A SIMULATION STUDY OF PERFORMANCE IN A MULTI-ECHELON DISTRIBUTION SYSTEM UNDER UNCERTAINTY

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PREFACE

The objective of this research is to present a framework for classifying and describing the uncertainties that affect the performance of a multi-echelon distribution system and to determine effective policies for allocating safety stocks under various operating conditions within the system. Computer simulation programs written in FORTRAN programming language are used to model a multi-echelon distribution system which has the assumed environmental conditions and the identified experimental factors to answer the research questions in this study.

I would like to express appreciation to all who have helped to make this study possible. My great sincere gratitude and appreciation is given to my major adviser, Dr. Kenneth E. Case, for his guidance, support and encouragement throughout this research. Recognition and appreciation are extended to Dr. Chrwan-jyh Ho for his advice and assistance in the preparation of the dissertation. I am also truly thankful to Dr. Manjunath Kamath, Dr. David Pratt and Dr. Sahadeb Sarkar for serving on my committee and providing valuable comments.

I also wish to thank my parents and family for their support and encouragement throughout my study in the United States. It is wonderful to know you are proud of me no matter what. To my mother, your boundless encouragement and confidence during my undertaking this task is a reassuring tonic. To my elder sister, Hsien-Chin Meng, I would like to give special thanks for taking good care of our parents. Without her great effort and support, I would not be as calm as I was during my study. Finally, I wish to dedicate this dissertation to my family.

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CHAPTER I

INTRODUCTION

Today, our uncertain economy is facing mature markets, the globalization of industry, high energy costs, potential energy and raw material shortages, high interest rates and a low growth rate in productivity. Maintaining corporate profit growth and return on investment is becoming increasingly difficult. It has become necessary for management to investigate alternative methods of generating revenue and/or reducing costs. Few areas offer the potential for system improvements that can be found in the logistics function. This is because logistics cost can exceed 25 percent of each sales dollar in numerous business operations (LaLonde, 1990).

Two major sub-systems in logistics are materials management and physical distribution. The Council of Logistics Management (CLM) defines materials management as an interest in the movement and storage of raw materials and semifinished goods and activities surrounding movement and storage up to the point of manufacturing. Physical distribution, which concerns the movement and storage of finished goods from the end of the production line or vendors to the customer, is the subject of interest in this research.

Everyone who is involved with the physical distribution of goods is concerned with increasing the efficiency and effectiveness of the channel system. Efficient is defined as "producing the desired effect or results with a minimum of effort, expense, or waste." Effective is defined as "producing a definite or desired result" or, "effectiveness is a measure of accomplishment with objectives." To achieve efficiency and effectiveness, it is necessary to understand how the overall distribution system operates, the forces that infringe upon the system and the effects of the forces on the successful operation on the system.

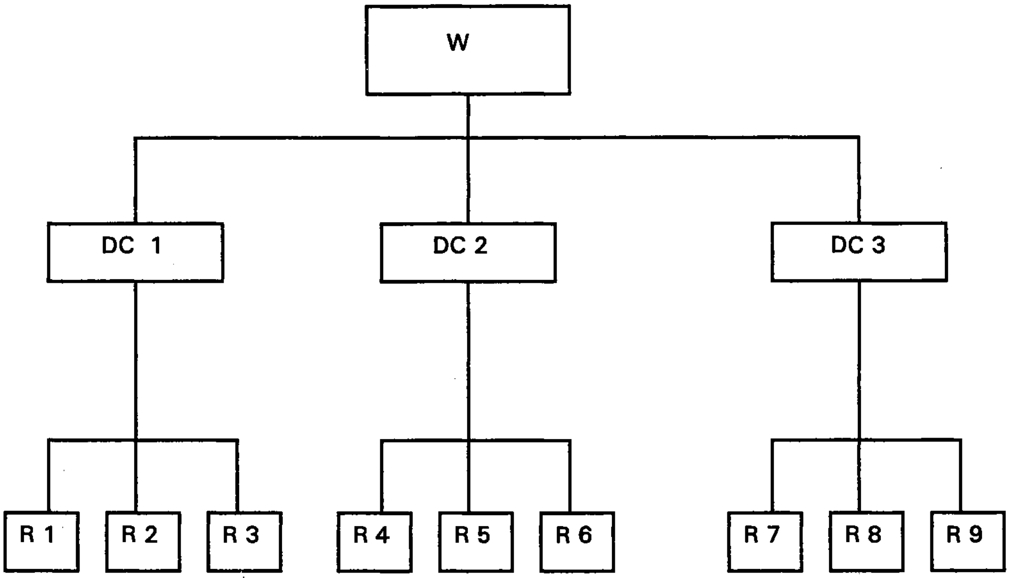
The major force that impedes understanding of the distribution system and hinders the achievement of efficient and effective operation is uncertainty. If a physical distribution system operates under conditions of certainty, then the problem of operating an efficient and effective system is easily solved. However, our world is not certain and operation of a distribution system is done with imperfect knowledge. Uncertainty is not new and it will always be with us as a simple fact in business.

Most efforts in past research to cope with uncertainty have attempted to reduce its impact, for example, more accurate sales forecasting, more effective inventory control methods, etc. However, a potentially fruitful approach to solving the same problem is to first accept that there will always be uncertainty and ask, can it be classified and described? If so, can one isolate how the various types of uncertainty affect a physical distribution system. This study attempts to answer these questions, specifically when a physical distribution system is operated under Distribution Requirement Planning (DRP).

Safety stock, defined as a quantity of stock planned to be in inventory to protect against fluctuations in demand or supply by the American Production and Inventory Control Society (APICS), is widely accepted as protection against uncertainty in a physical distribution system. While safety stock is generally considered to be necessary in the distribution system, where and how much safety stock to carry is still an open issue. Another important issue needing investigation is the performance of various safety stock policies in a multi-echelon distribution system under different operating conditions.

Multi-Echelon Distribution System

A typical example of a multi-echelon distribution system is shown in Figure 1.1. The physical flow of the system is as follows:(1) warehouse receives finished goods from factory or vendor and ships to two distribution centers, and (2) distribution centers then move the finished goods to retailers. Information flow is reversed, (1) from retailers to distribution centers, and then (2) from distribution centers to the warehouse or vendor.



W : warehouse
DC : distribution center
R : retailer

Figure 1.1 An Example of a Multi-Echelon Distribution System

The multi-echelon distribution system studied in this research has several important characteristics. Figure 1.1 shows an arborescent distribution system, which is a special type of multi-echelon distribution system. In an arborescent distribution system, the material flows from one upper echelon member directly to several lower echelon members (Clark 1972). Arborescent flow does not flow between members of the same echelon or back to an upper echelon member.

A second aspect of a multi-echelon distribution system is the means to determine the timing and quantity of flow in the system. After the development of Material Requirements Planning (MRP) in the late 1950's, the concept of working backwards from the due date of the end items to determine the time-phased requirement for component and raw materials was extended to a distribution system. This concept was developed by Whybark in 1975. DRP is used as the inventory control method in this study. DRP's logic and operation are introduced in a later section.

