cost when changing from "current situation" operating strategy to the CR(IOBPCS) (eliminate) operating strategy

From the simulation results, the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the CNMC changes its logistics operating strategy from "current situation" to the CR(IOBPCS) (eliminate) could be deduced using the following equations:

$$\% \ decrease \ in \ average \ stock \ = \ \frac{(average \ stock)_{current \ situation} \ - \ (average \ stock)_{CR(IOPBCS)(eliminate)}}{(average \ stock)_{current \ situation}} \times \ 100$$

$$\% \ increase \ in \ number \ of \ orders \ = \ \frac{(number \ of \ orders)_{CR(IOPBCS)(eliminate)} \ - \ (average \ stock)_{current \ situation}}{(number \ of \ orders)_{current \ situation}} \times \ 100$$

$$\% \text{ savings in inventory } \cos t = \frac{(inventory \cos t)_{current \; situation} - (inventory \cos t)_{CR(IOPBCS)(ele\,min\,ate)}}{(inventory \cos t)_{current \; situation}} \times 100$$

The calculated values of the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost for all items are summarised, respectively, in Figure 4.19 (a) & (b), Figure 4.19 (c) & (d), and Figure 4.19 (e) & (f).

As shown in Figure 4.19, for most items, the high % savings in inventory cost (about 95%) is mainly due to the high % decrease in inventory carrying cost caused by the high % decrease in average stock.

4.3.6 Inventory classification

In the previous section, the five operating strategies that were proposed to improve the dynamic behaviour of the CNMC logistics system assumed that all items are treated the same in terms of service level delivered (i.e. assumed that 100% service level is to be delivered for each item). As discussed in the literature review in Chapter Two, inventory classification has been used for a long time (Coyle *et al.*, 1996) as a simple yet very effective technique for stratifying individual items into logical groupings for management where "generic" control policies are set for each group. Under such policies, common logistics decisions (such as service level decisions) are applied to each item in a group. Therefore, in this section it is proposed, as one of the main contributions of this research work, to incorporate inventory classification into the redesigning strategies of health care logistics. In particular, it is proposed in this section to incorporate inventory classification into the CR(IOBPCS) (eliminate) operating strategy that were tested in the previous section.

Annual usage and unit cost are two main attributes of items that are usually taken into consideration when classifying inventory using the ABC inventory classification method which is the most frequently used method for item aggregation. However, in health care there is another important attribute of items that should be taken into consideration which is the criticality of items. A distinctive feature of health care logistics is the criticality of items used by hospitals and the life threatening situations that could happen due to the unavailability of these items.
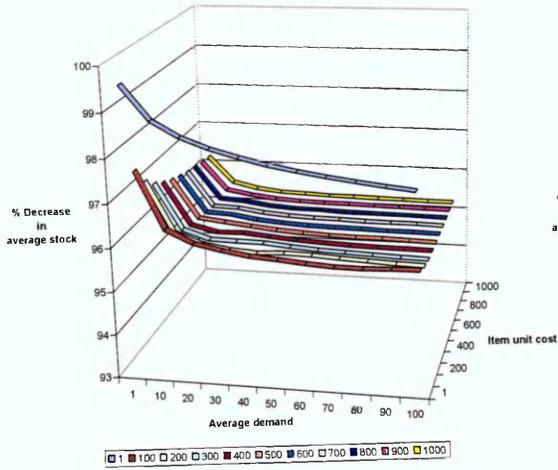
(a) % Decrease in average stock
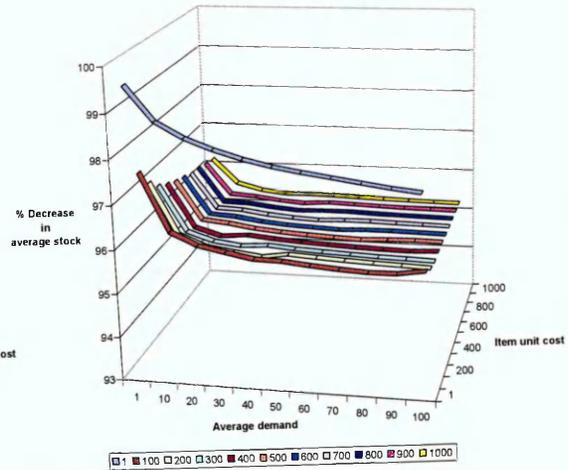
$(\sigma_D = (1/3)(Average \ Demand))$

(b) % Decrease in average stock

$(\sigma_D = (1/30)(Average \ Demand))$
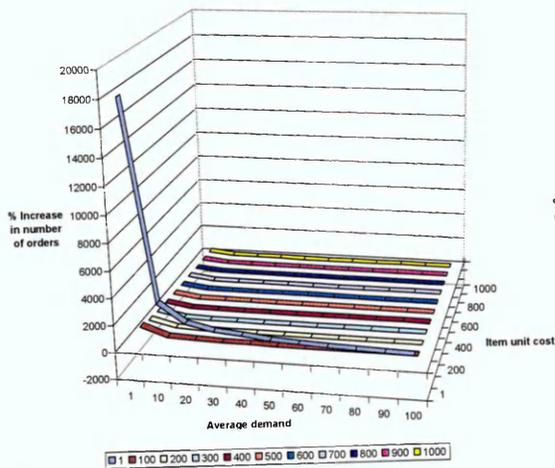
(c) % Increase in number of orders
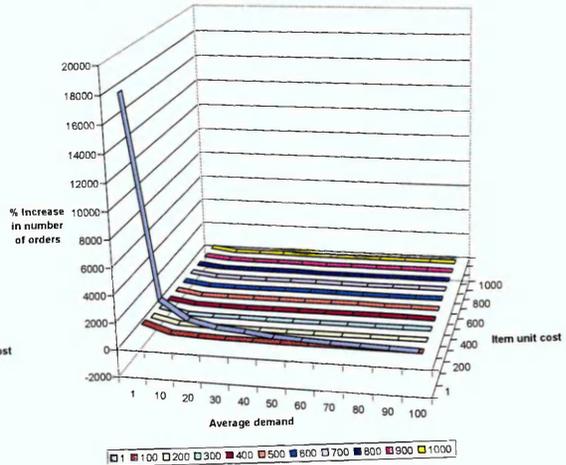
$(\sigma_D = (1/3)(Average \ Demand))$

(d) % Increase in number of orders

$(\sigma_D = (1/30)(Average \ Demand))$
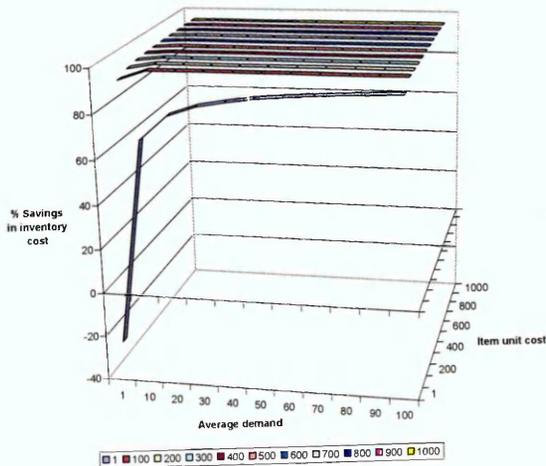
(e) % Savings in inventory cost
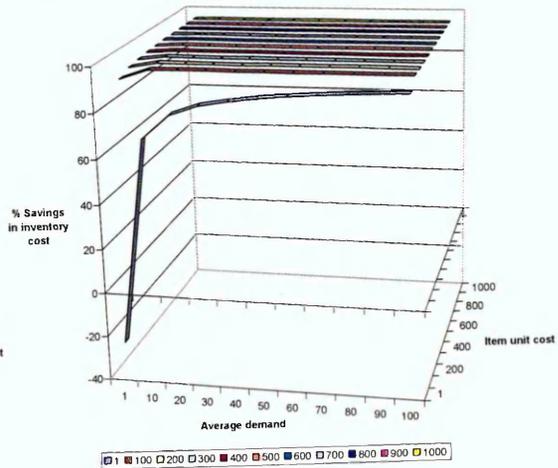
$(\sigma_D = (1/3)(Average \ Demand))$

(f) % Savings in inventory cost

$(\sigma_D = (1/30)(Average \ Demand))$

Figure 4.19: The % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when CNMC changes its logistics operating strategy from "current situation" to the CR(IOBPCS) (eliminate)

The critical review of the ABC inventory classification method, discussed in the literature review in Chapter Two, revealed a main limitation of using this method in health care which is that some critical items that may demonstrate low usage value will not receive priority attention under this method. Therefore, in this section, it is proposed to classify items using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items and study the impact of its use on logistics cost reduction.

Figure 4.20 shows the multi-criteria inventory classification method that is used in this section to classify items for the CNMC and which is adopted from Flores and Whybark (1985) and Partovi and Burton (1993).

Criticality classification

	High criticality	Medium criticality	Low criticality
A item			
B item			
C item			

ABC Analysis Classification

Source: Flores and Whybark (1985)

Figure 4.20: A multi-criteria inventory classification matrix

As shown in Figure 4.20, one dimension of the matrix classifies items in terms of criticality as high, medium and low according to the following criteria:

- High-critical items are either essential for the work carried out and/or have no immediate alternative.
- Medium-critical items are important for the work, but may have acceptable alternatives, or other sizes may be used in the event of stock-out.
- Low-critical items are unlikely to affect the well being of patients other than causing minor inconvenience.

The other dimension of the matrix, shown in Figure 4.20, classifies items according to the ABC analysis classification in terms of annual dollar usage as A item, B item and C item. The procedure for conducting an ABC analysis classification is described at length elsewhere (Reid, 1986; Fernandez, 1987; Reid, 1987). However, the main steps for conducting an ABC analysis classification, as described by Reid (1987), are provided here for convenience as follows:

1. Select those SKUs[7] to be classified.
2. Determine the total number of units issued or utilised during the past fiscal year for each SKU.
3. Determine the average unit cost for each SKU by dividing total purchase costs by total number of SKUs received during the past fiscal year.
4. Calculate the total annual dollar usage cost by multiplying the number of units used by the average unit cost for each SKU.
5. Sort SKUs according to total annual usage value and place in descending sequence of total usage value.
6. Label each SKU descriptively and sequentially number the items.
7. Calculate the cumulative percentage associated with the number of each SKU by dividing the sequentially assigned item number by the total number of SKUs.
8. Determine the cumulative total annual dollar usage value for each SKU.
9. Calculate the percentage of final cumulative total annual dollar usage value for each SKU by dividing the cumulative total amount by the grand cumulative total value for all SKUs.
10. Decide on appropriate divisions for the ABC classes. The percentage of SKUs in each of the three groupings depends on the nature of the SKUs being classified and their relationship to the goals of the department.

The results of the ABC analysis classification are further illustrated graphically. Figure 4.21 shows an example of a common approach for illustrating the ABC results graphically.

---

[7] SKU: Stock keeping unit
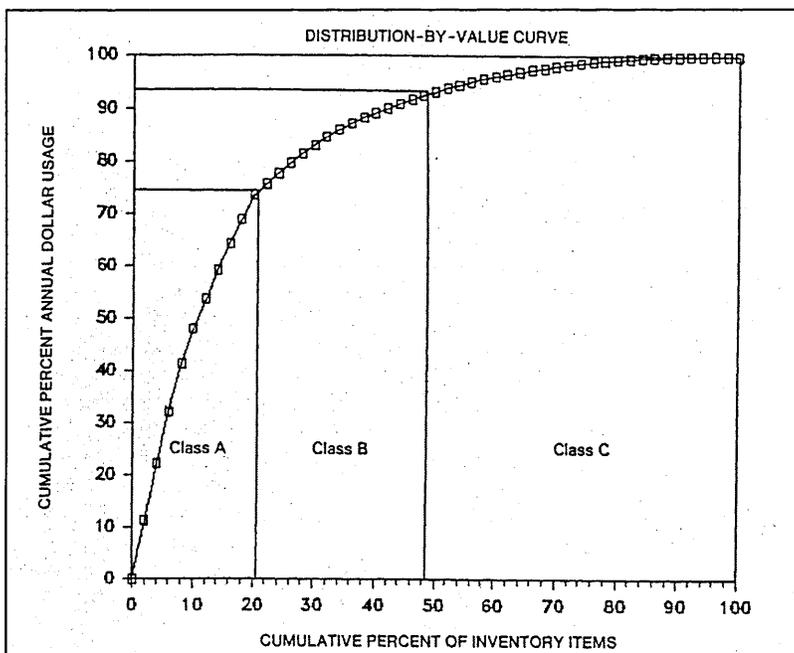
Figure 4.21: Example of graphical results from the application of the ABC inventory classification method

Once all items are classified into groups according to the multi-criteria inventory classification matrix shown in Figure 4.20, an appropriate % service level is specified for each group of items. In this section it is proposed to use the specified % service level and the specified *Service Level Factor* (k) as shown in Figure 4.22 when the CNMC uses the CR(IOBPCS) (eliminate) operating strategy.

<div align="center">Criticality classification</div>

		High criticality	Medium criticality	Low criticality
ABC Analysis Classification	A item	100 % service level ($k = 1$)	90 % service level ($k = 0.9$)	80 % service level ($k = 0.8$)
	B item	100 % service level ($k = 1$)	100 % service level ($k = 1$)	80 % service level ($k = 0.8$)
	C item	100 % service level ($k = 1$)	100 % service level ($k = 1$)	90 % service level ($k = 0.9$)

Figure 4.22: Proposed inventory classification for the CNMC

The new specified *Service Level Factor* (*k*) as shown in Figure 4.22 was then used to run the computer simulation model of the CR(IOBPCS) (eliminate) operating strategy for all items shown in the matrix illustrated in Figure 4.18. The resulting simulation output were used to study how incorporating inventory classification, as shown in Figure 4.22, into the CR(IOBPCS) (eliminate) operating strategy affects average stock, number of orders, and inventory cost.

Figure 4.23 (a) & (b), Figure 4.23 (c) & (d), and Figure 4.23 (e) & (f) show, respectively, the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the value of the *Service Level Factor* (*k*) changes from 1 to 0.9 and from 1 to 0.8.

As shown in Figure 4.23 (c) & (d), changing the value of the *Service Level Factor* (*k*) does not affect the number of orders (i.e. the % change in number of orders is zero). However, changing the value of the *Service Level Factor* (*k*) causes a change in average stock. This is because average stock depends on the value of target level which in turn depends on the value of *k* (see Table 3.4), such that the smaller the value of *k* the smaller the value of target level and hence the smaller the value of average stock. Therefore, as shown in Figure 4.23 (a) & (b), the % decrease in average stock when *k* changes from 1 to 0.8 is higher than when *k* changes from 1 to 0.9.

Consequently, as shown in Figure 4.23 (e) & (f), the % savings in inventory cost is caused by the % decrease in average stock, such that the higher the % decrease in average stock the higher the % savings in inventory cost. Therefore, the % savings in inventory cost when *k* changes from 1 to 0.8 is relatively more than when *k* changes from 1 to 0.9.

In this author's view, assigning different % service level to items according to their criticality, usage, and value reduces cost by reducing inventory cost. Therefore, this author would recommend that the CNMC should use the proposed inventory classification method.
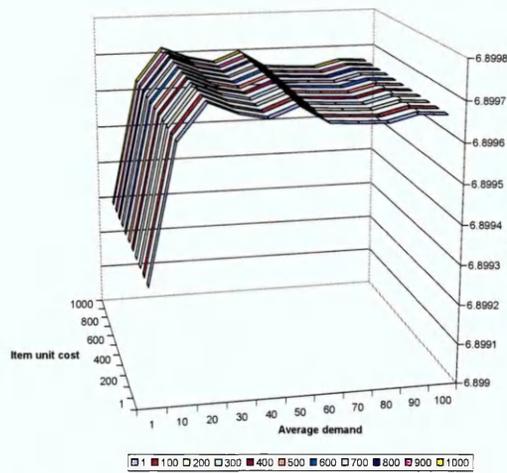
(a) % Decrease in average stock (*k* change from 1 to 0.9)
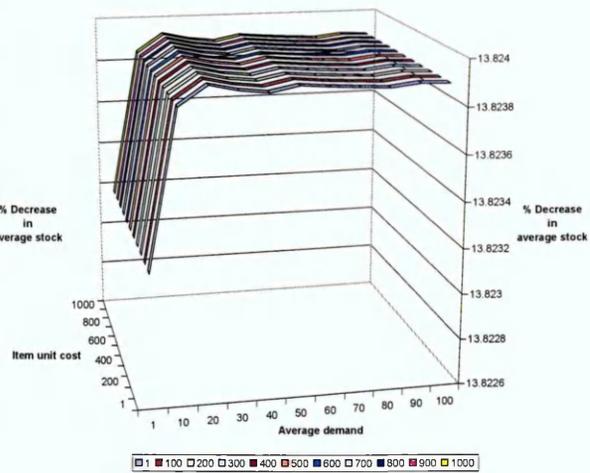
(b) % Decrease in average stock (*k* change from 1 to 0.8)
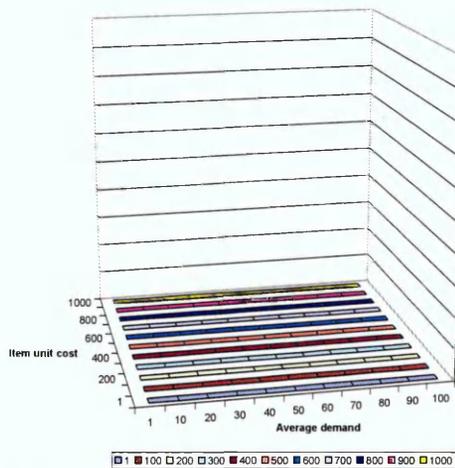
(c) % Increase in number of orders (*k* change from 1 to 0.9)
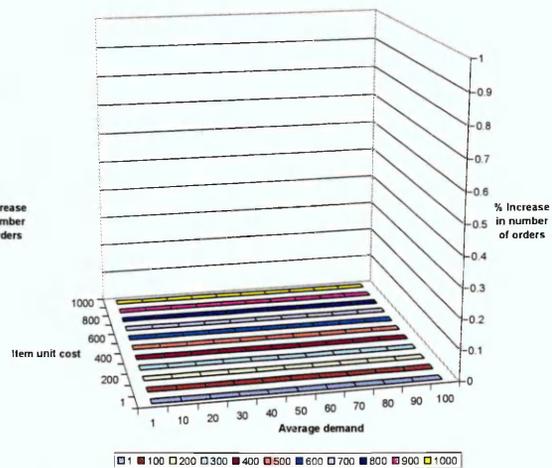
(d) % Increase in number of orders (*k* change from 1 to 0.8)
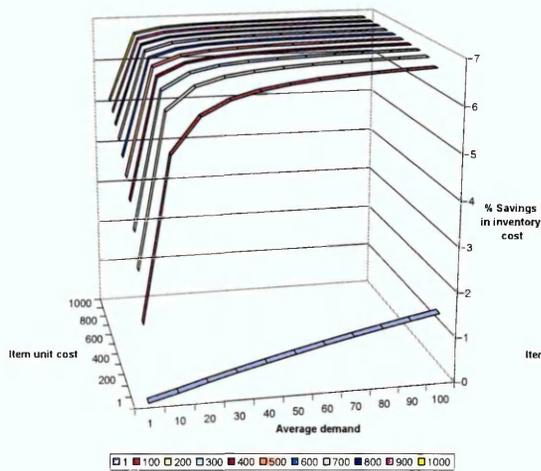
(e) % Savings in inventory cost (*k* change from 1 to 0.9)
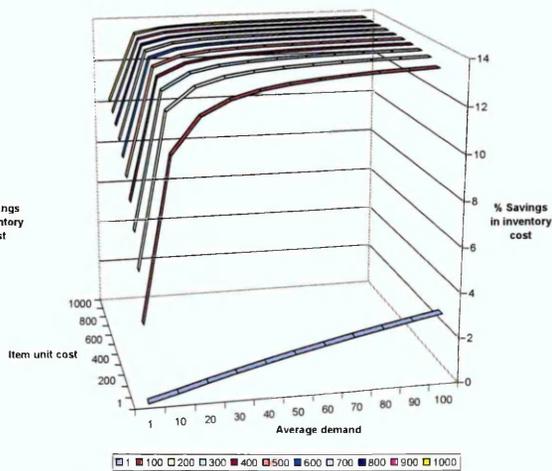
(f) % Savings in inventory cost (*k* change from 1 to 0.8)

Figure 4.23: The % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the value of the *Service Level Factor* (*k*) changes from 1 to 0.9 and from 1 to 0.8 for the CR(IOBPCS) (eliminate) strategy

4.4 Case Study Two: Derbyshire Royal Infirmary

Derbyshire Royal Infirmary[8] (DRI) is one of the public sector trusts in the UK. The UK National Health Service (NHS) is undergoing fundamental and tremendous changes, part of which have significant implications for the way in which purchasing and supply is approached and organized within the NHS. The NHS Purchasing and Supply Agency (NHS PASA) was established in April 2000 to streamline health service procurement (NHS Purchasing and Supply Agency, 2003). The NHS Logistics Authority (NHS LA) is a key player that works in partnership with NHS PASA to achieve purchasing and supply goals. The NHS Logistics Authority was formed in April 2000, as the main supply route for consumable products into the NHS (NHS Logistics Authority, 2003). It operates out of seven strategic distribution centres which serve a customer base of over 500 organisations in the English NHS by offering "pick and pack" customised services. It offers a fully automated process from order to payment through e-ordering, e-catalogue, and e-billing, along with supporting management information for every aspect of the activity.

A simplistic view of the DRI supply chain is shown in Figure 4.24 that includes product manufacturers, distributors, the NHS Logistics Authority, and the DRI who are linked together via information and material flows. The supplies department at the DRI is responsible for the availability of medical and non-medical products by ordering them either from the NHS Logistics Authority or directly from product manufacturers. The pharmacy, which is part of the DRI, is responsible for the availability of legally controlled pharmaceutical products by dealing directly with product manufacturers and distributors. The DRI contract with facilities management companies to run catering, cleaning, and sterile services. The items needed to run these services are either ordered by the facilities management companies directly from their supplier (such as, sterile soft packs for wards and theatres), or by the DRI supplies department on behalf of the facilities management companies under certain contractual agreements.

---

[8] The Derbyshire Royal Infirmary (DRI) and the Derby City General Hospital (DCGH) were merged into a single Hospital Trust on 1st April 1998.
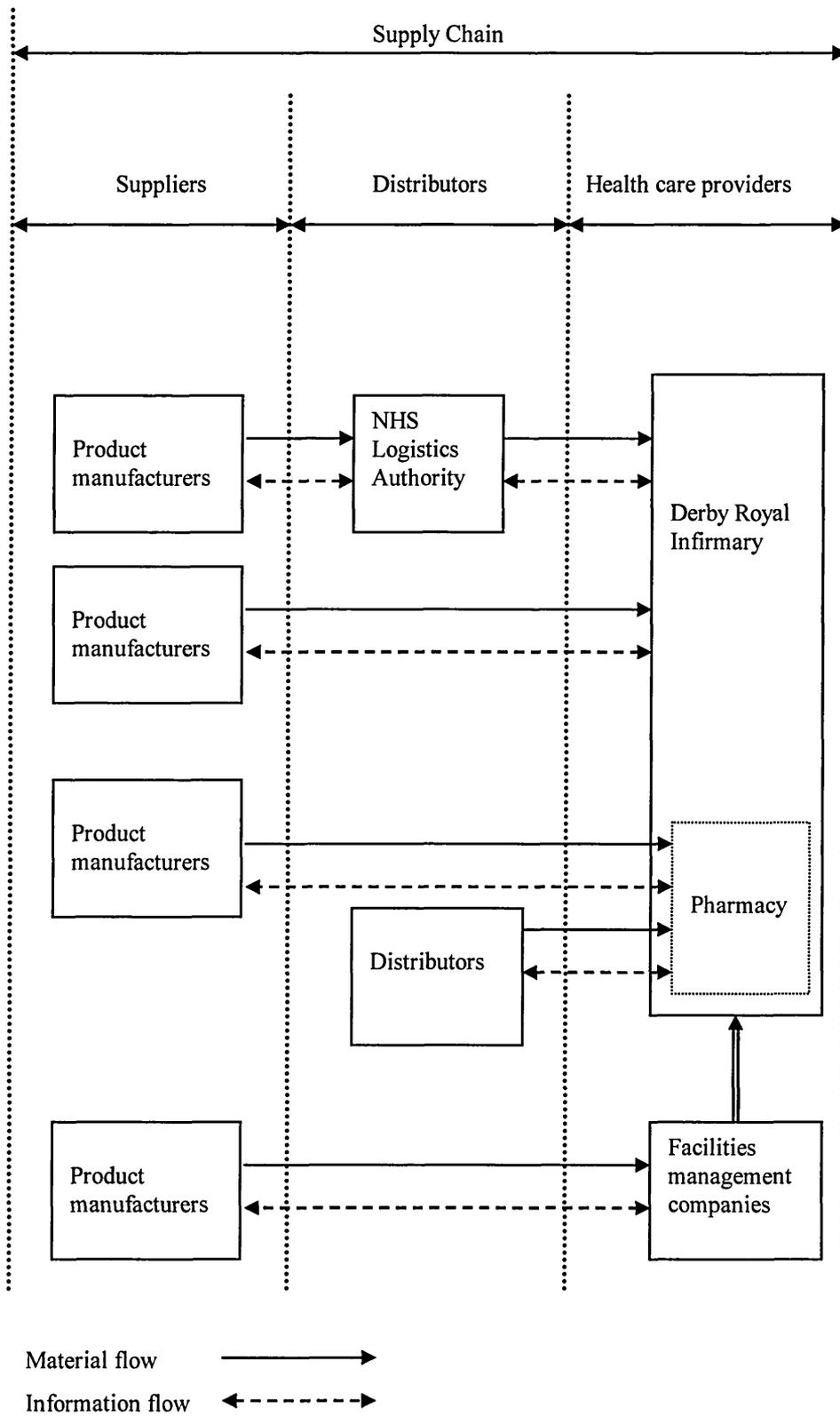
Figure 4.24: The overall material and information flow in the DRI supply chain

4.4.1 Qualitative analysis of the DRI logistics system

The following sections summarise the analysis that was performed using the information gathered in the meetings that were conducted with the Supplies Manager of the DRI. The analysis includes:

- Input-output analysis (IOA).
- Classification of items.
- Material, information, and cash flows.
- Purchasing, warehousing, and transportation decisions.
- Inventory control and service level decisions.

4.4.1.1 Input-output analysis (IOA)

An IOA was conducted first to identify the major DRI departments that are involved with the logistics activities and then for each department to identify main input and output flows associated with the logistics activities. As an example, the IOA for the DRI supplies department is illustrated in Figure 4.25. Subsequently, individual IOA diagrams were then linked together to develop an overall picture of the material, information, and cash flows through the DRI logistics system as described in section 4.4.1.3.

4.4.1.2 Classification of items

Items ordered by the DRI supplies department are classified into three types: stock items, non-stock items, and pharmaceutical products.

- Stock items: these are stocked in the inventory of the NHS Logistics Authority. They are listed in a certain catalogue published by the NHS logistics Authority.
- Non-stock items: these are not listed in the NHS Logistics Authority catalogue, and are usually infrequent or patient specific items.
- Pharmaceutical products: these are legally controlled products that can only be ordered by a registered pharmacist.
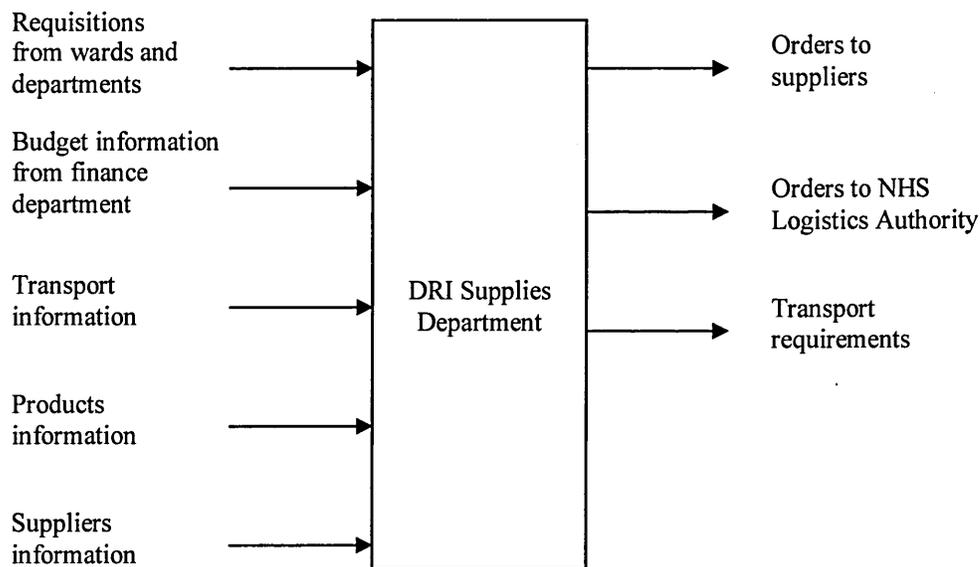
Figure 4.25: Input-output analysis of the DRI supplies department

4.4.1.3 Material, information and cash flows

Figure 4.26 illustrates the material, information, and cash flows for stock items, non-stock items, and pharmaceutical products. There are two approaches for ordering stock items. In the first approach, stocks level at the different wards and departments is checked on a periodical basis using hand-held computers. If the stocks level reaches a predetermined minimum, sufficient supplies are ordered to top up stocks to a maximum level. Ordering is done by feeding the information from the hand-held computers into the NHS Logistics Authority computer network at the DRI supplies department.

The second approach of ordering involves the wards' and departments' personnel themselves. Periodically, the stocks level is checked manually to draw up a shopping list, which is passed to the DRI supplies department in paper requisition form. These checks simply involve counting the remaining items. If the levels of stocks reach a predetermined minimum, sufficient supplies are ordered to top up stocks to a maximum level. Upon receiving paper requisition (blue forms) from the different wards and departments, the supplies department manually feed this information into the NHS Logistics Authority computer network.
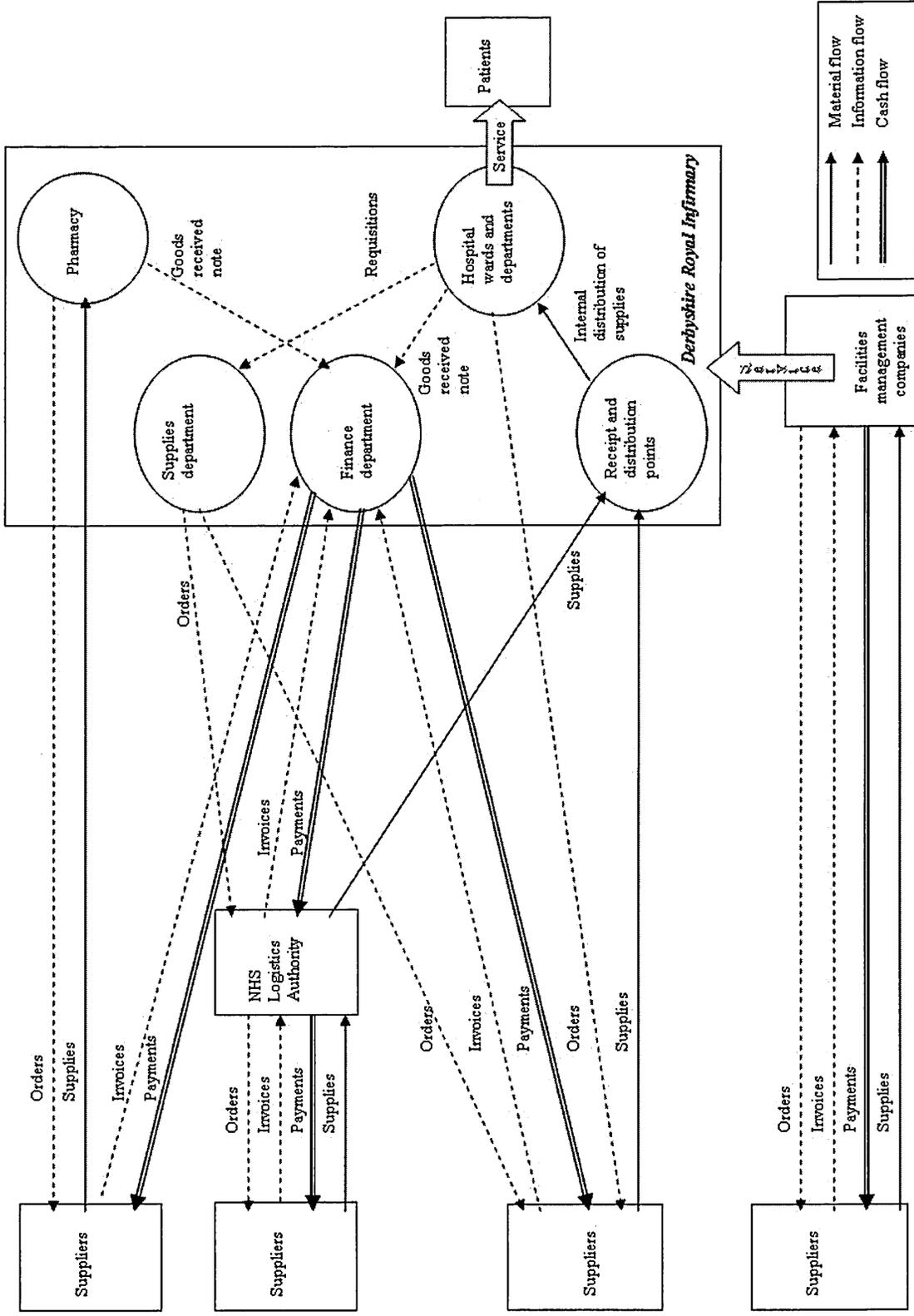
Figure 4.26: Material, information, and cash flows for stock items, non-stock items, and pharmaceutical products (DRI case study)

115

All wards are scheduled over the week such that the supplies department receives paper requisitions from 20 % of all wards every day. The distribution of wards for ordering purposes is based partly on physical location in order to assist distribution patterns.

The NHS Logistics Authority receives goods from their suppliers in bulk, and then they break the bulk loads into collections of items for particular outlets (called consolidated loads) ready to be dispatched as soon as possible. Invoices from the NHS Logistics Authority are sent to the finance department of the DRI, which in turn sends payments to them after it receives the goods-received note from the different wards. Orders between the DRI and the NHS Logistics Authority, as well as invoices and payments, are done through the NHS computer network.

In the case of non-stock items, whenever a ward or department needs a certain amount of these items, they send a paper requisition (white forms) to the DRI supplies department for the amount needed. The DRI supplies department orders these items from the supplier directly. If some of these items are found to be of high and frequent usage, a contract is made between the DRI and the supplier for a limited time frame called "call-off arrangements". Under this arrangement, whenever a ward or department needs a set quantity of these items, they directly contact the supplier by telephone or fax. Invoices from suppliers are sent to the DRI finance department, which is paid upon receiving the goods-received note from the relevant ward or department. In exceptional cases, certain fast moving items are ordered through the non-stock route due to their specialist nature or avoidance of inappropriate double handling (e.g. artificial hips, intra-ocular lenses, as well for frozen foods, fresh fruit and vegetables).

Pharmaceutical products are considered legally controlled and therefore are ordered by a registered pharmacist directly from suppliers. However, suppliers send invoices to the DRI finance department, which is paid upon receiving the goods-received note from the pharmacy. For non-stock items the DRI supplies department and pharmacy also utilizes nationally negotiated contracts in addition to locally negotiated contracts. This is a service provided by the NHS Purchasing and Supply Agency (PASA) who also negotiate the contracts for NHS Logistics.

All supplies via the NHS Logistics Authority or suppliers are delivered at the DRI receipt and distribution points. Except in the case of pharmaceutical products, they are sent directly to the pharmacy. As the receipt and distribution points at the DRI receive goods, they internally distribute these goods to the relevant wards and departments using internal transport arrangements.

4.4.1.4 Purchasing, warehousing, and transportation decisions

About 75 % of the DRI supplies activity is channelled via the NHS Logistics' route (i.e. stock items) with full e-commerce support from order to payment. The processes involve electronic demand capture at the start of the process from a consistent accurate catalogue and ending with the transmission of electronic invoice information integrated into the DRI financial system. The NHS Logistics Authority supply of products is picked and packed to ward/department level, in quantities required by the DRI and then delivered regularly at agreed times to suit the DRI using the NHS Logistics' fleet.

The DRI has no central store (i.e. stockless system). However, both stock and non-stock items are stored at points of use (i.e. stored at wards and departments). The NHS Logistics Authority and suppliers deliver products to the DRI receipt and distribution points where they are transported directly to wards and departments.

4.4.1.5 Inventory control and service level decisions

Wards and departments at the DRI use two inventory management approaches according to the item classification as follows:

Stock items:

The (R,s,S) inventory control approach is used for stock items. The abbreviations $R,s,$ and S in this approach are defined as follows (Blumenfeld, 2001):

- R: review period (time interval between reviews)
- s: reorder level

- *S*: order-up-to level

The values of *R, s,* and *S* used are experience-based and not algorithmically optimised. For stock items ordered by the materials management personnel, the values of *s* and *S* are agreed upon between the DRI supplies department and the wards and departments managers, whereas for stock items that are ordered by wards and departments personnel, the values of *s* and *S* are just unofficial targets set by the wards and departments managers. Wards and departments stocks are budget limited and this plays some part in setting the values of s and *S*. Table 4.6 summarises the inventory control and service level decisions for stock items.

Table 4.6: Inventory control and service level decisions for stock items

Inventory control approach	(R, s, S) (non-optimised)
Description of approach	Inventory position (items on hand plus items on order) is reviewed at regular instants, spaced at time intervals R. At each review, if inventory position is at level s or below, an order of sufficient quantity is placed to bring the inventory to a given level S.
Inventory control decision of: • *How Often to Review?* • *When to Order?* • *How Much to Order?*	 Inventory status is reviewed at regular instants, spaced at time intervals R, where $R = 7$ days An order is placed: If (inventory position) $\leq s$, where $s = 10\,D$ Order quantity $= (S -$ inventory position), where $S = 20\,D$
Variables used in the decision rule	• D = average demand (number of items per unit time)

Non-stock items:

An Ad-Hoc (as and when) approach is used for non-stock items. If wards or departments personnel decide (based on their experience) that there is need for a set quantity of a non-stock item, they make requisition for the amount needed. Therefore, the interval between orders is irregular and the quantity ordered each time is not fixed.

4.4.2 Conceptual model[9] of the DRI logistics system

In this case study, both causal-loop diagrams and stock-flow diagrams were used as mediums of conceptualization. Figure 4.27 shows a causal-loop diagram of the DRI logistics system for stock items. The causal-loop diagram, being simple to understand, was used as a tool to communicate with the Supplies Manager. A stock-flow diagram of the DRI logistics system for stock items, shown in Figure 4.28, was developed using the *ithink* Analyst Software. Both the causal-loop and the stock-flow diagrams were verified by the Supplies Manager who confirmed that both models are representative of the decision rules related to the different logistics activities adopted by the DRI supplies department.

4.4.3 Computer simulation model of the DRI logistics system

A computer simulation model of the DRI logistics system for stock items was developed using the verified stock-flow diagram in Figure 4.28. The simulation model was developed using the *ithink* Analyst Software. **Appendix H** provides all the equations that make up the simulation model. The data needed to run the computer simulation model is: *Consumption Rate, Average Demand, NHS LA To Ward or Department Average Transit Time.* The verified model was subjected to extensive dynamic analysis as explained in the subsequent sub-sections.

---

[9] In this case study, conceptual modelling and computer simulation modelling were conducted for stock items only, as they represent more than 75 % of all items.
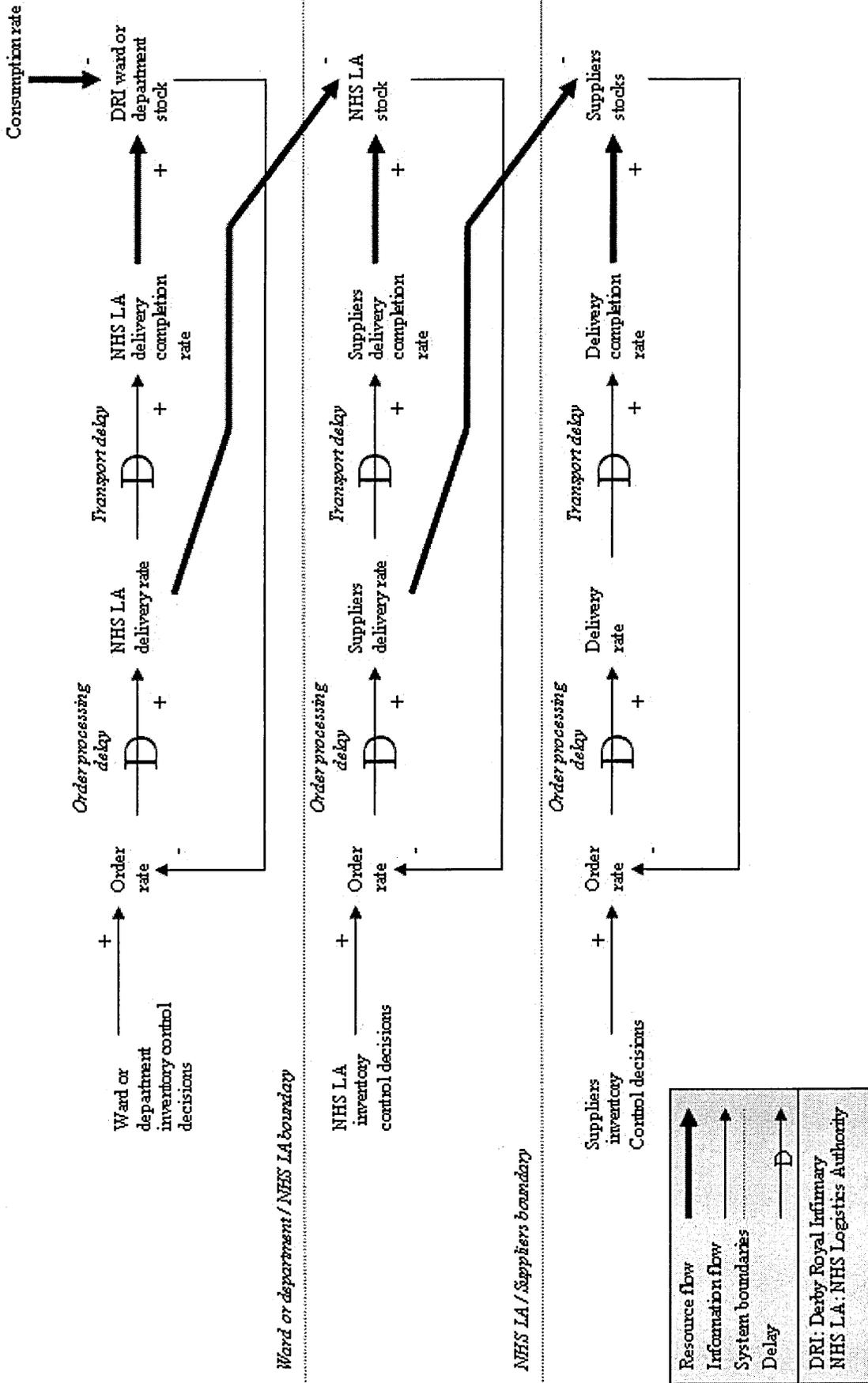
Figure 4.27: Causal-loop diagram of the DRI logistics system for stock items

120
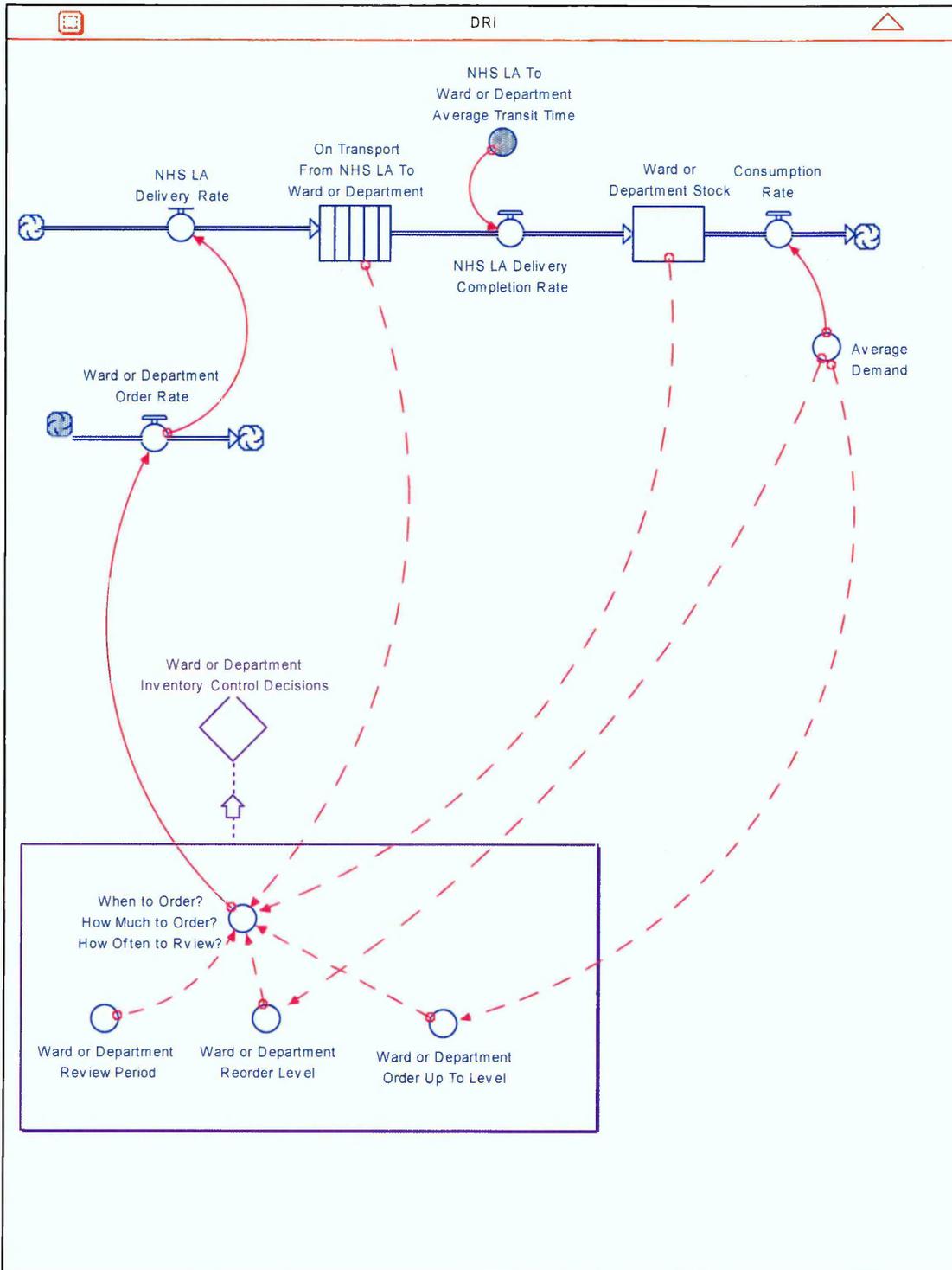
Figure 4.28: The overall stock-flow diagram of the DRI logistics system for stock items

4.4.4 Dynamic analysis

The simulation model was tested for different items. As an example, this author illustrates the simulation analysis for two stock items: Catheter central venous blister tray (item unit cost=£14.45) and Catheter suction straight tip (item unit cost=£0.25). The two items are used by the Intensive Care Unit[10]: The variables that are used in the simulation process for the two example items are defined in Table 4.7.

Table 4.7: The variables that are used in the simulation model

	Catheter central venous blister tray	Catheter suction straight tip
Average Demand (item/day)	0.47	23
NHS LA To Ward or Department Average Transit Time (days)	3	3

Figure 4.29 and Figure 4.30 show, respectively, the dynamic behaviour of the DRI logistics system for the two example items (i.e. Catheter central venous blister tray and Catheter suction straight tip). Each figure shows *Ward or Department Stock, Ward or Department Order Up To Level, Ward or Department Reorder Level, Consumption Rate, Ward or Department Order Rate*, and *NHS LA Delivery Completion Rate*.

---

[10] At the DRI there are 278 different wards and departments, each of them has its own budget. The Intensive Care Unit is considered one of the highest spend departments at the DRI (yearly expenditure is about £98,000). It uses 420 different stock items.
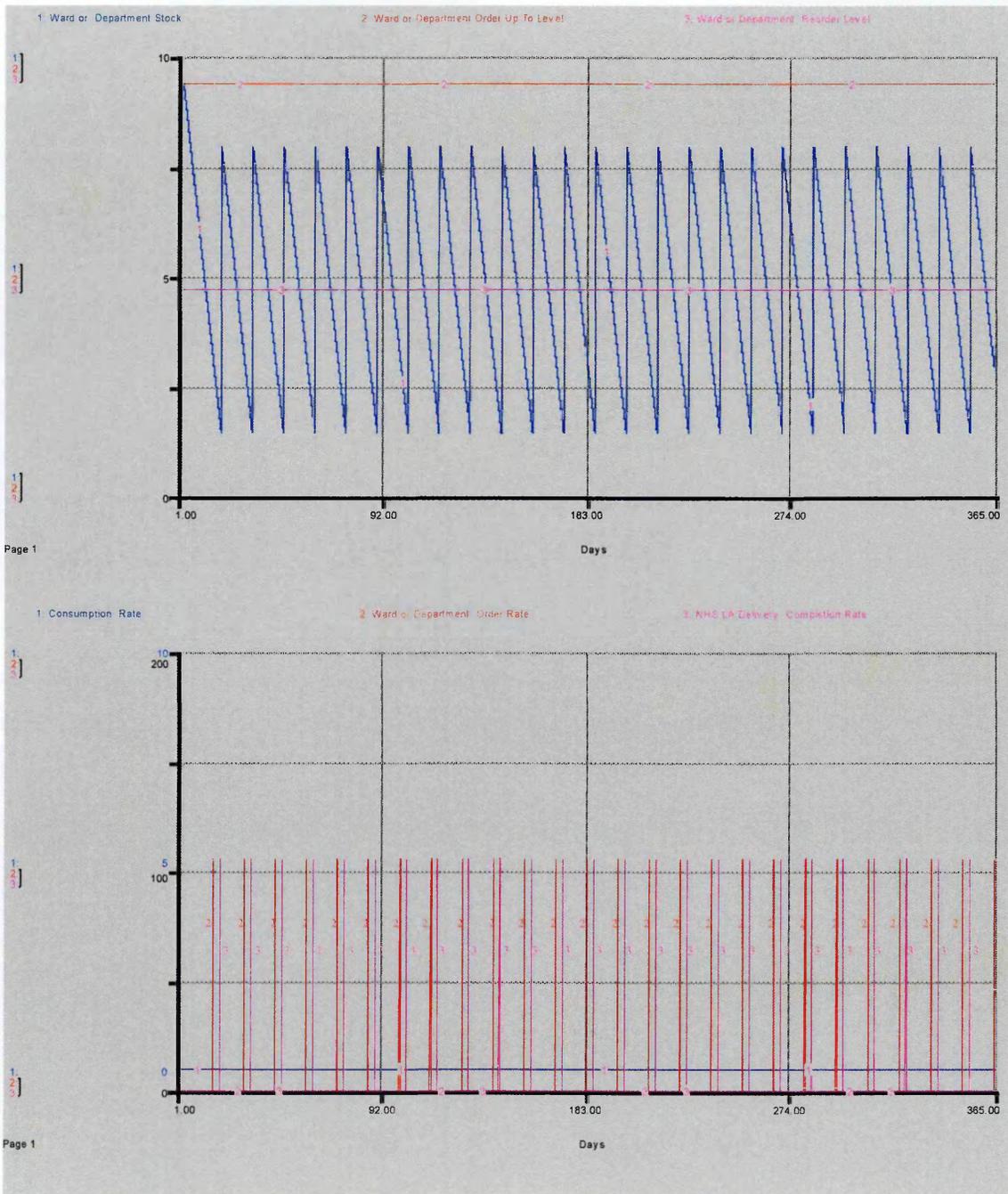
Figure 4.29: The dynamic behaviour of the DRI logistics system for the example item: Catheter central venous blister tray (see Table 4.7)
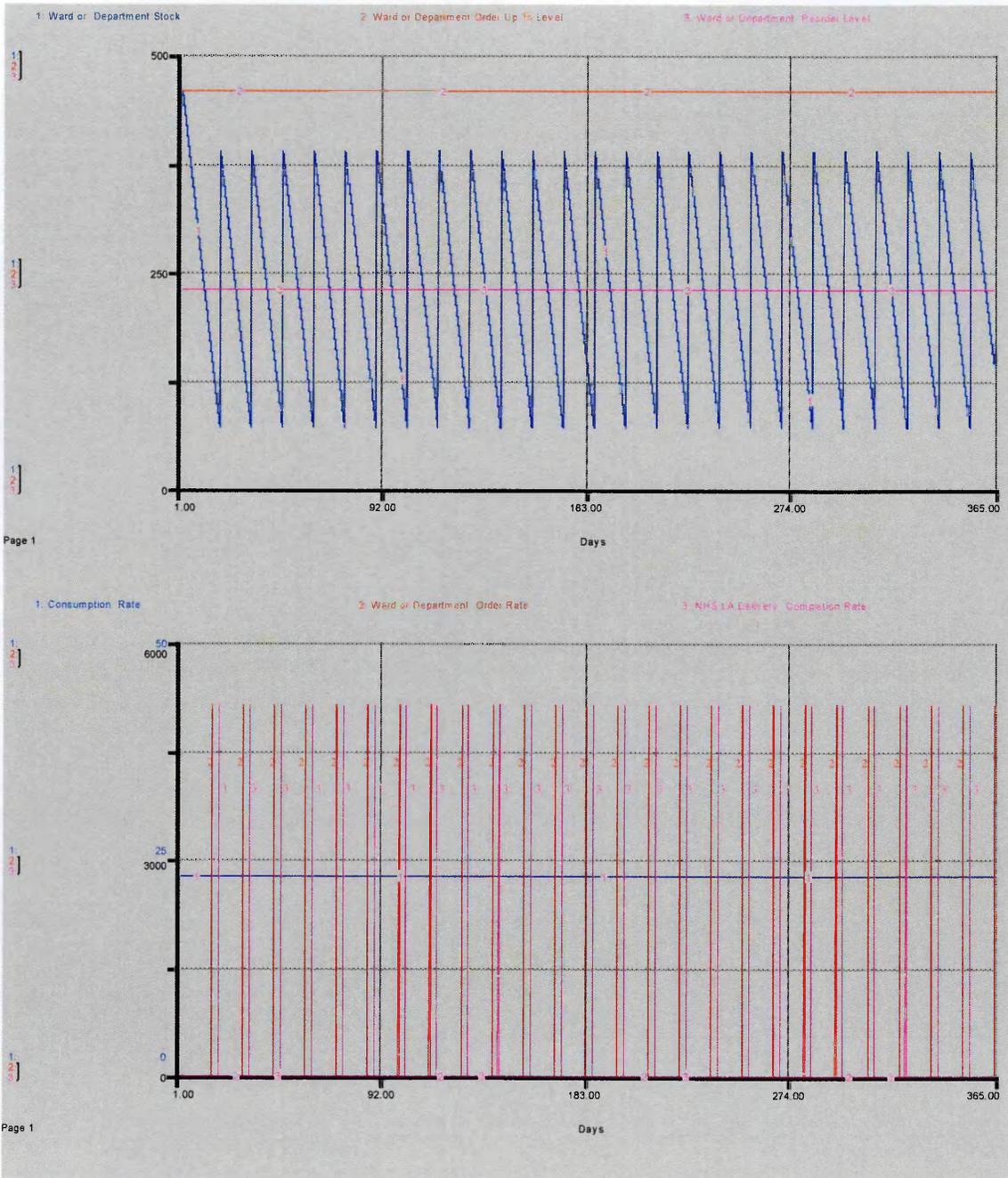
Figure 4.30: The dynamic behaviour of the DRI logistics system for the example item: Catheter suction straight tip (see Table 4.7)

As shown in Figure 4.29 and Figure 4.30, *Ward or Department Stock* depletes gradually till it reaches *Ward or Department Reorder Level*. Subsequently, at the first *Review Time* an order is generated. Therefore, at this *Review Time*, *Ward or Department Order Rate* is represented as a pulse of a height equal to (Q/dt), where Q is the ordered quantity, which is calculated according to the equation in Table 4.6. After a time (equal to *NHS LA To Ward or Department Average Transit Time*), *NHS LA Delivery Completion Rate* is translated as a pulse of height equal to (Q/dt), which causes *Ward or Department Stock* to increase its level by a value of Q. As a result, the dynamic behaviour of *Ward or Department Stock* resembles a sawtooth pattern.

As shown in Figure 4.29 and Figure 4.30, the dynamic behaviour of the DRI logistics system when using the non-optimised (*R*, *s*, *S*) inventory control approach behaves in the same way as when using the optimised (*R*, *s*, *S*) inventory control approach (see section 3.4). Specifically, the occurrence of order batching (i.e. the continuous demand for products has been transmitted to the NHS LA as order pulses), which is the main cause of the Burbidge Effect problem.

4.4.5 Redesigning the DRI logistics system

In this section this author proposes two operating strategies for the DRI logistics system. The most successful one in terms of lower inventory cost and more robust to unpredictable demand for a large number of items is identified. This author would like to point out that the comparison between the current operating strategy of the DRI logistics system and the proposed strategies is done, similar to the CNMC case study (see section 4.3.5), in terms of inventory cost only and not in terms of total logistics cost. The current operating strategy of the DRI logistics system and the proposed strategies are summarised in Table 4.8.

Figure 4.31, Figure 4.32 and Figure 4.33 show the stock-flow diagram of the DRI logistics system when using the following operating strategies, respectively: "current situation", (*R,s,S*), and CR(IOBPCS). Note that the only difference between Figure 4.28 and Figure 4.31 is that Figure 4.31 introduces uncertainty in the demand pattern. As with the CNMC case study, the computer simulation models developed from the stock-flow diagrams were run for items shown in Figure 4.18 (see section 4.3.5).

Table 4.8: Summary of the current operating strategy of the DRI logistics system and the proposed operating strategies for redesigning the DRI logistics system

Name of operating strategy	Inventory control decisions	Service level decisions	Purchasing decisions	Transportation decisions	Warehousing decisions
1- "current situation":	Non-optimised (R,s,S) inventory control approach. Stock level is checked manually.	100 % service level for all items.	Electronic requisitioning, primarily EDI ordering.	Daily deliveries between NHS LA and the DRI.	Central stockless system; both stock and non-stock items are stored at the point of use.
2- (R,s,S):	(R,s,S) inventory control approach. Stock level is checked manually.	100 % service level for all items. Service level factor (k) =3 (see Table 2.1)	Electronic requisitioning, primarily EDI ordering.	Daily deliveries between NHS LA and the DRI.	Central stockless system; both stock and non-stock items are stored at the point of use.
3- CR(IOBPCS):	CR(IOBPCS) inventory control approach. Stock level is checked using electronic POU*.	100 % service level for all items. Service level factor (k) =1 (see Table 2.4)	Electronic requisitioning, primarily EDI ordering.	Daily deliveries between NHS LA and the DRI.	Central stockless system; both stock and non-stock items are stored at the point of use.

* POU: Point of use (POU) equipment is an automatic dispensing system that provides secured storage of supplies close to where the supplies are used.

126
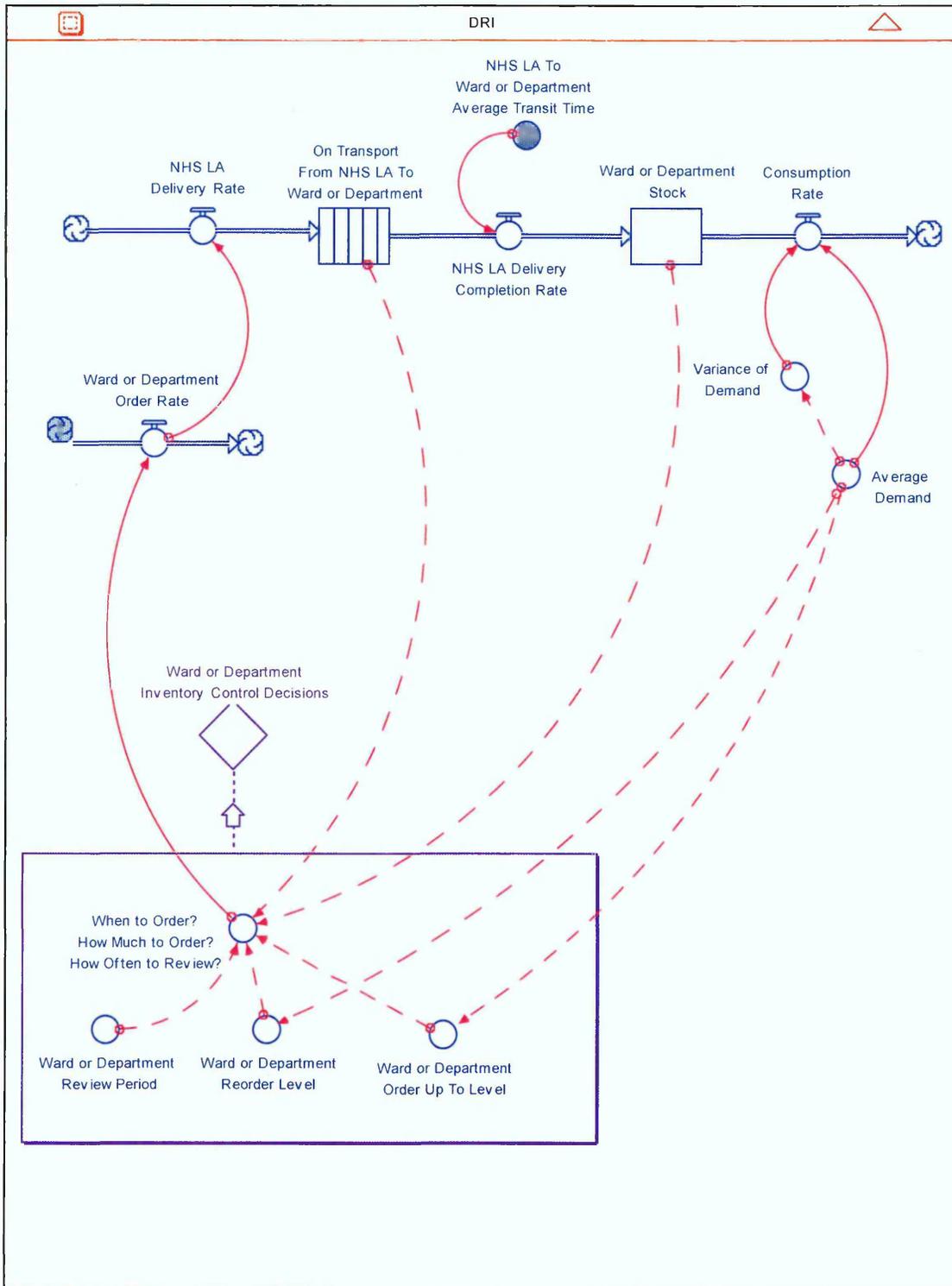
Figure 4.31: The stock-flow diagram of the DRI logistics system when using the "current situation" operating strategy (see Table 4.8)
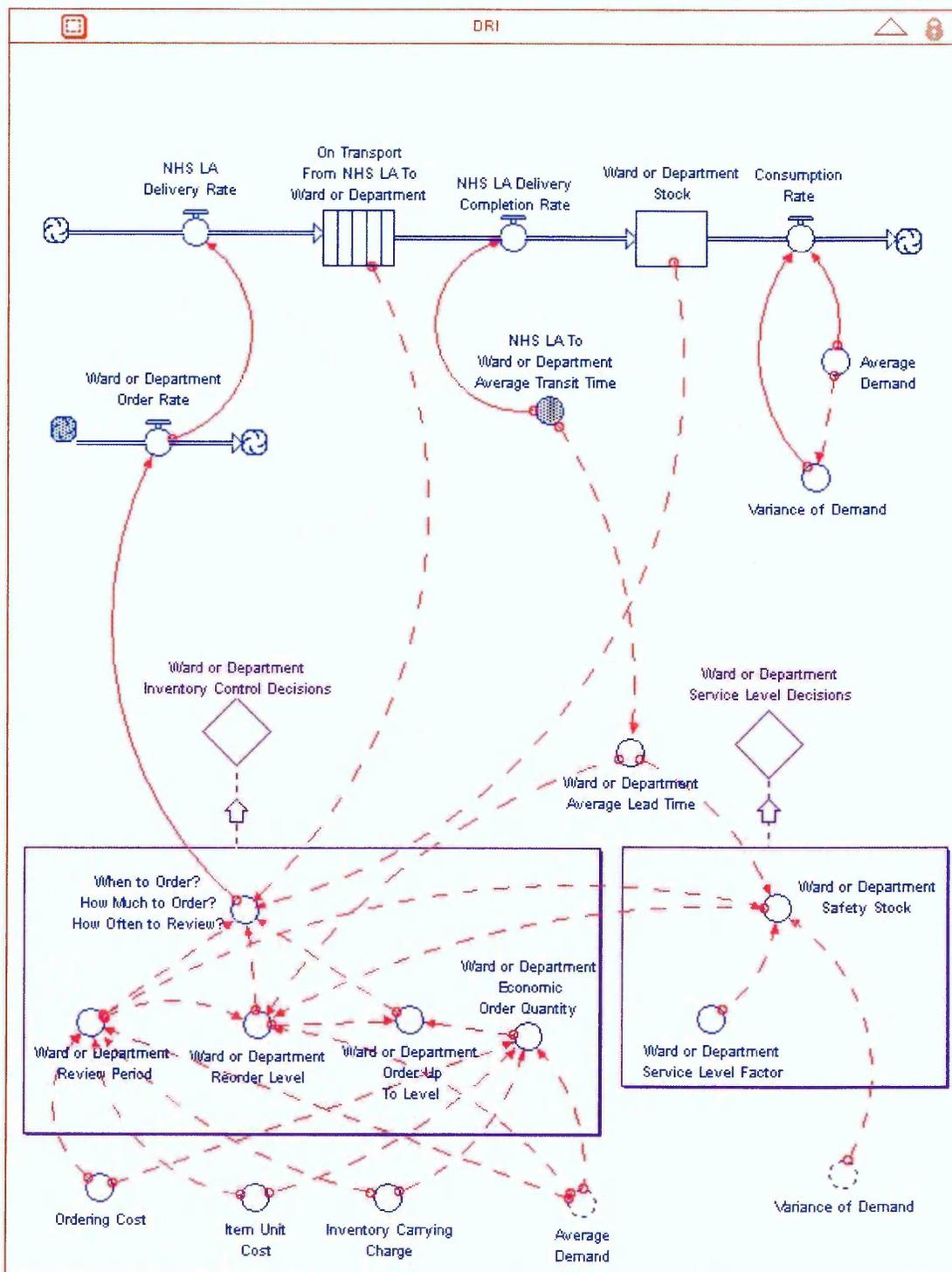
Figure 4.32: The stock-flow diagram of the DRI logistics system when using the (*R,s,S*) operating strategy (see Table 4.8)
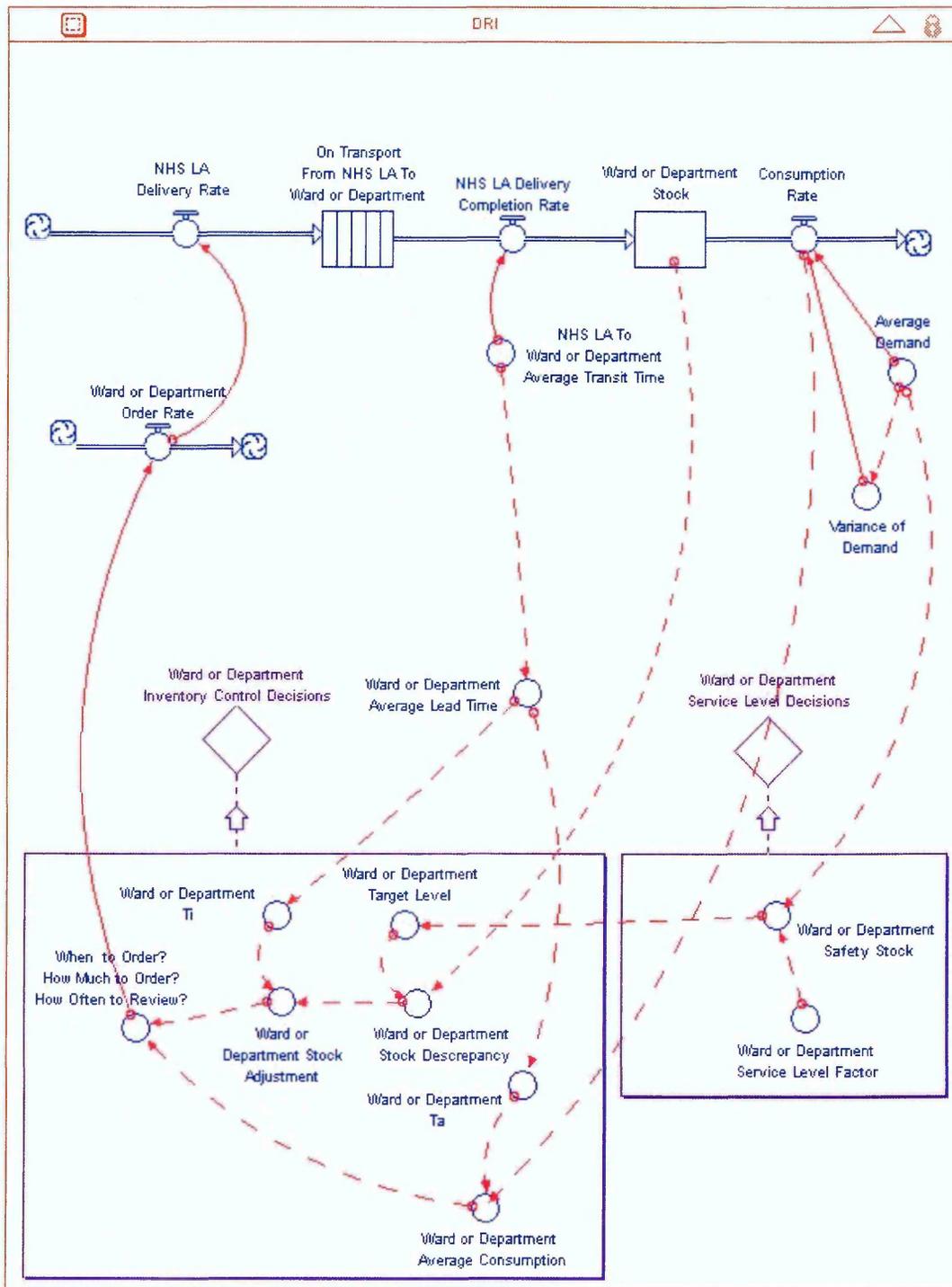
Figure 4.33: The stock-flow diagram of the DRI logistics system when using the CR(IOBPCS) operating strategy (see Table 4.8)

As with the CNMC case study, for all simulation runs *Consumption rate* was set as NORMAL (Average Demand, Standard Deviation of Demand, 5). For each simulation run, average stock and number of orders were recorded and then their values were used to calculate inventory carrying cost, order processing cost and inventory cost using the same equations used for the CNMC case study (see section 4.3.5). However, for the DRI case study, inventory carrying charge is fixed for all simulation runs and is equal to (0.07/year) and ordering cost is equal to (£ 0.43).

The data calculated for all simulation runs were summarised in spreadsheets and then used to construct graphs of average stock, number of orders, and inventory cost for the same purposes as for the CNMC case study, which are discussed in the following subsections.

4.4.5.1   Average stock, number of orders, and inventory cost for each operating strategy

In **Appendix I** (section I.1), Figure I.1 to Figure I.3 illustrate how average stock, number of orders, and inventory cost vary when changing *Average Demand* and *Item Unit Cost* as given in Figure 4.18 for the following operating strategies: "current situation", (*R,s,S*), and CR(IOBPCS). A cumulative and comparative impact of these behaviours is fully discussed in **Appendix I** (section I.1). However, Table 4.9 gives an overall summary of the effects of changing *Average Demand* and *Item Unit Cost* on average stock, number of orders, and inventory cost for the three operating strategies.

In the next section, the three operating strategies are compared in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for each *Average Demand*.

Table 4.9: Overall dynamic behaviour for the three operating strategies

Operating strategy	Variable under investigation	Effect of increasing *Average Demand*	Effect of increasing *Item Unit Cost*
"current situation"	Average stock	increases linearly	stay constant
	Number of orders	stay constant	stay constant
	Inventory cost	increases linearly	increases linearly
(R,s,S)	Average stock	increases as S-shaped curve	decreases as a goal-seeking exponential decay
	Number of orders	increases as S-shaped curve	increases as S-shaped curve
	Inventory cost	increases linearly	increases linearly
CR(IOBPCS)	Average stock	increases linearly	stay constant
	Number of orders	stay constant	stay constant
	Inventory cost	increases linearly	increases linearly

4.4.5.2 Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost

In **Appendix I** (section I.2), Figure I.4 to Figure I.14 compare the three operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for the following values of *Average Demand*, respectively: 1 item/day, 10 items/day, 20 items/day, 30 items/day, 40 items/day, 50 items/day, 60 items/day, 70 items/day, 80 items/day, 90 items/day, and 100 items/day. A full discussion of the comparison presented in Figure I.4 to Figure I.14 is provided in **Appendix I** (section I.2).

By analysing the overall results discussed in **Appendix I** (section I.2), in this author's view, among the proposed operating strategies in Table 4.8 the CR(IOBPCS) operating strategy is the most successful one –in terms of lower inventory cost- for a wide range of different items used by the DRI. In Chapter Three, this author concluded that the dynamic behaviour of hospitals logistics systems improves when using the CR(IOBPCS) inventory control approach, specifically, with regards to the problem of

order batching and the problem of demand amplification that are encountered when using the (R, s, S) inventory control approach or when using the current non-optimised (R, s, S) inventory control approach. Therefore, based on these two conclusions, this author suggests that the DRI should consider changing its logistics operating strategy from "current situation" to the CR(IOBPCS) operating strategy.

4.4.5.3 The % changes in average stock, number of orders, and inventory cost when changing from "current situation" operating strategy to the CR(IOBPCS) operating strategy

To benchmark the improvements, this author calculated from simulation output the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the DRI changes its logistics operating strategy from "current situation" to the CR(IOBPCS) as given in the following equations:

$$\% \ decrease \ in \ average \ stock = \frac{(average \ stock)_{current \ situation} - (average \ stock)_{CR(IOPBCS)}}{(average \ stock)_{current \ situation}} \times \ 100$$

$$\% \ increase \ in \ number \ of \ orders = \frac{(number \ of \ orders)_{CR(IOPBCS)} - (average \ stock)_{current \ situation}}{(number \ of \ orders)_{current \ situation}} \times \ 100$$

$$\% \ savings \ in \ inventory \ cos t = \frac{(inventory \ cos t)_{current \ situation} - (inventory \ cos t)_{CR(IOPBCS)}}{(inventory \ cos t)_{current \ situation}} \times \ 100$$

The calculated values of the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost for all items are summarised in Figure 4.34 (a) & (b), Figure 4.34 (c) & (d), and Figure 4.34 (e) & (f), respectively.

As shown in Figure 4.34, for most items, the high % savings in inventory cost (about 84%) is mainly due to the high % decrease in average stock which means a high % decrease in inventory carrying cost.
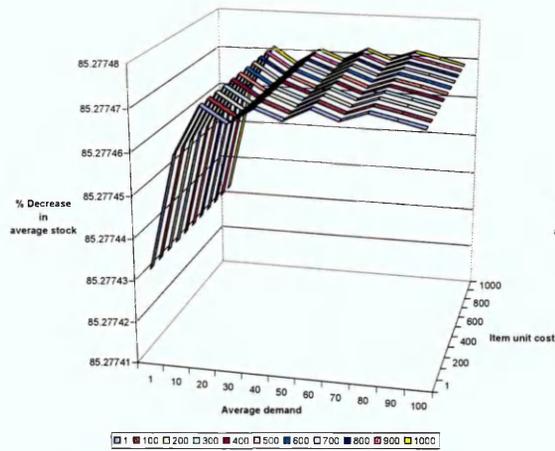
(a) % Decrease in average stock
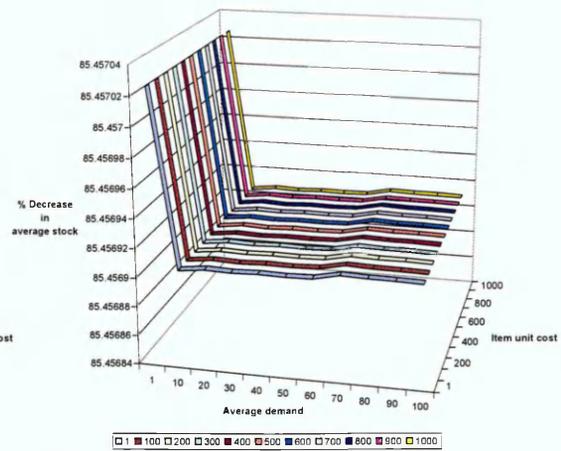
(σ_D = (1/3)(*Average Demand*))

(b) % Decrease in average stock

(σ_D = (1/30)(*Average Demand*))
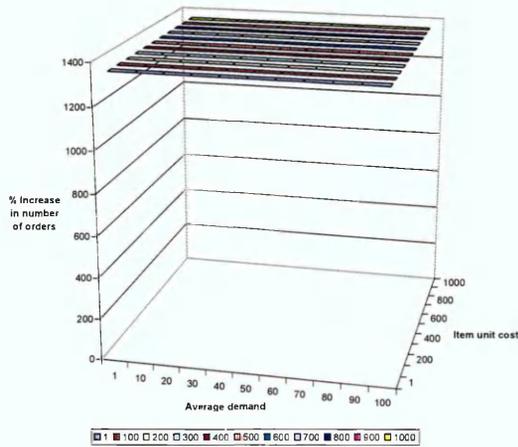
(c) % Increase in number of orders

(σ_D = (1/3)(*Average Demand*))
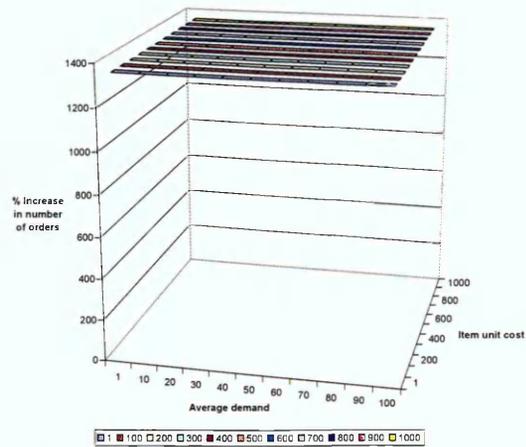
(d) % Increase in number of orders

(σ_D = (1/30)(*Average Demand*))
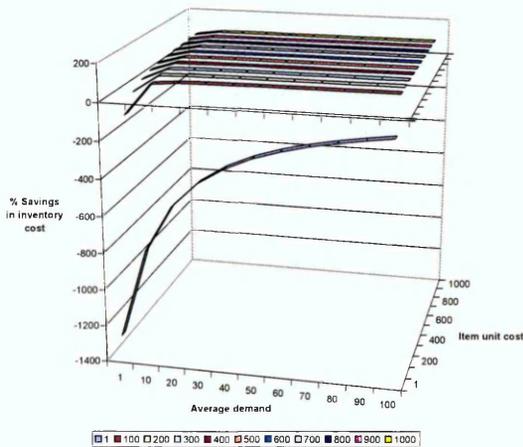
(e) % Savings in inventory cost

(σ_D = (1/3)(*Average Demand*))
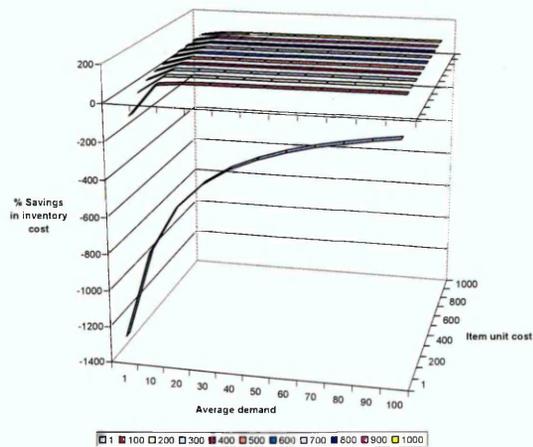
(f) % Savings in inventory cost

(σ_D = (1/30)(*Average Demand*))

Figure 4.34: The % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the DRI changes its logistics operating strategy from "current situation" to the CR(IOBPCS) operating strategy

4.4.6 Inventory classification

In the previous section, the three operating strategies that were proposed to improve the dynamic behaviour of the DRI logistics system assumed that all items are treated the same in terms of service level delivered (i.e. assumed that 100% service level is to be delivered for each item). As done for the CNMC case study, it is proposed in this section to incorporate inventory classification into the CR(IOBPCS) operating strategy that were tested in the previous section and study the impact of its use on logistics cost reduction. In this section, it is proposed to classify items using the same multi-criteria inventory classification method (shown in Figure 4.20) that where used for the CNMC and which takes into account the criticality, cost, and usage value of items.

In this section it is proposed to use the specified % service level and the specified *Service Level Factor* (*k*) for each group of items as shown in Figure 4.35 when the DRI uses the CR(IOBPCS) operating strategy.

| | | Criticality classification | | |
		High criticality	Medium criticality	Low criticality
ABC Analysis Classification	A item	100 % service level ($k = 1$)	90 % service level ($k = 0.9$)	80 % service level ($k = 0.8$)
	B item	100 % service level ($k = 1$)	100 % service level ($k = 1$)	80 % service level ($k = 0.8$)
	C item	100 % service level ($k = 1$)	100 % service level ($k = 1$)	90 % service level ($k = 0.9$)

Figure 4.35: Proposed inventory classification for the DRI

The new specified *Service Level Factor* (*k*) as shown in Figure 4.35 was then used to run the computer simulation model of the DRI CR(IOBPCS) operating strategy for all items shown in the matrix illustrated in Figure 4.18. The resulting simulation output were used to study how incorporating inventory classification, as shown in Figure 4.35, into the CR(IOBPCS) operating strategy affects average stock, number of orders, and inventory cost.

Figure 4.36 (a) & (b), Figure 4.36 (c) & (d), and Figure 4.36 (e) & (f) show, respectively, the % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the value of the *Service Level Factor* (*k*) changes from 1 to 0.9 and from 1 to 0.8.

As shown in Figure 4.36 (c) & (d), changing the value of the *Service Level Factor* (*k*) does not affect the number of orders (i.e. the % change in number of orders is zero). However, changing the value of the *Service Level Factor* (*k*) causes a change in average stock. This is because average stock depends on the value of target level which in turn depends on the value of *k* (see Table 3.4), such that the smaller the value of *k* the smaller the value of target level and hence the smaller the value of average stock. Therefore, as shown in Figure 4.36 (a) & (b), the % decrease in average stock when *k* changes from 1 to 0.8 is higher than when *k* changes from 1 to 0.9.

Consequently, as shown in Figure 4.36 (e) & (f), the % savings in inventory cost is caused by the % decrease in average stock, such that the higher the % decrease in average stock the higher the % savings in inventory cost. Therefore, the % savings in inventory cost when *k* changes from 1 to 0.8 is relatively more than when *k* changes from 1 to 0.9.

These conclusions match closely with the CNMC case study (section 4.3.6); that is, assigning different % service level to items according to their criticality, usage, and value will reduce cost by reducing inventory cost. Therefore, based on this conclusion, the DRI should consider the proposed inventory classification method.
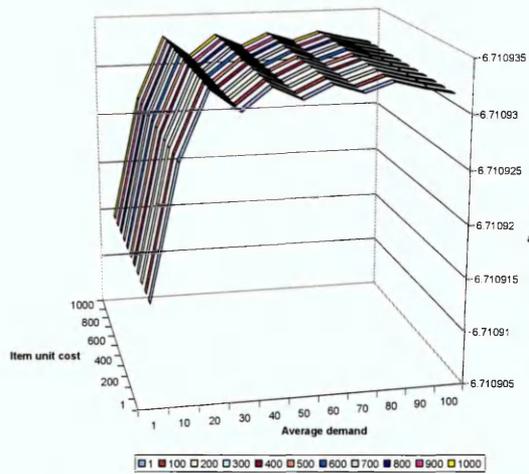
(a) % Decrease in average stock (*k* change from 1 to 0.9)
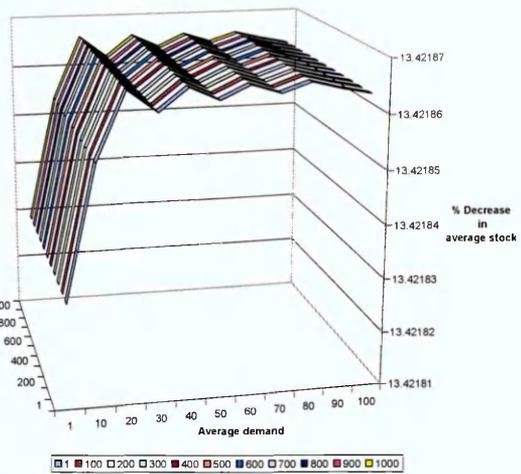
(b) % Decrease in average stock (*k* change from 1 to 0.8)
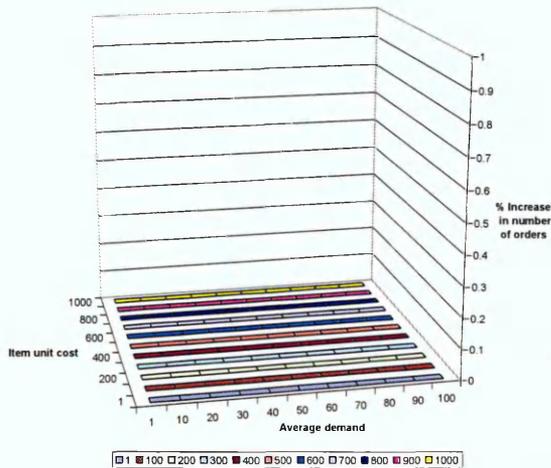
(c) % Increase in number of orders (*k* change from 1 to 0.9)
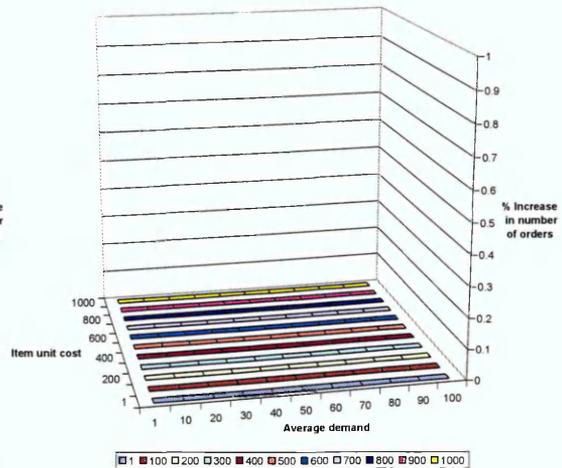
(d) % Increase in number of orders (*k* change from 1 to 0.8)
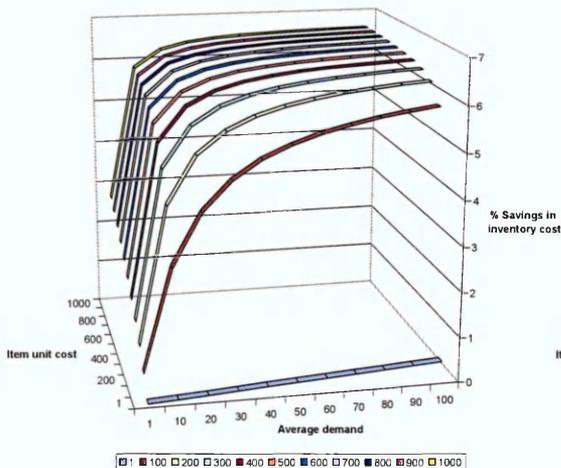
(e) % Savings in inventory cost (*k* change from 1 to 0.9)
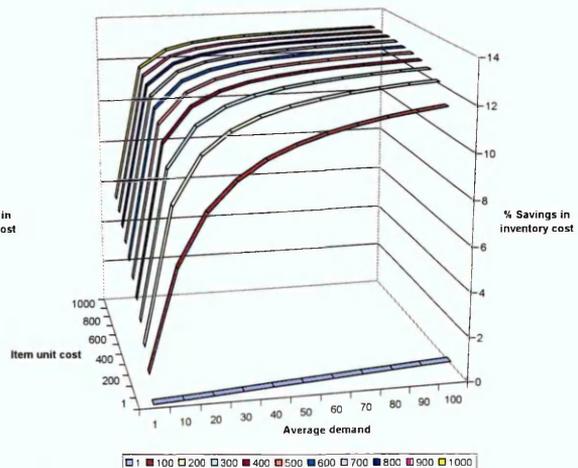
(f) % Savings in inventory cost (*k* change from 1 to 0.8)

Figure 4.36: The % decrease in average stock, the % increase in number of orders, and the % savings in inventory cost when the value of the *Service Level Factor* (*k*) changes from 1 to 0.9 and from 1 to 0.8 for the CR(IOBPCS) operating strategy

4.5 Discussion

The following discusses how, through conducting the two case studies in this chapter, this author answered the research questions that were developed in Chapter Two:

- *Is the integrated system dynamics framework for supply chain design applicable in the health care industry?*

Conducting the two case studies in this chapter showed the applicability of the proposed integrated system dynamics framework for supply chain design in analysing and modelling hospitals logistics systems in practice. This chapter illustrated the qualitative and quantitative analysis of the two case hospitals logistics systems, their dynamic behaviour, and the effect of different logistics decisions –specifically inventory control decisions and service level decisions- on their dynamic behaviour.

- *Does the integrated system dynamics framework provide a structured mechanism for analysing and modelling health care logistics systems and their dynamic behaviour?* and
  Does the analysis and evaluation of the effects of the different logistics decisions on the dynamic behaviour of health care logistics reveal any problematic behaviour?

Based on the qualitative analysis, causal-loop diagrams, stock-flow diagrams, and computer simulation models of the CNMC logistics system and the DRI logistics system were developed. The computer simulation models of the CNMC logistics system and the DRI logistics system were tested for different sample items. The data needed to run the computer simulation models for the sample items were collected from the respective hospital. Due to the lack of information about actual stock levels, this author was not able to validate the models against field data to see whether they can accurately reproduce past statistical data as observed in the real systems. However, this author gained confidence in the

simulation models by assessing their general behaviour characteristics and their ability to generate accepted responses to set policy changes.