A third aspect of a multi-echelon distribution system is the functional relationships between channel members, assuming the system is integrated. The system must recognize the importance of sharing information and resources between channel members. In other words, the channel members intend to optimize the efficiency and effectiveness of the whole system instead of only one individual's.

A fourth aspect of a multi-echelon distribution system is that the system owns the material from initial receipt at the warehouse to final demand occurring at retailers. Therefore, the purchasing cost of material remains the same for all channel members. The only changes are in inventory cost, which are caused by added-values from transportation costs. Actual distribution systems usually have multiple items and several sources. The number of items and the number of sources do not affect the nature of the uncertainty problem, and nor do they affect the question of allocating safety stock in a multi-echelon distribution system (Allen, 1983); this study uses a multi-echelon distribution system with a single source and only one item.

A fifth aspect in a multi-echelon distribution system is the channel members involved to ship products. Different products may go through different channel members in the distribution system, they are so-called different distribution networks. For example, product A is shipped from an outside vendor to warehouse, warehouse then ships to two distribution centers, and distribution centers move the product A to retailers. Product B is shipped from an outside vendor to the warehouse, and then product B moves directly from the warehouse to the retailers. This is a so-called "distribution network change".

A sixth aspect in a multi-echelon distribution system involves the relationships between customer demand at retailers. Customer demands are assumed independent; if a customer can't satisfy the demand at retailer 1, the customer will not go to retailer 2, 3, or 4. Therefore, an unsatisfied demand is regarded as a stockout at retailer 1.

Distribution Requirement Planning -- An Overview

Distribution Requirement Planning (DRP) is widely accepted as an effective inventory control method in physical distribution systems. Whybark (1975) first notes that the dependent demand in a multi-echelon distribution system is the same as the demand in a multi-stage production system. He then applies MRP logic to manage inventories in a multi-echelon distribution system. Stenger and Cavinato (1979) formalize the ideas of Whybark into Distribution Requirement Planning. They illustrate the potential benefits through an MRP approach to distribution planning.

A well-developed DRP system helps the company to plan delivery schedules more effectively and to increase customer service levels. For example, American Hardware Supply Company, a national-wide hardware distributor, improved their productivity, profit and service levels after replacement of a reorder point system with Distribution Requirement Planning (Smith, 1985). Also, Lipton Corp. in Canada managed inventories from plants to ten distribution centers using a PC-based DRP system (Krepchin, 1989). The system helped cut inventories even while sales increased. Martin (1980, 1982) and Ford (1981) suggest the potential benefits by implementation of DRP are substantial. More enhanced DRP systems are presented by Bregman (1990) and Ho (1990, 1992). Bregman recognizes the capacity limitations of transportation resources and manages the economic trade-off between inventory costs and transportation costs. Ho proposes a generalized DRP system for delivery scheduling in a multi-sourcing distribution system.

DRP derives from MRP logic and principles in similar environments to deal with delivery scheduling and inventory control problems in a multi-echelon distribution system. Orlicky (1975) explains the main objective of MRP is to provide the right part at the right time to meet the schedules for completed products. MRP makes it possible by constructing a time-phased requirement record for any part number. MRP data then also are used as input to the detailed capacity planning model. The logic of MRP is explained by a basic MRP record, which is shown in Table 1.1. There are three inputs to an MRP record: (1) a master production schedule (MPS), (2) a bill of material (BOM) for each part number, and (3) an inventory status record for each item. An MRP system explodes the MPS, using a bill of materials, into the lower level requirements needed to support the MPS. Net requirements are then obtaining by offsetting on-hand inventory and scheduled receipts. A lot-sizing rule is then applied to these time-phased net requirements. Finally, the order release dates are determined by offsetting lead time.

Table 1.1 A Basic MRP Record

Lead time : 1 period
Lot size : 50

Period		1	2	3	4	5
Gross requirements			10		40	10
Scheduled Receipts		50				
On-hand	4	54	44	44	4	44
Planned order releases					50	

DRP is a management process that determines the needs of inventory stocking locations and ensures that supply sources are able to meet the demand (Martin, 1993). Like MRP, there are three major inputs for a DRP system: (1) the time-phased replenishment requirements from retailers, (2) the inventory records at all channel members, and (3) the "bill of materials" type of distribution network structure. The data elements in a DRP system are detailed records for individual products at specific locations. A DRP record is shown in Table 1.2, which is a retailer DRP record. The record look likes an MRP record. It keeps the same format and processing logic as an MRP system to integrate a logistic system. The first row in the DRP record is the forecast requirements from customers. The equivalent row in the MRP record is called "gross requirements". The second row shows shipments in-transit to the retailer; it is equivalent to "scheduled receipts" in the MRP record. The third row shows the projected available balance that is calculated by using the forecast requirement and in-transit rows. The logic is the same as calculating on-hand inventory in an MRP record. The last row is planned shipments, which indicates when a shipment has to be made to avoid a stockout. For example, the projected balance for period 4 is 25 units, but the forecast requirement for period 5 is 30 units. Therefore, a shipment of product must be available in period 5. A planned shipment of 60 units is released in period 3, because it takes 2 periods to process the order. The equivalent row in the MRP record is called a "planned order release".

Table 1.2 DRP Record for Retailer

Period		1	2	3	4	5
Forecast requirements		20	20	20	20	30
In-transit			60			
Projected available balance	45	25	65	45	25	55
Planned shipments				60		

Safety stock = 20; shipping quantity = 60; lead time = 2.

Types of Uncertainty Affecting a Multi-Echelon Distribution System

Bowersox (1974) classifies uncertainty in a physical distribution system as demand uncertainty and lead time uncertainty. Demand is defined as a request by the ultimate consumer made upon the system to deliver a product or service. It is uncertain as to when demand occurs and how much is demanded. Lead time is defined as the amount of time between placing an order and receipt of that order. More specifically, it is broken down into three components: (1) order communication, (2) order processing , and (3) transportation. Each of these components represents a source of uncertainty. It is not known with certainty the overall time from order placement to receipt of the order. Allen (1983) categorizes uncertainty in a multi-echelon distribution system into: (1) customer demand, (2) system resupply, and (3) central to field shipment.

In summary, there are three major sources of uncertainty in a multi-echelon distribution system: (1) uncertainty in customer demand, (2) uncertainty in supply, and (3) uncertainty in order processing. Uncertainty in each source is timing uncertainty or/and quantity uncertainty. Although the actual distribution system experiences all types of uncertainty, this study focuses on quantity uncertainty of customer demand, quantity uncertainty of supply, and timing uncertainty in order processing.

Suggested Buffering Methods to Solve Uncertainty

This paper is concerned with the problem of effective management of a multi-echelon distribution system under uncertainty. Several alternatives are available to protect the physical distribution system against uncertainty. One approach is to use buffering methods. These suggested buffering methods use "slack" to protect the system against uncertainty. Two important types of "slacks" are safety stock and safety lead time.