The simulation analysis revealed that both the current operating strategy of the CNMC logistics system and the current operating strategy of the DRI logistics system were causing the following undesirable characteristics: holding high stocks level due to the use of non-optimised (R, s, S) inventory control approach, and the occurrence of order batching due to the use of non-linear inventory control decisions that generate a sequence of order impulses which in turn causes demand amplification.

As expected by this author, modelling and simulation provided this author and the decision makers at the CNMC and the DRI with a deeper understanding of their logistics systems and allowed them to directly visualise the impact of their logistics decisions on the dynamic behaviour of the systems. This understanding in turn helped to redesign the CNMC and the DRI logistics systems and suggest improving strategies in terms of performance and cost. Accordingly, several logistics operating strategies were then proposed for redesigning the CNMC logistics system as summarised in Table 4.4 and for redesigning the DRI logistics system as summarised in Table 4.8. Conceptual and computer simulation models were developed for all the proposed operating strategies in each case study.

- *How to quantify in terms of cost the relative improvements of redesign strategies in health care logistics?*

The computer simulation models of the current operating strategy and the proposed operating strategies in each case study were tested for all the items of the matrix in Figure 4.18. This author tested a wide range of items used by the hospitals by using this matrix that shows different combinations of Item Unit Cost, Average Demand, and Standard Deviation of Demand. The computer simulation outputs were used to quantify the effect of the different logistics decisions on inventory cost for each operating strategy. However, the comparison between the current operating strategy and the proposed strategies in each case study is conducted for the inventory cost and not in terms of total

logistics cost (inventory cost + purchasing cost + transportation cost + warehousing cost (Coyle *et al.*, 1996)). Nevertheless, this allowed the author to keep the focus on evaluating inventory control decisions, which is the main area of concern for this research.

For the CNMC case study, this author concludes that among the proposed operating strategies, the CR(IOBPCS) (eliminate) operating strategy is the most successful one in terms of lower inventory cost for a wide range of different items used by the CNMC. The analysis of the computer simulation outputs showed that this operating strategy yield the lowest average stock, but at the same time it had a relatively high number of orders to be placed to the supplier. Therefore, in this author's view, electronic requisitioning using EDI (i.e. very low ordering cost) is essential to ensure that the CR(IOBPCS) (eliminate) operating strategy has the lowest inventory cost. Also, the analysis of the computer simulation outputs showed that eliminating one stock level from the logistics system, such as the main warehouse, reduced inventory cost by reducing average stock in the system and reducing the number of orders. Based on these conclusions and drawing upon the conclusion in Chapter Two about the improvements in the dynamic behaviour of hospitals logistics systems when using the CR(IOBPCS) inventory control approach, this author suggests that the CNMC should consider changing its logistics operating strategy from the current situation to the CR(IOBPCS) (eliminate).

For the DRI case study, this author concludes that among the proposed operating strategies, the CR(IOBPCS) operating strategy is the most successful one in terms of lower inventory cost for a wide range of different items used by the DRI. Therefore, based on this conclusion and drawing upon the conclusion in Chapter Two about the improvements in the dynamic behaviour of hospitals logistics systems when using the CR(IOBPCS) inventory control approach, this author suggests that the DRI should consider changing its logistics operating strategy from the current situation to the CR(IOBPCS).

- *What is the role of inventory classification when incorporated into the redesigning strategies of health care logistics?* and

  What is the impact of using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items on logistics cost reduction?

One of the distinctive characteristics of logistics in the health care industry is that hospitals maintain a large number of different products that are ranged in between high-critical to low-critical items and that the unavailability of critical items could lead to life threatening situations. Accordingly, as part of redesigning the logistics system for both the CNMC and the DRI case studies, it was proposed to incorporate inventory classification into the redesigning strategies. In particular, it was proposed to classify items using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items and study the impact of its use on logistics cost reduction. Studies were conducted to measure the effect of assigning a different % service level to items according to their inventory classification on average stock, number of orders, and inventory cost for the CNMC CR(IOBPCS) (eliminate) operating strategy and for the DRI CR(IOBPCS) operating strategy. It is concluded that assigning a different % service level to items according to their criticality, usage, and value reduces inventory cost. Therefore, this author would recommend that the CNMC and the DRI should use the proposed inventory classification method.

In addition to answering the research questions, through conducting the two case studies, the qualitative analysis and conceptual modelling conducted for the USA and UK case studies allowed the author to compare both hospitals logistics systems and trace out the similarities and differences in the operating practices in terms of managing logistics activities. The quantitative modelling and dynamic analysis conducted in these two case studies allowed the author to compare the impact of these differences on the dynamic behaviour of the respective hospital logistics system. The main similarities and differences in managing the logistics activities between the CNMC and the DRI are summarised as follows:

i. The high level of organisation that traditionally existed in the UK NHS is reflected in the way in which purchasing and supply is approached and organised by the DRI. The establishment of the NHS Logistics Authority as the main supply route for consumable products into the NHS enabled the DRI to increase their buying power which they could not had achieved if they dealt directly with suppliers. Moreover, the NHS Logistics Authority -by offering a reliable fully automated process from order to payment through e-ordering, e-catalogue, and e-billing- enabled the DRI to have a stockless inventory system and reduce their inventory levels. Since the CNMC operates in a sector that is privately financed and privately organised, the CNMC increased their buying power by being a member of Premier. The CNMC, in accordance, orders most of their supplies from one primary distributor and three other secondary distributors as arranged by Premier, although 60% of supplies were ordered from the primary distributor. Yet the CNMC had two types of inventories in addition to wards stocks (i.e. main warehouse and central supply) to ensure the availability of their products. Therefore, the volume of kept inventory along the CNMC pipeline is higher than along the DRI pipeline.

ii. Management of logistics in both the CNMC and the DRI could be considered *centralised*, since the logistics function is formally written into the organizational chart of the hospital through "materials management". Moreover, there exists a specific department in both hospitals that has direct responsibility for managing the different logistics activities (i.e. the materials management department at the CNMC and the supplies department at the DRI).

iii. Although the CNMC and the DRI used different inventory control approaches, the two are considered as non-optimised (R, s, S) inventory control approaches that caused the two hospitals to hold higher stocks level than necessary. Moreover, the non-linearity of the inventory control decisions when using the non-optimised (R, s, S) inventory control approach causes the problem of order batching and in turn the problem of demand amplification.

iv. The CNMC and the DRI used similar inventory control approaches and had a similar desired service level for all items irrespective of their classification. The CNMC classified items according to their frequency of use, and used this

classification to decide whether to stock them at the main warehouse or not. Whereas, the DRI classified items according to whether they are listed in the NHS Logistics Authority catalogue or not and used this classification to decide on the way they order them. However, in both case studies, the criticality, cost and usage value of items were not taken into consideration in the classification criteria. Therefore, both hospitals missed the opportunity to choose the appropriate inventory control approaches and the appropriate desired service level for items which can reduce their inventory cost as proved by this author.

v.   Since the DRI is already operating an electronic requisitioning system using EDI, it makes it relatively more responsive than the CNMC to implement the proposed CR(IOBPCS) operating strategy which was proved to improve their logistics system in terms of performance and cost.

Moreover, through conducting the two case studies in this research work, this author found that modelling is not just a technology for producing answers but an essential part in the educational process and a tool for improving judgment and intuition upon which decisions are actually based.

Chapter Five: Conclusions and Future Research Work

5.1 Introduction

The aim of this chapter is to present the main concluding remarks as a result of the overall research illustrating the main contributions of this research work to the body of knowledge. This chapter also evaluates the research methodology used and highlights the key limitations of this research. Opportunities for future research work are outlined at the end of this chapter.

5.2 Contribution of the Research Work

The overall aim of this research work was to understand the dynamic behaviour of health care logistics systems to effectively manage their logistical activities. The research work had three objectives. The first objective was to provide a structured mechanism for modelling and analysing health care logistics to be able to understand its dynamic behaviour and effectively manage its logistical activities on the basis of the model. The second objective was the application of modelling system dynamics for health care logistics that incorporates service and cost dimensions. The third objective was to redesign health care logistics to improve its dynamic behaviour in terms of performance and cost, taking into consideration the distinctive feature of health care logistics concerning the criticality of items. In achieving the overall aim and objectives, several research questions were proposed. The answers to these questions were provided in Chapter Four, which enabled the achievement of the overall aim of this research work.

This research work has contributed to the understanding of hospitals logistics systems. At present, there are only a few studies to be found in the literature that have analysed logistics in a health care setting, most of which have focused on some specific logistical activity. This research work considers hospitals logistics systems as complex systems in

which the interaction of the feedback loop structures, non-linearity, and delays produce particular dynamic behaviour. This study takes into consideration all the elements of a hospital logistics system including the stocks, material flows, information flows and logistics decisions. Also it employs a structured integrated framework (Hafeez *et al.*, 1996) using qualitative and quantitative tools for analysing and modelling health care logistics systems for operational and strategic decision making. By providing a step by step implementation of the various stages of the framework, this research work is the first study that shows how to qualitatively analyse a hospital logistics system and build qualitative and quantitative models of it, how to conduct extensive dynamic analysis using the quantitative model to study related dynamic behaviour and the effect of the different logistics decisions on this dynamic behaviour, how to reveal problems in the dynamic behaviour and understand why this problematic behaviour emerged, and how to redesign the hospital logistics system and develop better logistics operating strategies in terms of performance and cost. This research work provided a general conceptual model of hospitals logistics systems that can be considered as a baseline, high level qualitative model and that can be further developed for different scenarios. Moreover, this research work provided a clear understanding of the effect of the inventory control decisions and service level decisions on the dynamic behaviour of hospitals logistics systems. This study has demonstrated the main flaw of the traditional (R, s, S) inventory control approach that can lead to the problems of order batching and demand amplification. Furthermore, this study has investigated a number of strategies to improve the dynamic behaviour of hospitals logistics systems by using the CR(IOBPCS) inventory control approach. Also, as a main part of this investigation, this study has assessed the role of inventory classification when incorporated into the redesigning strategies of health care logistics. It has clearly illustrated how to reduce inventory cost by assigning a different % service level to items according to their criticality, usage, and value.

The main contributions of this research work to the body of knowledge are summarised as follows:

1. An analysis of a structured mechanism using system dynamics that can be successfully applied in the health care industry for modelling and analysing health care logistics to allow understanding its dynamic behaviour in order to effectively manage its logistical activities on the basis of the computer model.

2. Analysing and assessing the dynamic behaviour of health care logistics in terms of performance and revealing demand amplification problems in the dynamic behaviour caused by the current inventory control decisions practiced in the health care industry (such as (R, s, S) inventory control approach).

3. Quantifying the impact of inventory control decisions and service level decisions on the dynamic behaviour of hospitals logistics systems in terms of average stock, number of orders and inventory cost which allows choosing the best logistics operating strategy in terms of performance and cost.

4. Reducing inventory cost by using a multi-criteria inventory classification method that takes into account the criticality, cost, and usage value of items and assigning an appropriate percentage service level to items according to their inventory classification.

Also, as part of the contribution of this research work, two papers related to this research work have been presented and published in the following:

i. Hafeez, K., Al-Qatawneh, L. and Tahboub, Z. "Health care supply chain dynamics: systems design of an American health care provider", System Dynamics Conference, July 20-24, 2003, New York, USA.

ii. Hafeez, K., Al-Qatawneh, L. and Tahboub, Z., invited paper "Systems design of a UK NHS trust logistics supply chain", Operations Research Conference, July 2003, Istanbul, Turkey.

5.3 Evaluation of the Research Methodology

The appropriateness of the adopted integrated system dynamics framework for analysing, modelling and redesigning the logistics system for the two case hospitals with the aim of answering the research questions is discussed as follows:

- The integrated system dynamics framework for supply chain design -proposed in this research work- provides the health care decision makers and practitioners

with a structured mechanism (as verified by the practitioners of the two case hospitals) for:

a) Analysing hospitals logistics systems and their dynamic behaviour.

b) Analysing and evaluating the effect of the different logistics decisions on the dynamic behaviour of hospitals logistics systems.

c) Identifying successful logistics decisions and operating strategies that can deal with unpredictable demand for different critical and non-critical items.

- The step by step procedure of the integrated system dynamics framework under the qualitative and quantitative phases proved to be adequate and powerful tools for enhancing the practitioners understanding toward conceptual as well as technical problems associated with their logistics chain. The qualitative phase helps in describing and understanding hospitals logistics systems and their interrelated logistics decisions, whereas the quantitative phase helps in quantifying the impact of different logistics decisions on the dynamic behaviour of hospitals logistics systems.

- In the qualitative phase, tools such as content analysis, interviews, Pareto analysis, information flow analysis, and input-output analysis help in acquiring the conceptual knowledge needed to develop the required conceptual models. Specifically, conceptual models proved to be an essential tool for engaging with the relevant people concerned with the problem situation to capture their mental models.

- In the quantitative phase, the *ithink* Analyst Software that was used for developing the computer simulation models proved to have several advantages including:

a) It allows the creation of stock-flow diagrams directly on the computer screen as icons and the construction of appropriate mathematical relationships between key variables automatically.

b) It allows modelling non-linear, time invariant relationships that are evident or may be assumed.

c) The models developed are relatively easy to use and understood by users who are unfamiliar with mathematical difference and differential equations.

d) The models developed can be modified or expanded by including other linear and non-linear decisions without worrying about the complexity of the resulting equations for further manipulations.

- Developing qualitative and quantitative models proved to be a learning experience for this author and the participants of the two case studies. In particular, they learned how to analyse the impact of different logistics decisions – specifically inventory control and service level decisions - on the dynamic behaviour of the hospital logistics system. This learning experience proved to enhance their understanding how to design more effective logistics operating strategies.

- The computer simulation outputs proved to be very useful in quantifying the effect of different logistics decisions with regard to average stock, number of orders and inventory cost. This allows the decision makers to choose the best logistics operating strategy in terms of performance and cost.

However the methodology demands full commitment from the participants for data collection and verification stages. Sometime it is difficult to collect an unbiased view from participants at individual level.

5.4 Limitations of the Research Work

Several limitations have been faced while conducting this research work. Although the general conceptual model of a hospital logistics system developed here includes decision making for the different logistics activities (i.e. inventory control decisions, service level decisions, purchasing decisions, transportation decisions, and warehousing decisions), however, this research work focused only on studying inventory control decisions and service level decisions and evaluating their effects on the dynamic

behaviour of hospitals logistics systems. Also this study considered the inventory cost only during the optimisation process. In future, this can be further enriched by considering other logistics costs (i.e. transportation cost, purchasing cost, and warehousing cost) for cost optimisation.

At the technical level, one limitation is in representing the consumption rate data as constant, step or normal function while conducting the dynamic analysis using computer simulation models. Therefore, any conclusions that might be drawn on the results should be taken into consideration that in real time situations, consumption rates may behave in a continuous level for example similar to a learning curve. This study also considered only a selection of critical and non-critical items for testing the model and can be broadened to include more hospital products.

5.5 Future Research Work

One of the suggestions for future research work is to investigate other inventory control decisions and evaluate their impact on the dynamic behaviour of hospitals logistics systems. For example, it is suggested to study the replenishment rule that is proposed by Dejonckheere *et al.* (2003) to generate smooth ordering patterns and avoid demand amplification, based on automatic pipeline inventory and order based production control system (APIOBPCS) (John *et al.*, 1994; Mason-Jones *et al.*, 1995; Disney *et al.*, 2000). Further research is also suggested to confirm demand amplification phenomena in the health care industry by collecting more data and performing appropriate tests as given in the literature (Forrester, 1961; Sterman, 2000).

Another avenue for future research work could be to further improve our understanding of hospitals decision making through studying purchasing, transportation, and warehousing decisions. These can be modelled and evaluated through computer simulation based on system dynamics tool. This will allow teasing out the trade-off effects for the different logistics activities. This will help to design a set of "best practice" simulation models that would further optimise total logistics cost while improving the dynamic behaviour of the hospitals supply chain.

References

AHN, B., WATANABE, N. and HIRAKI, S., 1994. A mathematical model to minimize the inventory and transportation costs in the logistics systems. *Computers & Industrial Engineering,* **27**(1-4), pp. 229-232.

ALBIN, S., 1997. Building a system dynamics model part 1: Conceptualization (D-4597). *Road Maps: A Guide to Learning System Dynamics.* System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology.

AL-QATAWNEH, L., 1998. *Using an Integrated System Dynamics Framework in Modeling Derbyshire Royal Infirmary-NHS Supplies Authority's Supply Chain,* MSc. Thesis, Sheffield Hallam University.

ALSTROM, P. and MADSEN, P., 1992. Simulation of inventory control systems. *International Journal of Production Economics,* **26**(1-3), pp. 125-134.

APTEL, O. and POURJALALI, H., 2001. Improving activities and decreasing costs of logistics in hospitals: A comparison of U.S. and French hospitals. *The International Journal of Accounting,* **36**(1), pp. 65-90.

AXSATER, S., 2001. A note on stock replenishment and shipment scheduling for vendor-managed inventory systems. *Management Science,* **47**(9), pp. 1306-1310.

BALLOU, R.H., 1989. Heuristics: Rules of thumb for logistics decision making. *Journal of Business Logistics,* **10**(1), pp. 122-132.

BALLOU, R.H., 1992. Business Logistics Management. 3rd edn. Englewood Cliffs, NJ: Printice-Hall.

BANERJEA-BRODEUR, M., CORDEAU, J., LAPORTE, G. and LASRY, A., 1998. Scheduling linen deliveries in a large hospital. *Journal of the Operational Research Society,* **49**(8), pp. 777-781.

BECHTEL, C. and JAYARAM, J., 1997. Supply chain management: A strategic perspective. *International Journal of Logistics Management,* **8**(1), pp. 15-34.

BEIER, F.J., 1995. The management of the supply chain for hospital pharmacies: A focus on inventory management practices. *Journal of Business Logistics,* **16**(2), pp. 135-173.

BERRY, D. and NAIM, M.M., 1996. Quantifying the relative improvements of redesign strategies in a P.C. supply chain. *International Journal of Production Economics,* **46-47**, pp. 181-196.

BERTAZZI, L. and GRAZIA SPERANZA, M., 1999. Inventory control on sequences of links with given transportation frequencies. *International Journal of Production Economics,* **59**(1-3), pp. 261-270.

BLUMENFELD, D., 2001. Operations Research Calculations Handbook. Boca Raton: CRC Press.

BOWERSOX, D.J. and CLOSS, D.J., 1989. Simulation in logistics: a review of present practice and a look to the future. *Journal of Business Logistics,* **10**(1), pp. 133-148.

BOWERSOX, D.J. and CLOSS, D.J., 1996. Logistical Management: The Integrated Supply Chain Process. New York: McGraw-Hill.

BROCK, T.H., 2003. Hospitals, group purchasing organizations and the antitrust laws. *Healthcare Financial Management,* **57**(3), pp. 38.

BURBIDGE, J., 1983. Five golden rules to avoid bankruptcy. *The Production Engineer,* **62**(10), pp. 13-14.

CACHON, G., 1997. Campbell Soup's continuous replenishment program: Evaluation and enhanced inventory decision rules. *Production and Operations Management,* 6(3), pp. 266-276.

CETINKAYA, S. and LEE, C., 2000. Stock replenishment and shipment scheduling for vendor-managed inventory systems. *Management Science,* 46(2), pp. 217.

CHEN, E.J., LEE, Y.M. and SELIKSON, P.L., 2002. A simulation study of logistics activities in a chemical plant. *Simulation Modelling Practice and Theory,* 10(3-4), pp. 235-245.

CHEN, I.J. and PAULRAJ, A., 2004. Towards a theory of supply chain management: The constructs and measurements. *Journal of Operations Management,* 22(2), pp. 119-150.

CHIU, H.N., 1995. A heuristic (R, T) periodic review perishable inventory model with lead times. *International Journal of Production Economics,* 42(1), pp. 1-15.

COHEN, M.A. and ERNST, R., 1988. Multi-item classification and generic inventory stock control policies. *Production and Inventory Management Journal,* **Third Quarter,** pp. 6-8.

COX, J.F. and GIBSON, J.T., 1986. Inventory management for hospital pharmacies. *Hospital Materiel Management Quarterly,* 8(1), pp. 64-74.

COYLE, J.J., BARDI, E.J. and LANGLEY, J.C., 1996. The Management of Business Logistics. 6th edn. St. Paul: West Publishing Company.

COYLE, R.G., 1977. Management System Dynamics. New York: John Wiley & Sons.

COYLE, R.G., 1984. A systems approach to the management of a hospital for short-term patients. *Socio-economic planning sciences,* 18(4), pp. 219-226.

COYLE, R.G., 1996. System Dynamics Modelling: A Practical Approach. London: Chapman and Hall.

CSC CONSULTING, INC. (CSC), 1996. *Efficient health-care consumer response: Improving the efficiency of the health-care supply chain.*

DANGERFIELD, B. and ROBERTS, C., 1999. Optimisation as a statistical estimation tool: An example in estimating the AIDS treatment-free incubation period distribution. *System Dynamics Review,* **15**(3), pp. 273-292.

DEJOHN, P., 1997. UPN code standards may be the next issue. *Hospital Materials Management,* **22**(10), pp. 18-20.

DEJONCKHEERE, J., DISNEY, S.M., LAMBRECHT, M.R. and TOWILL, D.R., 2003. Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research,* **147**(3), pp. 567-590.

DELLAERT, N. and VAN DE POEL, E., 1996. Global inventory control in an academic hospital. *International Journal of Production Economics,* **46-47**, pp. 277-284.

DISNEY, S.M., NAIM, M.M. and TOWILL, D.R., 2000. Genetic algorithm optimisation of a class of inventory control systems. *International Journal of Production Economics,* **68**(3), pp. 259-278.

DISNEY, S.M., POTTER, A.T. and GARDNER, B.M., 2003. The impact of vendor managed inventory on transport operations. *Transportation Research Part E: Logistics and Transportation Review,* **39**(5), pp. 363-380.

DISNEY, S.M. and TOWILL, D.R., 2002. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. *International Journal of Production Research,* **40**(1), pp. 179-204.

DISNEY, S.M. and TOWILL, D.R., 2003. Vendor-managed inventory and bullwhip reduction in a two-level supply chain. *International Journal of Operations & Production Management,* **23**(6), pp. 625.

DOCTEUR, E. and OXLEY, H., 2003. Health care: A quest for better value. *The Observer,* **July**(238).

EDGHILL, J. and TOWILL, D.R., 1989. The use of system dynamics in manufacturing systems engineering. *Trans Institute of MC,* **11**(4), pp. 208-216.

ELWANY, M.H. and BADDAN, A.E., 1998. The sensitivity of jobshop due date lead time to changes in the processing time. *Computers & Industrial Engineering,* **35**(3-4), pp. 411-414.

EVANS, G.N., NAIM, M.M. and TOWILL, D.R., 1998. Application of a simulation methodology to the redesign of a logistical control system. *International Journal of Production Economics,* **56-57**, pp. 157-168.

FERNANDEZ, F., 1987. Sticking to the basics while exploring new direction. *Hospital Materiel Management Quarterly,* **9**(2), pp. 60-64.

FERRIS, J.S. and TOWILL, D.R., 1993. Benchmarking a generic family of dynamic manufacturing ordering and control models. *Journal of Systems Engineering,* **3**, pp. 170-182.

FLEISCHMANN, M. and KUIK, R., 2003. On optimal inventory control with independent stochastic item returns. *European Journal of Operational Research,* **151**(1), pp. 25-37.

FLORES, B.E. and WHYBARK, D.C., 1986. Multiple criteria ABC analysis. *International Journal of Operations & Production Management,* **6**(3), pp. 38.

FORRESTER, J.W., 1961. Industrial Dynamics. Waltham: Pegasus Communications, Inc.

FORRESTER, J.W., 1994. System Dynamics, Systems Thinking, and Soft OR. *System Dynamics Review,* **10**(2), pp. 245-256.

FRY, M.J., KAPUSCINSKI, R. and OLSEN, T.L., 2001. Coordinating production and delivery under a (z, Z)-Type vendor-managed inventory contract. *Manufacturing and Service Operations Management,* **3**(2), pp. 151-173.

GANESHAN, R. and HARRISON, T.P., 1995-last update. An introduction to supply chain management. Available: http://lcm.csa.iisc.ernet.in/scm/supply_chain_intro.html.

GONZALEZ-BUSTO, B. and GARCIA, R., 1999. Waiting lists in Spanish public hospitals: A system dynamics approach. *System Dynamics Review,* **15**(3), pp. 201-225.

GRUBBSTROM, R.W. and WIKNER, J., 1996. Inventory trigger control policies developed in terms of control theory. *International Journal of Production Economics,* **45**(1-3), pp. 397-406.

GUNASEKARAN, A., 2004. Supply chain management: Theory and applications. *European Journal of Operational Research,* **159**(2), pp. 265-268.

HAAVIK, S., 2000. Building a demand-driven, vendor-managed supply chain. *Healthcare Financial Management,* **54**(2), pp. 56.

HAFEEZ, K., GRIFFITHS, M., GRIFFITHS, J. and NAIM, M.M., 1996. Systems design of a two-echelon steel industry supply chain. *International Journal of Production Economics,* **45**(1-3), pp. 121-130.

HALEY, G.T. and KRISHNAN, R., 1995. It's time for CALM: Computer-aided logistics management. *International Journal of Physical Distribution & Logistics Management,* **25**(4), pp. 46.

HEINBUCH, S.E., 1995. A case of successful technology transfer to health care: Total quality materials management and just-in-time. *Journal of Management in Medicine,* **9**(2), pp. 48-56.

HENNING, W.K., 1986. Logistics management: The administrator's opportunity. *Hospital Materiel Management Quarterly,* **8**(2), pp. 85-89.

HOLWEG, M. and BICHENO, J., 2002. Supply chain simulation - a tool for education, enhancement and endeavour. *International Journal of Production Economics,* **78**(2), pp. 163-175.

HOULIHAN, J.B., 1987. International supply chain management. *International Journal of Physical Distribution and Materials Management,* **17**(2), pp. 51-66.

HUARNG, F. and LEE, M.H., 1996. Using simulation in out-patient queues: A case study. *International Journal of Health Care Quality Assurance,* **9**(6), pp. 21-25.

HWANG, H., 2002. Design of supply-chain logistics system considering service level. *Computers & Industrial Engineering,* **43**(1-2), pp. 283-297.

JARRETT, P.G., 1998. Logistics in the health care industry. *International Journal of Physical Distribution & Logistics Management,* **28**(9/10), pp. 741.

JOHN, S., NAIM, M.M. and TOWILL, D.R., 1994. Dynamic analysis of a WIP compensated decision support system. *International Journal of Manufacturing System Design,* **1**(4), pp. 283-297.

JOST, T.S. and HUGHES, D., 1995. The British health care reforms, the American health care revolution, and purchaser/provider contracts. *Journal of Health Politics, Policy & Law,* **20**(4), pp. 885.

KALDOR, D.K., KOWALSKI, J.C. and TANKERSLEY, M.A., 2003. Evaluating group purchasing organizations. *Healthcare Financial Management,* **57**(1), pp. 36.

KAPUR, R. and MOBERG, C., 1987. Evaluating inventory turns for a hospital environment. *Computers & Industrial Engineering,* **13**(1-4), pp. 73-77.

KIM, D.H., 1995. A heuristic for replenishment of deteriorating items with a linear trend in demand. *International Journal of Production Economics,* **39**(3), pp. 265-270.

KIM, I. and TANG, C.S., 1997. Lead time and response time in a pull production control system. *European Journal of Operational Research,* **101**(3), pp. 474-485.

KONTZER, T., 2003. Owens & Minor takes supply chain deeper. *InformationWeek,* **September 22**, pp. 47-50.

KORUPOLU, M.R., PLAXTON, C.G. and RAJARAMAN, R., 2000. Analysis of a Local Search Heuristic for Facility Location Problems. *Journal of Algorithms,* **37**(1), pp. 146-188.

KOTZAB, H., 1999. Improving supply chain performance by efficient consumer response? A critical comparison of existing ECR approaches. *Journal of Business & Industrial Marketing,* **14**(5/6), pp. 364.

LAI, C.L., LEE, W.B. and IP, W.H., 2003. A study of system dynamics in just-in-time logistics. *Journal of Materials Processing Technology,* **138**(1-3), pp. 265-269.

LA LONDE, BERNARD J. and MASTERS, J.M., 1994. Emerging logistics strategies. *International Journal of Physical Distribution & Logistics Management,* **24**(7), pp. 35.

LAMBERT, D.M., ed, 2004. *Supply Chain Management: Processes, Partnerships, Performance.* Sarasota, Florida: Supply Chain Management Institute.

LANE, D.C. and OLIVA, R., 1998. The greater whole: Towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operational Research,* **107**(1), pp. 214-235.

LEE, H.L. and PADMANABHAN, V., 1997. Information distortion in a supply chain: The bullwhip effect. *Management Science,* **43**(4), pp. 546.

LEUNG, S.C.H., WU, Y. and LAI, K.K., 2002. An optimization model for a cross-border logistics problem: a case in Hong Kong. *Computers & Industrial Engineering,* **43**(1-2), pp. 393-405.

LEVIN, Y. and BEN-ISRAEL, A., 2004. A heuristic method for large-scale multi-facility location problems. *Computers & Operations Research,* **31**(2), pp. 257-272.

MASON-JONES, R., 1995. Dynamics of pipeline control, *14th European Conference on Operational Research,* Jerusalem, 3-6 July 1995.

MASON-JONES, R., BERRY, D. and NAIM, M.M., 1998. A systems engineering approach to manufacturing systems analysis. *Integrated Manufacturing Systems,* 9(6), pp. 350-365.

MASON-JONES, R., NAIM, M.M. and TOWILL, D.R., 1997. The Impact of Pipeline Control on Supply Chain Dynamics. *International Journal of Logistics Management,* 8(2), pp. 47-62.

MEADOWS, D.H., 1989. System dynamics meets the press. *System Dynamics Review,* 5(1), pp. 68-80.

MEHROTRA, A., DUDLEY, R.A. and LUFT, H.S., 2003. What's behind the health expenditure trends? *Annu. Rev. Public Health 2003,* 24, pp. 385-412.

MENTZER, J.T. and SCHUSTER, A.D., 1982. Computer modelling in logistics: existing models and future outlook. *Journal of Business Logistics,* 3(2), pp. 1-55.

MITTLER, S.J., 1998. Southampton University Hospital NHS Trust: Our approach to performance management. *International Journal of Health Care Quality Assurance,* 11(4), pp. 134-136.

MOREY, R.C., RETZLAFF-ROBERTS, D.L. and FINE, D.J., 1994. Getting something for nothing: Estimating service level improvements possible in hospitals. *International Transactions in Operational Research,* 1(3), pp. 285.

MOYNIHAN, J.J., 1998. Is now the time for bar coding? *Healthcare Financial Management,* 52(2), pp. 87.

MOYNIHAN, J.V., 1997. Improving the healthcare supply chain using EDI. *Healthcare Financial Management,* 51(3), pp. 78.

NAIM, M.M. and TOWILL, D.R., 1994. Establishing a framework for effective materials logistics management. *International Journal of Logistics Management,* 5(1), pp. 81-88.

NEUMANN, L., 2003. Streamlining the supply chain. *Healthcare Financial Management,* **57**(7), pp. 56.

NHS LOGISTICS AUTHORITY, 2003-last update. Available: http://www.logistics.nhs.uk/ [March, 2003].

NHS PURCHASING AND SUPPLY AGENCY, 2003-last update. Available: http://www.pasa.doh.gov.uk/ [March, 2003].

NICHOLSON, L., VAKHARIA, A.J. and SELCUK ERENGUC, S., 2004. Outsourcing inventory management decisions in healthcare: Models and application. *European Journal of Operational Research,* **154**(1), pp. 271-290.

NORLING, R.A., 2002. On group purchasing: people and opinions. *Healthcare Purchasing News,* **July**.

NORTH, L.H., 1994. Beyond just-in-time: The UCLA Medical Center experience. *Hospital Materiel Management Quarterly,* **15**(3), pp. 36-41.

OECD HEALTH DATA, June 8, 2005-last update, Table 6: Total expenditure on health, % of gross domestic product. Available: http://www.oecd.org/document/16/0,2340,en_2825_495642_2085200_1_1_1_1,00.html [July, 2005].

OLIVER, R.K. and WEBBER, M.D., 1992. Supply-chain management: Logistics catches up with strategy. In: M. CHRISTOPHER, ed, *Logistics: The Strategic Issues.* London: Chapman & Hall, pp. 63-75.

OTTO, A. and KOTZAB, H., 2003. Does supply chain management really pay? Six perspectives to measure the performance of managing a supply chain. *European Journal of Operational Research,* **144**(2), pp. 306-320.

PARTOVI, F.Y. and BURTON, J., 1993. Using the analytic hierarchy process for ABC analysis. *International Journal of Operations & Production Management,* **13**(9), pp. 29-44.

PEREA, E., GROSSMANN, I., YDSTIE, E. and TAHMASSEBI, T., 2000. Dynamic modeling and classical control theory for supply chain management. *Computers & Chemical Engineering,* **24**(2-7), pp. 1143-1149.

PERSSON, F. and OLHAGER, J., 2002. Performance simulation of supply chain designs. *International Journal of Production Economics,* **77**(3), pp. 231-245.

PINA, V. and TORRES, L., 1996. Methodological aspects in efficiency evaluation of public hospitals. *Financial Accountability & Management.*

PINKERTON, J., 1987. Using a spreadsheet to analyze inventory. *Purchasing World,* **August,** pp. 46-47.

POULIN, E., 2003. Benchmarking the hospital logistics process. *CMA Management,* **March,** pp. 21-23.

POWERS, R.F., 1989. Optimization models for logistics decisions. *Journal of Business Logistics,* **10**(1), pp. 106-121.

PRASHANT, N.D., 1991. A systematic approach to optimization of inventory management functions. *Hospital Materiel Management Quarterly,* **12**(4), pp. 34-38.

RAGHUNATHAN, S. and YEH, A.B., 2001. Beyond EDI: Impact of continuous replenishment program (CRP) between a manufacturer and its retailers. *Information Systems Research,* **12**(4), pp. 406-419.

RANDHAWA, S.U. and RAI, N., 1995. A scheduling decision aid in glass fiber manufacturing. *Computers & Industrial Engineering,* **29**(1-4), pp. 255-259.

REID, R.A., 1986. Simple tool improves policy development in materiel management. *Hospital Materiel Management Quarterly,* **7**(4), pp. 85-92.

REID, R.A., 1987. The ABC method in hospital inventory management: A practical approach. *Production and Inventory Management Journal,* **Fourth Quarter,** pp. 67-70.

REISMAN, A., 1981. Materials Management for Health Services. Lexington, Massachusetts: D.C. Heath and Company.

RICHARDSON, G.P. and PUGH, A.L., 1981. Introduction to System Dynamics Modeling with DYNAMO. Cambridge, MA: MIT Press.

RICHMOND, B., 2001. An Introduction to Systems Thinking. Hanover, NH: High Performance Systems, Inc.

RITCHIE, L., BURNES, B., WHITTLE, P. and HEY, R., 2000. The benefits of reverse logistics: The case of the Manchester Royal Infirmary Pharmacy. *Supply Chain Management: An International Journal,* 5(5), pp. 226-233.

RIVARD-ROYER, H., LANDRY, S. and BEAULIEU, M., 2002. Hybrid stockless: A case study Lessons for health-care supply chain integration. *International Journal of Operations & Production Management,* 22(4), pp. 412-424.

RODWIN, V.G., 1999. Comparative analysis of health systems: An international perspective. In: A.R. KOVNER and S. JONAS, eds, *Health Care Delivery in the United States.* 6th edn. New York: Springer Publishing Company, pp. 116-151.

RUIZ-TORRES, A.J. and TYWORTH, J.E., 1997. Simulation based approach to study the interaction of scheduling and routing on a logistic network, *Proceedings of 1997 Winter Simulation Conference,* 7-10 December 1997.

SAVAGE, G.T. and MICHAEL, E.W., 1995. International health care: A comparison of the U.S., Canada, and Western Europe. In: L.F. WOLPER, ed, *Health Care Administration: Principles, Practices, Structure and Delivery.* 2nd edn. Gaithersburg, Maryland: Aspen Publishers, pp. 643-679.

SCHEYER, W.L., 1995. Materials Management. In: L.F. WOLPER, ed, *Health Care Administration: Principles, Practices, Structure and Delivery.* 2nd edn. Gaithersburg, Maryland: Aspen Publishers, pp. 643-679.

SILVER, E.A. and PETERSON, R., 1985. Decision Systems for Inventory Management and Production Planning. 2nd edn. New York: John Wiley & Sons.

SLATS, P.A., BHOLA, B., EVERS, J.J.M. and DIJKHUIZEN, G., 1995. Logistic chain modelling. *European Journal of Operational Research,* **87**(1), pp. 1-20.

SMITH, J., 1999. Let suppliers help plan purchase needs. *Hospital Materials Management,* **24**(1), pp. 12-13.

SOUZA, G.C., WAGNER, H.M. and WHYBARK, D.C., 2001. Evaluating focused factory benefits with queuing theory. *European Journal of Operational Research,* **128**(3), pp. 597-610.

SPEDDING, P.E., 1998. Revisiting time-phased order in the health care industry. *IIE Solutions,* **30**(2), pp. 22.

SPERANZA, M.G. and UKOVICH, W., 1994. Analysis and integration of optimization models for logistic systems. *International Journal of Production Economics,* **35**(1-3), pp. 183-190.

STERMAN, J.D., 1991. A skeptic's guide to computer models. In: G.O. BARNEY, W.B. KREUTZER and M.J. GARRETT, eds, *Managing a Nation: The Microcomputer Software Catalog.* Boulder, CO: Westview Press, pp. 209-229.

STERMAN, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. New York: Irwin/McGraw-Hill.

STEVENS, G.C., 1989. Integrating the supply chain. *International Journal of Physical Distribution and Materials Management,* **9**(8), pp. 3-8.

STEVENS, G.C., 1990. Successful supply-chain management. *Management Decision,* **28**(8), pp. 25-30.

SYSTEM DYNAMICS SOCIETY, August, 2004-last update. Available: http://www.systemdynamics.org/ [September, 2004].

TERZI, S. and CAVALIERI, S., 2004. Simulation in the supply chain context: a survey. *Computers in Industry,* **53**(1), pp. 3-16.

THE CONCISE OXFORD DICTIONARY OF MATHEMATICS, 2005-last update. Oxford University Press. Available: http://www.oxfordreference.com/.

THE *ithink* AND STELLA TECHNICAL DOCUMENTATION, 2002. High Performance Systems, Inc.

TOWILL, D.R., 1982. Dynamic analysis of an inventory and order based production control system. *International Journal of Production Research,* **20**(6), pp. 671.

TOWILL, D.R., 1984. An introduction to the dynamics of production control systems. *Journal of the Institute of Production Control,* **12**, pp. 1-8.

TOWILL, D.R., 1991. Supply chain dynamics. *International Journal of Computer Integrated Manufacturing,* **4**(4), pp. 197-208.

TOWILL, D.R. and DEL VECCHIO, A., 1994. The application of filter theory to the study of supply chain dynamics. *Production Planning & Control,* **5**(1), pp. 82.

TOWILL, D.R., NAIM, M.M. and WIKNER, J., 1992. Industrial dynamics simulation models in the design of supply chains. *International Journal of Physical Distribution and Logistics Management,* **22**(5), pp. 3-13.

VAN ACKERE, A. and SMITH, P.C., 1999. Towards a macro model of National Health Service waiting lists. *System Dynamics Review,* **15**(3), pp. 225-253.

VERGIN, R.C. and BARR, K., 1999. Building competitiveness in grocery supply through continuous replenishment planning: Insights from the field. *Industrial Marketing Management,* **28**(2), pp. 145-153.

WHITSON, D., 1997. Applying just-in-time systems in health care. *IIE Solutions,* **29**(8), pp. 32.

WIKNER, J., TOWILL, D.R. and NAIM, M., 1991. Smoothing supply chain dynamics. *International Journal of Production Economics,* **22**(3), pp. 231-248.

WILSON, J.W. and CUNNINGHAM, W.A., 1992. Stockless inventory systems for the health care provider: Three successful applications. *Journal of health care marketing,* **12**(2), pp. 39-45.

WOLSTENHOLME, E.F., 1990. System Enquiry: A System Dynamics Approach. New York: John Wiley & Sons.

WOLSTENHOLME, E.F., 1999. Qualitative *vs* quantitative modelling: The evolving balance. *Journal of the Operational Research Society,* **50**(4), pp. 422-429.

WOLSTENHOLME, E., MCKELVIE, D., SMITH, G. and MONK, D., 2004. *Using System Dynamics in Modelling Health and Social Care Commissioning in the UK.* Middlesex: OLM Consulting.

Appendix A: System Dynamics

The aim of this Appendix is to provide a brief discussion of the main concepts of system dynamics. In learning the basic concepts behind the study of complex systems using system dynamics, this research depended on two main sources, which are:

1. *"Road Maps, A Guide to Learning System Dynamics"*: It is a self-study guide to learning system dynamics. It is organised as a series of chapters, and is being developed by the System Dynamics in Education Project at MIT under the direction of Professor Jay Forrester.

2. *"Introduction to System Dynamics"*: It is an online book prepared for the Department of Energy by Michael J. Radzicki, PhD. Of Sustainable Solutions, Inc. While the examples are directed to energy policy, anyone interested in learning system dynamics will find it valuable.

Both sources above can be found on the System Dynamics Society website << http://www.systemdynamics.org/ >>. However, this research work used other sources and references to reinforce the knowledge of these concepts. The following points discuss briefly the main concepts of system dynamics. These summary points are taken from the above two sources as follows:

1. In system dynamics, a system is defined as a collection of elements that continually interact over time to form a unified whole.

2. The structure of the system is those underlying relationships and connections between the components of the system.

3. The behaviour of the system is the way in which the elements or variables composing a system vary over time.

4. System dynamics is concerned with the behaviour of a system over time.

5. Real systems often generate clearly identifiable time patterns or time paths of behaviour. These systems behavioural patterns can be placed into one or a combination of five distinct categories, including: linear family, exponential family, goal-seeking family, oscillation family, and S-shaped family. The linear family of paths includes: equilibrium, linear growth, and linear decline. The exponential family consists of exponential growth and exponential decay. Goal-seeking behaviour is related to exponential decay, however, with one difference in which the time path is either seeking a goal of zero, or seeking a non-zero goal. Oscillation family includes sustained, damped, exploding, and chaos. S-shaped family includes: S-shaped growth, S-shaped growth with overshoot, and overshoot and collapse.

6. In system dynamics, dynamic behaviour is thought to arise due to the "*Principle of Accumulation*". More precisely, this principle states that all dynamic behaviour in the world occurs when flows accumulate in stocks.

7. In terms of a metaphor, a stock can be thought of as a bathtub and a flow can be thought of as a faucet and pipe assembly that fills or drains the stock as shown in Figure A.1. The stock-flow structure in Figure A.1 is the simplest dynamical system in the world.
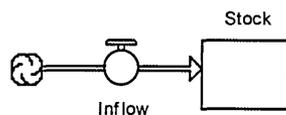
Figure A. 1: Example of a simple stock and flow structure

8. In system dynamics, both informational and non-informational entities can move through flows and accumulate in stocks.

9. In order to identify stocks and flows, it is essential to determine which variables in the system experiencing the problem define its state (its stocks), and which variables define the changes in its state (its flows).

10. Stocks possess four characteristics that are crucial in determining the dynamic behaviour of systems. More specifically, stocks have memory, change the time shape of flows, "decouple" or interrupt flows, and create delays.

11. The stocks and flows in real world systems are part of feedback loops. And the feedback loops are often joined together by non-linear couplings that often cause counter initiative behaviour.

12. From a system dynamics point of view, a system can be classified as either "open" or "closed". Open systems have outputs that respond to, but have no influence upon, their inputs. Closed systems, on the other hand, have outputs that respond to, and influence their inputs.

13. Given the fundamental role of feedback in the control of closed systems, then, an important rule in system dynamics can be stated as: every feedback loop in a system dynamics model must contain at least one stock. Figure A.2 shows an example of a simple system dynamics stock-flow structure of a closed system with a positive feedback loop. As shown in Figure A.2, the feedback path for the closed system includes, in sequence, a stock, information about the stock, and a decision rule that controls the change in the flow. An information link is drawn between the stock and flow to transmit information back to the flow variable about the state of the stock variable. This information is used to make decisions on how to alter the flow setting.
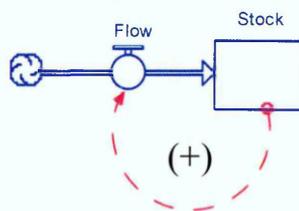
Figure A. 2: Simple system dynamics stock-flow structure of a closed system with a positive feedback loop

14. Closed systems are controlled by two types of feedback loops: positive loops and negative loops.

15. Positive loops portray self-reinforcing processes wherein an action creates a result that generates more of the action, and hence more of the result. The simplest and most fundamental positive feedback loop consists of one level and one rate, as shown in Figure A.2, and the rate is directly proportional to the level.

16. Negative feedback loops, on the other hand, describe goal-seeking processes that generate actions aimed at moving a system toward, or keeping a system at, a desired state. The simplest and most fundamental negative feedback loop contains one rate and one level, as shown in Figure A.3, and the rate is directly proportional to the level.
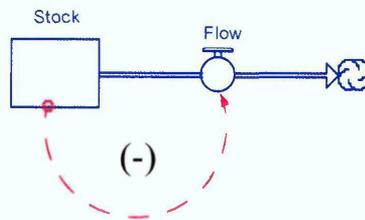
Figure A. 3: Simple system dynamics stock-flow structure of a closed system with a negative feedback loop

17. The two types of feedback, positive and negative, combine to create all of the behaviour observed in complex systems. Frequently, a system's feedback loops will be joined together in non-linear relationships. These non-linear couplings can cause the dominance of a system's feedback loops to change endogenously. That is, over time, a system whose behaviour is being determined by a particular feedback loop, or set of loops, can (sometimes suddenly) endogenously switch to a behaviour determined by another loop or set of loops. This particular characteristic of non-linear feedback systems is partially responsible for their complex, and hard-to-understand behaviour.

Appendix B: The *ithink* Analyst Software

The *ithink* Analyst Software is one of the industry standard system dynamics software. The *ithink* and STELLA Technical Documentation (2002) provides the essential "how to" information concerning the use of the *ithink* Analyst Software. The aim of this Appendix is to provide the reader with enough information about the *ithink* Analyst Software to enable him/her to understand the content of this thesis. Therefore, in this Appendix, parts of the above documentation will be provided to give a general picture of how the software works; mainly about:

- The software three-layer operating environment.
- The purpose of the Map/Model level building blocks (which are used in building all stock-flow diagrams in this thesis).
- The purpose of the Ghost tool which is available only on the Map/Model level.
- The simulation algorithm.

The software three-layer operating environment

Figure B.1 provides an overview of the software's three-layer operating environment. As the Figure indicates, the software has three distinct layers: the Interface layer, the Map/Model layer, and the Equations layer.

The software opens on the Map/Model layer. This layer is where you will lay out your thinking in the form of a map[1]. On this layer, you will transform maps into models that can be simulated on the computer. The Map/Model layer thus is the "engine room" for the models you create.

Above the Map/Model layer, you'll find the Interface layer. As the name suggests, the Interface layer provides you with the tools needed for engaging end-user interfaces to your models. You'll use these Interface layer tools to create, for example, flight simulator cockpits in which users can interact with the model as the simulation

---

[1] In this research the words "stock-flow diagram" is used instead of the word map; as the word "map" may imply other meaning to the reader.

progresses. Finally, below the Map/Model layer you'll find the Equations layer. This layer gives you a list of all the equations that make up your model.

The Interface Layer
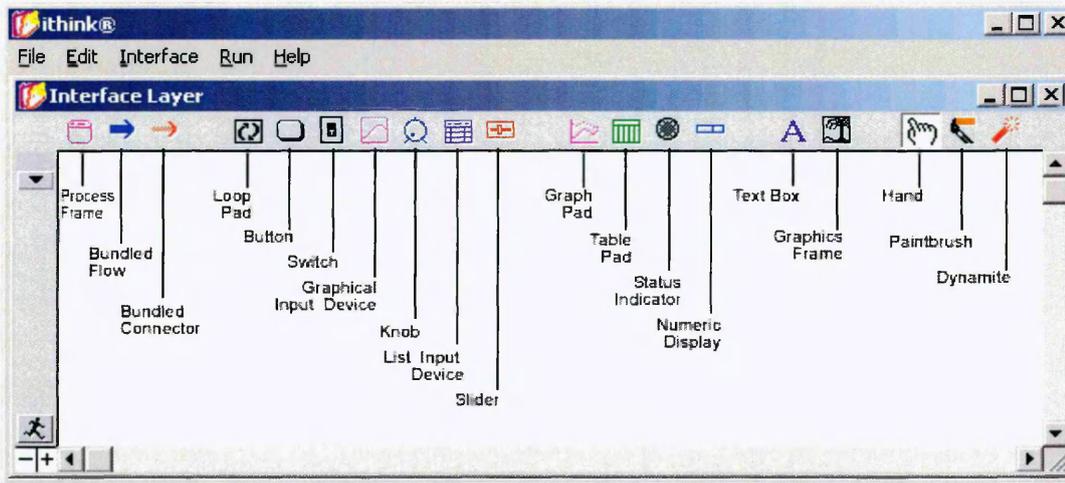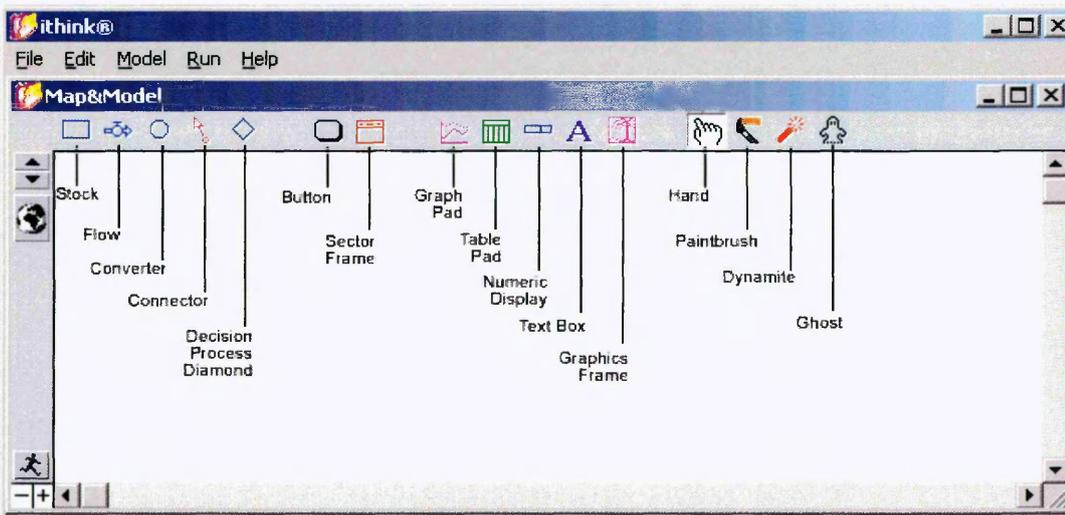
The Map / Model Layer

The Equations Layer
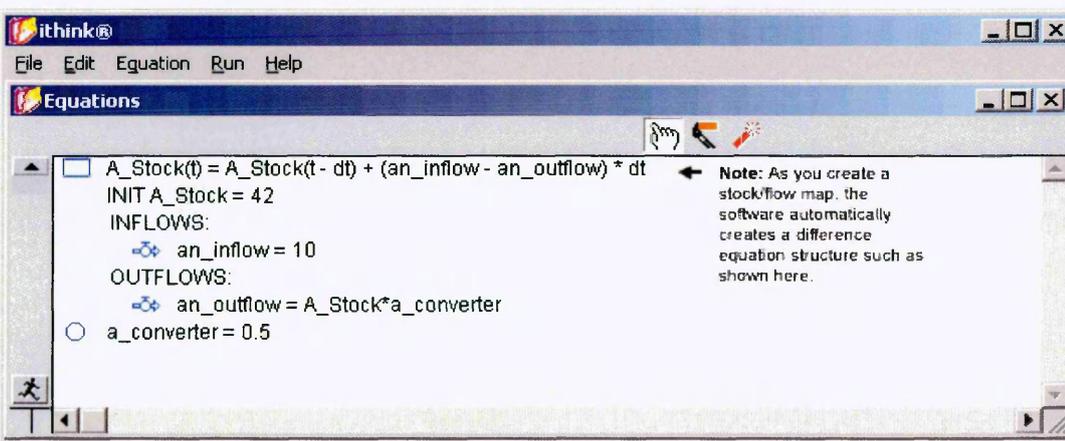
Figure B. 1: An Overview of the Operating Environment

The purpose of the Map/Model level building blocks

On the Map/Model layer, you'll find four basic building blocks: the Stock, the Flow, the Converter, and the Connector. The graphical representation and the purpose of each building block are provided here as follows:

Reservoir Stock

- Stocks: They are accumulations. They collect whatever flows into them, net of whatever flows out of them. The default stock type is the Reservoir. There are other types of stocks including: conveyor, queue, and oven.

Conveyor Stock   Queue Stock   Oven Stock
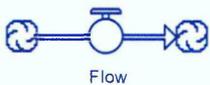
Flow

- Flows: The job of flows is to fill and drain accumulations. The unfilled arrow head on the flow pipe indicates the direction of positive flow.

Converter

- Converters: The converter serves a utilitarian role in the software. It holds values for constants, defines external inputs to the model, calculates algebraic relationships, and serves as the repository for graphical functions. In general, it converts inputs into outputs. Hence, the name "converter."

Action
Connector

Information
Connector

- Connectors: As its name suggests, the job of the connector is to connect model elements. The software provides for two distinct types of connector: the action connector and the information connector. Action connectors are signified by a solid, directed wire. Information connectors are signified by a dashed wire.

DecisionProcess
Diamond

- The Decision Process Diamonds: The Decision Process Diamond (DPD) is a mechanism for managing the diagram complexity associated with the representation of decision processes within your models. With DPDs, you can "bury" the intricacies of the decision rules that drive the flows into a "black box" (actually, a lavender diamond). On the surface, you and the users of your models can clearly see both the inputs and the outputs associated with a decision process. When the need arises, you can "drill down" into the detail of the decision process itself. As a result, your models can maintain a bi-focal perspective, displaying the macro- and micro-structure as needed.

The purpose of the Ghost tool

The Ghost tool is available only on the Map/Model level. Its purpose is to make replicas, aliases, or shortcuts for individual stocks, flows, and converters. A Ghost of an entity has no independent identity. It is simply an image of the building block -drawn in dashed lines- from which it was ghosted. The ghosted replica has no equation of its own. When you double-click on a ghosted replica, the dialog box that opens actually belongs to the original from which the replica was made. No matter how many ghosted replicas of a given building block you create, only one dialog box exists - because only one building block exists! The Ghost tool is thus really of value only for cosmetic purposes. A ghost adds no real structure to a model.

In particular, ghosted stocks can have no inflows or outflows; ghosted flows and ghosted converters (when you "Ghost" a flow, its Ghost will appear as a converter) can have no input connectors. Ghosts are thus read-only information holders. You can draw connectors from them. Nothing can go into them.

In your modelling efforts, Ghosts serve the primary role of keeping your diagram tidy. When connectors might otherwise run all over the screen, leading to diagram "spaghetti," ghosted images can help to the connections neat and clean. Figure B.2, illustrates this role of Ghosts.

Without ghosting, it's necessary to stretch a connector across an entire page ...

By creating a ghost, the associated connector is much shorter!
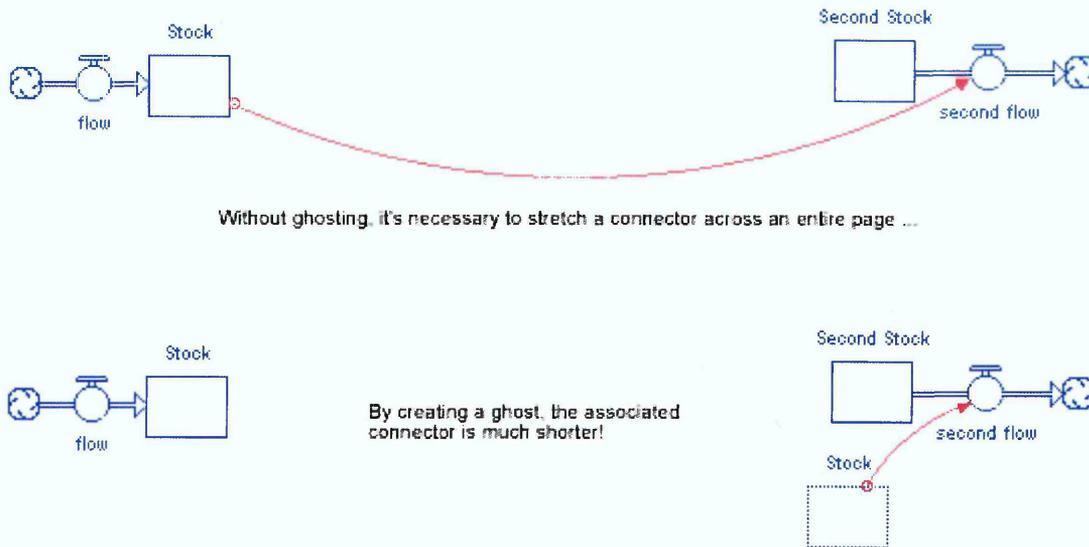
Figure B. 2: Ghosting as an Antidote to Spaghetti

The simulation algorithm

In the software, the equation structure underlying the model diagram is of vital importance. The equations created behind the scenes as you hook together stocks and flows are known as "Finite Difference Equations." In a model, each stock equation is a finite difference equation. Conceptually, solving finite difference equations is straightforward. It involves a two step initialization phase, and a three step iterative evaluation phase:

Initialization Phase:

Step 1. Create a list of all equations in required order of evaluation.
Step 2. Calculate initial values for all stocks, flows and converters (in order of evaluation).

Iteration Phase:

Step 1. Estimate the change in stocks over the interval DT. Calculate new values for stocks based on this estimate.

Step 2. Use new values of stocks to calculate new values for flows and converters.

Step 3. Update simulation time by an increment of DT. Stop iterating when Time >= simulation To Time.

Step 1 of the iteration phase is a critical one: How does one estimate the change in the value of stocks over the interval DT? The software provides three algorithms for doing this estimation - Euler's, 2nd-order Runge-Kutta, and 4th-order Runge-Kutta.

DT, or dt (depending on your level of disdain), is the interval of time between calculations. DT is expressed in whatever time unit you've chosen for your model. Therefore, DT answers the question: Is my model having its numerical values re-calculated once every time period, twice, three times...? Your choice of time unit provides the denominator of the units-of-measure for all of the flows in your model. For example, if you have flows of widgets, people, and dollars (and you are using the default time unit of "Months"), then the units-of-measure for your flows will be widgets/month, people/month, and $/month. If DT in this model is 1.0, then a round of calculations will be performed once each month. If DT is 0.25, then a round of calculations would be performed every 1/4 of a month (or, four rounds of calculations would be performed per month). And, so on.

Appendix C: Conceptual and Simulation Models of a Hospital Logistics System that is Using a Traditional (*R,s,S*) Inventory Control Approach

The aim of this Appendix is to provide a full explanation of how the stock-flow diagram of a hospital logistics system that is using a traditional (*R,s,S*) inventory control approach -shown in Figure 3.3 in Chapter Three- is developed, and all the equations that make up the simulation model of that system. The stock-flow diagram and the simulation model are developed using *ithink* Analyst Software.

The main stock that we are interested in studying its dynamic behaviour in the stock-flow diagram shown in Figure 3.3 is *Hospital Stock*. Consumption of all hospital wards and departments are represented as *Consumption Rate*. Whereas, all deliveries from distributors are represented as *Distributor Delivery Rate*. *Consumption Rate* can be constant or variable (e.g. step input, pulse input, or random input, etc.).

The *Hospital Stock* is decreased due to *Consumption Rate* and increased due to *Distributor Delivery Completion Rate*. Delivering materials from distributor stock to *Hospital Stock* takes *Transit Time*. Materials do not go immediately from distributor to *Hospital Stock*. This pipeline effect is represented by the stock *On Transport from Distributor to Hospital* (i.e. the stock of those materials that have been out of distributor stock but not yet received by *Hospital Stock*).

The pipeline delay is used to model the material delay; since it captures the physical flow of materials between the distributor and hospital. Pipeline delays preserve the order of entry to a delay so the output is exactly the same as the input, but shifted by the time delay, and also assume no mixing of the contents of the stock in transit at all (Sterman, 2000). For the pipeline delay in Figure 3.3, the outflow (*Distributor Delivery Completion Rate*) is simply the inflow (*Distributor Delivery Rate*) lagged by the average delay time (*Transit Time*). Also, the *Distributor Delivery Completion Rate* does not depend on how much material *On Transport From Distributor To Hospital* –an assumption made by this author that there is no transportation capacity limit.

Conveyors –one of the four varieties of stocks used in the *ithink* Analyst software- are great for representing "pipeline delays" (Richmond, 2001). Therefore, the stock *On Transport From Distributor To Hospital* is represented as a conveyor. However, the *Hospital Stock* is represented as reservoir –another type of stocks used in the *ithink* Analyst. The reservoir operates most like a bathtub, where stuff flows in, and once it does, individual entities become indistinguishable (Richmond, 2001). Usually, delay times can change. In *ithink* Analyst, the transit time for a conveyor can be either constant or variable. However, in Figure 3.3, the transit time is assumed by this author to be constant and equals *Transit Time*.

How much material the distributor should deliver to *Hospital Stock* depends on how much material the hospital orders according to their *Inventory Control Decisions*. In Figure 3.3, *Order Completion Rate* is connected to the *Distributor Delivery Rate* with a solid wire –one of the two types of connectors in the *ithink* Analyst software. The solid wire is called an "action connector". Therefore, once an order is issued by the hospital and received by the distributor, materials are delivered from distributor to *Hospital Stock*. Although, the *Distributor Delivery Rate* and the *Order Completion Rate* are assumed to be numerically equal and both are measured in the same units, they are distinct concepts. The *Distributor Delivery Rate* is the rate physical product leaves the distributor's stock, while the *Order Completion Rate* represents an information flow (i.e. information about how much material should be delivered).

Ordering process also takes time. There is an information delay between the moment when the need for materials are realized by the hospital and the moment when this information is received by the distributor in the form of an order. A pipeline delay is used to model the information delay in the ordering process. This is represented in the model structure in Figure 3.3 as a conveyor called *Order Backlog*, which is increased by *Order Rate* and decreased by *Order Completion Rate*. The *Order Completion Rate* is exactly the *Order Rate* lagged by the *Order Processing Delay Time*. It is assumed by this author that there is no ordering capacity limit. The amount of materials that are ordered by the hospital depends on their *Inventory Control Decisions*. A solid wire then is used to connect the *Inventory Control Decisions* diamond with the *Order Rate* to transmit the action resulting from the decision.

The inputs to the *Inventory Control Decisions* and the *Service Level Decisions* —which are used to build the decisions logic- are information transmitted from other parts of the model using information connectors (dashed connectors) —the second type of connectors in the *ithink* Analyst.

The values of *Transit Time* and *Order Processing Delay Time* are either variables or constants. The value of *Average Lead Time* is equal to the value of *Transit Time* plus the value of *Order Processing Delay Time*. The value of *Standard Deviation of Lead Time* is equal to a fraction of *Average Lead Time*. The values of *Ordering Cost, Item Unit Cost, Inventory Carrying Charge, Service Level Factor*, and *Average Demand* are all constants. The value of *Standard Deviation of Demand* is equal to a fraction of *Average Demand*.

Information about the values of *Service Level Factor, Average Demand, Standard Deviation of Demand, Average Lead Time*, and *Standard Deviation of Lead Time* are used to determine the value of *Safety Stock* according to the equation in Table 3.1 in Chapter Three.

Information about the values of *Average Demand, Inventory Carrying Charge, Item Unit Cost*, and *Ordering Cost* are used to determine the value of *Economic Order Quantity* according to the equation in Table 3.1 in Chapter Three.

Information about the values of *Average Demand, Inventory Carrying Charge, Item Unit Cost*, and *Ordering Cost* are used to determine the value of *Review Period* according to the equation in Table 3.1 in Chapter Three; yet, with adding two functions to the equation. The first function is the ROUND function which is added to round the answer that comes from the equation to its nearest integer value. Because, in practice, with traditional inventory control approaches, review is done every day or multiple of a day (for example, not every 3.75 days). The second function is MAX(<expression>,<expression>,...) function which gives the maximum value among the expressions contained within parentheses. And here, the two expressions are 1, and the value that comes out of the ROUND function. So, if the value that comes from the ROUND function is zero, then the value of *Review Period* is 1; because *Review Period* should never be zero.

Information about *Review Period, Average Demand, Average Lead Time*, and *Safety Stock* are used to determine the value of *Reorder Level* according to the equation in Table 3.1 in Chapter Three. Information about *Reorder Level* and *Economic Order Quantity* are used to determine the value of *Order Up To Level* according to the equation in Table 3.1 in Chapter Three.

Information about the values of *Review Period, Reorder Level*, and *Order Up To Level*, and information about the level of *Hospital Stock, On Transport From Distributor To Hospital*, and *Order Backlog* are all used to determine the inventory control decision of (*How Often to Review?, When to Order?*, and *How Much to Order?*) according to the conditional statement which states in words: "At each review, if inventory position (items on hand plus items on order) is at level *s* or below, an order is placed for a sufficient quantity to bring the inventory position up to a given level *S*". An IF...THEN...ELSE statement is used to perform this conditional statement. In the IF...THEN...ELSE statement, a COUNTER function is used to represent the time interval *R*.

The initial value of *Hospital Stock* is equal to *Order Up To Level*. The initial values of both *On Transport From Distributor To Hospital* and *Order Backlog* are zero.

The equations that make up the simulation model of the hospital logistics system that is using a traditional (*R,s,S*) inventory control approach are listed in Table C.1. The equations are listed according to the order of execution.

Table C. 1: The equations that make up the simulation model of the hospital logistics system that is using a traditional (*R,s,S*) inventory control approach

```
{ INITIALIZATION EQUATIONS }

O   Order_Processing__Delay_Time = 1
O   Transit_Time = 3
▥   INIT Order__Backlog = 0
      TRANSIT TIME = varies
      INFLOW LIMIT = INF
      CAPACITY = INF
▥   INIT On_Transport__From_Distributor__To_Hospital = 0
      TRANSIT TIME = varies
      INFLOW LIMIT = INF
      CAPACITY = INF
⧓   Distributor_Delivery__Completion_Rate = CONVEYOR OUTFLOW
      TRANSIT TIME = Transit_Time
⧓   Consumption__Rate = 100
O   Ordering_Cost = 15
O   Average_Demand = 100
O   Item_Unit__Cost = 100
O   Inventory_Carrying__Charge = 30/100
O   Review_Period = MAX(1,
      ROUND(SQRT((2*Ordering_Cost)/(Average_Demand*365*Item_Unit__Cost*Inventory_Carrying__Charge))))
O   Average__Lead_Time = Order_Processing__Delay_Time+Transit_Time
O   Service_Level__Factor = 3
O   Standard_Deviation__of_Demand = (1/3)*Average_Demand
O   Standard__Deviation_of_Lead_Time = (1/3)*Average__Lead_Time
O   Safety_Stock =
      Service_Level__Factor*SQRT(((Average__Lead_Time+Review_Period)*Standard_Deviation__of_Demand*Standard_Deviation__of_
      Demand)+(Average_Demand*Average_Demand*Standard__Deviation_of_Lead_Time*Standard__Deviation_of_Lead_Time))
O   Reorder_Level = (Average_Demand*(Average__Lead_Time+Review_Period))+Safety_Stock
O   Economic__Order_Quantity = SQRT((2*Ordering_Cost*Average_Demand*365)/(Item_Unit__Cost*Inventory_Carrying__Charge))
O   Order_Up__To_Level = Reorder_Level+Economic__Order_Quantity
▢   INIT Hospital_Stock = Order_Up__To_Level
O   When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = IF(COUNTER(1,1+Review_Period)=1)
      AND((Hospital_Stock+Order__Backlog+On_Transport__From_Distributor__To_Hospital)<=Reorder_Level)
      THEN((Order_Up__To_Level-Hospital_Stock)/dt)
      ELSE(0)
⧓   Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
⧓   Order_Completion__Rate = CONVEYOR OUTFLOW
      TRANSIT TIME = Order_Processing__Delay_Time
⧓   Distributor_Delivery_Rate = Order_Completion__Rate


{ RUNTIME EQUATIONS }

▢   Hospital_Stock(t) = Hospital_Stock(t - dt) + (Distributor_Delivery__Completion_Rate - Consumption__Rate) * dt
▥   Order__Backlog(t) = Order__Backlog(t - dt) + (Order_Rate - Order_Completion__Rate) * dt
▥   On_Transport__From_Distributor__To_Hospital(t) = On_Transport__From_Distributor__To_Hospital(t - dt) +
      (Distributor_Delivery_Rate - Distributor_Delivery__Completion_Rate) * dt
⧓   Distributor_Delivery__Completion_Rate = CONVEYOR OUTFLOW
      TRANSIT TIME = Transit_Time
O   Review_Period = MAX(1,
      ROUND(SQRT((2*Ordering_Cost)/(Average_Demand*365*Item_Unit__Cost*Inventory_Carrying__Charge))))
O   Average__Lead_Time = Order_Processing__Delay_Time+Transit_Time
O   Standard_Deviation__of_Demand = (1/3)*Average_Demand
O   Standard__Deviation_of_Lead_Time = (1/3)*Average__Lead_Time
O   Safety_Stock =
      Service_Level__Factor*SQRT(((Average__Lead_Time+Review_Period)*Standard_Deviation__of_Demand*Standard_Deviation__of_
      Demand)+(Average_Demand*Average_Demand*Standard__Deviation_of_Lead_Time*Standard__Deviation_of_Lead_Time))
O   Reorder_Level = (Average_Demand*(Average__Lead_Time+Review_Period))+Safety_Stock
O   Economic__Order_Quantity = SQRT((2*Ordering_Cost*Average_Demand*365)/(Item_Unit__Cost*Inventory_Carrying__Charge))
O   Order_Up__To_Level = Reorder_Level+Economic__Order_Quantity
O   When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = IF(COUNTER(1,1+Review_Period)=1)
      AND((Hospital_Stock+Order__Backlog+On_Transport__From_Distributor__To_Hospital)<=Reorder_Level)
      THEN((Order_Up__To_Level-Hospital_Stock)/dt)
      ELSE(0)
⧓   Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
⧓   Order_Completion__Rate = CONVEYOR OUTFLOW
      TRANSIT TIME = Order_Processing__Delay_Time
⧓   Distributor_Delivery_Rate = Order_Completion__Rate
```

Appendix D: Conceptual and Simulation Models of a Hospital Logistics System that is Using CR(IOBPCS) Inventory Control Approach

The aim of this Appendix is to provide a full explanation of how the stock-flow diagram of a hospital logistics system that is using CR(IOBPCS) inventory control approach - shown in Figure 3.8 in Chapter Three- is developed, and all the equations that make up the simulation model of that system. The stock-flow diagram and the simulation model are developed using *ithink* Analyst Software.

The main stock that we are interested in studying its dynamic behaviour in the stock-flow diagram shown in Figure 3.8 is *Hospital Stock*. Consumption of all hospital wards and departments are represented as *Consumption Rate*. Whereas, all deliveries from distributors are represented as *Distributor Delivery Rate*. *Consumption Rate* can be constant or variable (e.g. step input, pulse input, or random input, etc.).

The *Hospital Stock* is decreased due to *Consumption Rate* and increased due to *Distributor Delivery Completion Rate*. Delivering materials from distributor stock to *Hospital Stock* takes *Transit Time*. Materials do not go immediately from distributor to *Hospital Stock*. This pipeline effect is represented by the stock *On Transport from Distributor to Hospital* (i.e. the stock of those materials that have been out of distributor stock but not yet received by *Hospital Stock*).

The pipeline delay is used to model the material delay; since it captures the physical flow of materials between the distributor and hospital. Pipeline delays preserve the order of entry to a delay so the output is exactly the same as the input, but shifted by the time delay, and also assume no mixing of the contents of the stock in transit at all (Sterman, 2000). For the pipeline delay in Figure 3.8, the outflow (*Distributor Delivery Completion Rate*) is simply the inflow (*Distributor Delivery Rate*) lagged by the average delay time (*Transit Time*).

Also, the *Distributor Delivery Completion Rate* does not depend on how much material *On Transport From Distributor To Hospital* –an assumption made by this author that there is no transportation capacity limit.

Conveyors –one of the four varieties of stocks used in the *ithink* Analyst software- are great for representing "pipeline delays" (Richmond, 2001). Therefore, the stock *On Transport From Distributor To Hospital* is represented as a conveyor. However, the *Hospital Stock* is represented as reservoir –another type of stocks used in the *ithink* Analyst. The reservoir operates most like a bathtub, where stuff flows in, and once it does, individual entities become indistinguishable (Richmond, 2001). Usually, delay times can change. In *ithink* Analyst, the transit time for a conveyor can be either constant or variable. However, in Figure 3.8, the transit time is assumed by this author to be constant and equals *Transit Time*.

How much material the distributor should deliver to *Hospital Stock* depends on how much material the hospital orders according to their *Inventory Control Decisions*. Usually the use of CR(IOBPCS) inventory control approach is accompanied by the use of point-of-sale (POS) and electronic data interchange (EDI). Therefore, it is assumed that the Ordering process does not take time[1]. And therefore, in Figure 3.8, *Order Rate* is connected directly to the *Distributor Delivery Rate* with a solid wire –one of the two types of connectors in the *ithink* Analyst software. The solid wire is called an "action connector". Therefore, once an order is issued by the hospital using EDI technology, and received immediately by the distributor, materials will be delivered from distributor to *Hospital Stock*. Although, the *Distributor Delivery Rate* and the *Order Rate* are assumed to be numerically equal and both are measured in the same units, they are distinct concepts. The *Distributor Delivery Rate* is the rate physical product leaves the distributor's stock, while the *Order Rate* represents an information flow (i.e. information about how much material should be delivered).

The amount of materials that are ordered by the hospital depends on their *Inventory Control Decisions*. A solid wire then is used to connect the *Inventory Control Decisions* diamond with the *Order Rate* to transmit the action resulting from the decision.

---

[1] In fact, any process takes time. But, since the ordering process using EDI takes very little time compared to the time for delivering materials, it is assumed that order processing delay time is equal zero.

The inputs to the *Inventory Control Decisions* and the *Service Level Decisions* –which are used to build the decisions logic- are information transmitted from other parts of the model using information connectors (dashed connectors) –the second type of connectors in the *ithink* Analyst.

The value of *Transit Time* is either variable or constant. The value of *Average Lead Time* is equal to the value of *Transit Time*. The value of *Average Demand* is constant. Information about the values of *Service Level Factor* and *Average Demand* are used to determine the value of *Safety Stock* according to the equation in Table 3.4 in Chapter Three.

Information about the values of *Safety Stock, Consumption Rate, Hospital Stock,* and *Average Lead Time* are used to determine the values of T_a, T_i, *Target Level, Stock Discrepancy, Stock Adjustment* and *Average Consumption* according to the equations in Table 3.4 in Chapter Three.

Information about the values of *Average Consumption* and *Stock Adjustment* are then used to determine the inventory control decision of (*How Often to Review?*, *When to Order?*, and *How Much to Order?*) according to the equations in Table 3.4 in Chapter Three.

The initial value of *Hospital Stock* is equal to *Target Level*. The initial value of *On Transport From Distributor To Hospital* is equal to *Consumption Rate* multiplied by *Transit Time*; to begin the system in an equilibrium state.

The equations that make up the simulation model of the hospital logistics system that is using CR(IOBPCS) inventory control approach are listed in Table D.1. The equations are listed according to the order of execution.

Table D. 1: The equations that make up the simulation model of the hospital logistics system that is using CR(IOBPCS) inventory control approach

{ INITIALIZATION EQUATIONS }

○ Transit_Time = 3
▥ INIT On_Transport_From__Distributor_To_Hospital = 300
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
⋘ Distributor_Delivery__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = Transit_Time
⋘ Consumption__Rate = 100
○ Average__Lead_Time = Transit_Time
○ Ta = Average__Lead_Time
○ Average__Consumption = SMTH1(Consumption__Rate,Ta)
○ Ti = 3*Average__Lead_Time
○ Service_Level_Factor = 1
○ Average__Demand = 100
○ Safety_Stock = Service_Level_Factor*Average__Demand
○ Target_Level = Safety_Stock
▢ INIT Hospital_Stock = Target_Level
○ Stock__Discrepancy = Target_Level-Hospital_Stock
○ Stock__Adjustment = (1/Ti)*Stock__Discrepancy
○ When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = Average__Consumption+Stock__Adjustment
⋘ Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
⋘ Distributor__Delivery_Rate = Order_Rate

{ RUNTIME EQUATIONS }

▢ Hospital_Stock(t) = Hospital_Stock(t - dt) + (Distributor_Delivery__Completion_Rate - Consumption__Rate) * dt
▥ On_Transport_From__Distributor_To_Hospital(t) = On_Transport_From__Distributor_To_Hospital(t - dt) +
    (Distributor__Delivery_Rate - Distributor_Delivery__Completion_Rate) * dt
⋘ Distributor_Delivery__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = Transit_Time
○ Average__Lead_Time = Transit_Time
○ Ta = Average__Lead_Time
○ Average__Consumption = SMTH1(Consumption__Rate,Ta)
○ Ti = 3*Average__Lead_Time
○ Safety_Stock = Service_Level_Factor*Average__Demand
○ Target_Level = Safety_Stock
○ Stock__Discrepancy = Target_Level-Hospital_Stock
○ Stock__Adjustment = (1/Ti)*Stock__Discrepancy
○ When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = Average__Consumption+Stock__Adjustment
⋘ Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
⋘ Distributor__Delivery_Rate = Order_Rate

Appendix E: Criterion for Optimising the Values of the Design Parameters (T_a / T_p) and (T_i / T_p) in a CR(IOBPCS) Model

The aim of this Appendix is to explain the criterion which the author carried out to choose the optimum values for the design parameters (T_a / T_p) *and* (T_i / T_p) in a CR(IOBPCS) model –shown in Figure 3.8 in Chapter Three- that will give an acceptable system performance based on a trade-off between stock fluctuation and order rate variations.

The criterion adopted here is used by Ferris and Towill (1993), John *et al*. (1994), and Towill and Del Vecchio (1994). In this criterion, the dynamic behaviour of the system – when subjected to a step increase in consumption- is assessed by a variety of measurements. Figure E.1 shows the dynamic-behaviour measurements that are selected for assessing stock level fluctuation and order rate variation.

To choose the optimum values for the design parameters (T_a / T_p) *and* (T_i / T_p), the CR(IOBPCS) model is subjected to 20 % step increase in *Consumption Rate* from an initial steady state rate of 100 items (T_p =1 day, Length of simulation = 30 days, and Dt= 0.0625). Figure E.2 shows the investigation of the dynamic behaviour of *Hospital Stock* and *Order Rate* for seven different combinations of (T_a and T_i). From a preliminary study of the dynamic behaviour of *Hospital Stock* and *Order Rate* in Figure E.2, some of the combinations are excluded.

Figure E.3 shows the investigation of the dynamic behaviour of *Hospital Stock* and *Order Rate* for the four combinations of (T_a and T_i) that will be assessed using the criterion in Figure E.1. Table E.1 summarises the results of the dynamic-behaviour measurements as taken from Figure E.3, where the shaded region in the table is for the optimum response. Whereas, Table E.2 summarises the effect of increasing T_a and T_i on the dynamic-behaviour measurements.

Since hospitals are usually most concerned with the stock deficit and duration of deficit, the author suggest that (T_a / T_p) =1 and (T_i / T_p) = 3 are good design parameters for the CR(IOBPCS). The smallest maximum-stock deficit and the shortest duration of deficit of *Hospital Stock* is obtained when (T_a / T_p) =1 and (T_i / T_p) = 3. However, when (T_a / T_p) =1 and (T_i / T_p) = 3, peak overshoot in *Order Rate* as a percentage of nominal value is still acceptable.
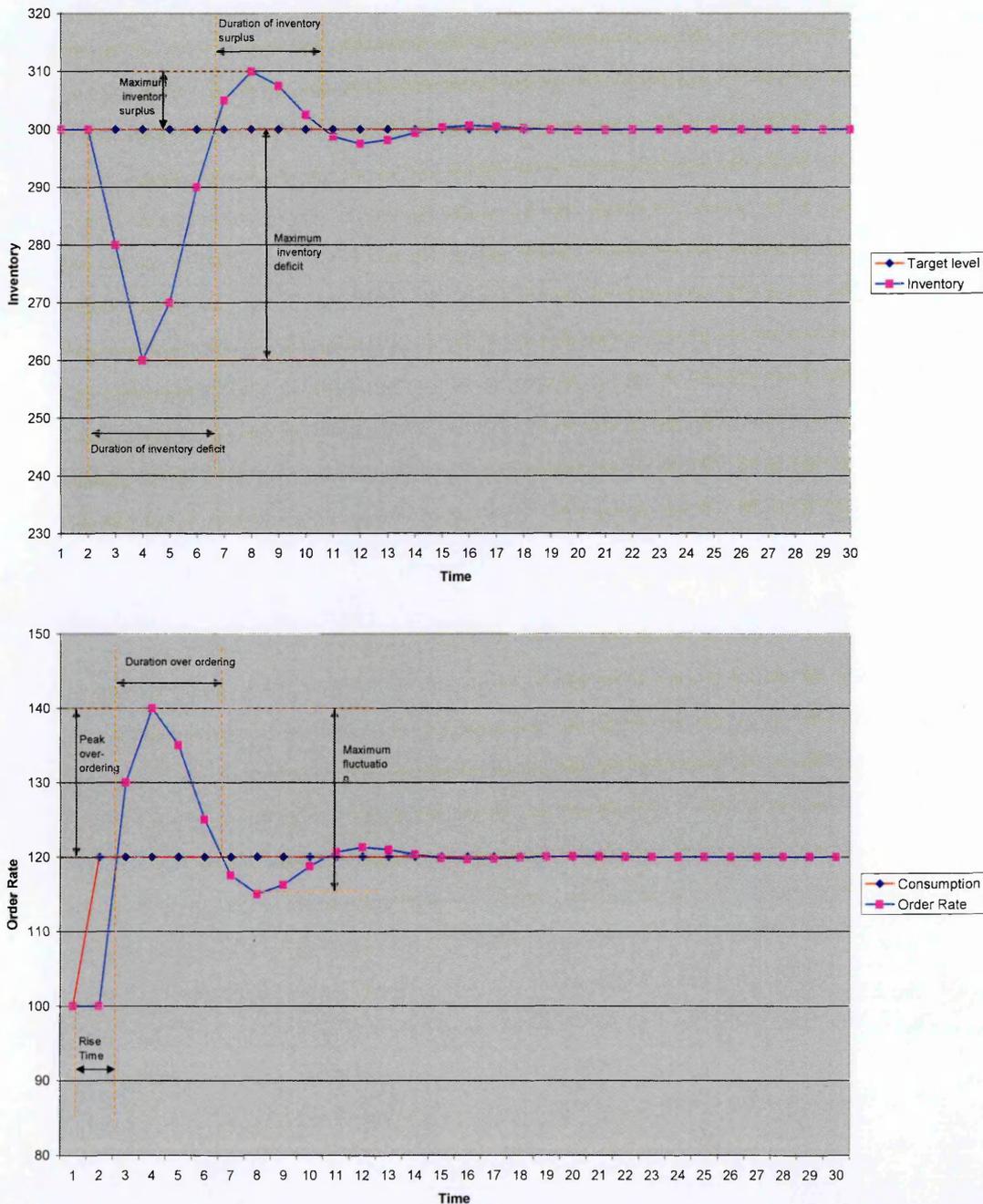
Figure E. 1: Dynamic-behaviour measurements selected for system optimisation

Appendix E

Criterion for Optimising the Values of the Design Parameters (T$_a$ / T$_p$) and (T$_i$ / T$_p$) in a CR(IOBPCS) Model
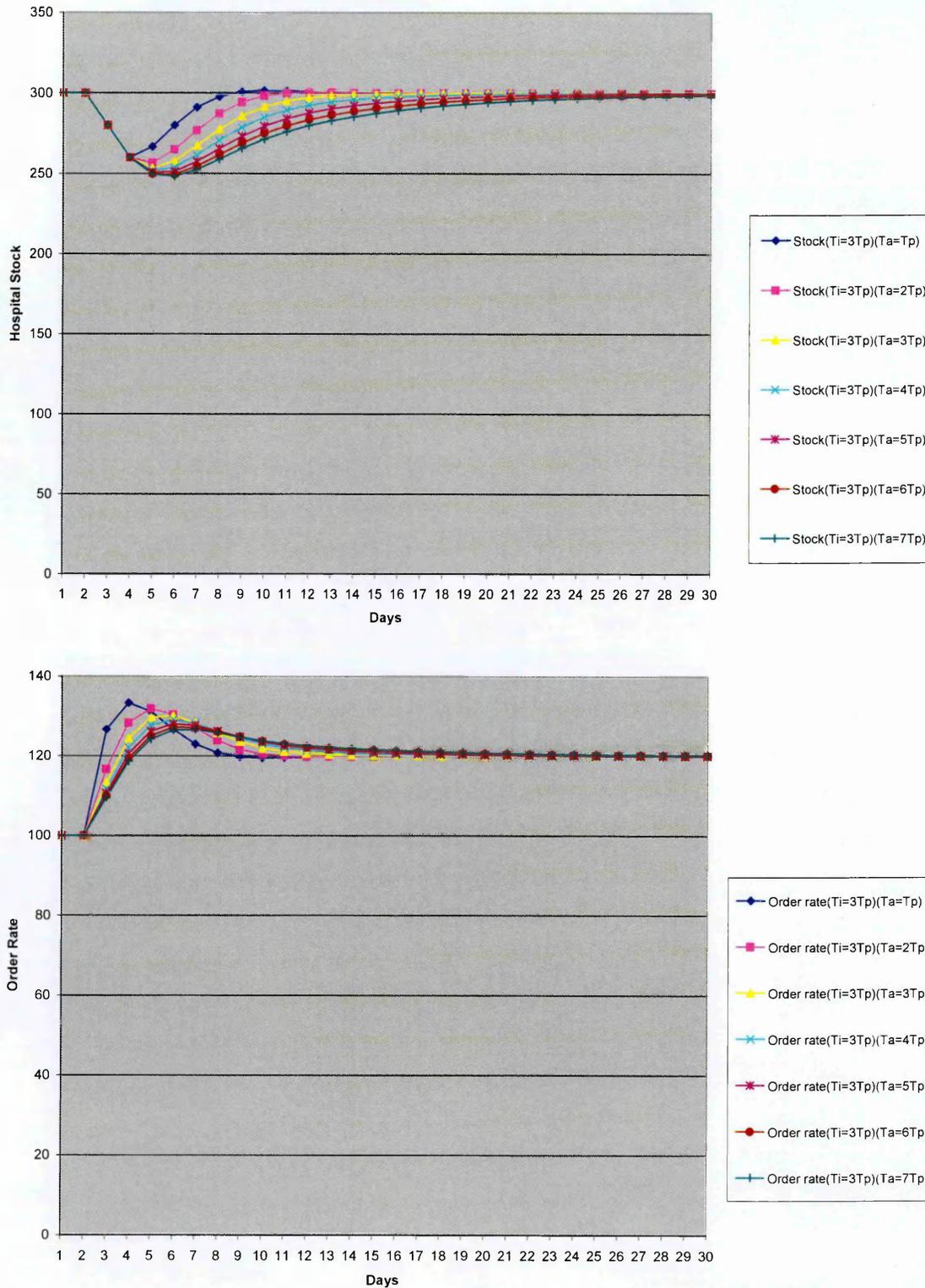
Figure E. 2: The investigation of the dynamic behaviour of *Hospital Stock* and *Order Rate* for seven different combinations of (*T$_a$* and *T$_i$*)
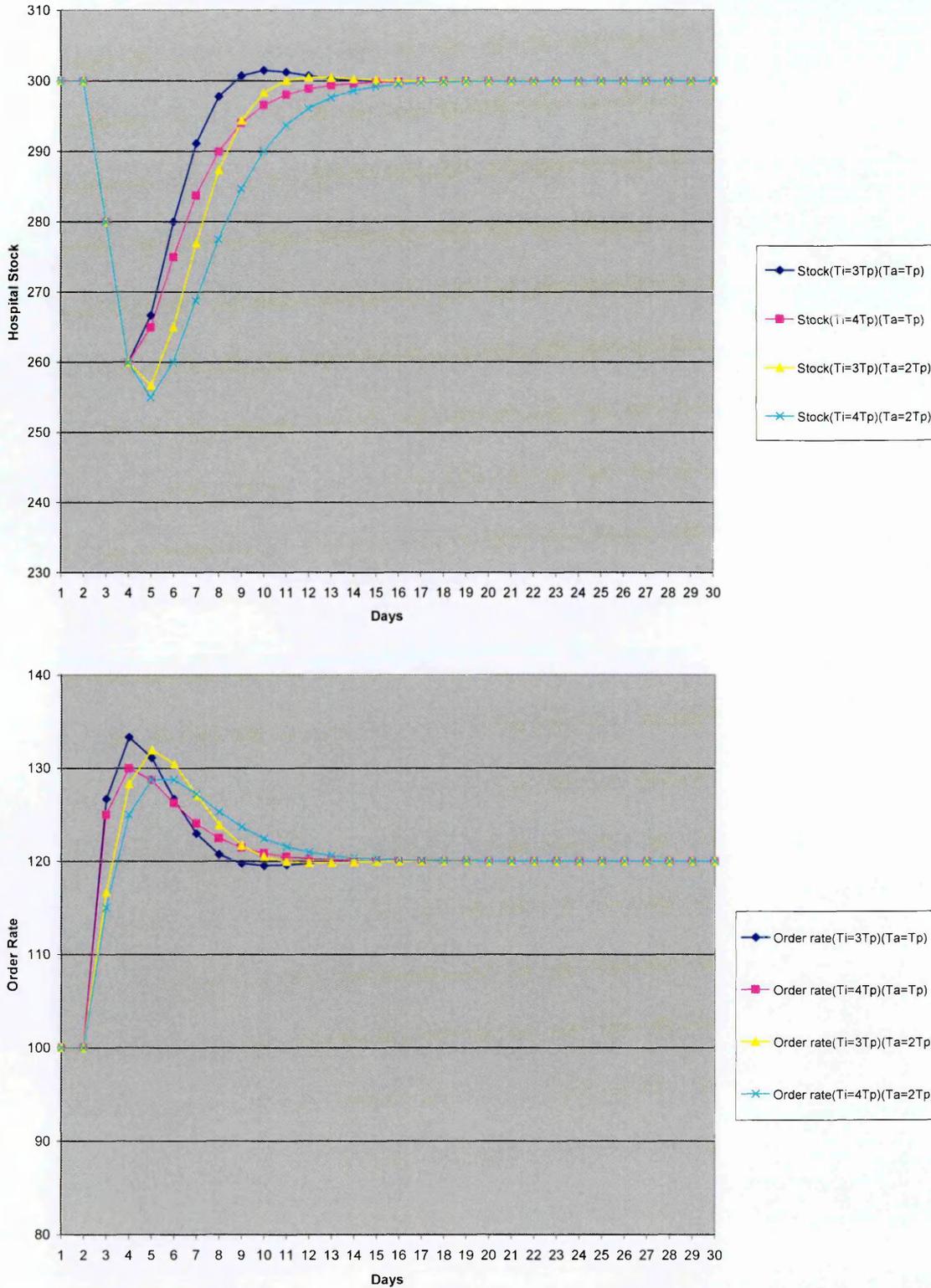
Figure E. 3: The investigation of the dynamic behaviour of *Hospital Stock* and *Order Rate* for the four combinations of (T_a and T_i) that will be assessed using the criterion in Figure E.1

Table E. 1: Summary of the results of the dynamic-behaviour measurements as taken from Figure E.3

dynamic-behaviour measurements		(Ti=3Tp)(Ta=Tp)	(Ti=4Tp)(Ta=Tp)	(Ti=3Tp)(Ta=2Tp)	(Ti=4Tp)(Ta=2Tp)
Hospital Stock measurements	maximum inventory deficit (items)	40	40	43.33	45
	maximum inventory deficit as percentage of target level	13.33%	13.33%	14.44%	15%
	duration of deficit (days)	6	18	8	21
	maximum inventory surplus (items)	1.48	0	0.51	0
	maximum inventory surplus as percentage of target level	0.49%	0	0.17%	0
	duration of surplus (days)	5	0	6	0
Order Rate measurements	peak of over ordering (items per day)	13.33	10	11.94	8.75
	peak of over ordering as percentage of nominal value	11.10%	8.33%	9.95%	7.29%
	duration of over ordering (days)	6	16	7	18
	rise time of ordering (days)	2	2	3	3
	maximum fluctuation in ordering (items per day)	13.82	10	12.04	8.75
	maximum fluctuation in ordering as percentage of nominal value	11.52%	8.33%	10.03%	7.29%

24

Table E. 2: Summary of the effect of increasing T_a and T_i on the dynamic-behaviour measurements

dynamic-behaviour measurements		Ti increases	Ta increases
Hospital Stock measurements	maximum inventory deficit	No effect	increases
	maximum inventory deficit as percentage of target level	No effect	increases
	duration of deficit	increases	increases
	maximum inventory surplus	decreases till it reaches zero then it has no effect	decreases
	maximum inventory surplus as percentage of target level	decreases till it reaches zero then it has no effect	decreases
	duration of surplus	decreases till it reaches zero then it has no effect	increases
Order Rate measurements	peak of over ordering	decreases	decreases
	peak of over ordering as percentage of nominal value	decreases	decreases
	duration of over ordering	increases	slightly increase
	rise time of ordering	no effect	increases
	maximum fluctuation in ordering	decreases	decreases
	maximum fluctuation in ordering as percentage of nominal value	decreases	decreases

Appendix F: Computer Simulation Model of the CNMC Logistics System

The aim of this Appendix is to provide all the equations that make up the computer simulation model of the CNMC logistics system –for stock items- which was developed using the verified stock-flow diagram shown in Figure 4.8 in Chapter Four. The simulation model was developed using the *ithink* Analyst Software. The equations that make up the simulation model are listed in Table F.1 according to the order of execution.