Safety stock is the method to solve uncertainty by putting more inventory at channel members in the distribution system. Although the inventory investment is increased, this cost is justified by improving service level, or reducing total related cost of the system. Regarding safety lead time, the principle is to bring materials into stock before the requirement indicates a planned need for them. For example, if the safety lead time is one period, the planned shipments should be released one period ahead, so the order is received one period before the normal schedule.

The Research Question

The purpose of this study is to present a framework for classifying and describing the uncertainties that can affect the performance of a multi-echelon distribution system, and then to determine effective polices for allocating safety stocks within a multi-echelon distribution system. Current literature has partially addressed these problems, but does not provided detailed cross comparison of various types of uncertainties. No previous work has evaluated the performance of various safety stock policies in a multi-echelon distribution system operated by DRP.

The research questions asked include:

(1) Can demand uncertainty, supply uncertainty, and order processing uncertainty be described and classified and, if so, how will each affect the performance of a multi-echelon distribution system?

(2) What are the main effects of various types of uncertainties and interactions among different performance measures, including total related cost(TRC), customer service level, average stockout units, and average inventory level?

(3) What are the best ways to allocate safety stocks at distribution channel members under different operating conditions?

Importance of the Research

The answers to the research questions have theoretical and practical value. Few studies have been performed to discuss the uncertainty problem in a multi-echelon distribution system. The studies that have been performed restrict their investigation to a single type of uncertainty (Brown, Lusch and Koenig, 1984, Speh, 1974, and Wagenheim, 1974). They do not address multiple types of uncertainties, nor do they consider the possible impact of interaction on the multi-echelon distribution system, where various types of uncertainties are considered at the same time. This study is an exploratory work to consider the impacts from three different types of uncertainties on a the performance of a multi-echelon distribution system. The results of this study will provide a guideline about the nature of various types of uncertainties existing in a multi-echelon distribution system or even outside the system.

Another important task in this study is to compare the performances of various safety stock policies in a multi-echelon distribution system under different operating conditions. Most of the efforts in past research related to the safety stock problem in a multi-echelon distribution system are based on a reorder point system or other inventory control method. This study is a pilot study to find a more effective safety stock policy in a multi-echelon distribution system under DRP's operation. The results can give practitioners a rule about positioning safety stocks in a multi-echelon distribution system. To academicians, the results offer an opportunity to clarify some of the theoretical uncertainty about inventory control policies in a multi-echelon distribution system, and to compare the results from MRP's research.

Research Objectives

The primary objectives of this research are listed as follows.

(1) To provide insights into the behavior and operation of a multi-echelon distribution system under three sources of uncertainties.

(2) To give a procedure for choosing effective safety stock policies at all channel members in a multi-echelon distribution system under different operating conditions, which include different cost values, lot-sizing rules, and degrees of uncertainty.

To accomplish the above two objectives, several tasks must be undertaken. There are also several sub-tasks within each task. Those tasks and sub-tasks are:

(1) To classify and describe the sources and types of uncertainties which potentially affect the performance of a multi-echelon distribution system.

- To conduct a literature review in uncertainty related topics in an MRP system.
- To conduct a literature review in uncertainty related topics in a physical distribution system.

(2) To develop several performance measures of a multi-echelon distribution system to evaluate different sources and types of uncertainties' impacts.

- To find out one single cost performance measure and its components, which are appropriate in this study.

- To identify some non-monetary performance measures, which may be viewed as supplementary performance measures to examine the impacts of demand quantity uncertainty, supply quantity uncertainty and transportation lead time uncertainty on a multi-echelon distribution system.

(3) To develop a computer program to evaluate alternative safety stock policy performance under different operating conditions in a multi-echelon distribution system.

- To study the differences among several safety stock policies described in earlier studies, and then develop several safety stock policies used to test those performances in a multi-echelon distribution system.
- To develop general language programs to resolve those research questions defined in this study.
- To compare the safety stock policies used in a multi-level production system and a multi-level distribution system.

(4) To conduct sensitivity analyses to evaluate the multi-echelon distribution system's performance due to distribution network changes.

- To decide the way to change the distribution network, which reflects a different product shipped in the distribution system.
- To test the impacts on some distribution system performances under various operating conditions, if a different distribution network is used.

(5) To conduct sensitivity analysis to evaluate the multi-echelon distribution system's performance due to cost structure change. The cost structure is used to determine the inventory costs incurred at each channel member in a distribution system.

- To develop several different cost structures of a multi-echelon distribution system to present different market channels.
- To test the impacts on some distribution system performances under various operating conditions, if different cost structures are used.

CHAPTER II

LITERATURE REVIEW

The inventory control method (DRP) studied in this research is only a branch of a wide tree of inventory theory. This chapter begins by reviewing the classification of inventory theory. Because the environment of a multi-echelon distribution system is similar to the environment of a multi-level production system, some significant literature relevant to multi-echelon distribution systems and MRP systems are also studied in this chapter. Topics included are: (1) uncertainties in the physical distribution system, (2) uncertainties in the MRP system, (3) safety stock in the physical distribution system, and (4) safety stock in the MRP system.

Classification of Inventory Systems

The inventory problem involves making decisions concerning an inventory system to minimize total system cost, which includes inventory holding cost, stockout cost, or to achieve such goals as improving service level or reducing average inventory level. Though inventory is a large and costly investment, it does exist in most manufacturing and distribution systems.

Inventory serves five purposes within the firm: (1) it enables the firm to achieve economies of scale; (2) it balances demand and supply; (3) it enables specialization in manufacturing; (4) it provides protection against uncertainties in demand and order cycles; and (5) it acts as a buffer between critical interfaces within the channel of distribution (Lambert and Stock, 1993). The basic decisions in inventory control are the timing and quantity of inventory to order for stock. To develop an appropriate inventory policy one needs to consider the cost limit and decision variables involved in the system.

There are several schemes for classifying inventory systems presented in surveys about inventory theory (Aggarwal, 1974, Clark, 1972, Hollier and Vrat, 1977, Silver, 1981). Hollier and Vrat (1977) classify inventory systems into four groups: (1) structure, (2) environmental limit, (3) inventory policies, and (4) inventory related cost. Within each group, there are additional classification items. Table 2.1 depicts the groups and sub-categories from the Hollier and Vrat scheme. Considering the research questions and research scope of this study, the inventory system of interest is classified as a single-item, single source, multi-echelon, arborescent flow, stochastic demand, non-zero random lead time, fixed cost of parameters, lost sales, and time-phased requirements planning replenishment policy. The settings of these alternatives are addressed in a later section.