Table F. 1: The equations that make up the computer simulation model of the CNMC logistics system

```
{ INITIALIZATION EQUATIONS }

O   MWH_Average__Order_Processing__Delay_Time = 1
O   MWH_To_CS__Average__Transit_Time = .125
O   CS_Average__Order_Processing__Delay_Time = .125
O   Suppliers_To_MWH__Average__Transit_Time = 1
▥   INIT On_Transport__From_MWH_To_CS = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
▥   INIT CS_Order__Backlog = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
▥   INIT On_Transport_From_Suppliers_to_MWH = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
▥   INIT MWHOrder__Backlog = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
O   Average__Demand = 100
⊘   MWH_Delivery__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = MWH_To_CS__Average__Transit_Time
⊘   Consumption__Rate = NORMAL(Average__Demand,.3,5)
⊘   CS_Order__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = CS_Average__Order_Processing__Delay_Time
⊘   Suppliers_Delivery_Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = Suppliers_To_MWH__Average__Transit_Time
⊘   MWH__Delivery_Rate = CS_Order__Completion_Rate
O   CS__Review__Period = 1
O   CS_Average__Lead_Time = CS_Average__Order_Processing__Delay_Time+MWH_To_CS__Average__Transit_Time
O   CS__Safety_Stock = 2*7*Average__Demand
O   CS__Reorder__Level = (Average__Demand*(CS_Average__Lead_Time+CS__Review__Period))+CS__Safety_Stock
O   Ordering__Cost = 15
O   Item_Unit__Cost = 1000
O   Inventory__Carrying__Charge = 30/100
O   CS_Economic__Order_Quantity =
    SQRT((2*Ordering__Cost*Average__Demand*365)/(Item_Unit__Cost*Inventory__Carrying__Charge))
O   CS_Order_Up__To_Level = CS__Reorder__Level+CS_Economic__Order_Quantity
☐   INIT CS_Stock = CS_Order_Up__To_Level
O   CS_When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = IF(COUNTER(1,CS__Review__Period+1)=1)
    AND((CS_Stock+CS_Order__Backlog+On_Transport__From_MWH_To_CS)<=CS__Reorder__Level)
    then((CS_Order_Up__To_Level-CS_Stock)/dt)
    else (0)
⊘   CS__Order_Rate = CS_When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
⊘   MWH_Order__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = MWH_Average__Order_Processing__Delay_Time
⊘   Suppliers__Delivery_Rate = MWH_Order__Completion_Rate
O   MWH__Review__Period = 1
O   MWH_Average__Lead_Time = MWH_Average__Order_Processing__Delay_Time+Suppliers_To_MWH__Average__Transit_Time
O   MWH__Safety_Stock = 2*7*Average__Demand
O   MWH__Reorder__Level = (Average__Demand*(MWH_Average__Lead_Time+MWH__Review__Period))+MWH__Safety_Stock
O   MWH_Economic__Order_Quantity =
    SQRT((2*Ordering__Cost*Average__Demand*365)/(Item_Unit__Cost*Inventory__Carrying__Charge))
O   MWH__Order_Up_To_Level = MWH__Reorder__Level+MWH_Economic__Order_Quantity
☐   INIT MWH_Stock = MWH__Order_Up_To_Level
O   MWH_When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = if (COUNTER(1,1+MWH__Review__Period)=1)
    and ((MWH_Stock+MWHOrder__Backlog+On_Transport_From_Suppliers_to_MWH)<=MWH__Reorder__Level)
    then ((MWH__Order_Up_To_Level-MWH_Stock)/dt)
    else (0)
⊘   MWH__Order_Rate = MWH_When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
```

Table F.1: The equations that make up the computer simulation model of the CNMC logistics system (continued)

```
{ RUNTIME EQUATIONS }
CS_Stock(t) = CS_Stock(t - dt) + (MWH_Delivery__Completion_Rate - Consumption__Rate) * dt
MWH_Stock(t) = MWH_Stock(t - dt) + (Suppliers_Delivery_Completion_Rate - MWH__Delivery_Rate) * dt
On_Transport__From_MWH_To_CS(t) = On_Transport__From_MWH_To_CS(t - dt) + (MWH__Delivery_Rate -
   MWH_Delivery__Completion_Rate) * dt
CS_Order__Backlog(t) = CS_Order__Backlog(t - dt) + (CS__Order_Rate - CS_Order__Completion_Rate) * dt
On_Transport_From_Suppliers_to_MWH(t) = On_Transport_From_Suppliers_to_MWH(t - dt) + (Suppliers__Delivery_Rate -
   Suppliers_Delivery_Completion_Rate) * dt
MWHOrder__Backlog(t) = MWHOrder__Backlog(t - dt) + (MWH__Order_Rate - MWH_Order__Completion_Rate) * dt
MWH_Delivery__Completion_Rate = CONVEYOR OUTFLOW
   TRANSIT TIME = MWH_To_CS__Average__Transit_Time
Consumption__Rate = NORMAL(Average__Demand,.3,5)
CS_Order__Completion_Rate = CONVEYOR OUTFLOW
   TRANSIT TIME = CS_Average__Order_Processing__Delay_Time
Suppliers_Delivery_Completion_Rate = CONVEYOR OUTFLOW
   TRANSIT TIME = Suppliers_To_MWH__Average__Transit_Time
MWH__Delivery_Rate = CS_Order__Completion_Rate
CS_Average__Lead_Time = CS_Average__Order_Processing__Delay_Time+MWH_To_CS__Average__Transit_Time
CS__Safety_Stock = 2*7*Average__Demand
CS__Reorder__Level = (Average__Demand*(CS_Average__Lead_Time+CS__Review__Period))+CS__Safety_Stock
CS_Economic__Order_Quantity =
   SQRT((2*Ordering__Cost*Average__Demand*365)/(Item_Unit__Cost*Inventory__Carrying__Charge))
CS_Order_Up__To_Level = CS__Reorder__Level+CS_Economic__Order_Quantity
CS_When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = IF(COUNTER(1,CS__Review__Period+1)=1)
   AND((CS_Stock+CS_Order__Backlog+On_Transport__From_MWH_To_CS)<=CS__Reorder__Level)
   then((CS_Order_Up__To_Level-CS_Stock)/dt)
   else (0)
CS__Order_Rate = CS_When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
MWH_Order__Completion_Rate = CONVEYOR OUTFLOW
   TRANSIT TIME = MWH_Average__Order_Processing__Delay_Time
Suppliers__Delivery_Rate = MWH_Order__Completion_Rate
MWH_Average__Lead_Time = MWH_Average__Order_Processing__Delay_Time+Suppliers_To_MWH__Average__Transit_Time
MWH__Safety_Stock = 2*7*Average__Demand
MWH__Reorder__Level = (Average__Demand*(MWH_Average__Lead_Time+MWH__Review__Period))+MWH__Safety_Stock
MWH_Economic__Order_Quantity =
   SQRT((2*Ordering__Cost*Average__Demand*365)/(Item_Unit__Cost*Inventory__Carrying__Charge))
MWH__Order_Up_To_Level = MWH__Reorder__Level+MWH_Economic__Order_Quantity
MWH_When_to_Order?_How_Much_to_Order?_How_Often_to_Review? = if (COUNTER(1,1+MWH__Review__Period)=1)
   and ((MWH_Stock+MWHOrder__Backlog+On_Transport_From_Suppliers_to_MWH)<=MWH__Reorder__Level)
   then ((MWH__Order_Up_To_Level-MWH_Stock)/dt)
   else (0)
MWH__Order_Rate = MWH_When_to_Order?_How_Much_to_Order?_How_Often_to_Review?
```

Appendix G: Simulation Results of Redesigning the CNMC Logistics System

The aim of this Appendix is to provide a detailed discussion of the simulation results of redesigning the CNMC logistics (section 4.3.5 in Chapter Four). This Appendix contains two sections. The aim of the first section is to investigate how average stock, number of orders, and inventory cost change when changing *Average Demand* and *Item Unit Cost* for each operating strategy. The aim of the second section is to compare all operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for each *Average Demand*.

G.1 Average stock, number of orders, and inventory cost for each operating strategy

Figure G.1 to Figure G.5 illustrate how average stock, number of orders, and inventory cost vary when changing *Average Demand* and *Item Unit Cost* as given in Figure 4.18 in Chapter Four for the following operating strategies: "current situation", (R,s,S), (R,s,S)(eliminate), CR(IOBPCS), and CR(IOBPCS) (eliminate). A cumulative and comparative impact of these behaviours is discussed subsequently.

- **Average stock behaviour:**

    a) **Changing *Average Demand*:**

    As shown in Figure G.1 (a) & (b) for the "current situation" operating strategy, Figure G.2 (a) & (b) for the (R,s,S) operating strategy, and Figure G.3 (a) & (b) for the (R,s,S)(eliminate) operating strategy, average stock is a function of *Average Demand*, such that average stock follows an S-shaped curve with respect to *Average Demand*. This is because average stock depends on the values of reorder level and order-up-to level, where the equation of order-up-to level (see Table 3.1 and Table 4.2) includes a square-root function of *Average Demand*.
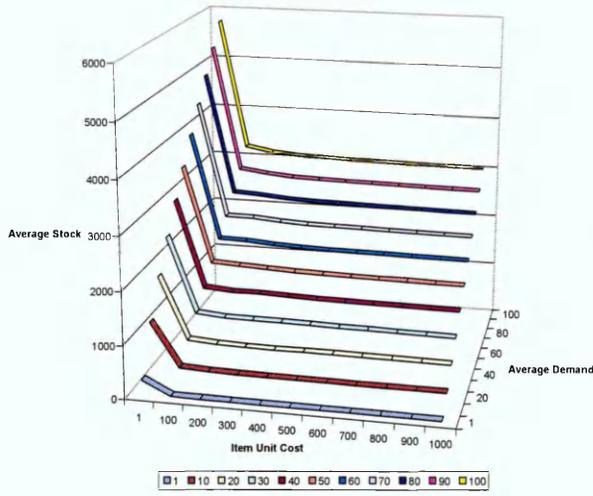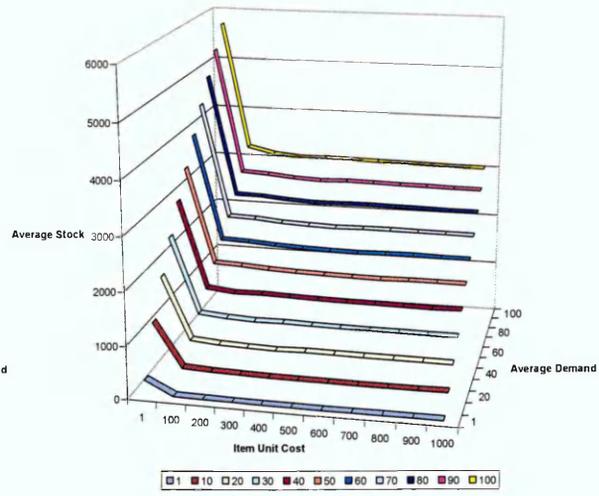
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)

(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)
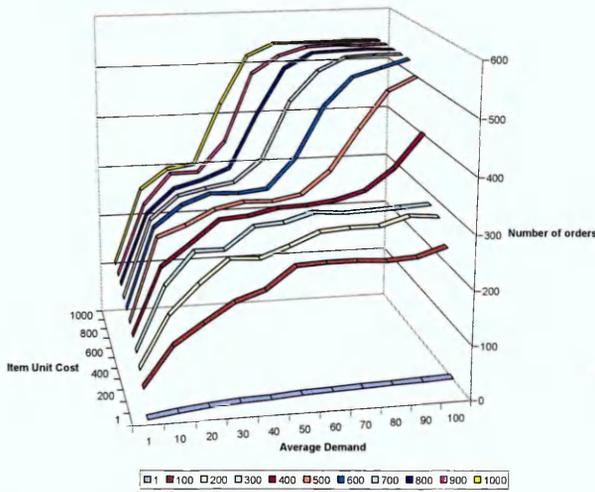
(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
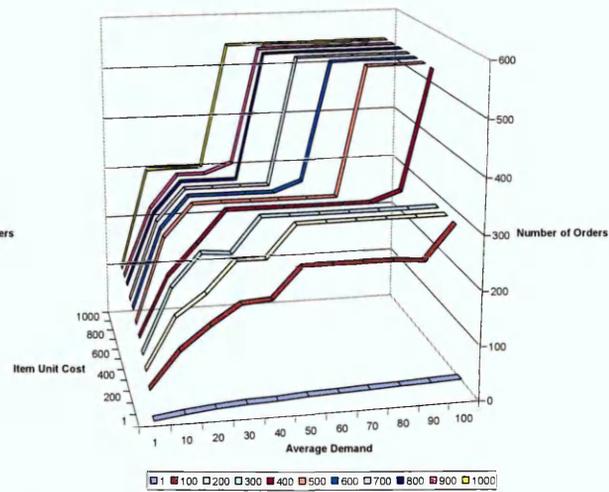
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
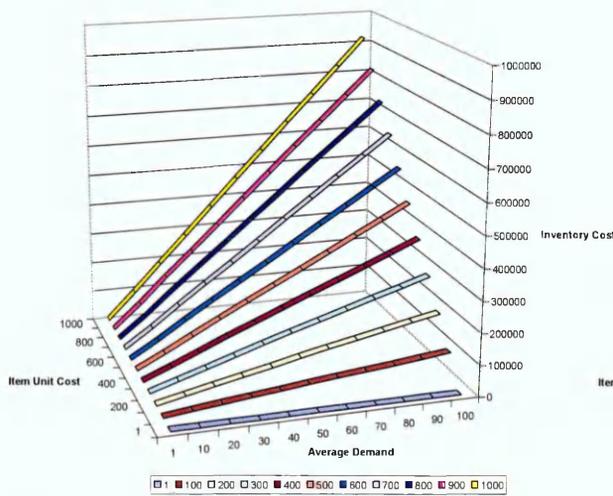
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
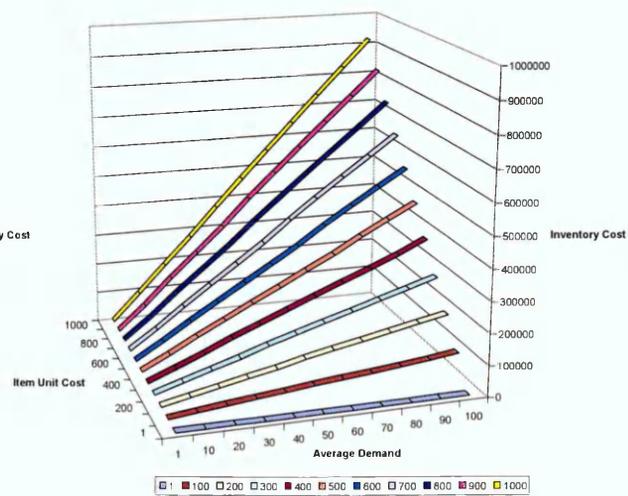
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure G. 1: Average stock, number of orders, and inventory cost for the "current situation" operating strategy
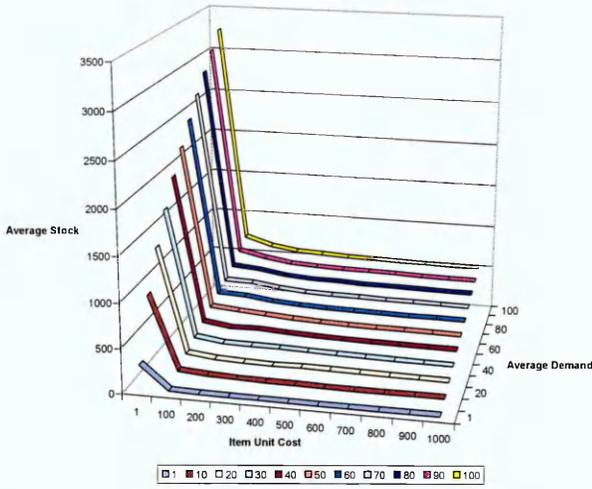
(a) Average stock (σ_D = (1/3)(*Average Demand*))
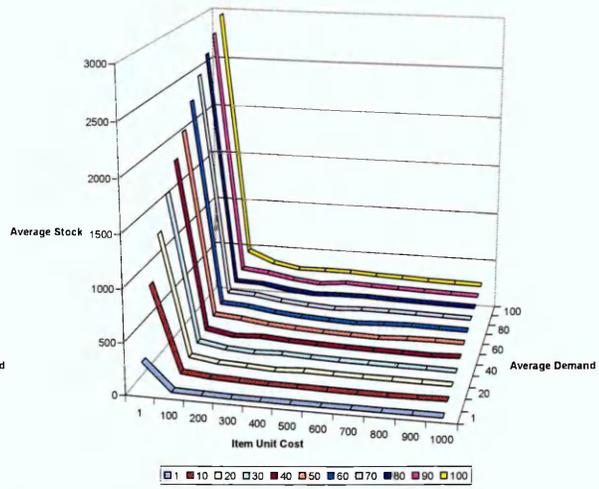
(b) Average stock (σ_D = (1/30)(*Average Demand*))
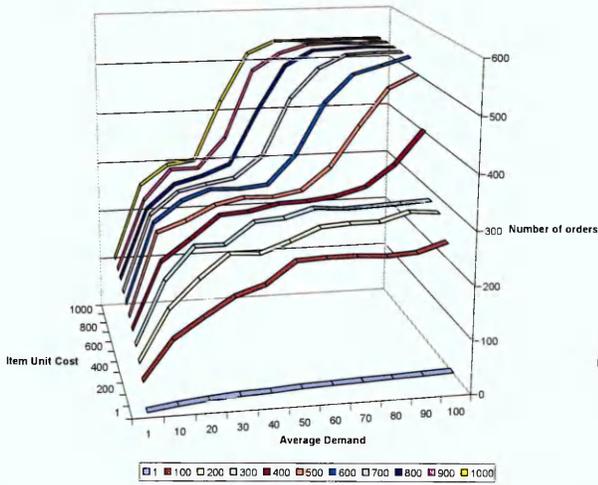
(c) Number of orders (σ_D = (1/3)(*Average Demand*))
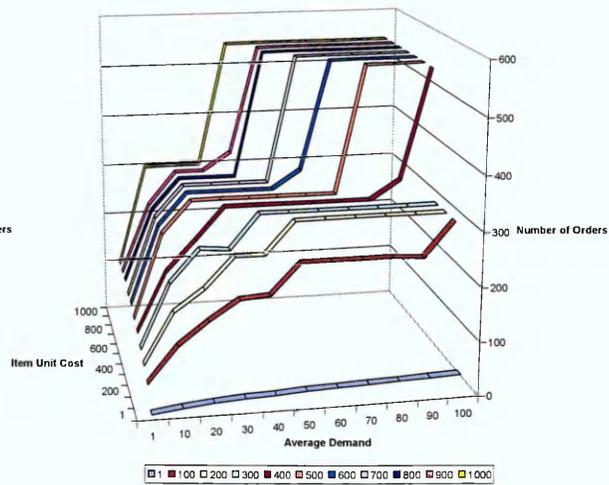
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
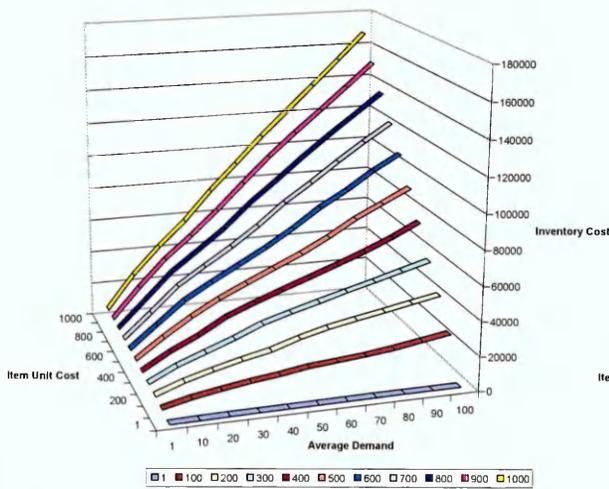
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
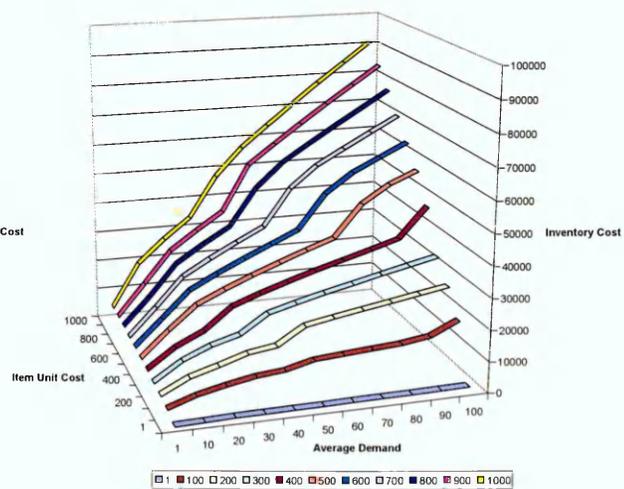
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 2: Average stock, number of orders, and inventory cost for the (R,s,S) operating strategy
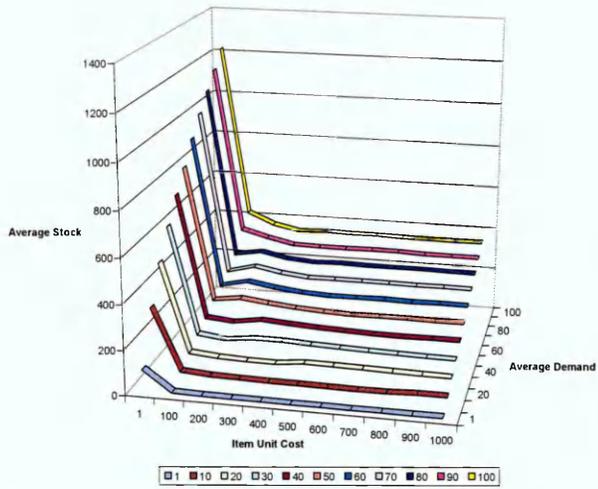
(a) Average stock (σ_D = (1/3)(*Average Demand*))
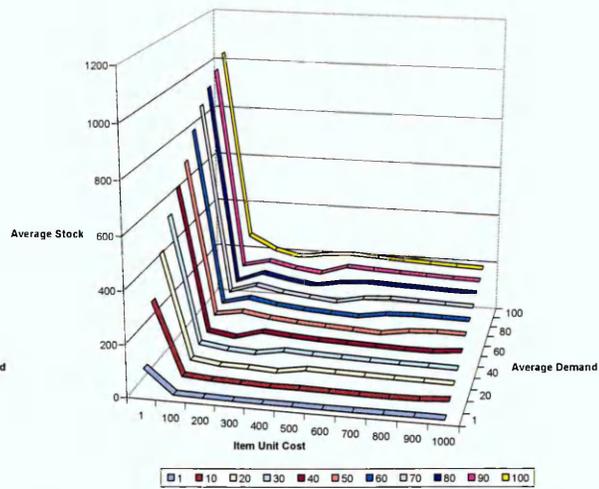
(b) Average stock (σ_D = (1/30)(*Average Demand*))
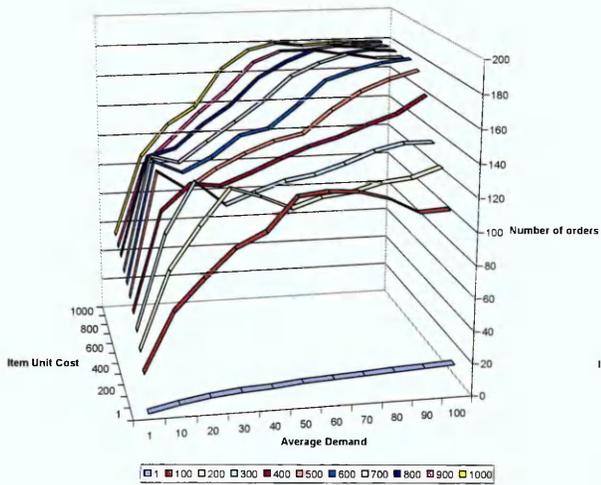
(c) Number of orders (σ_D = (1/3)(*Average Demand*))
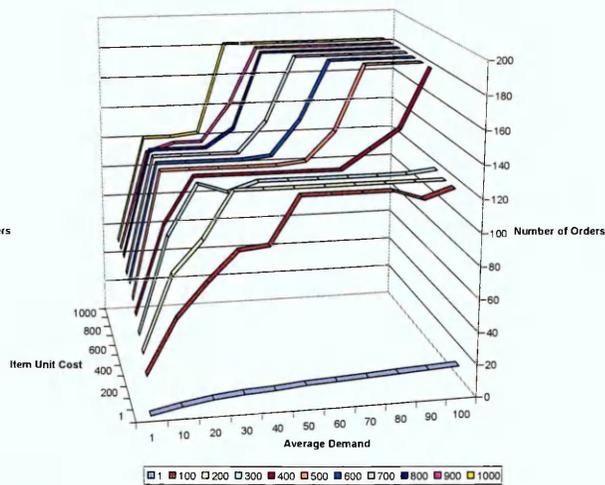
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
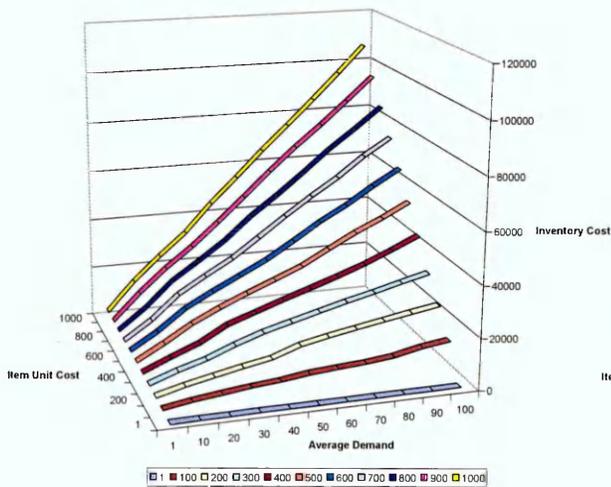
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
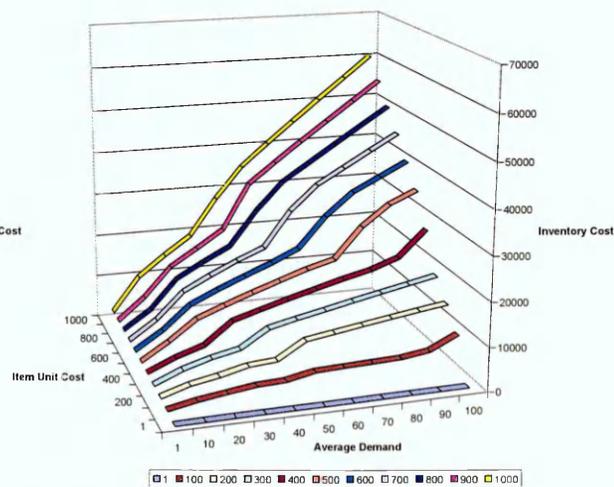
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 3: Average stock, number of orders, and inventory cost for the (R,s,S)(eliminate) operating strategy
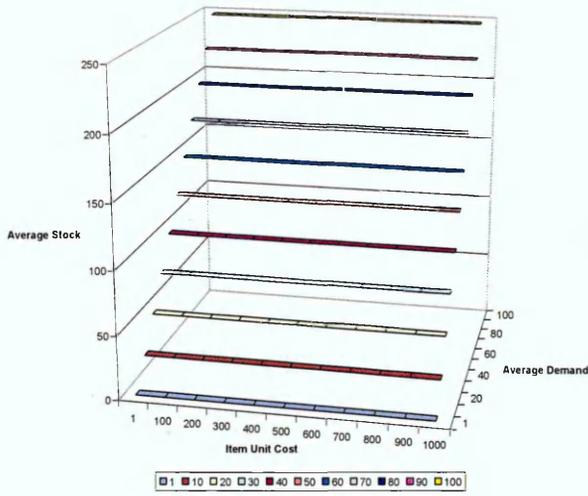
(a) Average stock (σ_D = (1/3)(*Average Demand*))
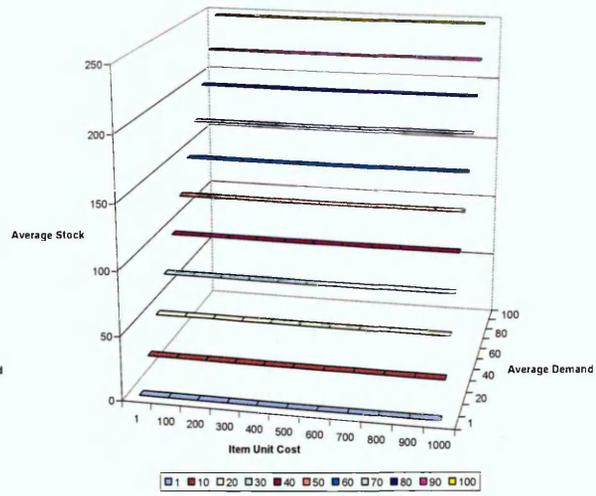
(b) Average stock (σ_D = (1/30)(*Average Demand*))
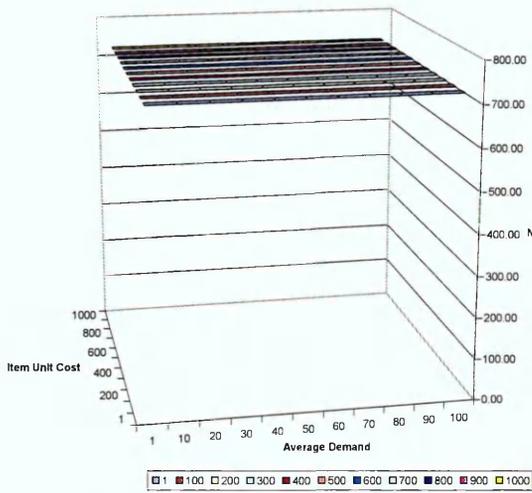
(c) Number of orders (σ_D = (1/3)(*Average Demand*))
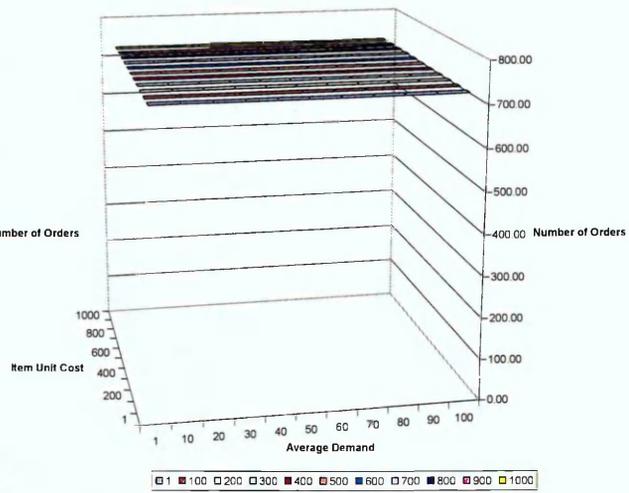
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
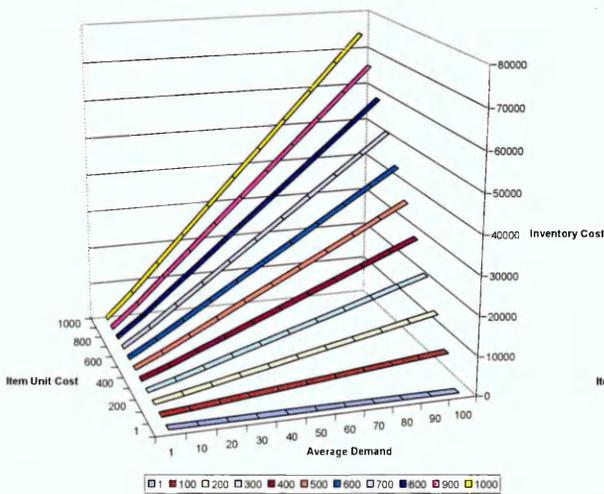
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
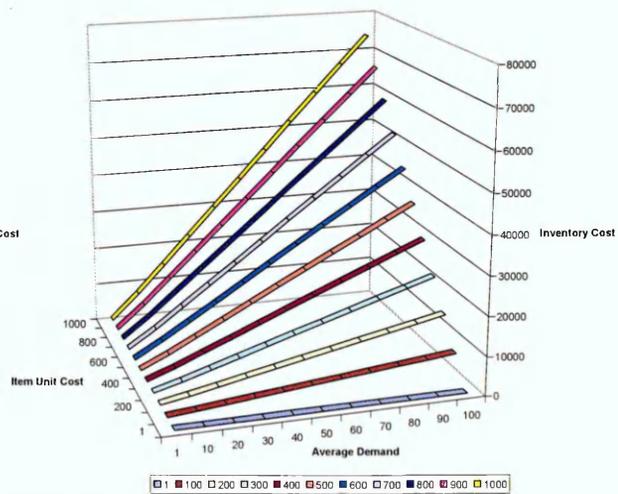
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 4: Average stock, number of orders, and inventory cost for the CR(IOBPCS) operating strategy
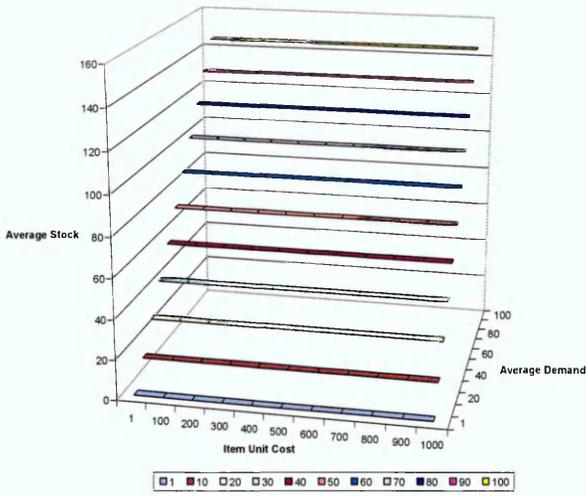
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
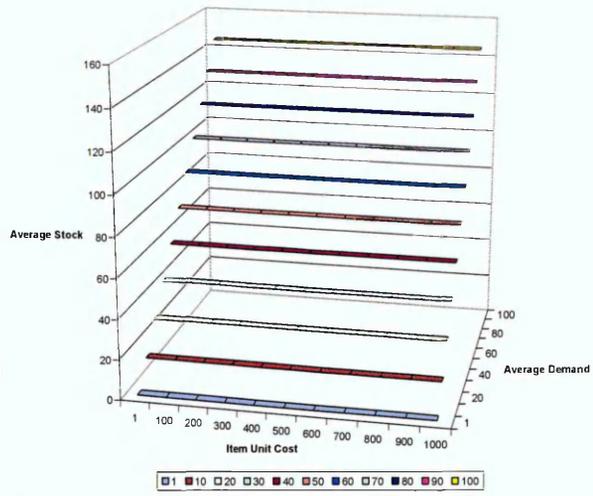
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)
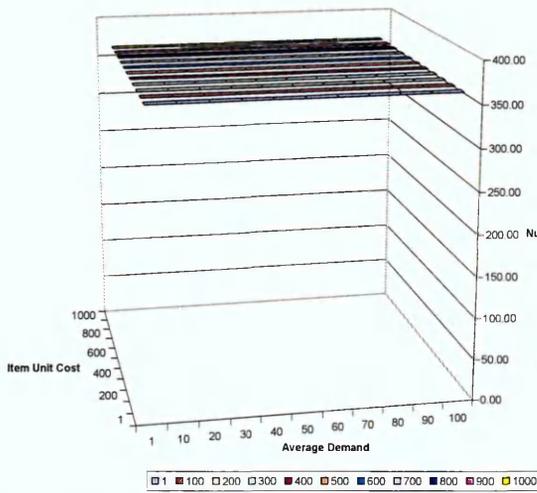
(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
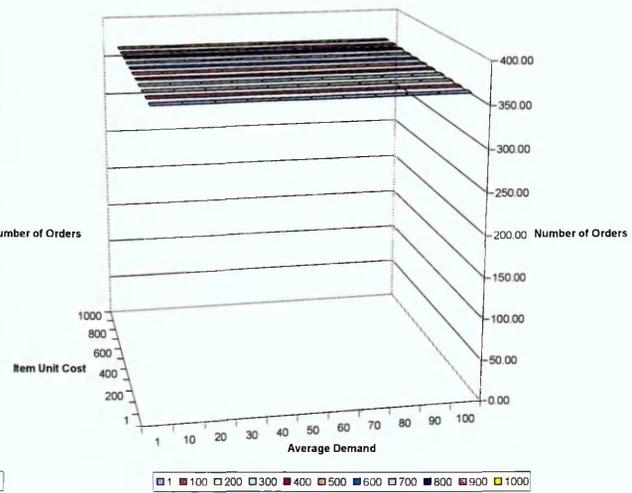
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
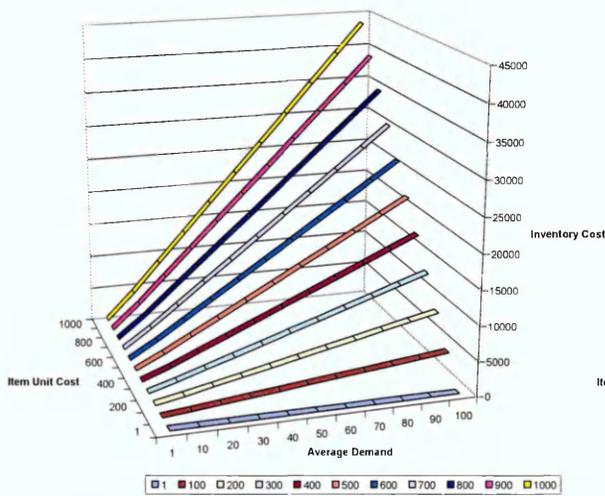
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
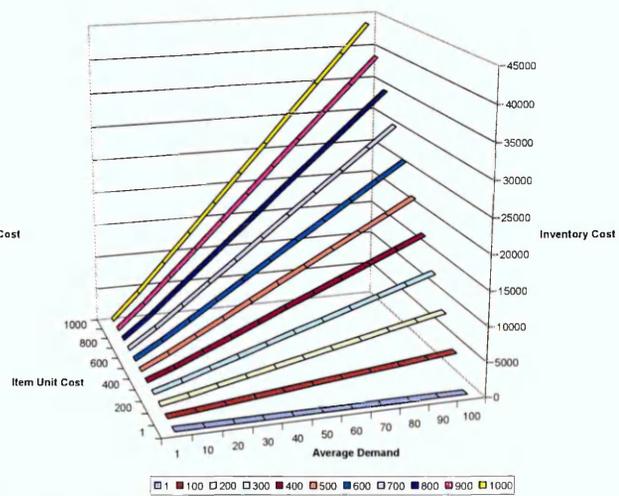
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

**Figure G. 5: Average stock, number of orders, and inventory cost for the CR(IOBPCS) (eliminate) operating strategy**

Whereas, as shown in Figure G.4 (a) & (b) for the CR(IOBPCS) operating strategy, and Figure G.5 (a) & (b) for the CR(IOBPCS) (eliminate) operating strategy, average stock is a function of *Average Demand*, such that average stock varies linearly with *Average Demand*. This is because average stock depends on the value of target level; where the equation of target level (see Table 3.4) is a linear function of *Average Demand*.

b) Changing *Item Unit Cost*:

As shown in Figure G.1 (a) & (b) for the "current situation" operating strategy, Figure G.2 (a) & (b) for the (R,s,S) operating strategy, and Figure G.3 (a) & (b) for the (R,s,S)(eliminate) operating strategy, average stock is a function of *Item Unit Cost*, such that average stock decreases as a goal-seeking exponential decay with increased *Item Unit Cost*. This is because average stock depends on the values of reorder level and order-up-to level, where the equation of order-up-to level (see Table 3.1 and Table 4.2) includes an inverse square-root function of *Item Unit Cost*.

Whereas, as shown in Figure G.4 (a) & (b) for the CR(IOBPCS) operating strategy, and Figure G.5 (a) & (b) for the CR(IOBPCS) (eliminate) operating strategy, average stock is not a function of *Item Unit Cost*. Therefore, average stock stays constant when increasing *Item Unit Cost*. This is because average stock depends on the value of target level; where *Item Unit Cost* is not a variable in the equation of target level (see Table 3.4).

- **Number of orders behaviour:**

a) Changing *Average Demand*:

As shown in Figure G.1 (c) & (d) for the "current situation" operating strategy, Figure G.2 (c) & (d) for the (R,s,S) operating strategy, and Figure G.3 (c) & (d) for the (R,s,S)(eliminate) operating strategy, number of orders is a function of *Average Demand*, such that number of orders follows a kind of S-shaped growth pattern with increasing *Average Demand*. This is especially true for the lower *Average*

Demand patterns of 1, 10 and 20. For the higher *Average Demand* patterns and higher *Item Unit Cost*, say above ($300 to $1000), there is a discontinuity noticed in the behaviour. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where the equation of order-up-to level contains a square-root function of *Average Demand*, and the equation of review period[1] contains a square-root function of the inverse of *Average Demand* (see Table 3.1 and Table 4.2).

However, as shown in Figure G.4 (c) & (d) for the CR(IOBPCS) operating strategy, and Figure G.5 (c) & (d) for the CR(IOBPCS) (eliminate) operating strategy, number of orders is not a function of *Average Demand*. This is because in the IOBPCS a constant order is placed at each period *t* (see Table 3.4).

b) Changing *Item Unit Cost*:

As shown in Figure G.1 (c) & (d) for the "current situation" operating strategy, Figure G.2 (c) & (d) for the (*R,s,S*) operating strategy, and Figure G.3 (c) & (d) for the (*R,s,S*)(eliminate) operating strategy, number of orders is a function of *Item Unit Cost*, such that number of orders follows a kind of S-shaped growth pattern (as explained earlier) with increasing *Item Unit Cost*. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where both the equation of order-up-to level and the equation of review period[2] contains a square-root function of the inverse of *Item Unit Cost* (see Table 3.1 and Table 4.2).

However, as shown in Figure G.4 (c) & (d) for the CR(IOBPCS) operating strategy, and Figure G.5 (c) & (d) for the CR(IOBPCS) (eliminate) operating strategy, number of orders is not a function of *Item Unit Cost*. This is because number of orders is constant (i.e. ordering is done each period *t* (see Table 3.4)).

---

[1] This is only for the (*R,s,S*) operating strategy and the (*R,s,S*)(eliminate) operating strategy. Whereas, for the "current situation" operating strategy, review period is constant.

[2] This is only for the (*R,s,S*) operating strategy and the (*R,s,S*)(eliminate) operating strategy. Whereas, for the "current situation" operating strategy, review period is constant.

- **Inventory cost behaviour:**

a) **Changing** *Average Demand*:

For all operating strategies as shown in Figure G.1 (e) & (f) for the "current situation" operating strategy, Figure G.2 (e) & (f) for the (*R,s,S*) operating strategy, Figure G.3 (e) & (f) for the (*R,s,S*)(eliminate) operating strategy, Figure G.4 (e) & (f) for the CR(IOBPCS) operating strategy, and Figure G.5 (e) & (f) for the CR(IOBPCS) (eliminate) operating strategy, inventory cost is a function of *Average Demand*, such that inventory cost increases linearly with *Average Demand*. This is because the effect of *Average Demand* on inventory cost combines the effects of *Average Demand* on both average stock and number of orders according to the inventory cost equation (see section 4.3.5).

b) **Changing** *Item Unit Cost*:

For all operating strategies as shown in Figure G.1 (e) & (f) for the "current situation" operating strategy, Figure G.2 (e) & (f) for the (*R,s,S*) operating strategy, Figure G.3 (e) & (f) for the (*R,s,S*)(eliminate) operating strategy, Figure G.4 (e) & (f) for the CR(IOBPCS) operating strategy, and Figure G.5 (e) & (f) for the CR(IOBPCS) (eliminate) operating strategy, inventory cost is a function of *Item Unit Cost*, such that inventory cost increases linearly with *Item Unit Cost*. This is because the effect of *Item Unit Cost* on inventory cost combines the effects of *Item Unit Cost* on both average stock and number of orders according to the inventory cost equation (see section 4.3.5).

G.2 Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost

Figure G.6 to Figure G.16 compare the five operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for the following values of *Average Demand*, respectively: 1 item/day, 10 items/day, 20 items/day, 30 items/day, 40 items/day, 50 items/day, 60 items/day, 70 items/day, 80 items/day, 90 items/day, and 100 items/day. Discussion of the Figures is provided subsequently.

(a) Average stock (σ_D = (1/3)(*Average Demand*))
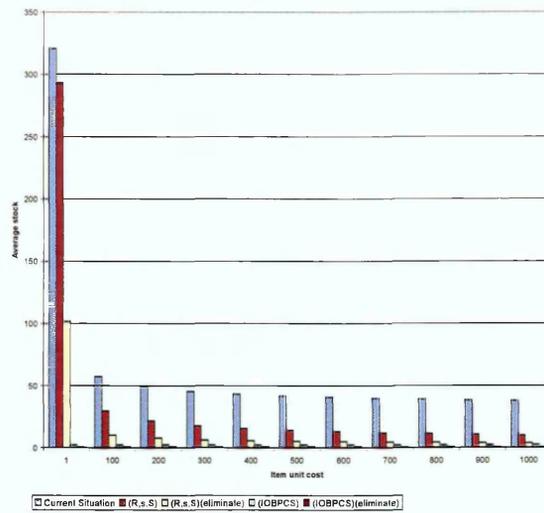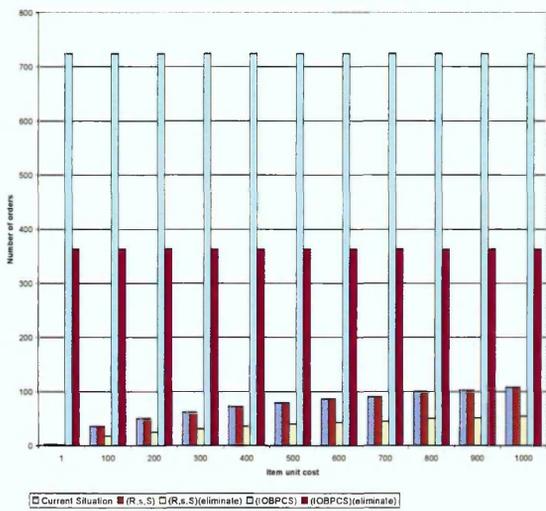
(b) Average stock (σ_D = (1/30)(*Average Demand*))

(c) Number of orders (σ_D = (1/3)(*Average Demand*))
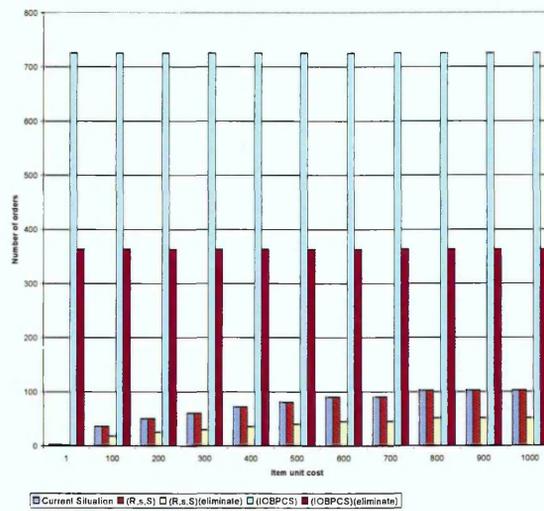
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
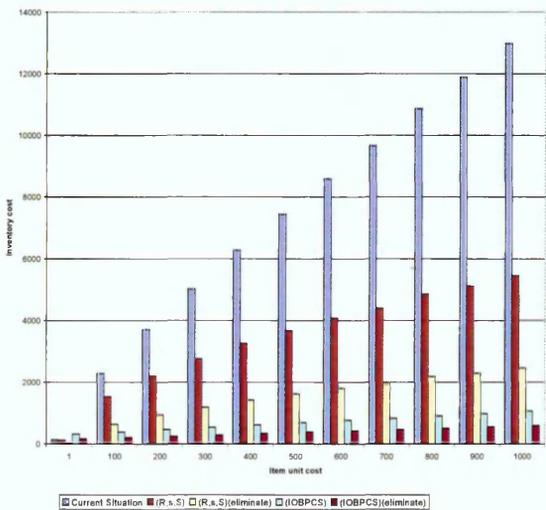
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
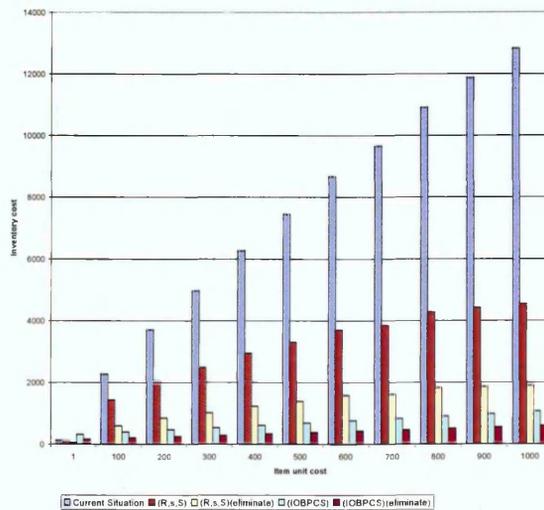
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 6: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 1 item/day
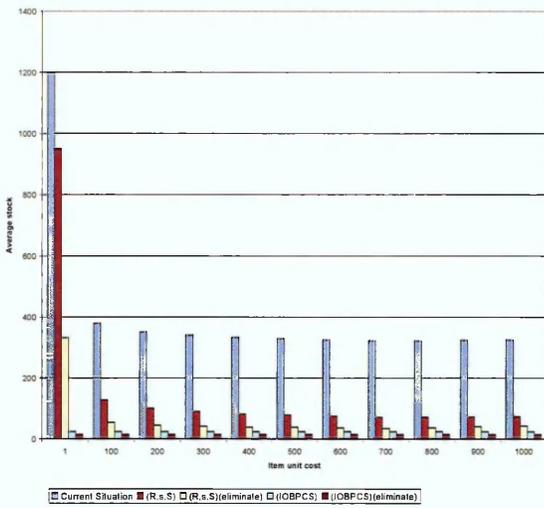
(a) Average stock (σ_D = (1/3)(*Average Demand*))
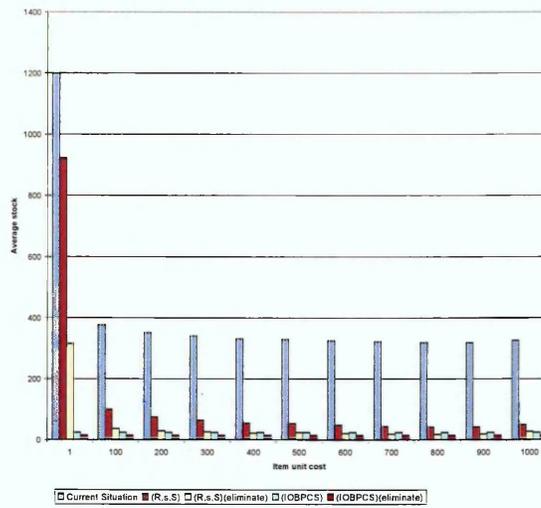
(b) Average stock (σ_D = (1/30)(*Average Demand*))
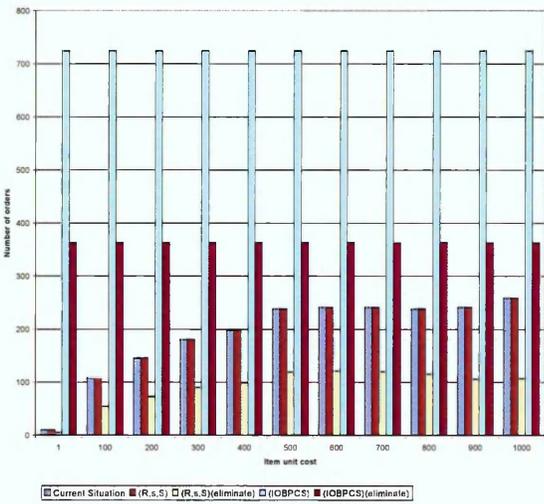
(c) Number of orders (σ_D = (1/3)(*Average Demand*))
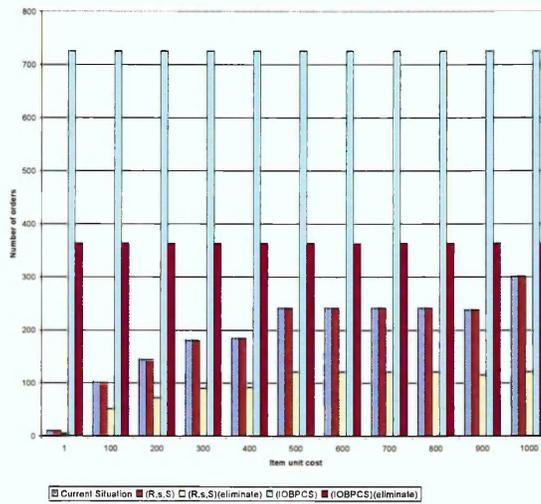
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
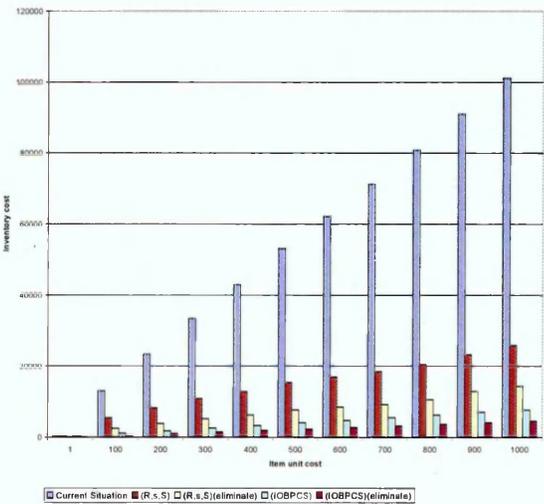
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
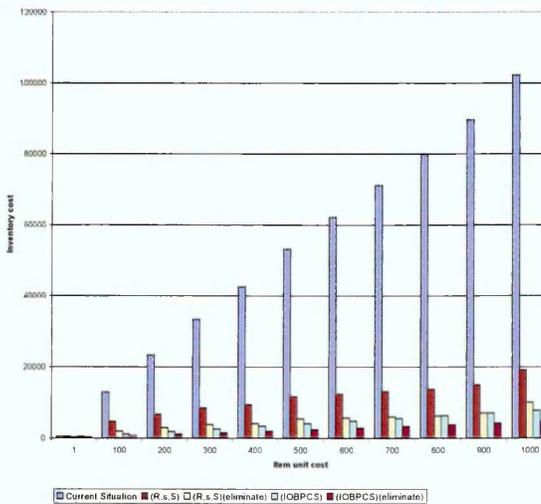
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 7: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 10 items/day
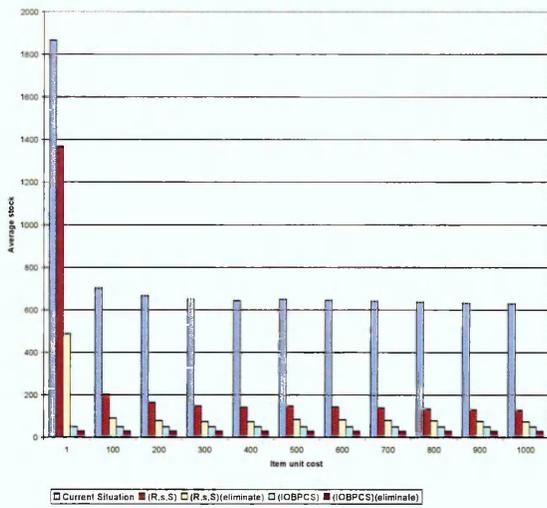
(a) Average stock (σ_D = (1/3)(*Average Demand*))
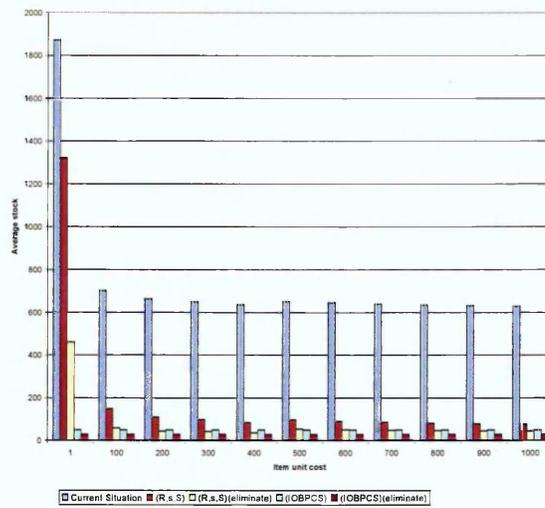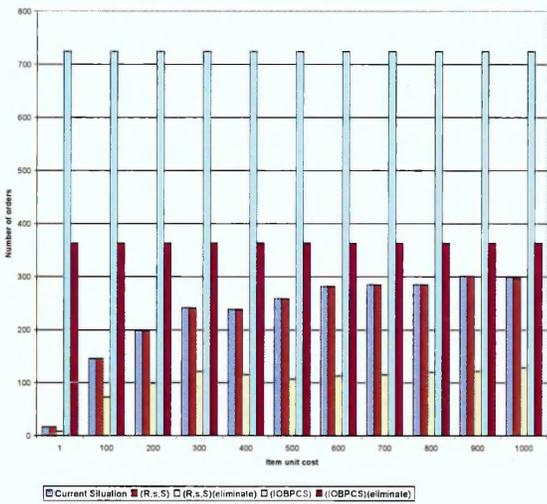
(b) Average stock (σ_D = (1/30)(*Average Demand*))

(c) Number of orders (σ_D = (1/3)(*Average Demand*))
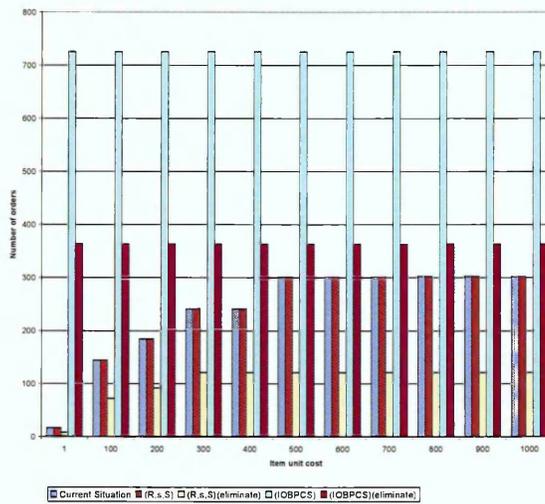
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
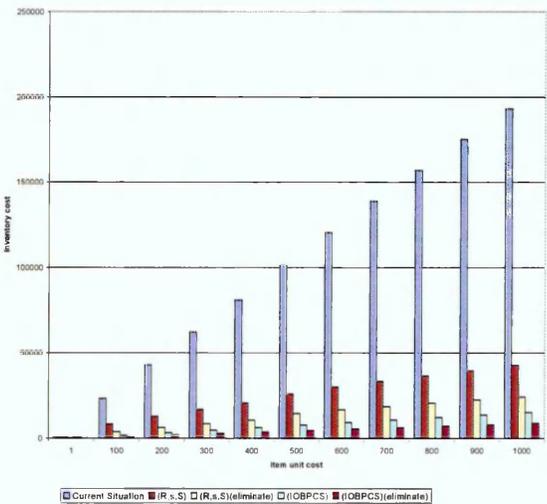
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
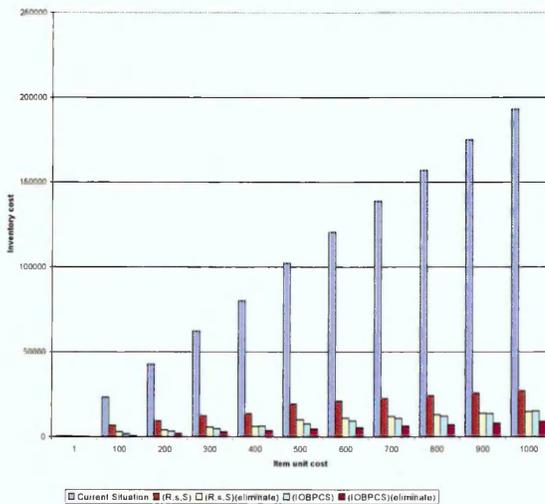
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 8: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 20 items/day
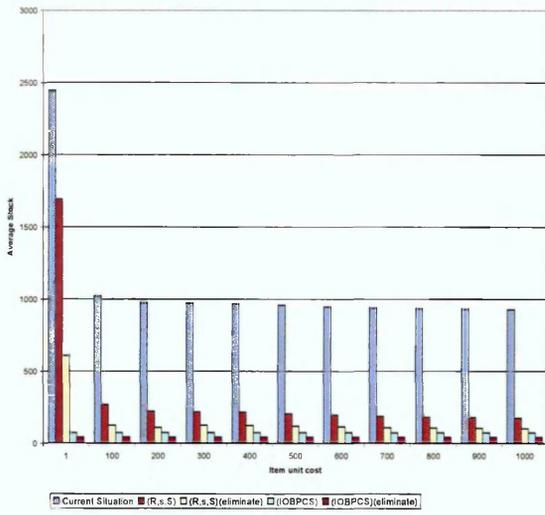
(a) Average stock (σ_D = (1/3)(*Average Demand*))
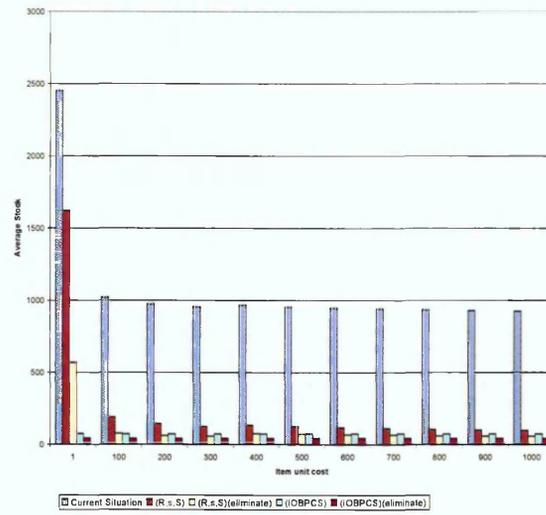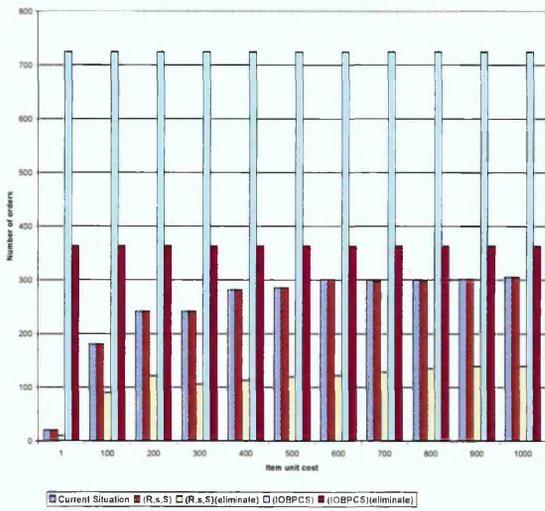
(b) Average stock (σ_D = (1/30)(*Average Demand*))

(c) Number of orders (σ_D = (1/3)(*Average Demand*))
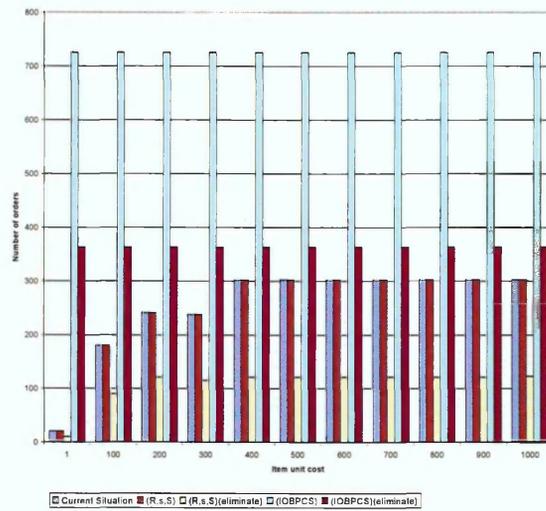
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
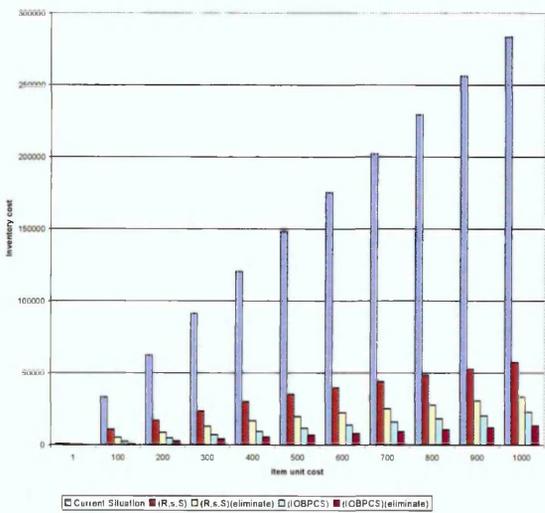
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
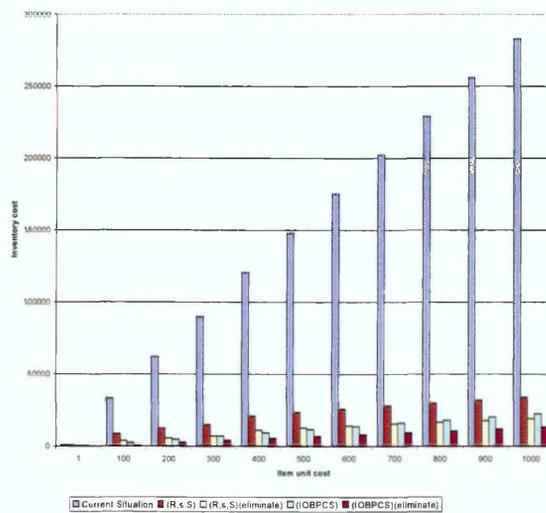
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 9: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 30 items/day
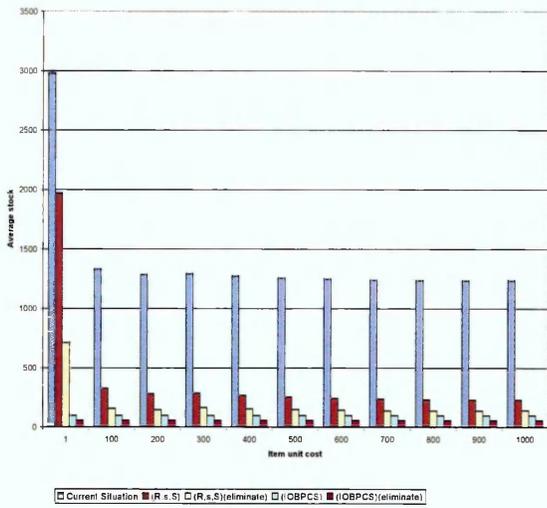
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
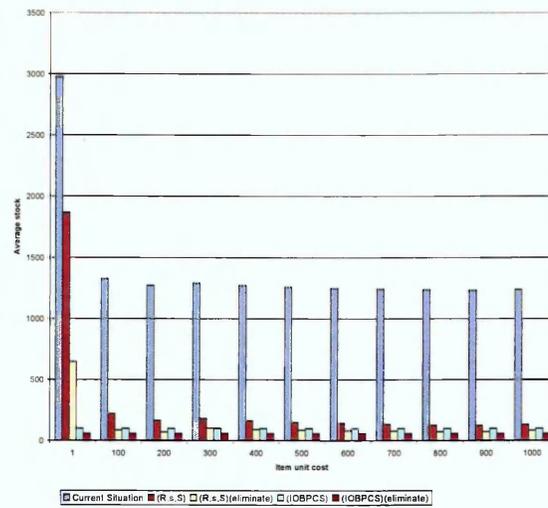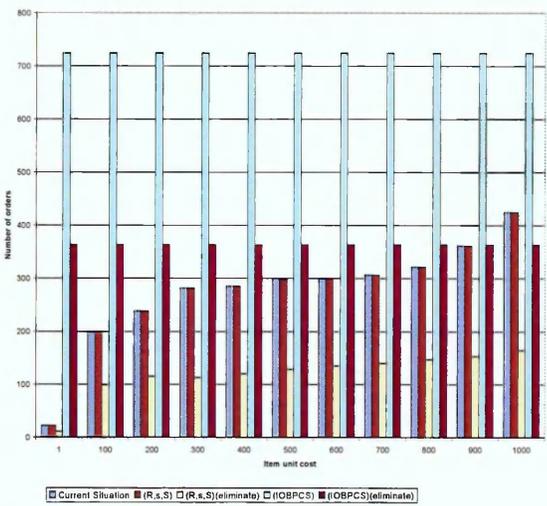
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
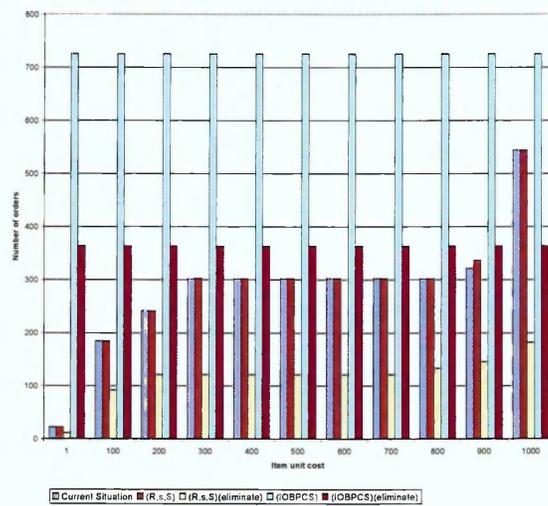
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
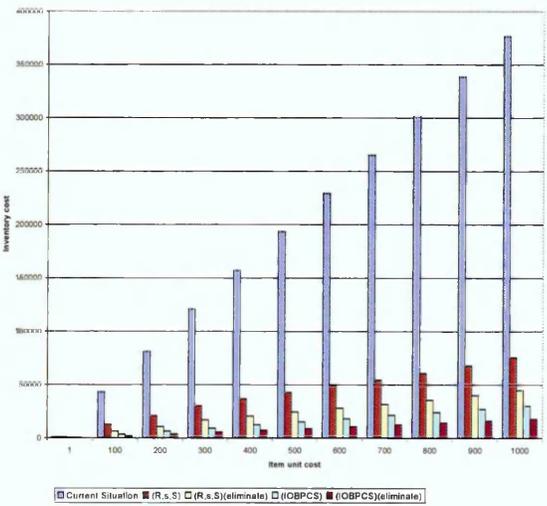
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
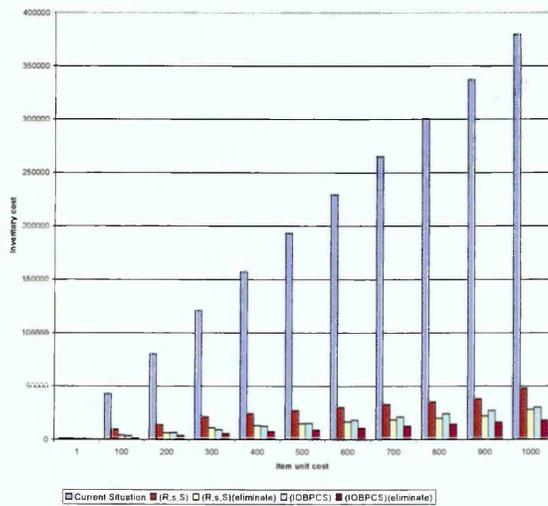
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure G. 10: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 40 items/day
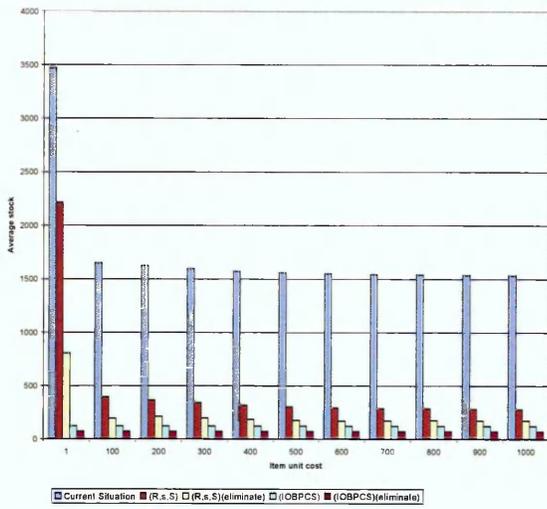
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
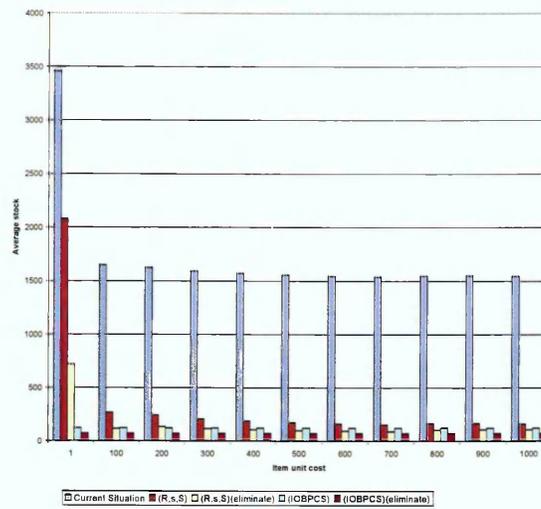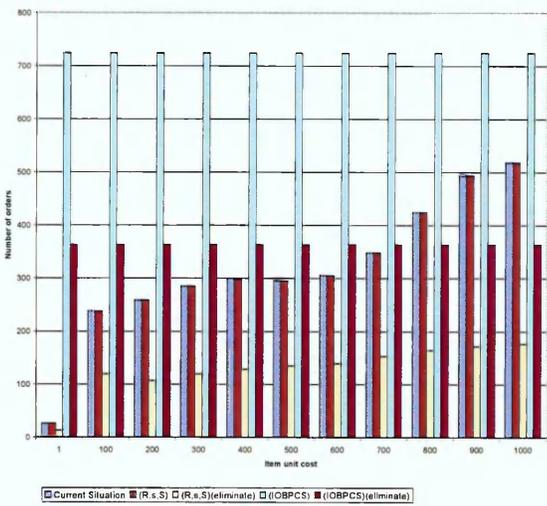
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
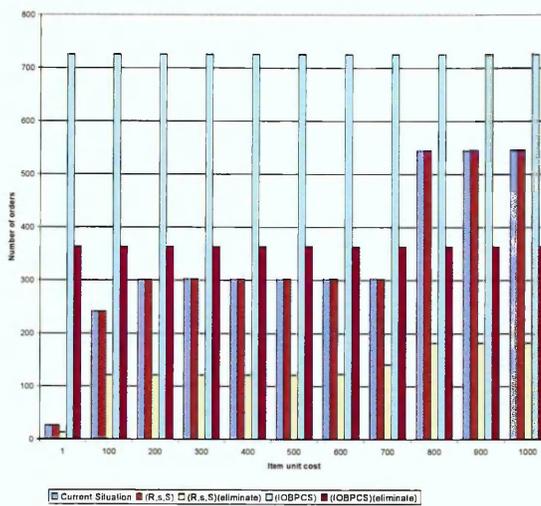
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
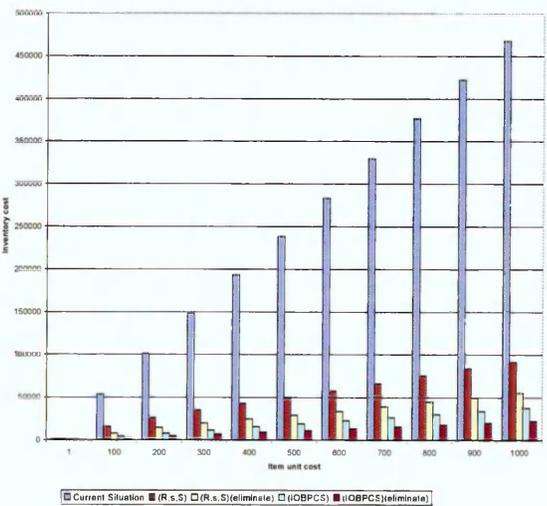
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
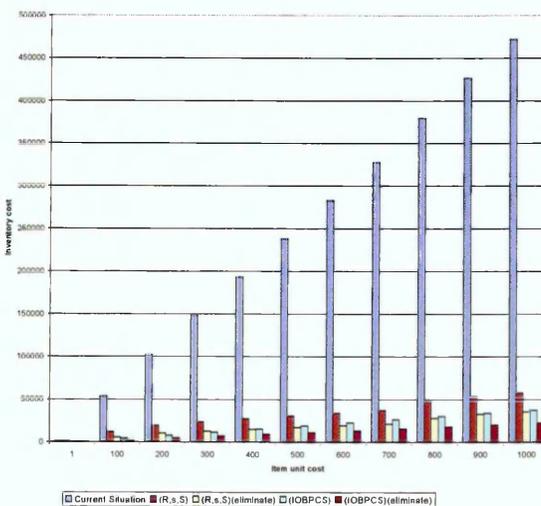
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure G. 11: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 50 items/day
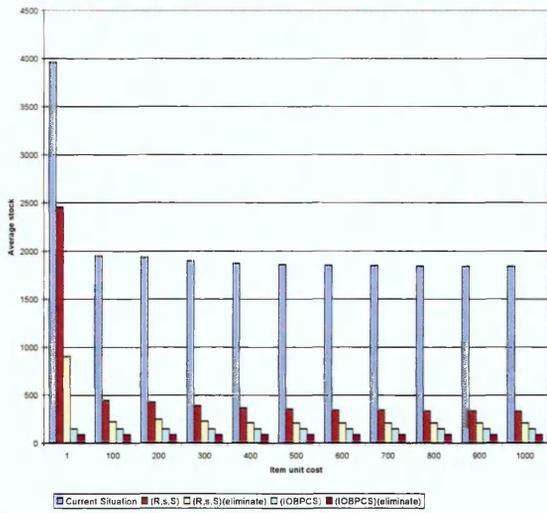
(a) Average stock ($\sigma_D = (1/3)$(*Average Demand*))
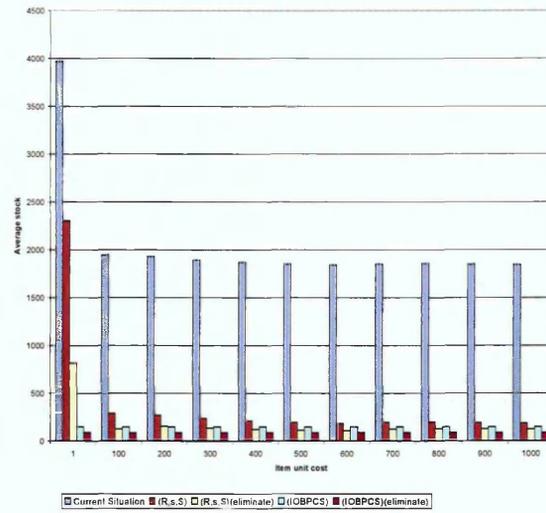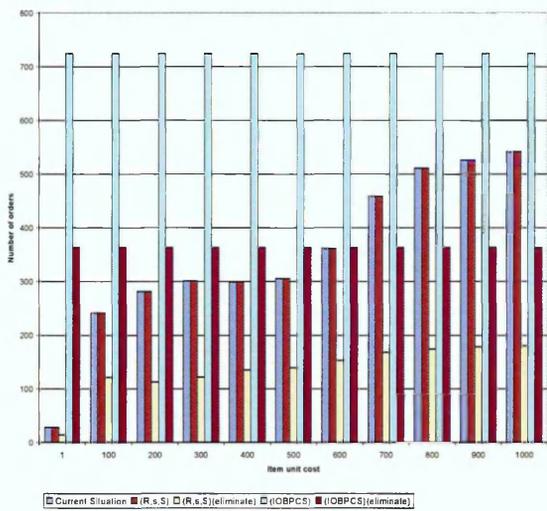
(b) Average stock ($\sigma_D = (1/30)$(*Average Demand*))

(c) Number of orders ($\sigma_D = (1/3)$(*Average Demand*))
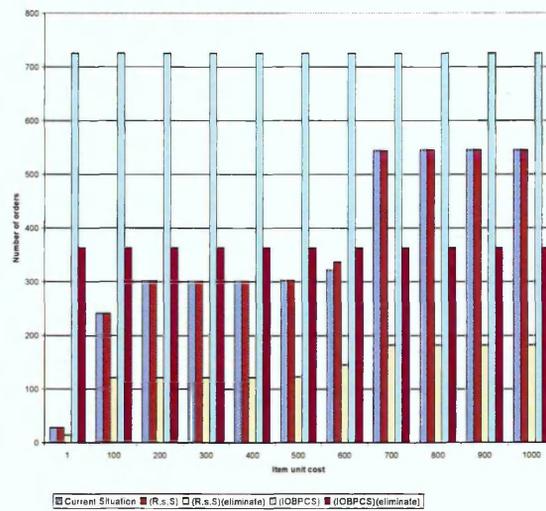
(d) Number of orders ($\sigma_D = (1/30)$(*Average Demand*))
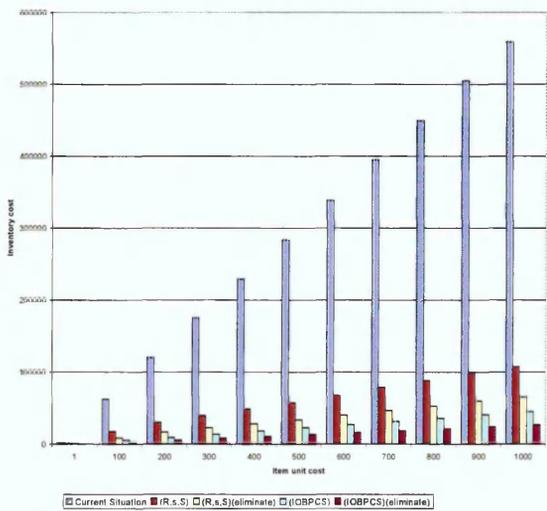
(e) Inventory cost ($\sigma_D = (1/3)$(*Average Demand*))
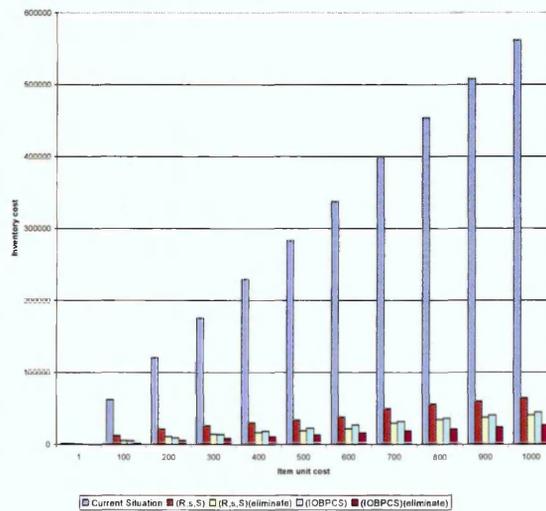
(f) Inventory cost ($\sigma_D = (1/30)$(*Average Demand*))

Figure G. 12: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 60 items/day
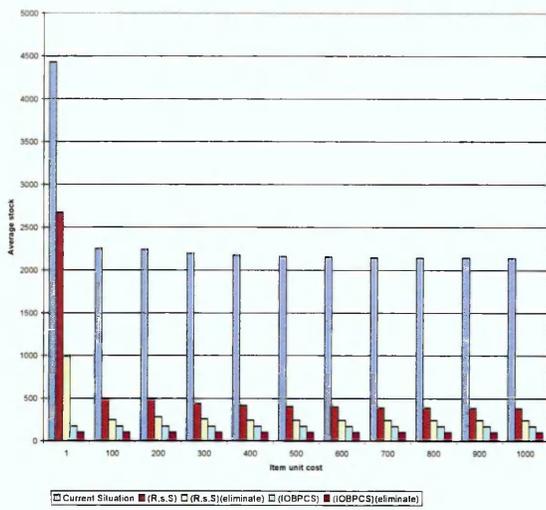
(a) Average stock (σ_D = (1/3)(*Average Demand*))
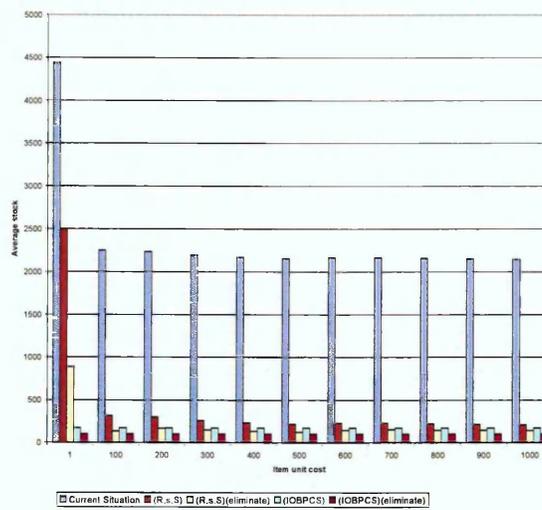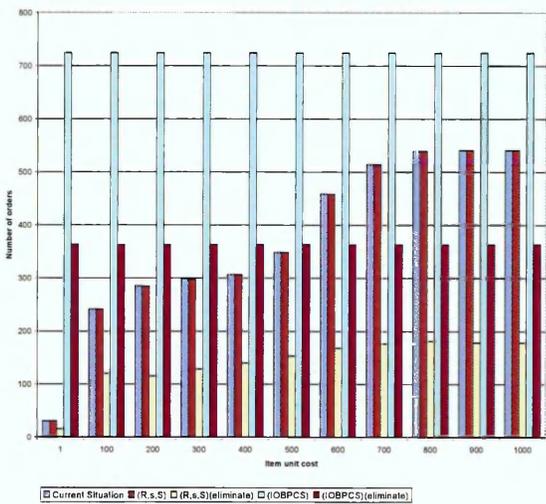
(b) Average stock (σ_D = (1/30)(*Average Demand*))