Table 2.1 Classification of Inventory Systems Adapted from Scheme of Hollier and Vrat (1977)

Group	Category	Alternatives
Structure	Number of items	Single/Multiple
	Number of sources	Single/Multiple
	Number of echelons	Single/Multiple
	Number of stock locations	Single/Multiple
	Item flow	Arborescent/Transship/Return
Environment	Demand	Deterministic/Stochastic
	Replenishment time	Constant/Random Zero/None-zero
	Shortage action	Backlog/Lost Sale/Emergency Ship
Policy	Statistical Order Point	QR/QT/SR/ST
	Replenishment Cycle	S-1,S /s,S
	Dynamic Models	Dynamic Programming/ Linear Programming/Markov Chain
	Requirements Planning	Time-Phased Net Requirements
Costs	Carrying Shortage Ordering Procurement	Fixed/Linear/Concave/Convex

Aggarwal's (1974) classification scheme is less specific than Hollier and Vrat's. He uses categories of static/dynamic, deterministic/stochastic, known/unknown distribution, single/multi-item, and single/multi-location/multi-echelon. Most of the past research in inventory theory concentrates on the simple inventory systems, especially the single-level system. These results obtained from single-level systems are applied at all levels in a multi-echelon system. Aggarwal and Dhavale (1975) find those simulation results in a complex environment are not simple extensions of a single-level model. Aggarwal (1974) describe the distinction of a static or dynamic system with the variation over time of limit values. A static system assumes uniform demand, fixed lead time, and constant cost values. His distinction of a deterministic or stochastic system refers to the certainty or uncertainty of period demand and lead time used in the inventory policy. According to Aggarwal's classification, this research is a stochastic, known distribution, single item and multi-echelon inventory system. This classification is useful for deciding upon the experimental design and developing the simulation model of the distribution system.

Uncertainty in the Physical Distribution System

Uncertainty is the major force that impedes understanding of the distribution system and hinders the achievement of efficient and effective operations of the distribution system. Leading-edge companies are making major efforts to solve problems caused by uncertainties (Stenger, 1994). The most important uncertainties existing in a distribution system are demand uncertainty and supply uncertainty. The simplest way to interpret them is as follows: (1) demand uncertainty - it is difficult to know exactly what demand will be in the future. (2) supply uncertainty - when an order is released to supplier, it cannot be certain that it will arrive on time. Bowersox (1974) identifies another source of uncertainty in a physical distribution system. It is transportation lead time uncertainty, which occurs within the distribution system.

Methods to Solve Uncertainties Problems in a Physical Distribution System

The analysis of distribution systems requires consideration and selection of distribution channels, inventory, transportation, and location of warehouses. These problems are interrelated, dynamic, characterized by uncertainty and, therefore, complicated to resolve. Numerous methods have been raised to solve uncertainty problems in the distribution system. Developing relationships, where information is shared between channel members in the distribution system, can reduce the impacts from demand uncertainties. Stenger and Cavinato (1979) find that the firm can reduce wholesale safety stocks substantially by forecasting aggregate retail demand for each product and using the DRP inventory control method to develop wholesale inventory requirements. The old way of controlling the warehouse inventory consists of forecasting wholesale demand based on the past history of warehouse shipments. In fact, reducing demand uncertainty requires close cooperation with the downstream demand points. Major retailers in the United States have taken the lead in this area, using their point-of-sale (POS) systems to collect demand at the lowest possible level and then communicating these data electronically to their suppliers (Stalk, Evan and Schulman, 1992). Manufacturers like Procter and Gamble, and Polaroid use this type of information to push inventories to downstream customers (Byrne and Shapiro, 1992).

Improving forecasting accuracy can also reduce the impacts from demand uncertainties. Better forecasts lead to lower safety stock inventories, because safety stock levels vary with the size of the forecast error. Thus, reducing forecast error can reduce inventories. Another method to reduce demand uncertainties involves working with the marketing function. Sales incentives and promotions generally create "noise" in the actual demand. Some companies have taken action to avoid such noise. For example, Kumar and Sharman (1992) report that at one company, "the president announces that he will fire anyone who takes the orders in the last week of the month for delivery before the end of the month." Several consumer product manufacturers have changed their policy of promotion to customers; customers have to buy large quantities only during price discount periods, and do not buy at times between these promotions (Sellers, 1992).

Stenger (1994) addresses the cause and the solution of supply uncertainties. He describes that supply uncertainty arises from the nature of operations at the supply source providing the replenishment shipment and the nature of transportation operations regarding delivery from the source. To reduce supply uncertainties, the supply source needs advance information about future requirements it will have to supply, just as does the demand source. Therefore, the demand source needs to develop the same kind of information-sharing relationships with its key supply sources. Stenger presents some transportation modes, in which uncertainty may occur, such as in the railroad, less-than truckload, and water carrier businesses. This uncertainty, compounded with supply source uncertainty, leads to substantial safety stocks to protect against these uncertainties. In this study, he proposes using better information sharing on the part of the supplier, carrier, and receiver can lead to great improvements in on-time delivery and hence reductions in inventory.

Types and Impacts of Uncertainties in the Physical Distribution System

The sources of uncertainty existing in a physical distribution system are varied. Many cannot be identified and, if identifiable, then the measurement can be difficult. All physical distribution activities (inventory, warehousing, handling, communication, and transportation) may be affected by various sources of uncertainty.

Connors, Coray, Cuccaro, Green, Low, and Markowitz (1972) design a software system called Distribution System Simulator (DSS), which is a modeling tool which produces a mathematical representation of a distribution system. The options of the model allow the user to take the characteristics of customers' demand and order shipment lead time into account. They use separate inventory policies at each stock location. These behave like an independent unit and use their own inventory policies for each of their stocked items. This simulation still can not be regarded as a total system approach. The objective of DSS is to aid the user in finding better ways for the distribution system to respond to the variations in demand points and lead time based on inventory and service information.

Spen and Wagenheim (1975) describe the behavior of a simulated physical distribution system under conditions of variable demand and variable lead time. They use the gamma distribution and the normal distribution for demand distributions to indicate the range of possible quantities demanded and their probability of occurrence. Likewise, they choose the exponential distribution and gamma distribution for lead time to indicate the possible time to complete an order cycle. They mention that the impact of demand and lead time uncertainties upon a channel of distribution are evidenced in two material ways: (1) the cost, and (2) the service capability of the physical distribution operations. Therefore, a simulation model of a physical distribution system is selected to measure the cost and service response under various types and levels of uncertainty.

Spen and Wagenhein (1975) find that; (1) the percentage of demand stockouts is greater than it is under either the variable lead time (fixed demand) or variable demand (fixed lead time) case, and the lead time has a much stronger impact upon stockouts than does demand uncertainty; (2) the total cost per unit incurred by the channel system falls between the total cost levels associated with those conditions where one of the experimental variables is held constant; and (3) in general, lead time uncertainty creates more serious impacts on the physical distribution system than demand uncertainty in their study.

Aggarwal and Dhavale (1975) conduct simulation experiments based on empirical data to analyze the influence of various factors that affect the performance measures of a distribution system. The factors in this experiment are demand, lead time and cost-rate structure. Three levels of demand, three different lead times, and three sets of inventory-related costs are considered. In their study, weekly demands are nearly normally distributed with a standard deviation, which is one third of the respective mean demand for each. Lead times are fixed for each location based on empirical data. From the results of their study, the following important findings are: (1) The average inventory investment and inventory carrying costs of the system increase in direct proportion to the mean demands of the system, but they increases by a very small proportion of the increase in lead time. (2) The annual shortage costs of a system are most sensitive to lead times, and less sensitive to mean demands. (3) Lead times affect the annual number of orders placed in the system. As the lead time increases, the number of reorders decreases. The conclusions drawn by Aggarwal and Dhavale are different from Spen and Wagenheim's results. This is because Aggarwal and Dhavale only consider different levels of factors (demand, lead time, cost structure), and Spen and Wagenhein try two different distributions and coefficients of variation of demand and lead time in their study.