(c) Number of orders (σ_D = (1/3)(*Average Demand*))
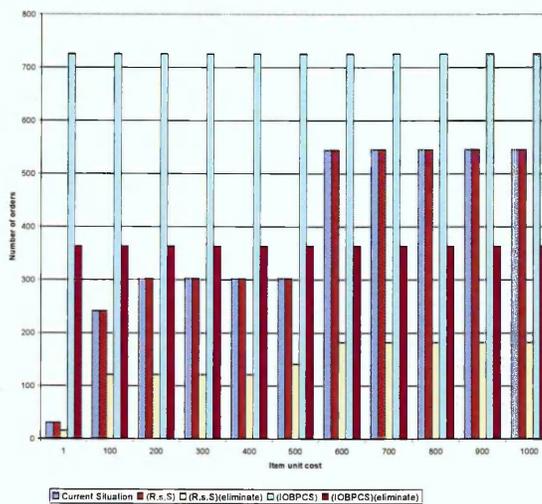
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
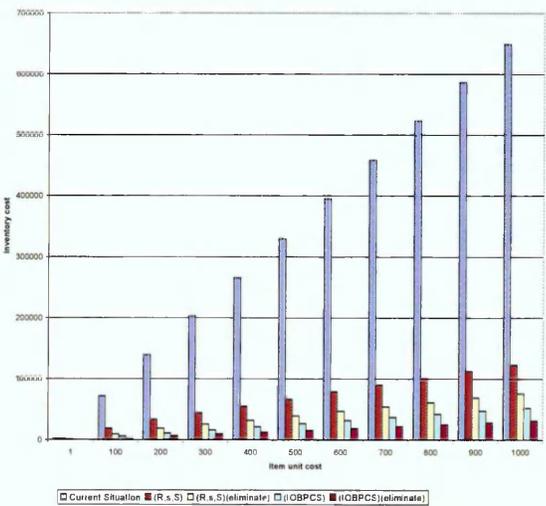
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
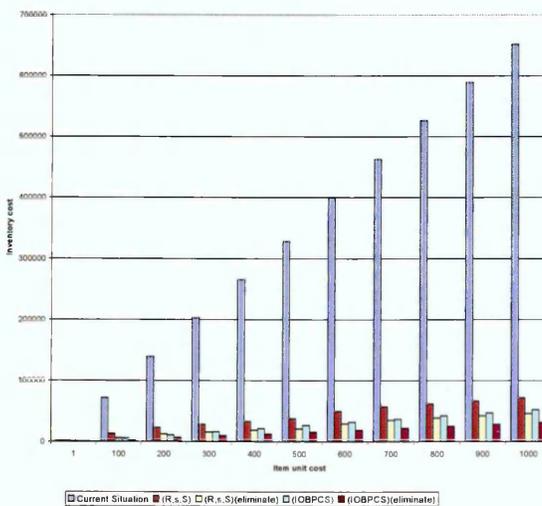
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure G. 13: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 70 items/day
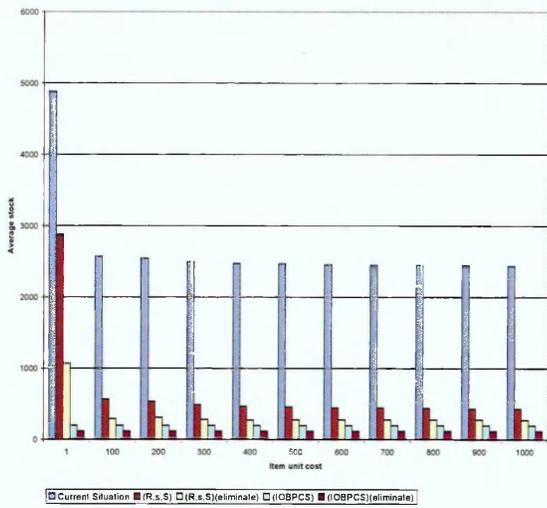
(a) Average stock ($\sigma_D = (1/3)$(*Average Demand*))
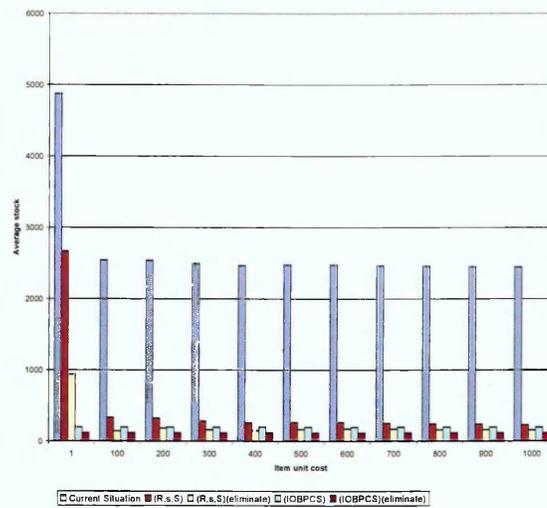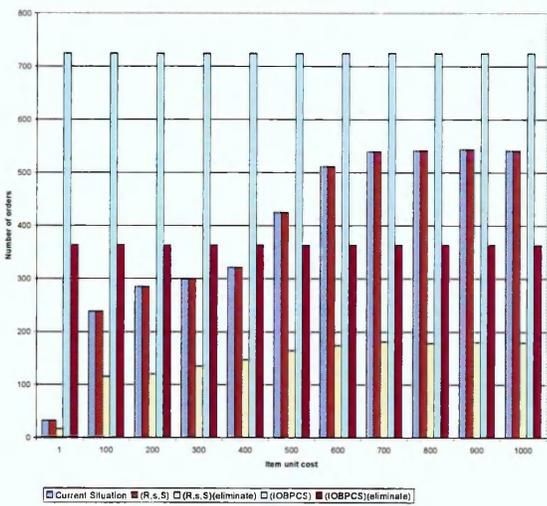
(b) Average stock ($\sigma_D = (1/30)$(*Average Demand*))

(c) Number of orders ($\sigma_D = (1/3)$(*Average Demand*))
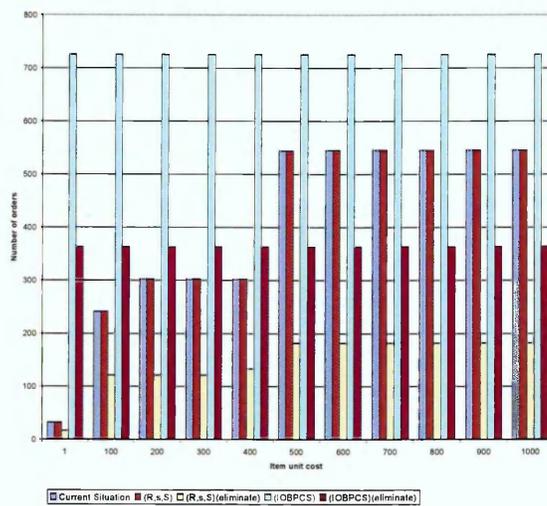
(d) Number of orders ($\sigma_D = (1/30)$(*Average Demand*))
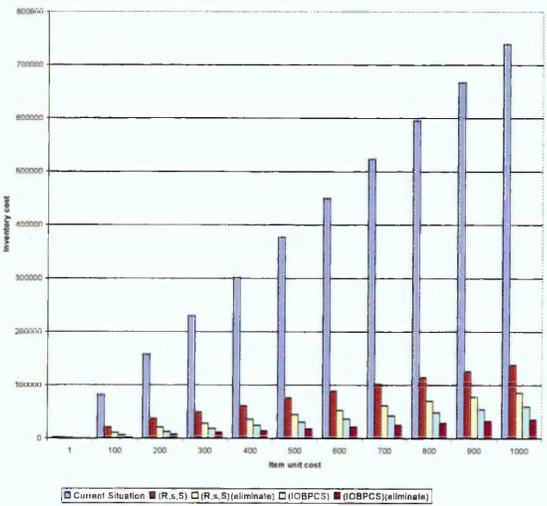
(e) Inventory cost ($\sigma_D = (1/3)$(*Average Demand*))
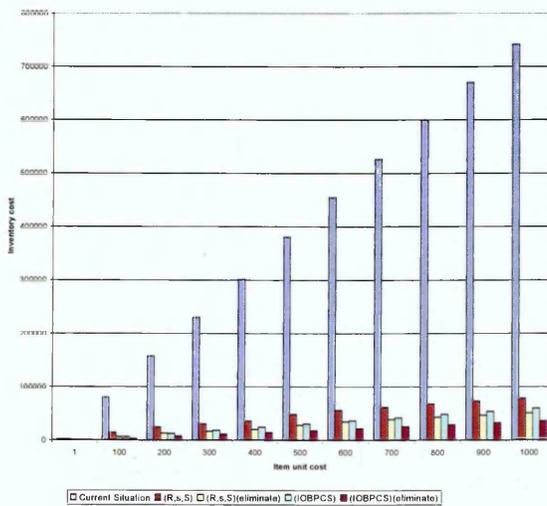
(f) Inventory cost ($\sigma_D = (1/30)$(*Average Demand*))

Figure G. 14: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 80 items/day
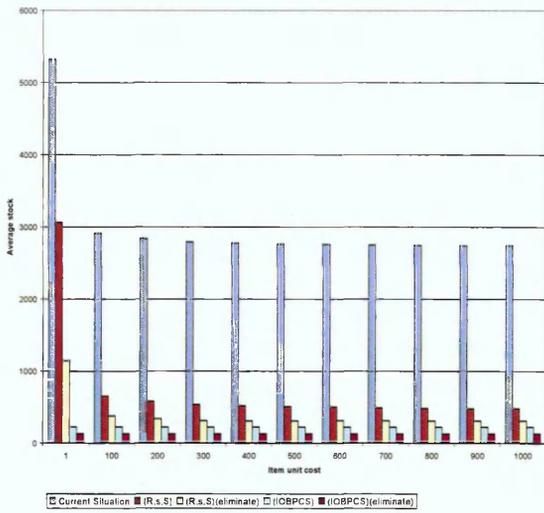
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
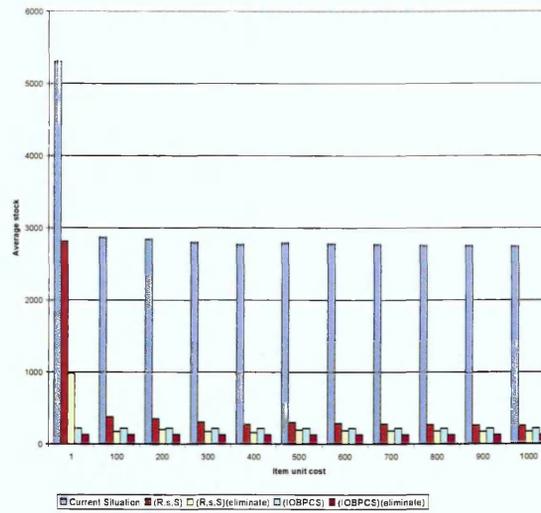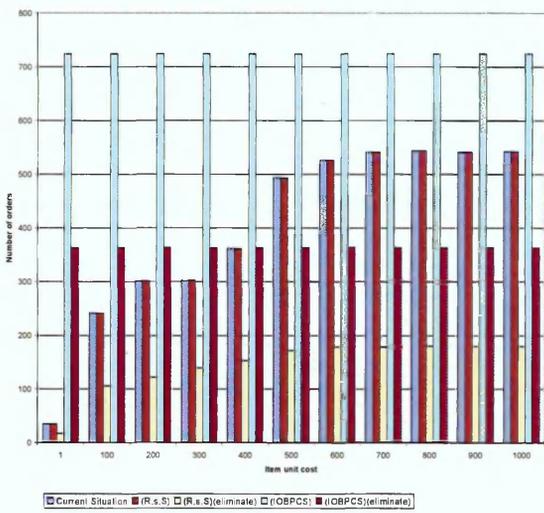
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
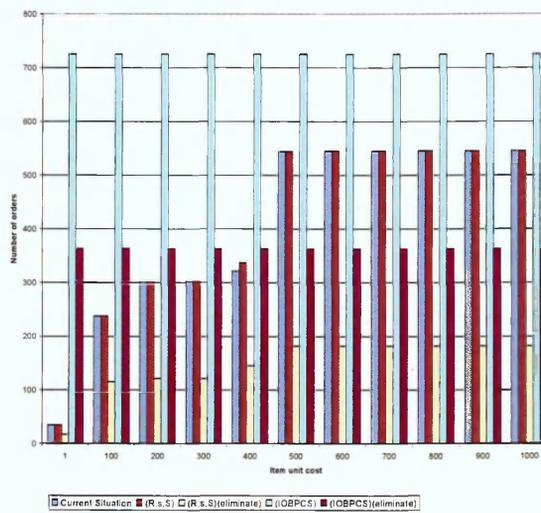
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
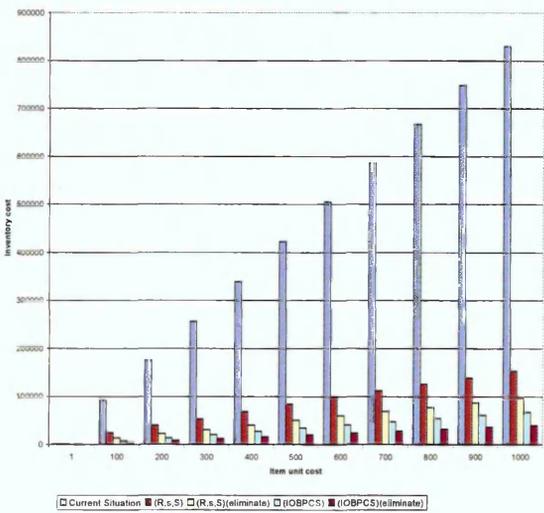
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
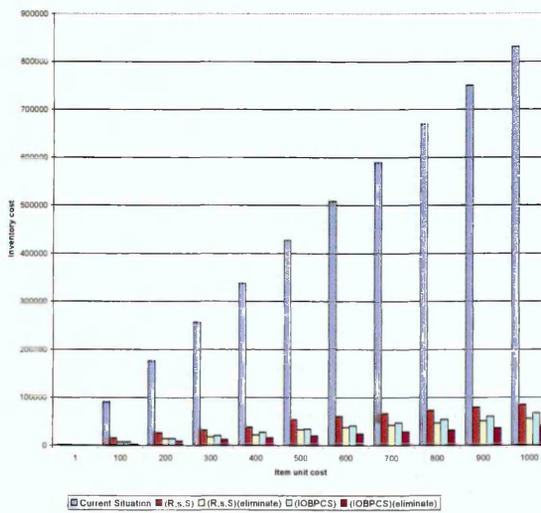
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure G. 15: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 90 items/day
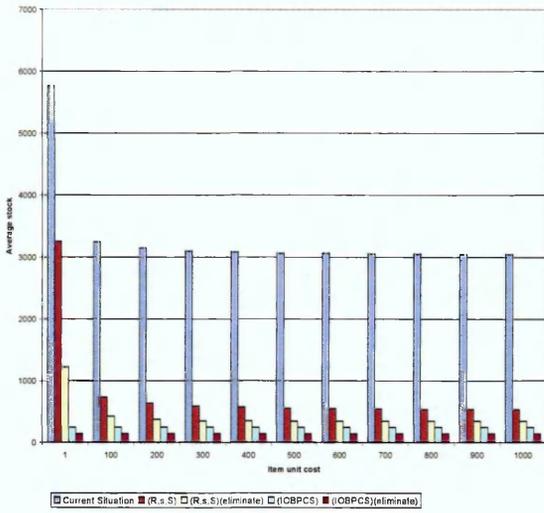
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
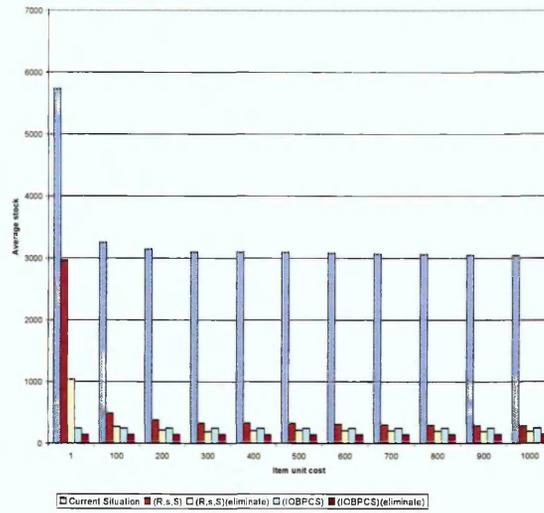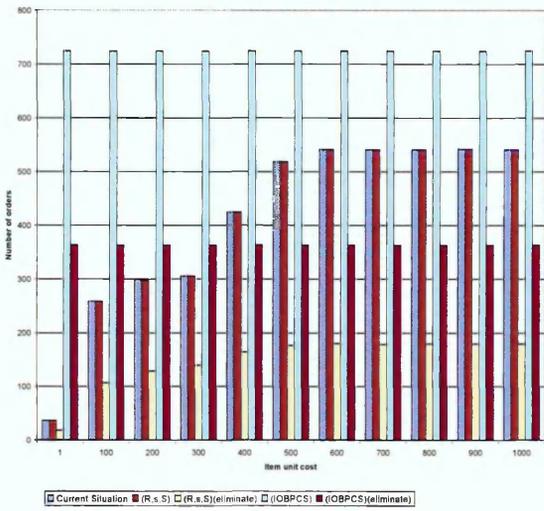
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
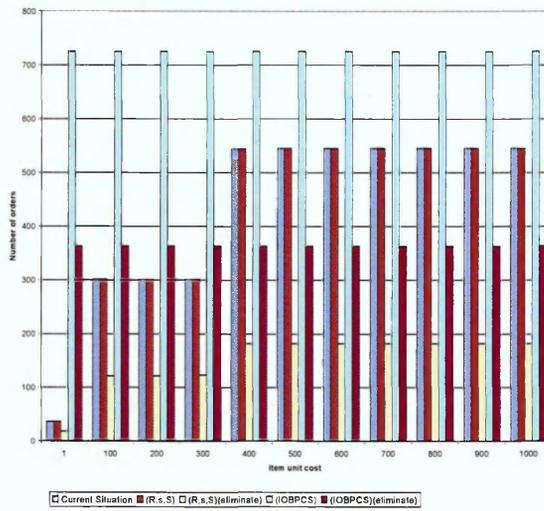
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
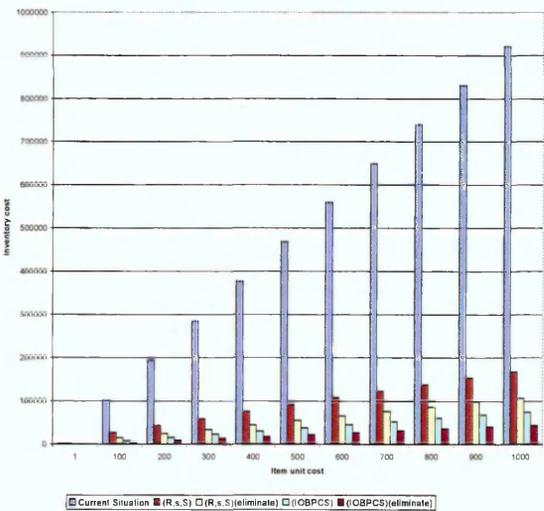
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
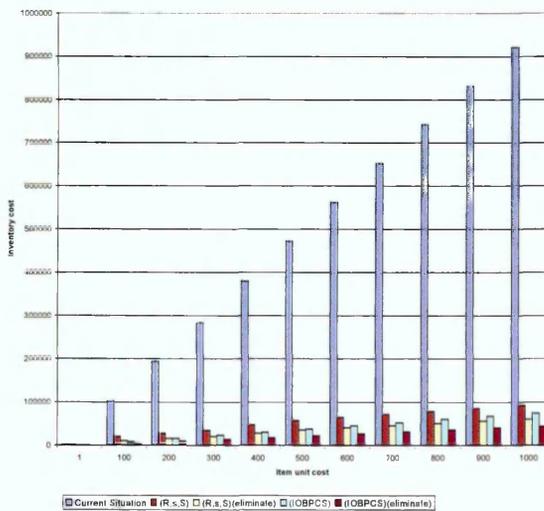
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure G. 16: Comparison of the five operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 100 items/day

- **Average stock comparison:**

By comparing Figure G.6 (a) & (b) to Figure G.16 (a) & (b), for all items (i.e. for all values of *Average Demand* and for all values of *Item Unit Cost*), average stock is the highest for the "current situation" operating strategy and the lowest for the CR(IOBPCS) (eliminate) operating strategy.

It can be noticed from the above figures that there is a large difference –for all items-between the values of average stock for the "current situation" operating strategy against the remaining four operating strategies. These results are verified by the CNMC Materials Management Director who emphasised the problem of having very high stock levels.

- **Number of orders comparison:**

By comparing Figure G.6 (c) & (d) to Figure G.16 (c) & (d), for all items (i.e. for all values of *Average Demand* and for all values of *Item Unit Cost*), number of orders is the highest for the CR(IOBPCS) operating strategy and the lowest for the (*R,s,S*)(eliminate) operating strategy. This is because, for the CR(IOBPCS) operating strategy, continuous replenishment means a constant order is placed at each period *t* (see Table 3.4). However, for the (*R,s,S*)(eliminate) operating strategy, number of orders depends on a trade-off between inventory carrying cost and ordering cost.

- **Inventory cost comparison:**

By comparing Figure G.6 (e) & (f) to Figure G.16 (e) & (f), for all items (i.e. for all values of *Average Demand* and for all values of *Item Unit Cost*), inventory cost is the highest for the "current situation" operating strategy. While, for all items except items with *Average Demand* = 1 and *Item Unit Cost* = 1, inventory cost is the lowest for the CR(IOBPCS) (eliminate) operating strategy. However, for items with *Average Demand* = 1 and *Item Unit Cost* = 1, inventory cost is the lowest for the (*R,s,S*)(eliminate) operating strategy.

The above comparison results of the five operating strategies in terms of average stock, number of orders, and inventory cost is the same for $(\sigma_D = (1/3)(\textit{Average Demand}))$ and for $(\sigma_D = (1/30)(\textit{Average Demand}))$. $\sigma_D = (1/3)(\textit{Average Demand})$ was chosen to represent items with high variable demand, whereas $\sigma_D = (1/30)(\textit{Average Demand})$ was chosen to represent items with low variable demand.

Appendix H: Computer Simulation Model of the DRI Logistics System

The aim of this Appendix is to provide all the equations that make up the computer simulation model of the DRI logistics system –for stock items- which was developed using the verified stock-flow diagram shown in Figure 4.28 in Chapter Four. The simulation model was developed using the *ithink* Analyst Software. The equations that make up the simulation model are listed in Table H.1 according to the order of execution.

Table H. 1: The equations that make up the computer simulation model of the DRI logistics system

```
{ INITIALIZATION EQUATIONS }

O   NHS_LA_To__Ward_or_Department__Average_Transit_Time = 3
▥   INIT On_Transport__From_NHS_LA_To__Ward_or_Department = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = INF
    CAPACITY = INF
O   Average__Demand = 100
⌾   NHS_LA_Delivery__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = NHS_LA_To__Ward_or_Department__Average_Transit_Time
⌾   Consumption__Rate = Average__Demand
O   Ward_or_Department__Review_Period = 7
O   Ward_or_Department_Order_Up_To_Level = 20*Average__Demand
▢   INIT Ward_or__Department_Stock = Ward_or_Department_Order_Up_To_Level
O   Ward_or_Department__Reorder_Level = 10*Average__Demand
O   When_to_Order?_How_Much_to_Order?_How_Often_to_Rview? = IF(COUNTER(1,1+Ward_or_Department__Review_Period)=1)

    AND((Ward_or__Department_Stock+On_Transport__From_NHS_LA_To__Ward_or_Department)<=Ward_or_Department__Reorder
    _Level)
    THEN((Ward_or_Department_Order_Up_To_Level-Ward_or__Department_Stock)/dt)
    ELSE(0)
⌾   Ward_or_Department__Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Rview?
⌾   NHS_LA__Delivery_Rate = Ward_or_Department__Order_Rate


{ RUNTIME EQUATIONS }
▢   Ward_or__Department_Stock(t) = Ward_or__Department_Stock(t- dt) + (NHS_LA_Delivery__Completion_Rate -
    Consumption__Rate) * dt
▥   On_Transport__From_NHS_LA_To__Ward_or_Department(t) = On_Transport__From_NHS_LA_To__Ward_or_Department(t- dt) +
    (NHS_LA__Delivery_Rate - NHS_LA_Delivery__Completion_Rate) * dt
⌾   NHS_LA_Delivery__Completion_Rate = CONVEYOR OUTFLOW
    TRANSIT TIME = NHS_LA_To__Ward_or_Department__Average_Transit_Time
⌾   Consumption__Rate = Average__Demand
O   Ward_or_Department_Order_Up_To_Level = 20*Average__Demand
O   Ward_or_Department__Reorder_Level = 10*Average__Demand
O   When_to_Order?_How_Much_to_Order?_How_Often_to_Rview? = IF(COUNTER(1,1+Ward_or_Department__Review_Period)=1)

    AND((Ward_or__Department_Stock+On_Transport__From_NHS_LA_To__Ward_or_Department)<=Ward_or_Department__Reorder
    _Level)
    THEN((Ward_or_Department_Order_Up_To_Level-Ward_or__Department_Stock)/dt)
    ELSE(0)
⌾   Ward_or_Department__Order_Rate = When_to_Order?_How_Much_to_Order?_How_Often_to_Rview?
⌾   NHS_LA__Delivery_Rate = Ward_or_Department__Order_Rate
```

Appendix I: Simulation Results of Redesigning the DRI Logistics System

The aim of this Appendix is to provide a detailed discussion of the simulation results of redesigning the DRI logistics (section 4.4.5 in Chapter Four). This Appendix contains two sections. The aim of the first section is to investigate how average stock, number of orders, and inventory cost change when changing *Average Demand* and *Item Unit Cost* for each operating strategy. The aim of the second section is to compare all operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for each *Average Demand*.

I.1   Average stock, number of orders, and inventory cost for each operating strategy

Figure I.1 to Figure I.3 illustrate how average stock, number of orders, and inventory cost vary when changing *Average Demand* and *Item Unit Cost* as given in Figure I.8 for the following operating strategies: "current situation", (R,s,S), and CR(IOBPCS). A cumulative and comparative impact of these behaviours is discussed subsequently.

- **Average stock behaviour:**

    a) **Changing *Average Demand*:**

    As shown in Figure I.1 (a) & (b) for the "current situation" operating strategy, average stock is a function of *Average Demand*, such that average stock increases linearly when increasing *Average Demand*. This is because average stock depends on the values of reorder level and order-up-to level, where the equations of reorder level and order-up-to level (see Table 4.6) are linear functions of *Average Demand*.
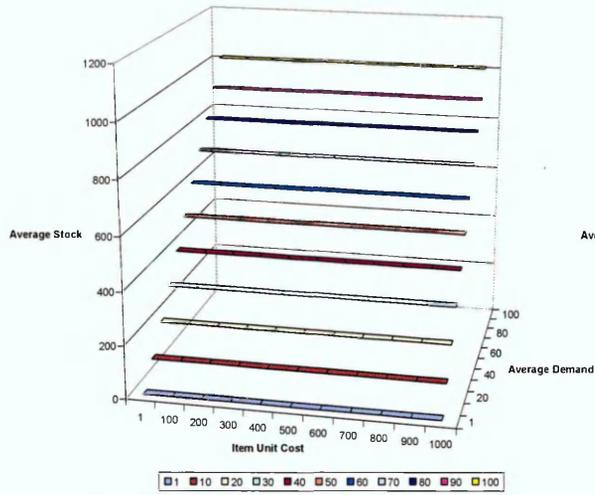
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)

(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)

(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)

(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)

(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 1: Average stock, number of orders, and inventory cost for the "current situation" operating strategy
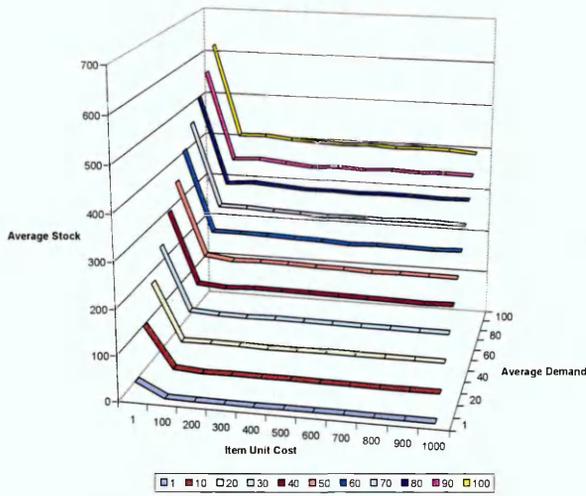
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
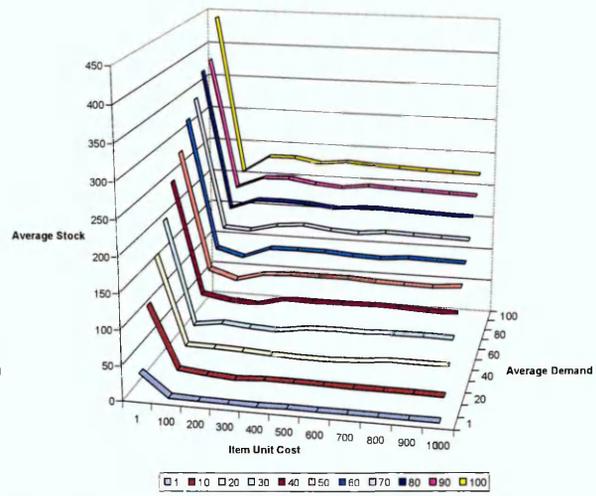
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)
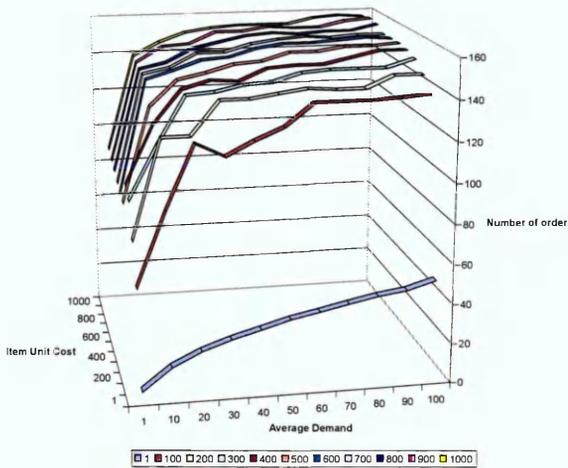
(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
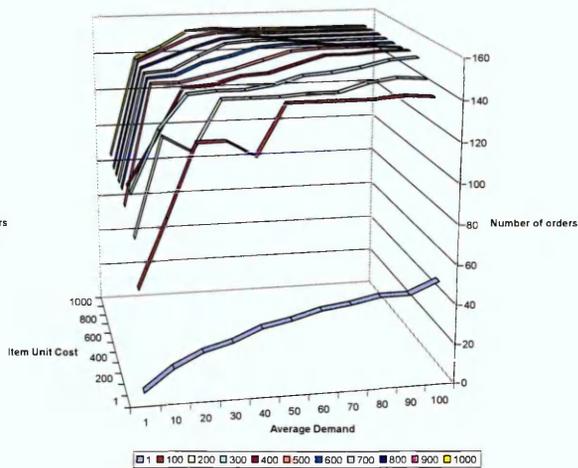
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
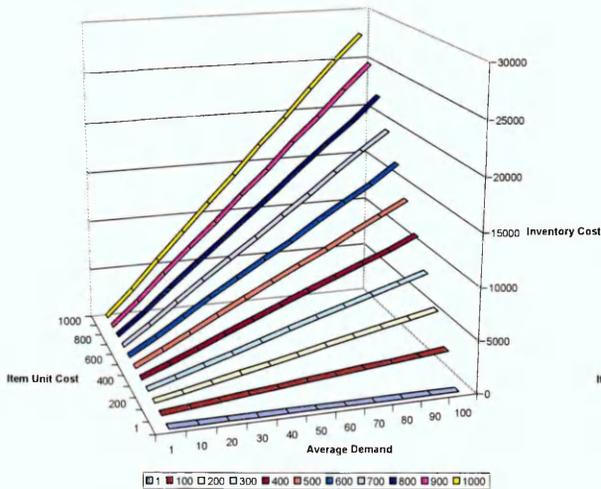
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
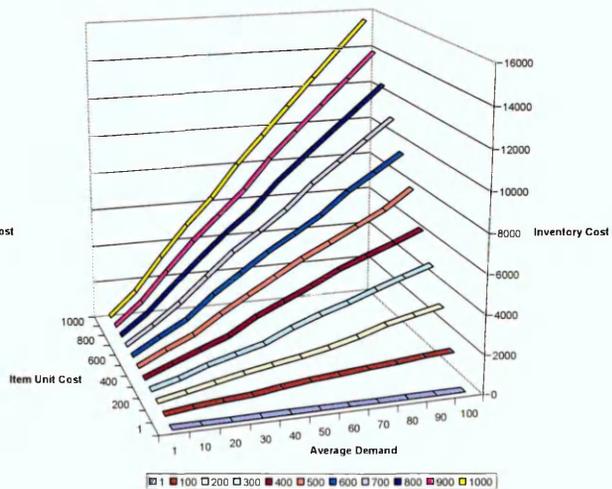
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 2: Average stock, number of orders, and inventory cost for the (R,s,S) operating strategy
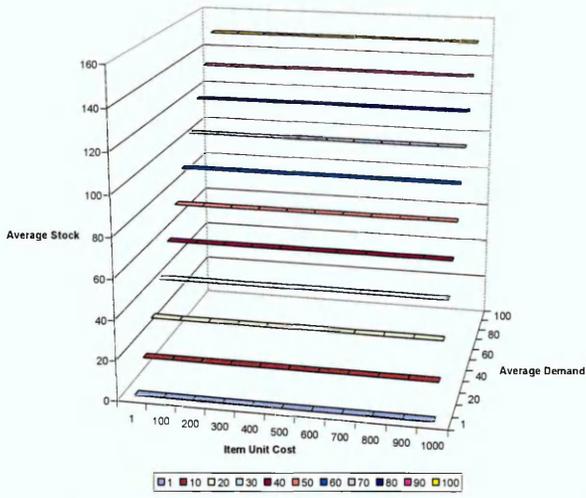
(a) Average stock (σ_D = (1/3)(*Average Demand*))
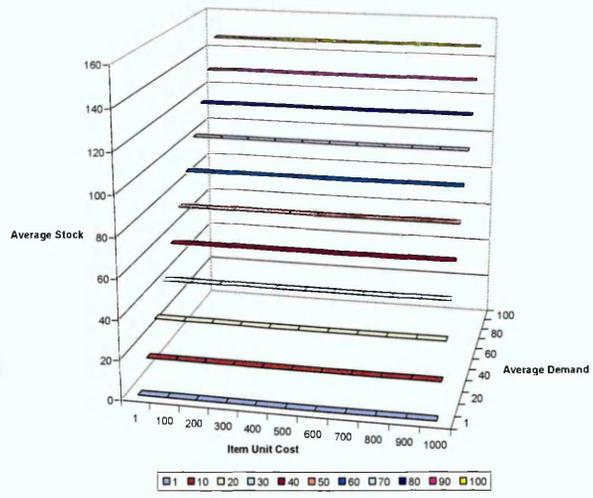
(b) Average stock (σ_D = (1/30)(*Average Demand*))
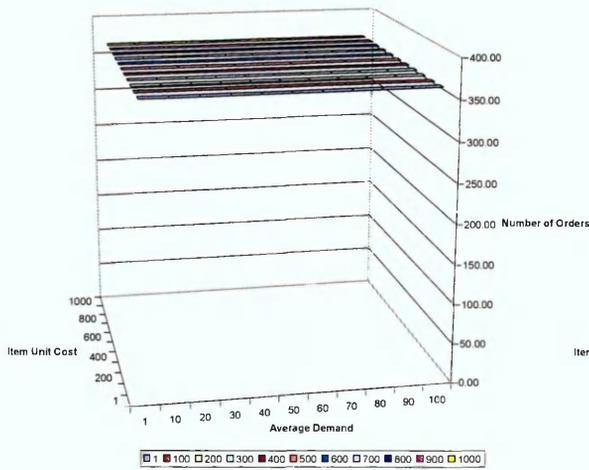
(c) Number of orders (σ_D = (1/3)(*Average Demand*))
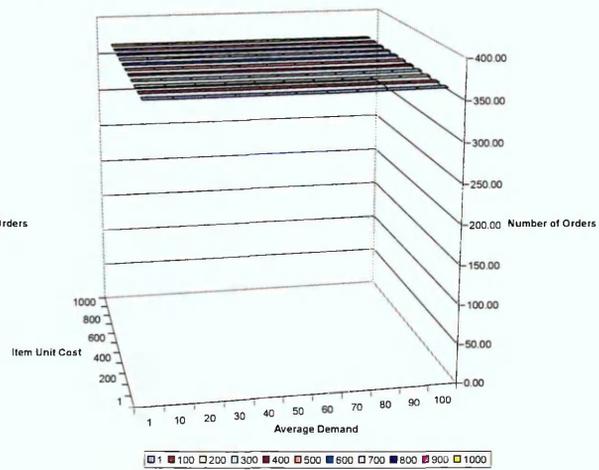
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
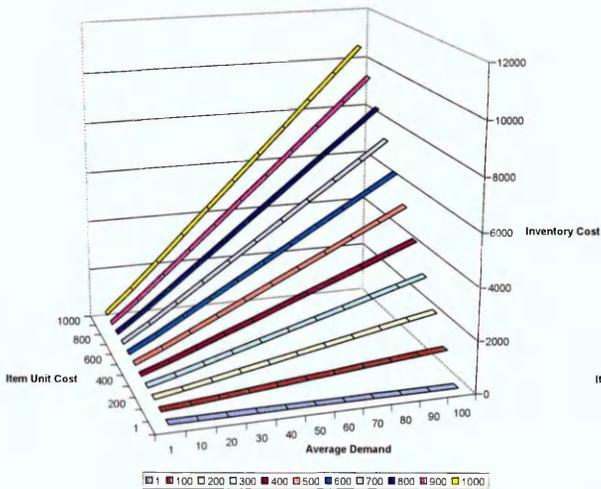
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
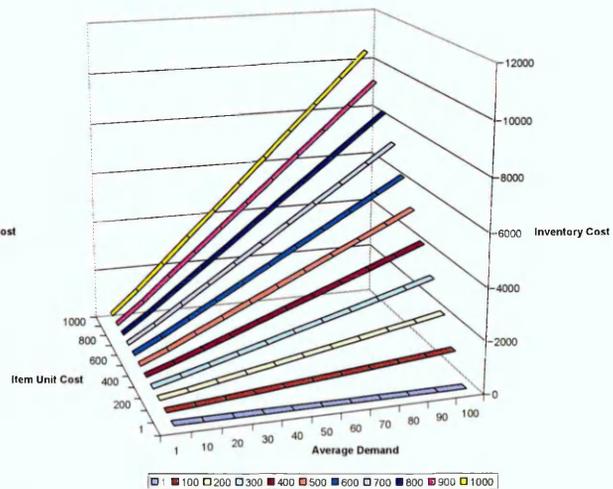
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure I. 3: Average stock, number of orders, and inventory cost for the CR(IOBPCS) operating strategy

As shown in Figure I.2 (a) & (b) for the *(R,s,S)* operating strategy, average stock is a function of *Average Demand*, such that average stock increases as an S-shaped growth when increasing *Average Demand*. This is because average stock depends on the values of reorder level and order-up-to level, where the equation of order-up-to level (see Table 3.1) contains a square-root function of *Average Demand*.

As shown in Figure I.3 (a) & (b) for the CR(IOBPCS) operating strategy, average stock is a function of *Average Demand*, such that average stock increases linearly when increasing *Average Demand*. This is because average stock depends on the value of target level; where the equation of target level (see Table 3.4) is a linear function of *Average Demand*.

b) Changing *Item Unit Cost*:

As shown in Figure I.1 (a) & (b) for the "current situation" operating strategy, average stock is not a function of *Item Unit Cost*, such that average stock stays constant when increasing *Item Unit Cost*. This is because average stock depends on the values of reorder level and order-up-to level, where *Item Unit Cost* is not a variable in the equations of reorder level and order-up-to level (see Table 4.6).

As shown in Figure I.2 (a) & (b) for the *(R,s,S)* operating strategy, average stock is a function of *Item Unit Cost*, such that average stock decreases as a goal-seeking exponential decay when increasing *Item Unit Cost*. This is because average stock depends on the values of reorder level and order-up-to level; where the equation of order-up-to level (see Table 3.1) contains a square-root function of the inverse of *Item Unit Cost*.

As shown in Figure I.3 (a) & (b) for the CR(IOBPCS) operating strategy, average stock is not a function of *Item Unit Cost*, such that average stock stay constant when increasing *Item Unit Cost*. This is because average stock depends on the value of target level, where *Item Unit Cost* is not a variable in the equation of target level (see Table 3.4).

- **Number of orders behaviour:**

a) **Changing** *Average Demand*:

As shown in Figure I.1 (c) & (d) for the "current situation" operating strategy, number of orders is not a function of *Average Demand*. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where the equations of consumption, reorder level and order-up-to level (see Table 4.6) are linear functions of *Average Demand*, whereas review period is constant.

As shown in Figure I.2 (c) & (d) for the *(R,s,S)* operating strategy, number of orders is a function of *Average Demand*, such that number of orders follows an S-shaped curve with increasing *Average Demand*. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where the equation of order-up-to level includes a square-root function of *Average Demand*, and the equation of review period contains a square-root function of the inverse of *Average Demand* (see Table 3.1).

As shown in Figure I.3 (c) & (d) for the CR(IOBPCS) operating strategy, number of orders is not a function of *Average Demand*. This is because number of orders is constant (i.e. ordering is done each period *t* (see Table3.4)).

b) **Changing** *Item Unit Cost*:

As shown in Figure I.1 (c) & (d) for the "current situation" operating strategy, number of orders is not a function of *Item Unit Cost*. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where *Item Unit Cost* is not a variable in the equations of reorder level and order-up-to level (see Table 4.6), whereas, review period is constant.

As shown in Figure I.2 (c) & (d) for the (R,s,S) operating strategy, number of orders is a function of *Item Unit Cost*, such that number of orders follows an S-shaped curve with increasing *Item Unit Cost*. This is because number of orders depends on the inverse value of (order-up-to level minus reorder level), on the inverse value of review period, and on consumption, where both the equation of order-up-to level and the equation of review period contains a square-root function of the inverse of *Item Unit Cost* (see Table 3.1).

As shown in Figure I.3 (c) & (d) for the CR(IOBPCS) operating strategy, number of orders is not a function of *Item Unit Cost*. This is because number of orders is constant (i.e. ordering is done each period t (see Table 3.4)).

- **Inventory cost behaviour:**

a) **Changing *Average Demand*:**

For all operating strategies as shown in Figure I.1 (e) & (f) for the "current situation" operating strategy, Figure I.2 (e) & (f) for the (R,s,S) operating strategy, Figure I.3 (e) & (f) for the CR(IOBPCS) operating strategy, inventory cost is a function of *Average Demand*, such that inventory cost increases linearly when increasing *Average Demand*. This is because the effect of *Average Demand* on inventory cost combines the effects of *Average Demand* on both average stock and number of orders according to the inventory cost equation (see section 4.3.5).

b) **Changing *Item Unit Cost*:**

For all operating strategies as shown in Figure I.1 (e) & (f) for the "current situation" operating strategy, Figure I.2 (e) & (f) for the (R,s,S) operating strategy, Figure I.3 (e) & (f) for the CR(IOBPCS) operating strategy, inventory cost is a function of *Item Unit Cost*, such that inventory cost increases linearly when increasing *Item Unit Cost*. This is because the effect of *Item Unit Cost* on inventory cost combines the effects of *Item Unit Cost* on both average stock and number of orders according to the inventory cost equation (see section 4.3.5).

## I.2 Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost

Figure I.4 to Figure I.14 compare the three operating strategies in terms of average stock, number of orders, and inventory cost when changing *Item Unit Cost* for the following values of *Average Demand*, respectively: 1 item/day, 10 items/day, 20 items/day, 30 items/day, 40 items/day, 50 items/day, 60 items/day, 70 items/day, 80 items/day, 90 items/day, and 100 items/day. Discussion of the Figures is provided subsequently.

- **Average stock comparison:**

  For all items (except items with low *Average Demand* and very low *Item Unit Cost*) as shown in Figure I.4 (a) & (b) to Figure I.14 (a) & (b), average stock is the highest when using the "current situation" operating strategy. However, for items with low *Average Demand* and very low *Item Unit Cost*, average stock is the highest when using the (*R,s,S*) operating strategy. While for all items, average stock is the lowest when using the CR(IOBPCS) operating strategy.