Brown, Lusch and Koenig (1984) examine the environment uncertainty regarding inventory ordering in a two-echelon physical distribution system. They design a questionnaire, which includes 12 items (Table 2.2) to reflect uncertainties in a physical distribution system. The findings indicate that increased levels of environmental uncertainties

Table 2.2 Uncertainty Item
Adapted from Brown, Lusch and Koenig. (1984)

(1) Difficulty in determining inventory level*
(2) Reliability of supplier's deliveries
(3) Difficulty in obtaining forecasting information*
(4) Predictability in seasonal fluctuations in demand
(5) Supplier's order filling accuracy
(6) Stability of supplier's price
(7) Influence of forecasting accuracy on store's profitability
(8) Availability of forecasting information
(9) Rapidity in market growth
(10) Fluctuations in market demand*
(11) Intensity of competition*
(12) Difficulty in determining inventory mix*

* Items dropped from the final environmental uncertainty

regarding inventory ordering result in high levels of retailer-supplier conflict. Suppliers can offer retailers better service to reduce environmental uncertainties and to improve their relationship with retailers. Therefore, a more efficient distribution system can be developed.

Dorairaj (1989) presents a simulation model for a multi-echelon production-distribution system (PDS), which includes a plant warehouse, branches, and dealers in the physical distribution network. In this simulation model, demands from customers and order processing lead times are deterministic. Different levels (3 levels) of lead times are tested on the total cost per day. The one-way Analysis of Variance (ANOVA) is used to test the influence of lead time; the results show that the variation in lead times has no significant effect on the total cost at all the service levels. This conclusion is different from previous related study (Connors, et al., 1972, Aggarwal, 1975).

DRP has been successfully implemented in several industries. For example, Stenger and Cavinato (1979) report implementation for a state liquor control agency; Martin (1982) reports for a pharmaceutical company. Bookbinder and Heath (1988) conduct simulation research on the distribution system of the Grocery Division of Canada Packers, Inc. The physical distribution system of this company includes a national distribution center and four regional distribution centers. A simulation model of DRP in a two-level environment is used to examine the performance of five lot-sizing rules under conditions of both certain and uncertain demand.

Three different patterns of demand are used in this study: constant, uniform distribution, and normal distribution with the same mean. The effect of different demand patterns is significant, when a lot-for-lot ordering procedure is used to evaluate system performance in terms of total costs of the system. This lot-sizing study in a distribution system is perhaps the earliest study for a multi-echelon system with random demand.

Bregman, Ritzman and Krajewiki (1989) develop a heuristic algorithm to manage inventory in a multi-echelon environment, the algorithm is an improved heuristic that can be implemented as an add-on module to a DRP system. They consider the capacity of transportation and storage resources in their simulation model. The example scenario used in this research consists of four distribution centers ordering from two regional warehouses, which in turn order from a central warehouse. They examine the demand uncertainty to determine if the performance of the heuristic is affected by the amount of demand uncertainty. The results show that demand uncertainty is found to have a significant effect on customer service performance by Multivariate Analysis of Variance (MANOVA) analysis. The average customer service level falls from 90.8% to 63.1% when the standard deviation of forecasted demand increases from 10% to 50%.

Ho (1992) examines one operational problem in the implementation of DRP within the physical distribution system. This problem is called "system nervousness", which is a situation of frequent rescheduling in a requirement planning because of some uncertainties within or even outside the distribution system. A simulation experiment is conducted to investigate the effect of uncertainty in transportation lead time on DRP system performance measured by the total related cost and weighted rescheduling measure. In his findings, the presence of lead time uncertainty indeed causes system nervousness, and deteriorates the performance of the DRP system.

Uncertainties in the Material Requirements Planning System

The use of MRP is well established in production control by Orlicky in 1975. MRP is a system approach used in the production process for planning. A well established MRP system can provide answers to the following questions: (1) what materials and components are needed, and (2) when and how many are needed to meet a specified demand. The study of MRP has received considerable attention and the literature on this topic is vast. Most of the early literature deals with deterministic MRP, but in industry many forms of uncertainties affect the production process. This leads to the examination of MRP under uncertainty. Previous research related to MRP under uncertainty and the impacts of uncertainty are reviewed in this section.

Types of Uncertainty in an MRP System

Ma and Murphy (1991) categorize the different types of uncertainties that affect a production process into two groups - (1) environmental uncertainty, and (2) system uncertainty, as indicated in Figure 2.1. This classification is used to organize the literature review related to uncertainty in an MRP system. Environmental uncertainty is comprised of uncertainties beyond the production process. This includes (1) demand uncertainty due to uncertainty in customer orders and uncertainty in forecasting (also called forecast errors) and, (2) supply uncertainty due to unreliable vendors. The supply uncertainty can be either in the quantities delivered and/or the timing of the delivery. System uncertainty comprises of uncertainties within the production process. These include operation yield uncertainty, production lead time uncertainty, quality uncertainty, failure of the production system, and changes to product structure. Obviously, the types of system uncertainties in an MRP system are more complex than those in a distribution system. The only type of system uncertainty studied in this research is transportation lead time within the distribution system.

Whybark and Williams (1976) present a framework for characterizing and studying the uncertainty which can affect inventory investment and service level performance in an MRP system. They combine sources and types of uncertainty into four categories, which are summarized in Table 2.3. They