- **Number of orders comparison:**

  For all items as shown in Figure I.4 (c) & (d) to Figure I.14 (c) & (d), number of orders is the highest when using the CR(IOBPCS) operating strategy, whereas for all items (except items with low *Average Demand* and very low *Item Unit Cost*) number of orders is the lowest when using the "current situation" operating strategy. However, for items with low *Average Demand* and very low *Item Unit Cost*, number of orders is the lowest when using the (*R,s,S*) operating strategy.
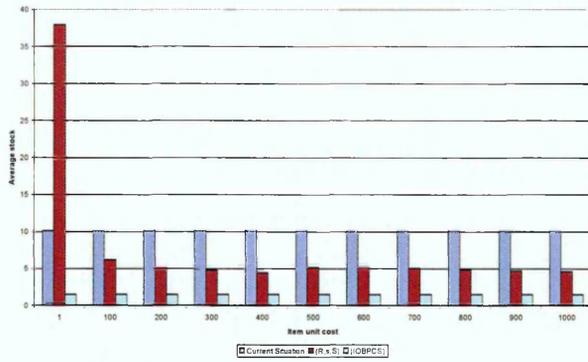
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
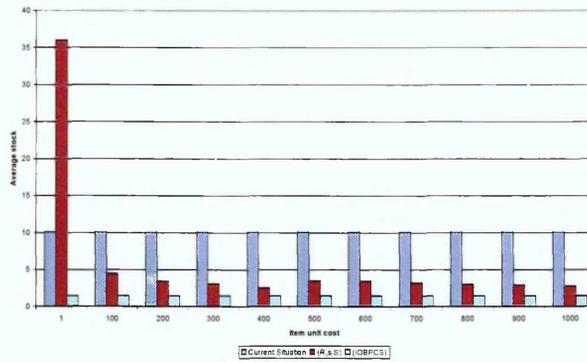

(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)
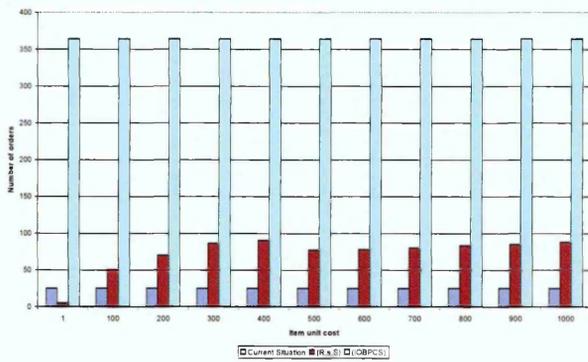
(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)

(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
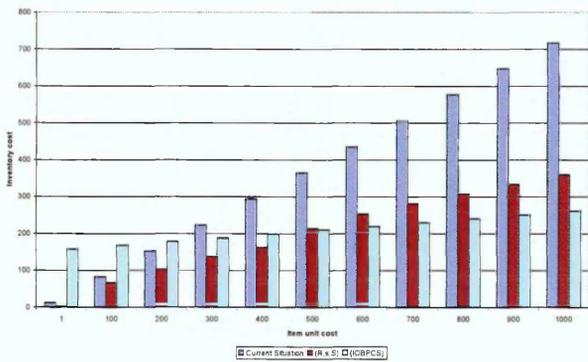


(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
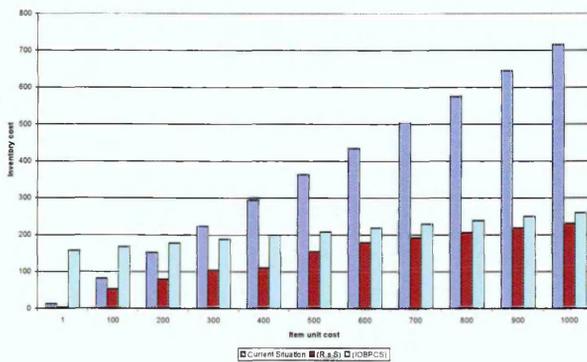
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 4: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 1 item/day
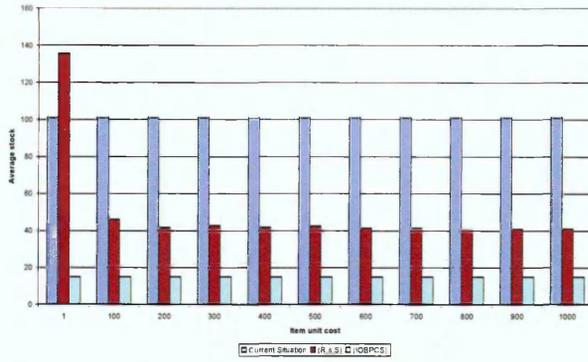
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
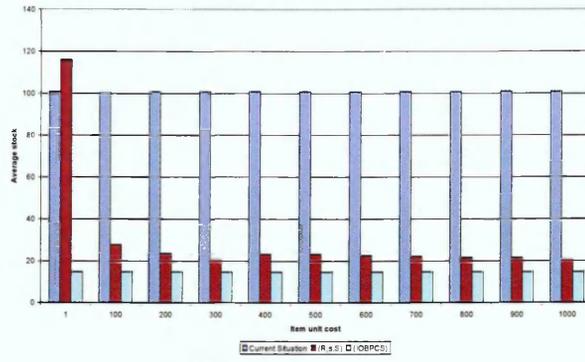
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)
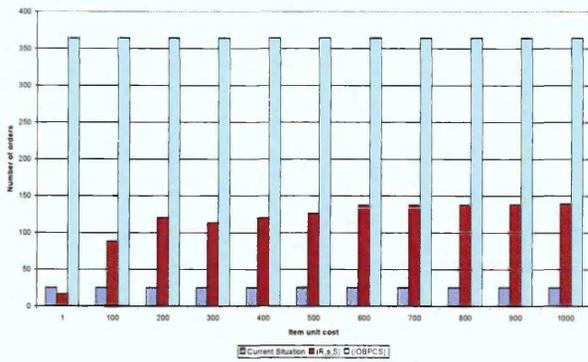
(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
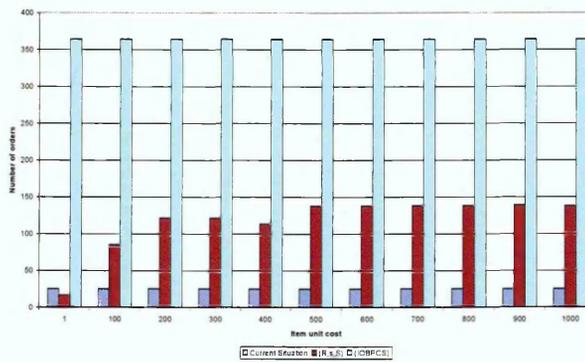
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
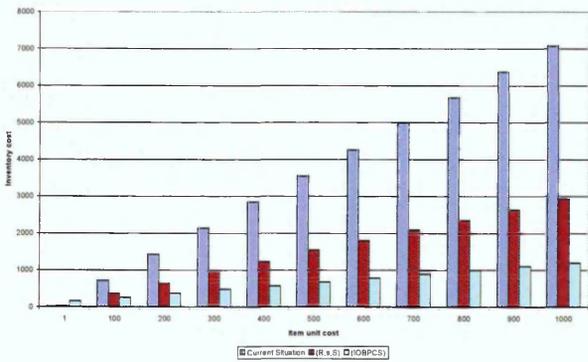


(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
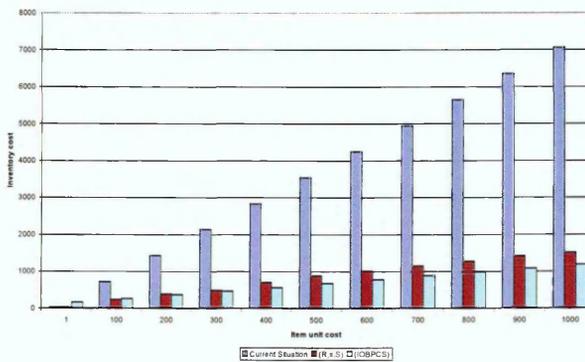
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 5: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 10 item/day
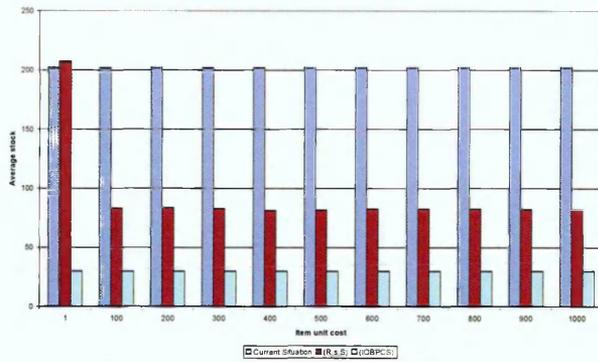
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
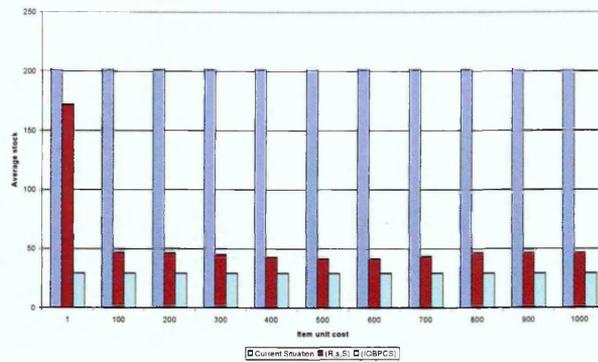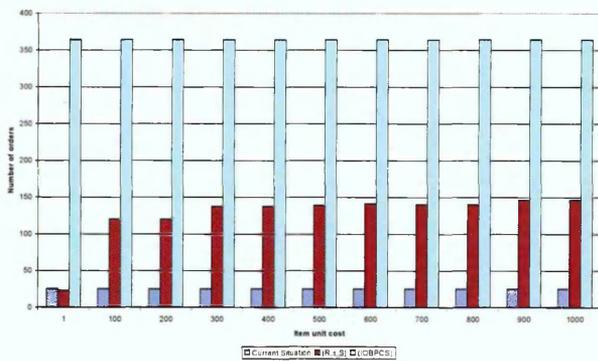
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
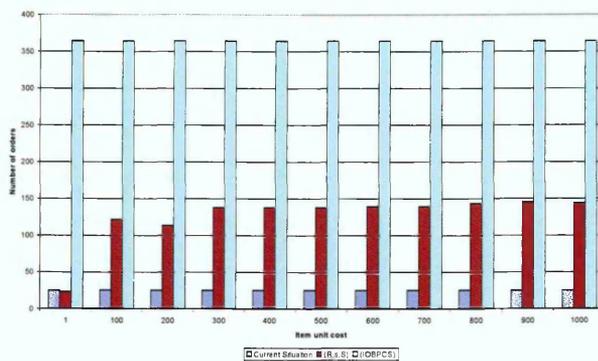
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
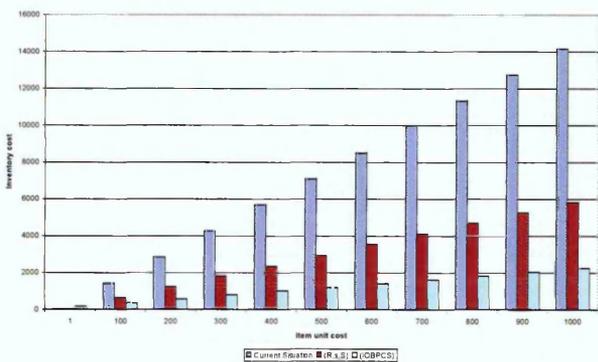
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
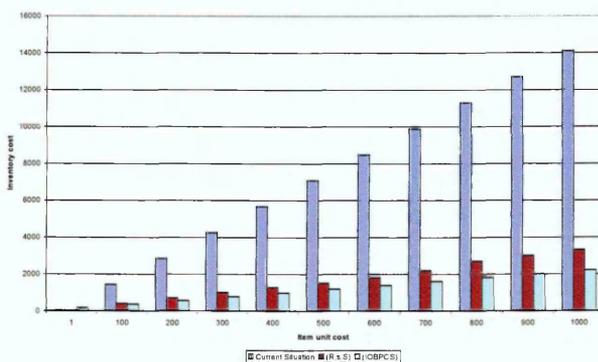
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 6: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 20 item/day
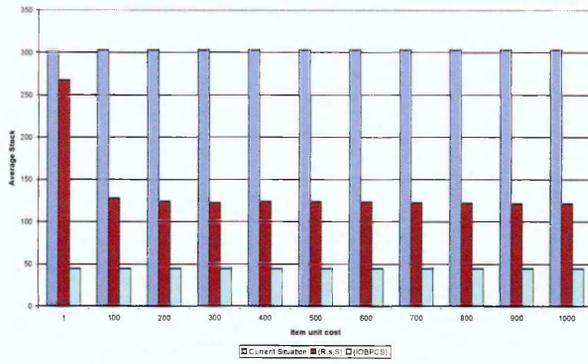
(a) Average stock (σ_D = (1/3)(*Average Demand*))
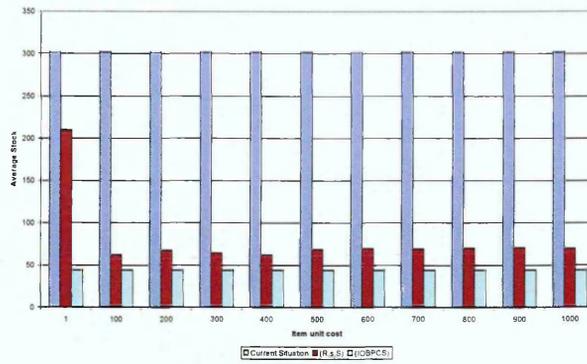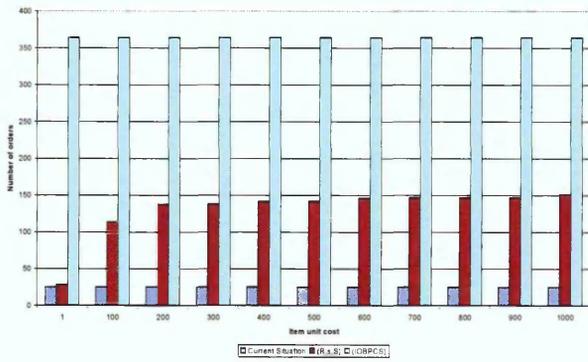
(b) Average stock (σ_D = (1/30)(*Average Demand*))

(c) Number of orders (σ_D = (1/3)(*Average Demand*))
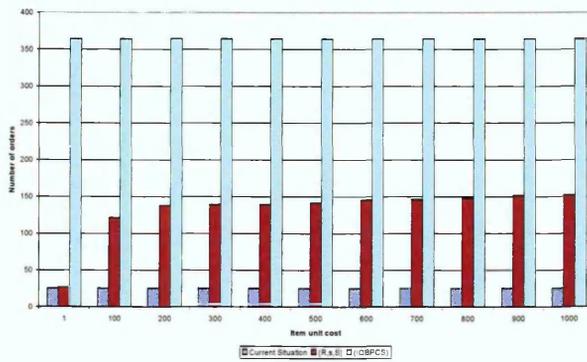
(d) Number of orders (σ_D = (1/30)(*Average Demand*))
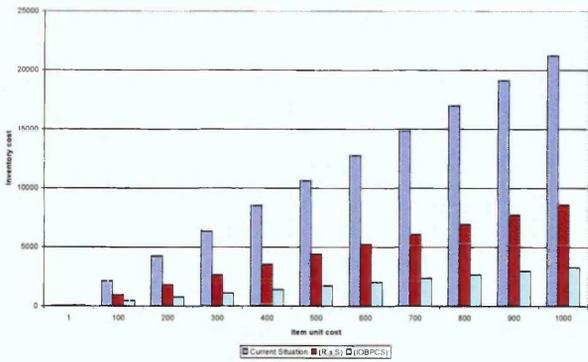
(e) Inventory cost (σ_D = (1/3)(*Average Demand*))
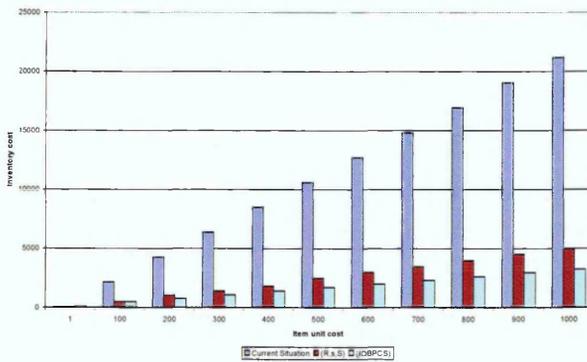
(f) Inventory cost (σ_D = (1/30)(*Average Demand*))

Figure I. 7: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 30 item/day
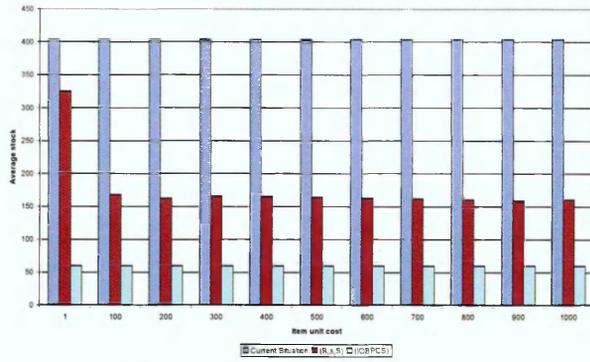
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
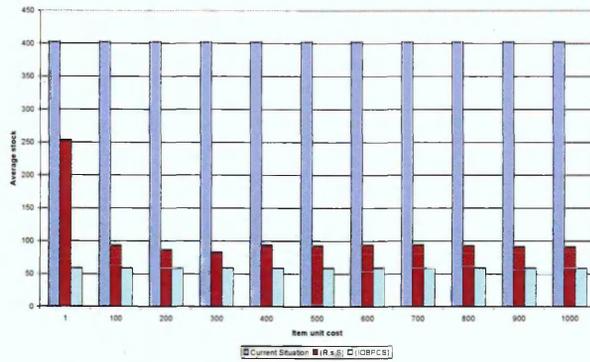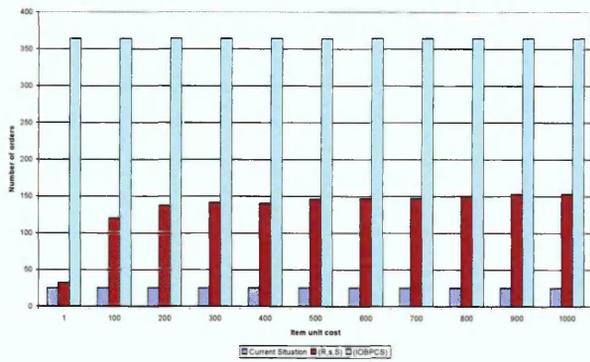
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
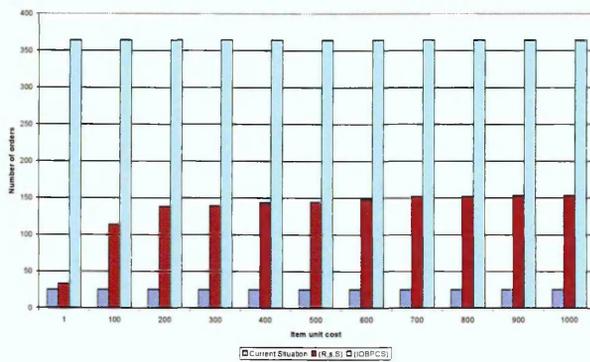
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
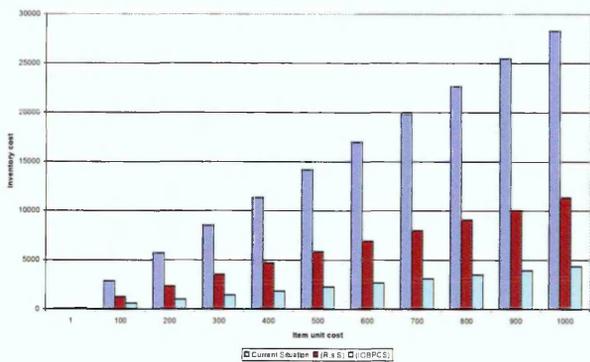
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
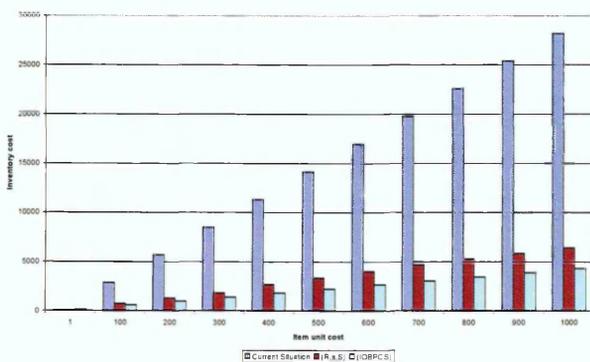
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 8: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 40 item/day
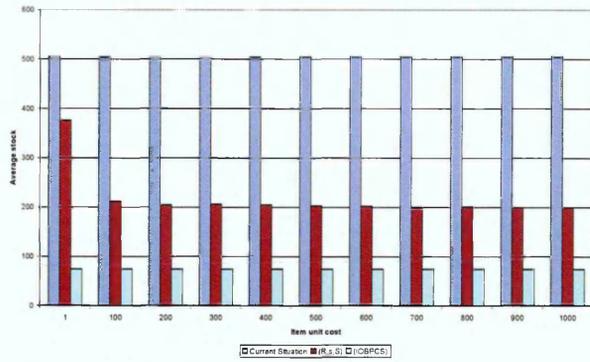
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
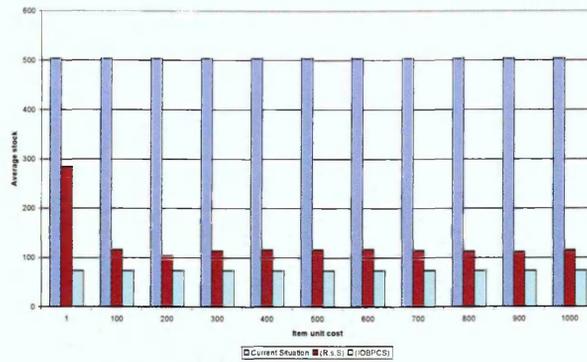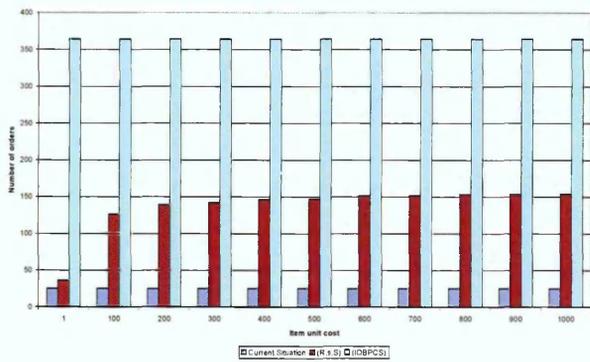
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
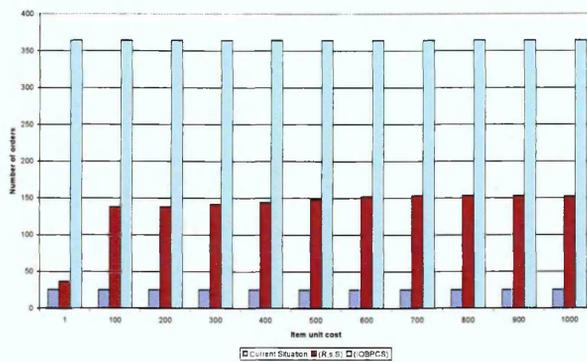
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
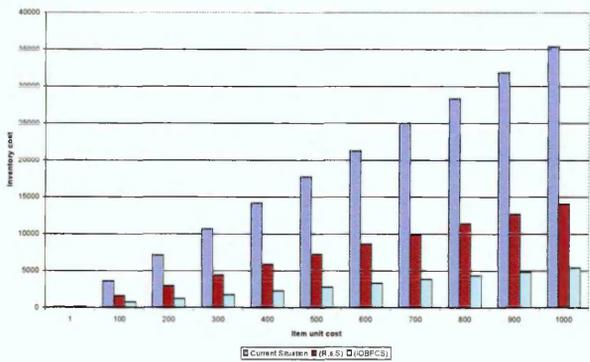
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
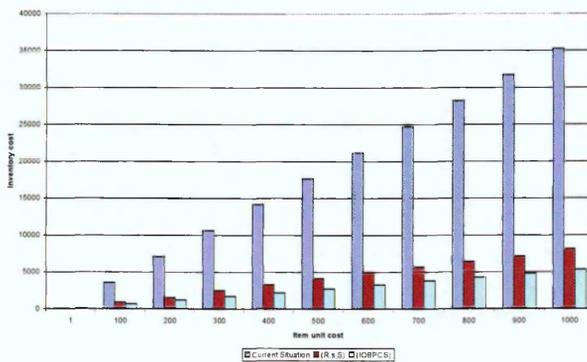
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 9: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 50 item/day
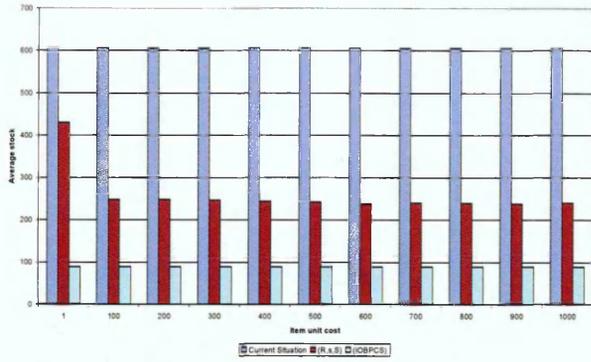
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
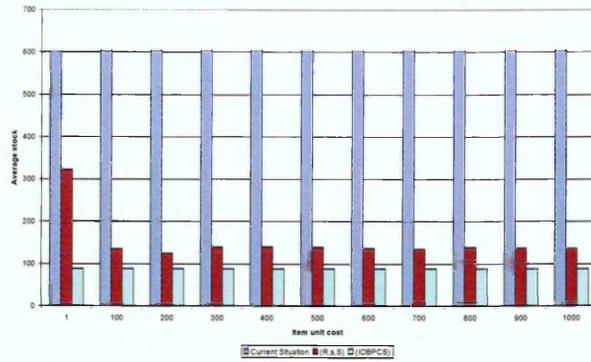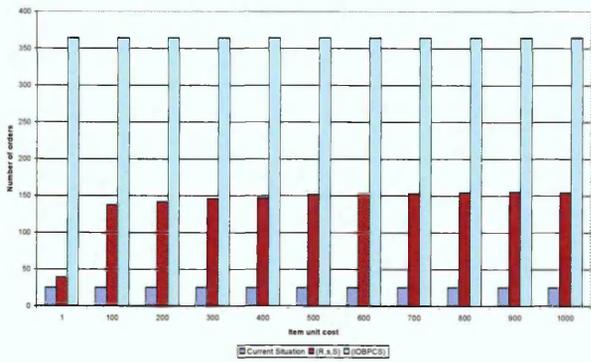
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
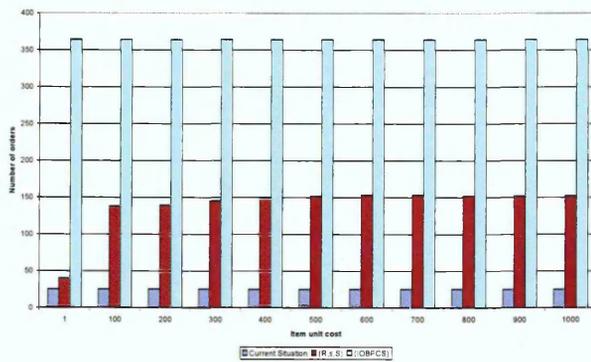
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
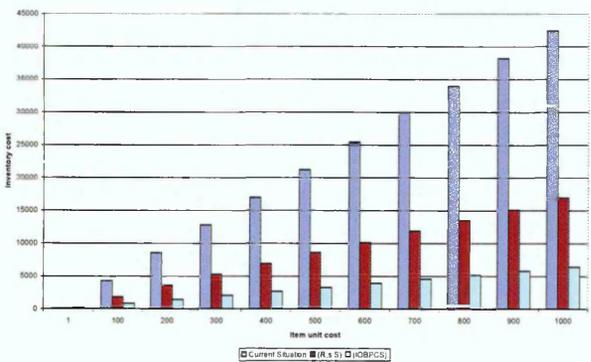
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
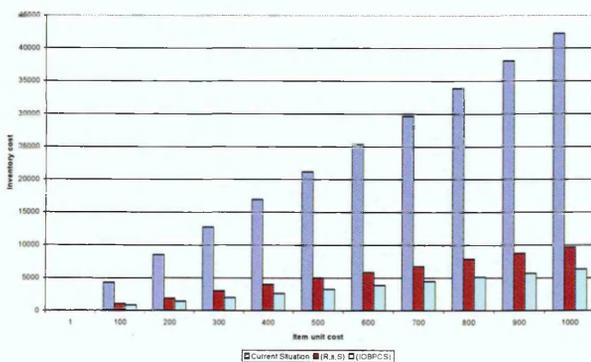
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 10: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 60 item/day
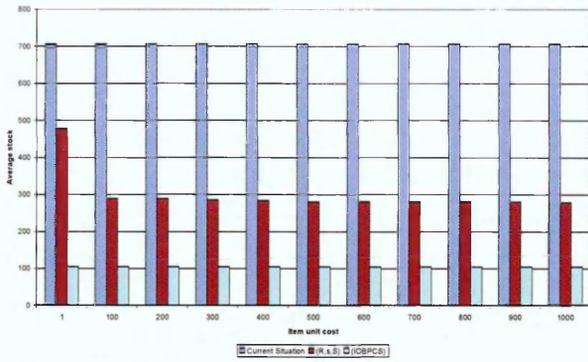
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
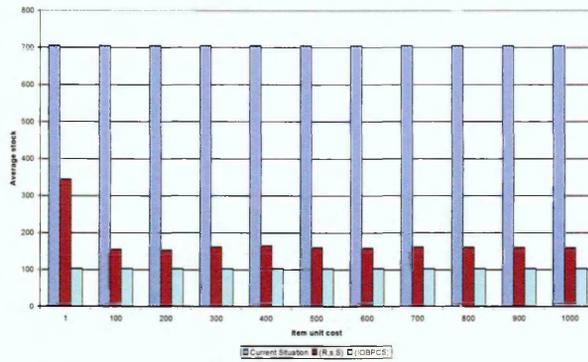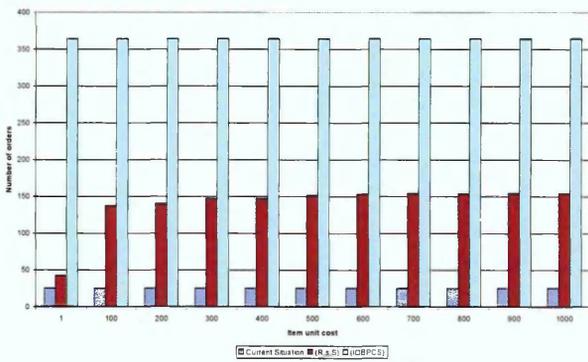
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
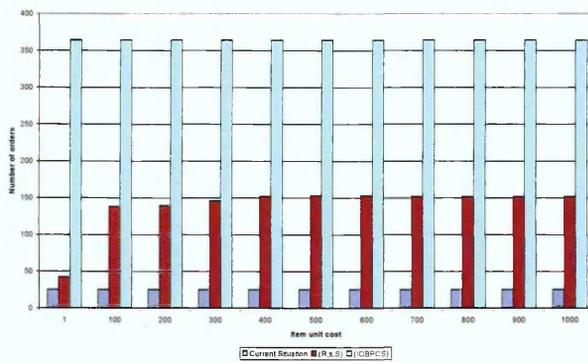
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
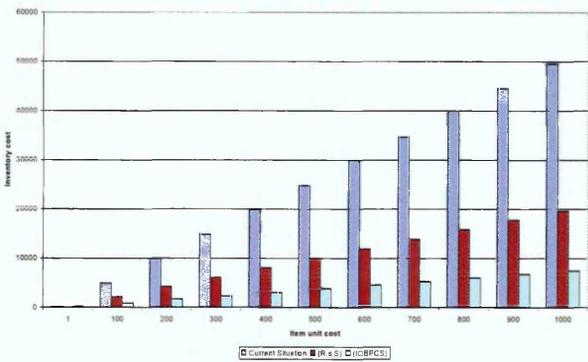
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
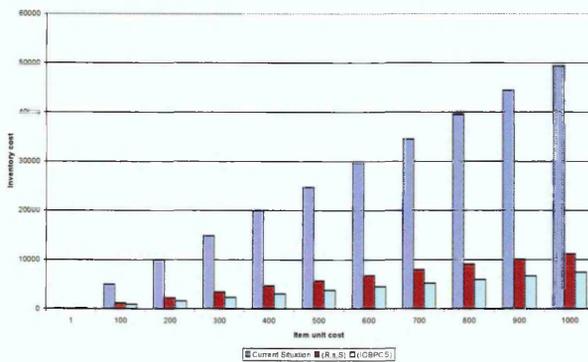
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

**Figure I. 11: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 70 item/day**
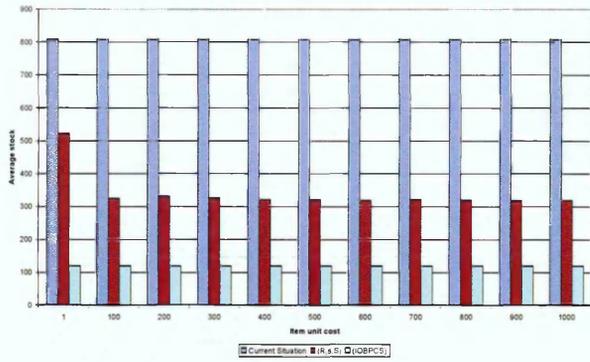
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
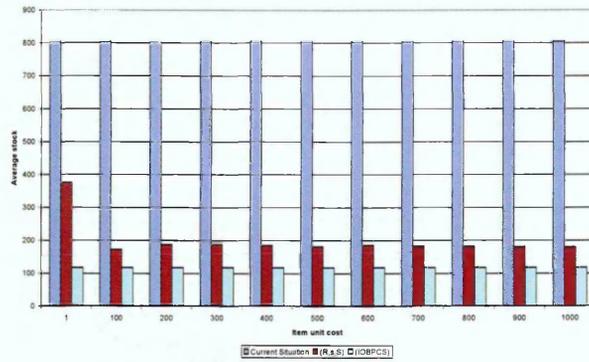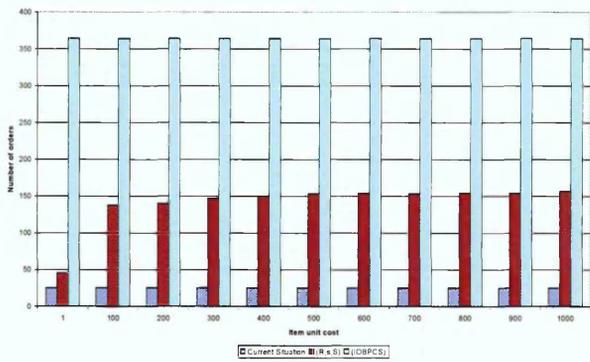
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
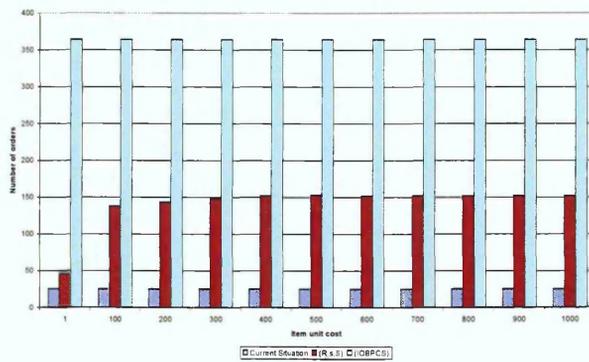
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
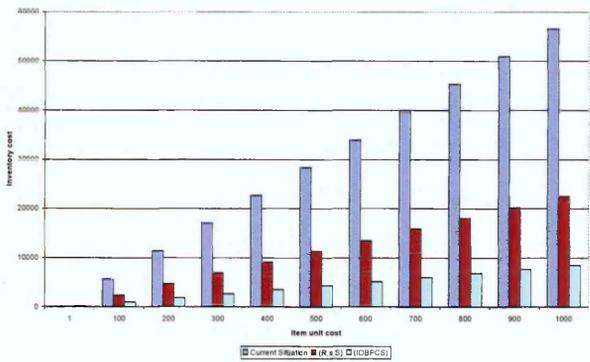
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
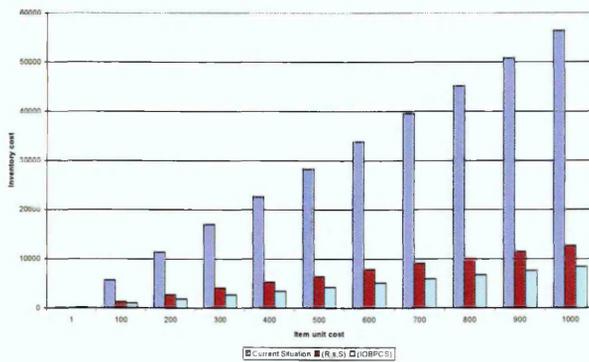
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 12: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 80 item/day
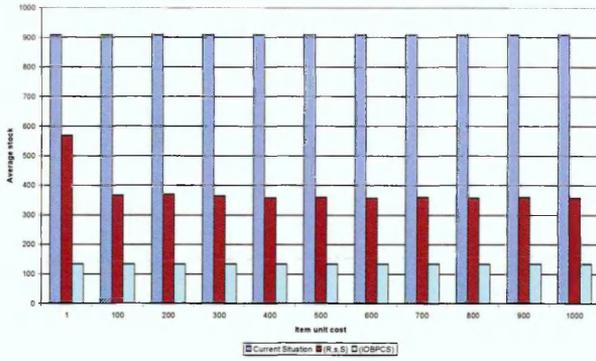
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
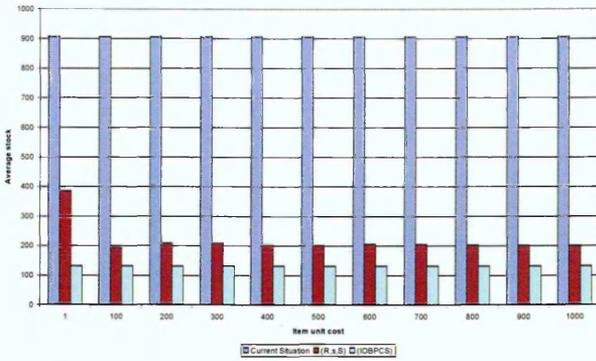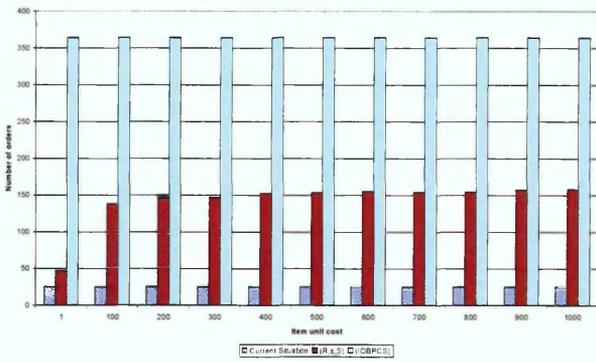
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
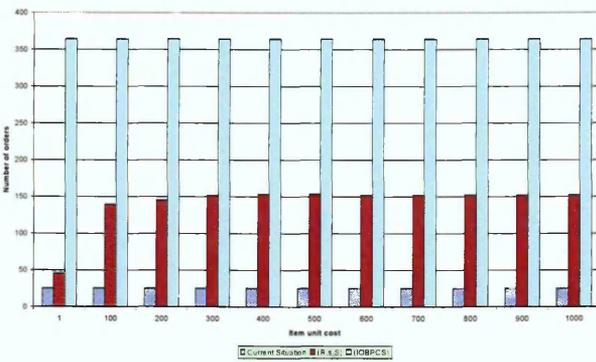
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
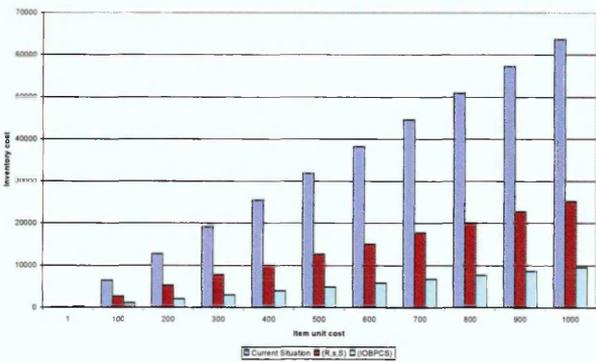
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
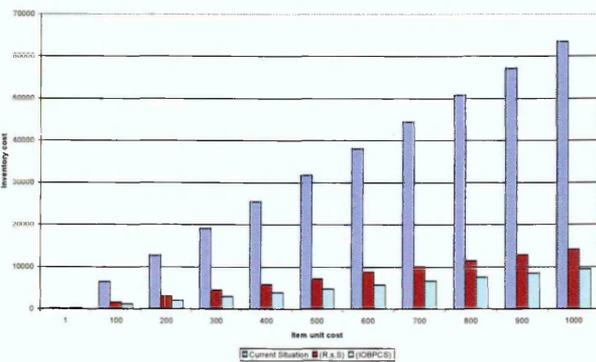
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 13: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 90 item/day
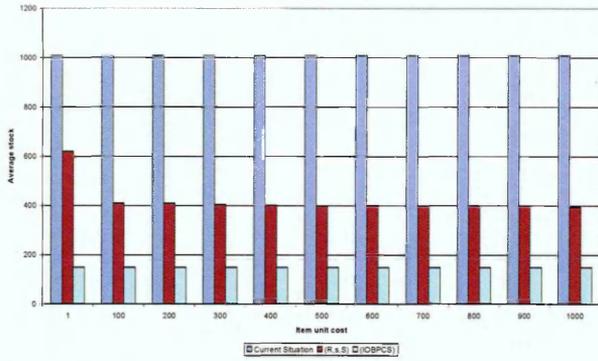
(a) Average stock ($\sigma_D = (1/3)(Average\ Demand)$)
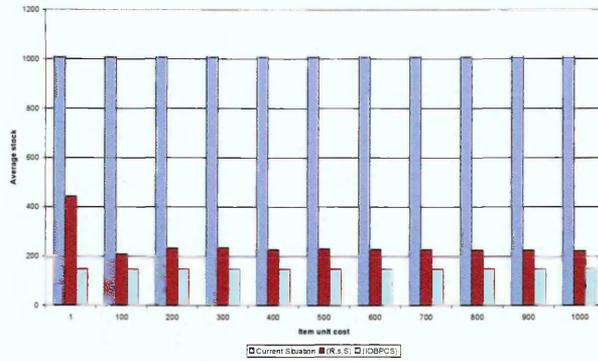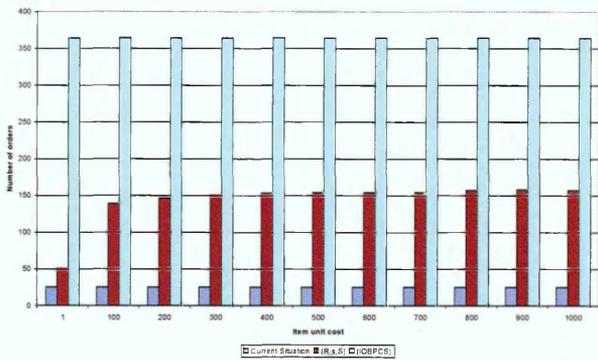
(b) Average stock ($\sigma_D = (1/30)(Average\ Demand)$)

(c) Number of orders ($\sigma_D = (1/3)(Average\ Demand)$)
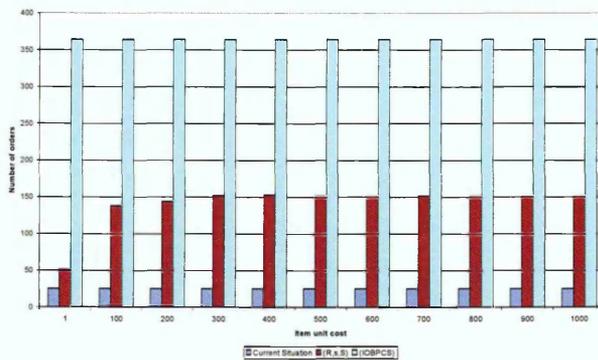
(d) Number of orders ($\sigma_D = (1/30)(Average\ Demand)$)
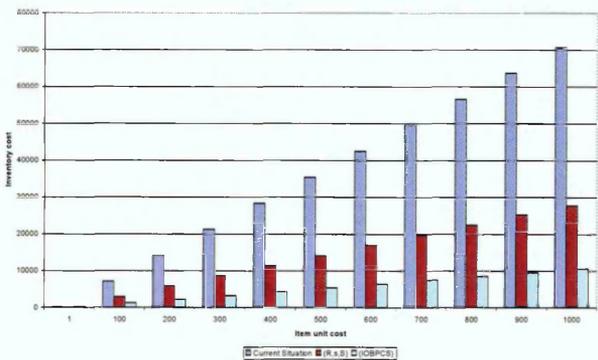
(e) Inventory cost ($\sigma_D = (1/3)(Average\ Demand)$)
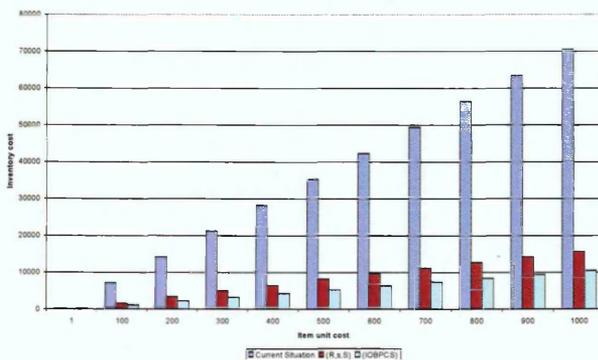
(f) Inventory cost ($\sigma_D = (1/30)(Average\ Demand)$)

Figure I. 14: Comparison of the three operating strategies in terms of average stock, number of orders, and inventory cost when *Average Demand* = 100 item/day

- **Inventory cost comparison:**

For all items (except items with very low *Average Demand* or items with very low *Item Unit Cost*) as shown in Figure I.4 (e) & (f) to Figure I.14 (e) & (f), inventory cost is the highest when using the "current situation" operating strategy and the lowest when using the CR(IOBPCS) operating strategy. However, for items with very low *Average Demand* or items with very low *Item Unit Cost*, inventory cost is the lowest when using the *(R,s,S)* operating strategy.

The above comparison results of the three operating strategies in terms of average stock, number of orders, and inventory cost is the same for (σ_D= (1/3)(*Average Demand*)) and for (σ_D= (1/30)(*Average Demand*)). σ_D= (1/3)(*Average Demand*) was chosen to represent items with high variable demand, whereas, σ_D= (1/30)(*Average Demand*) was chosen to represent items with low variable demand.