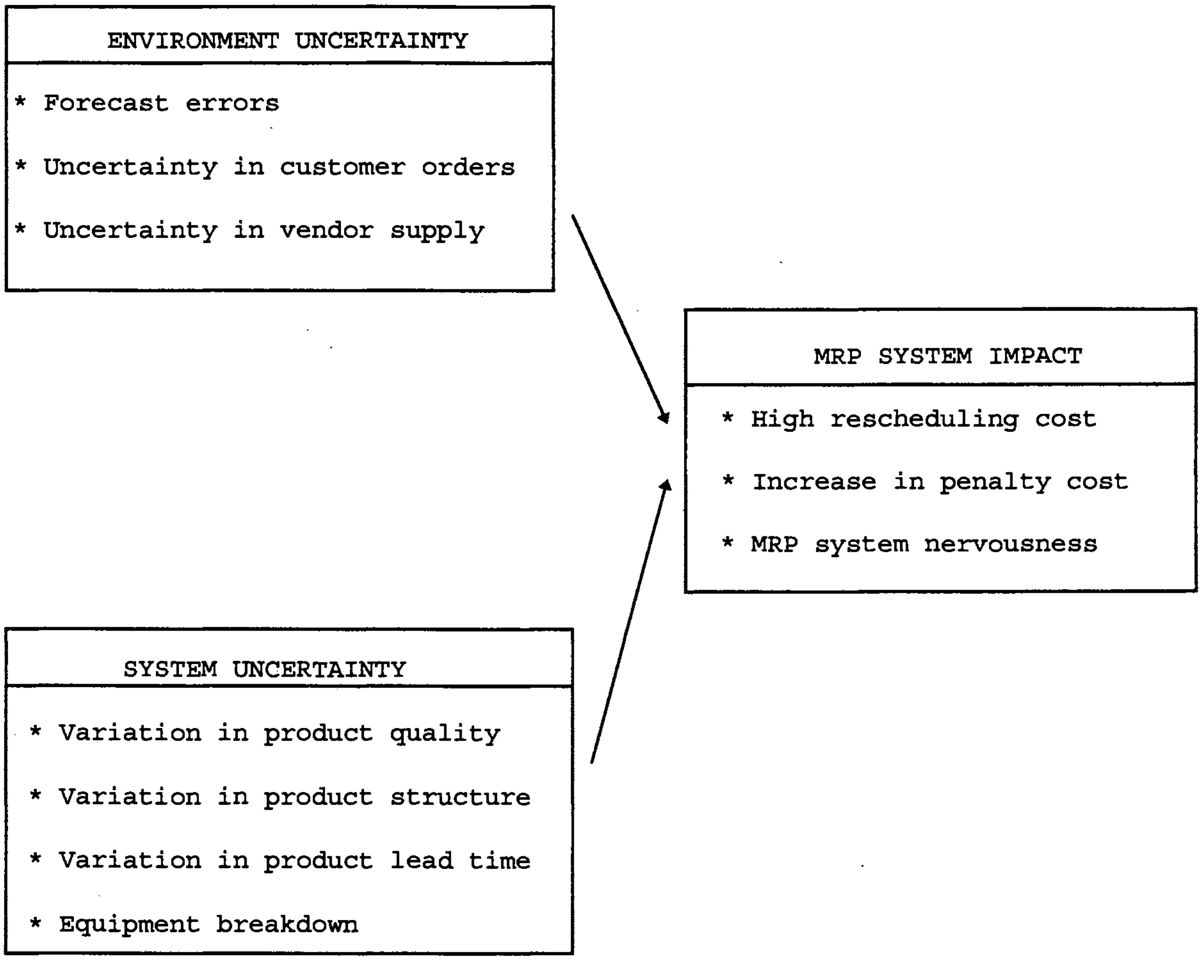


Figure 2.1 Uncertainty and Impact on MRP
Adapted from Ma and Murphy (1991)

Table 2.3 Categories of Uncertainty in MRP Systems
Adapted from Whybark and Williams (1976)

		Source	
		Demand	Supply
Types	Timing	Requirement shift from one period to another	Orders not received when scheduled
	Quantity	Requirements for more or less than planned	Orders received for more or less than planned

consider only environmental uncertainty in the MRP system, according to Ma and Murphy's classification. A simulation model of the period-by-period transactions for a representative part in an MRP system is developed for this study, but only one of the four categories of uncertainty is used one at a time. Whybark and Williams (1976) do not consider all types and sources of uncertainty in the MRP system which may occur simultaneously. The ANOVA results shows that both demand uncertainty and supply uncertainty have a significant effect on the customer service level. In their findings, they conclude safety lead time is the preferred technique to protect against uncertainty in timing, and safety stock is preferred under quantity uncertainty.

DeBodt and Wassenhove (1983a, 1983b) study lot sizing and safety stock decisions and the total system cost increments under demand uncertainty in a single level MRP system. They show that forecast errors in customer's demand have a tremendous effect on the cost effectiveness of lot sizing and safety stock decisions. Their results indicate that safety stocks and lot-sizing policies are important to a company using MRP in an uncertain environment.

Schmitt (1984) examines the effectiveness of three commonly used methods to resolve the uncertainty problem in a multi-stage manufacturing system. In this paper, he develops a simulation model of a multi-stage process to characterize the behavior of three resolution methods under demand uncertainty and process time uncertainty. The results indicate that choice among method depends upon the source of uncertainty.

After Whybark and Williams (1976) classify the sources of uncertainty in MRP in their paper, Grasso and Taylor III (1984) concentrate on the impacts of specific operating policies on the performance of an MRP system under conditions of supply uncertainty in terms of timing. Three different lead time distributions are used in this experimentation. They are the discrete uniform distribution, symmetrical discrete distribution, and asymmetrical discrete distribution. In their findings, the average total cost is highest when the lead time distribution is uniformly distributed, and the mean average total cost is lowest when the lead time distribution is asymmetrically distributed. Another important conclusion in this study is that the amount of safety lead time, but not the amount of safety stock, has an impact on the total cost of an MRP system. When buffering against uncertainty of the supply/timing variety, it is more effective to use safety stock instead of safety lead time. This conclusion is different from Whybark and Williams' results; they suggest that it is more appropriate to use safety lead time to deal with time uncertainty in an MRP system.

Melnyk and Piper (1985) study the impacts of lead time errors in an MRP system. They define the lead time errors as the difference between the time actually used to manufacture an item and the planned lead time used by MRP. It is a system uncertainty which occurs in production lead time. They set planned lead time as the average observed lead time plus a multiple of the standard deviation of the lead time error distribution. Through simulation experiments they show that increases in lead time allowance multipliers consistently improve the end item service level. They define the lead time allowance multiplier as follows:

$$\text{Multiplier} = \frac{(\text{Planned lead time - Actual lead time})}{(\text{Actual standard error})}$$

Wemmerlov (1986) considers the effects of demand uncertainty in connection with an MRP system. The system is observed under three conditions: (1) no demand uncertainty, (2) demand uncertainty present but no safety stocks, and (3) demand uncertainty present with safety stock to account for its effects. The results from a simulation experiment show that stockouts, larger inventories and more orders occur when demand uncertainty is introduced in the operating environment. Service levels are decreased and inventory levels increase when demand forecast errors become larger.

Minifie and Robert (1990) study the interaction effects on the MRP system by incorporating both demand and supply variability simultaneously. Most of previous studies hold demand or supply constant, and only consider one source of uncertainty in the problems. Most cases even ignore the supply uncertainty in their simulation environment. The conclusions of this study provide an opportunity to verify the results of previously related research with simplistic operation environments.

Ho and Lau (1994) extend some earlier works (Lee and Adam, 1986; Lee, Adam and Ebert, 1987) in the impact of lead time uncertainty in an MRP system. They investigate the effects of fluctuating manufacturing lead time on MRP system performance under various environmental factors such as the lot sizing rule and product/cost structures. Their results show that the expected lengths of lead times must be considered in studying the relative performance of lot-sizing rules in an MRP system with lead time uncertainty.

Impact of Uncertainties on MRP System

Several alternatives are suggested for preventing or reducing uncertainty. One approach is to reschedule the system more frequently, but this leads to "system nervousness". As a rule, the more frequent the rescheduling, the more nervous the system. And although rescheduling may avoid some uncertainty, it can not completely prevent shortages. MRP system nervousness generally refers to the frequent rescheduling of open orders that is beyond the capability of a production system to handle. Changes in production schedules in a multi-level manufacturing environment are indicated by the exception messages generated by the MRP system. These exception messages may be greater in number than the order release messages, and the material planner can't take action in time. The changes in production schedules are costly, since the schedule is the basis for manpower planning and material purchasing (Graves, 1981).

In multi-level manufacturing systems, due to manufacturing and /or purchasing lead times, lower level orders may be released to the shop as early as the cumulative lead times. When the planned orders at higher levels change due to a demand forecast revision, the lower level orders that have already been released may need to be rescheduled. The rescheduling of open orders have been studied by both academicians and practitioners (Campbell, 1971, Peterson, 1975, Steele, 1975, Mather, 1977, Wemmerlov, 1979, Grave, 1981). In summary, the negative effects of rescheduling are listed as increased costs, decreased productivity, and confusion on the shop floor (Campbell, 1971).

Many solutions are suggested in the literature to reduce nervousness in scheduling (see Blackburn, Kropp, and Millen, 1985, 1986 for a complete review). Some suggest freezing the master production schedule (MPS) to improve schedule stability (Blackburn, et al., 1986, Sridharan and LaForge, 1989, 1994 and Sridharan, et al., 1987). Carlson (1982) and Chand (1982) prove that forecasting beyond the planning horizon is an effective method to resolve system nervousness. Other approaches to deal with nervousness in an MRP system also exist, such as changing cost procedures (Carlson, 1979), using lot-sizing procedures (Blackburn and Millen, 1980, DeBodt and Wassenhove, 1983, Wemmerlov and Whybark, 1984), and using buffer stock at the end item level (Mather, 1977, Blackburn, Kropp and Millen, 1986, Chu and Hayya, 1988, Sridharan and LaForge, 1989).

Demand uncertainty can also affect inventory systems. Wemmerlov (1986) conducts a simulation experiment under demand uncertainty to achieve a cost-independent picture. The system is studied along several non-monetary dimensions: inventory levels, number of orders placed, number of stockouts, maximum number of units stocked out, service levels and safety stock levels. He states, based on his previous studies under demand uncertainty, that the introduction of forecast errors leads to an increased number of stock-outs, declining service levels, increased inventory, and increased ordering activities. Also, the situation gets worse as the forecast errors increase in size.

Grasso and Taylor III (1984) address the effects caused by supply/timing uncertainty in an MRP system. They conclude that supply lead time uncertainty has a significant effect on the average total cost of the system. The holding cost per week and the lateness penalty charges both increase to reflect this lead time uncertainty.

Melnyk and Piper (1985) investigate the processing lead time error in a manufacturing system. A simulation experiment is performed to measure the processing lead time uncertainty effects of five lot-sizing rules. The results show that part period balancing (PPB) and the Silver and Meal heuristic (S&M) are better rules than lot-for-lot (L4L), economic order quantity (EOQ) and period order quantity (POQ) under processing lead time errors.

Safety Stock in the Physical Distribution System

In a multi-level distribution system, the effect of a lumpy demand can cause stockouts or increase ordering activity. The problem becomes worse when stochastic supply lead time is involved. Supply interruption frequently filters through the whole distribution system, creating costly stockouts at different locations. Safety stock is one way to provide protection against uncertainty in a distribution system. Where and how much safety stock to carry in a distribution system is still an open issue; only a few studies discuss this issue during the past three decades.

Perhaps the first important theoretical model for multi-level production/inventory planning is the Clark and Scarf model (1960). They examine an N-location series production/inventory system with demand uncertainty occurring at the lowest stage where independent demand occurs. Under a periodic review policy, they demonstrate that the globally optimal system policy for an n-level problem may be determined by first determining the optimal policy at the lowest stage and the proceeding sequentially to determine the correspondingly optimal policy for the next-lowest stage, etc.

Schwarz (1981) discusses the effective safety stock and predecessor safety stock problems in a deterministic multi-level system. He considers a two-stage series system, and assumes that stage 1 faces constant customer demand, and the lead time needed to replenish inventories from stage 2 to stage 1 is fixed. The optimization problem of interest is to allocate a fixed system safety stock S to maximize customer fill rate (F) and minimize customer expected delay (T). Mathematically,

$$\begin{array}{ll} & \text{Max } F \\ \text{and} & \\ & \text{Min } T \\ \text{subject to} & \\ & S_1 + S_2 \le S \end{array}$$

Where S_1 is stage 1's safety stock and S_2 is stage 2's safety stock. The detailed definitions of "fill rate" and "expected delay" are found in Schwarz's paper (1981). He states, despite its simplicity, the deterministic model does provide some interesting and useful guidelines for understanding and modeling uncertainty in a multi-level system. He also compares two safety stock policies under stochastic demand. First consider a decentralized system with N identical stocking locations. Alternatively, consider centralizing these inventories at a single location. In his findings, the centralized system is more cost effective than the decentralized system. For example, if N=2, then total cost of a decentralized system is approximately 40% larger than those of a centralized system.; For N=9, cost is three times larger.

Allen (1983) compares three different policies for positioning safety stock in a two-echelon distribution system: (1) a "force-balance" policy which positions safety stock at the central echelon facility, (2) a "push-allocation" policy which positions safety stocks at both the central facility and the field facilities, and (3) a "fare-share" policy which positions safety stock at the field facilities and occasionally at the central facility. He use the results from simulation to compare the fill rate and inventory operating performance of the alternative safety stock policies. The results show that the "Force-balance" and "push-allocation" policies have significant lower average fill rate and higher average inventory than the "fair-share" policy.

Salameh and Schmidt (1984) try to identify the safety stock levels needed to minimize the expected annual total cost for a multi-level inventory system with known demand rate and stochastic supply lead time. They adopt an analytical approach to find the optimum safety levels in a multi-level inventory system. Finally, a relation equation based on total related costs is presented to find the optimum safety stock levels.

Chakravarty and Shtub (1986) discuss two important issues in a two-echelon inventory system operating under stochastic demand and stochastic lead time. The first issue is to decide the aggregate level of safety stock carried in the system. The second issue is the allocation of the total safety stock within the system. They perform a simulation study to investigate the sensitivity of the system to both issues. In their study, they develop a method to allocate safety stock among field facilities. The amount of safety stocks allocated in field facilities are in proportion to the standard deviation of demand during lead time and the z value that yields the desired probability of stock out. They define the entire system service level as the ratio of (total number of products supplied without backlog to the customers from all field facilities) / (total number of product units demanded from all field facilities). In their findings, they suggest that up to 20% of the system's safety stock be allocated to the central distribution center. Because the total safety stock in the system can be reduced up to about 80% of the level of a system in which no safety stock is carried in the central distribution to achieve the same level of system service. This also implies that by allocating a fraction of the total safety stock to the central distribution center, an increase in service level is achieved without additional investment in the total system's safety stock.

Safety Stock in the Material Requirements Planning System

Safety stocks were introduced long ago to protect an MRP system against uncertainty. A general statement of a safety stock problem is that "given an inventory system, determining the optimal buffer, by trading off the risk of shortage with the cost of excess inventory." Though much research has been done in the past two decades, the use of buffers in an MRP system still raises some questions that are yet unanswered. One of those questions is where to place safety stocks in a multi-level system such as MRP. That is the similar problem for MRP that is discussed in this study for DRP. A comparison will be conducted between a multi-level production system and a multi-level distribution system, if the same conclusions of safety stock policies from MRP system can be applied directly in a multi-level distribution system.

Safety stock is one buffering method to deal with uncertainty in an MRP system. Chu and Hayya (1988) review the buffering issues in an MRP system and develop an information flow for buffering decisions as shown in Figure 2.2 This information flow also provides a guideline to make decisions in choosing safety stock policies. In summary, three-step decisions are made to allocate safety stocks in an MRP system: (1) decide where to place safety stocks, (2)

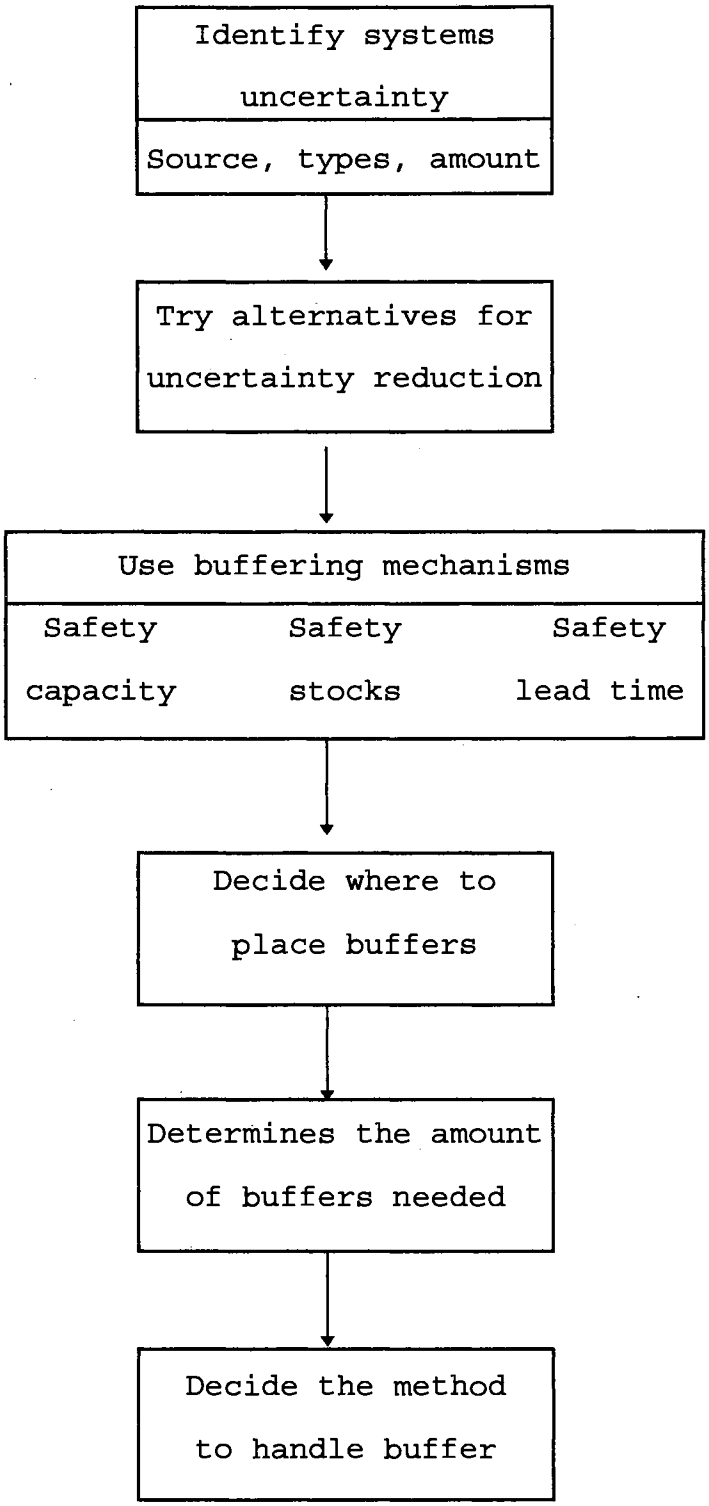


Figure 2.2 An Information Flow for Buffering Decisions Adopted from Chu and Hayya (1988)

determine the amounts of safety stocks at all channel members, and (3) decide the method to handle safety stocks. After a safety stock policy is made, it is important to find some criteria for evaluating the effect of buffering. For example, the effects can be measured in terms of customer service level, total number of stockouts, average inventory, and total related cost. Previous research related to safety stock policy will be reviewed by the same order to make a decision.

Where to Place Safety Stocks?

There are at least three different types of safety stock in a multi-level production system; (1)finished product, (2)work-in-process (WIP) inventory, and (3)raw materials. Magee (1956) outlines the functions of those safety stocks with order point systems as follows:

a. Finished inventories serve to protect individual products or sizes, to protect the operating manning levels, and to protect the warehouse or dealer against the time to place and receive an order, or the factory against the time to schedule and make a run.

b. In the case of WIP inventories, they serve to shorten times for serving erratic needs of later operations (in a job shop) or to absorb fluctuations in production rates (in an assembly line).

c. In the case of raw materials inventories, they serve to protect against uncertainty in availability or delivery times and variations in usage rates.

In a multi-level MRP system, uncertainty can occur at one or more levels. To provide enough protection and to keep low inventory, a decision of where to place safety stocks must be made. The most generally accepted one is to place safety stocks at the end items to protect against demand uncertainty and at the raw material level to protect against supply uncertainty (Moore, 1973, and Orlicky, 1975).

The second view is to put safety stocks at the lower levels. Because it is better to use pipeline safety stocks than finished-goods safety stocks according to the principle of forecast delay and the concept of value-added over time (Miller, 1979).

The third view is that safety stocks shall be put at all levels. This is because every effort shall be made to protect against uncertainty, and that may occur at all levels (Liaw, 1979, Chu, 1984).

How Much Safety Stock?

How much buffer is not an easy question to be answered. The amount of safety stock necessary to satisfy a given service level can be determined by computer simulation or by a statistical approach (Lambert and Stock, 1993). Early researchers assume that safety stocks can be calculated statistically even under demand uncertainty and lead time uncertainty. The statistical approach can only work under single-level, single location conditions, and may not be appropriate for a time-phased demand item (New, 1975).

New (1975) shows two methods for determining safety stocks. These include: (1) the economic approach, and (2) the service level approach. The economic approach tries to set safety stock levels such that the total variable costs of setting-up, holding stock and incurring shortages is minimized. The shortcoming of the economic approach is to decide the shortage cost. Lambert, Luyten, and Eecken (1985) conduct a simulation experiment to find an optimal solution in a two-stage system. Under the service level approach, management must decide what level of customer service to achieve, and safety stocks can then be set in order to achieve such service levels (Miller, 1979).

How to Handle Safety Stocks?

Moore (1973) illustrates two methods to deal with safety stocks in an MRP system. The general approach used to handle safety stocks in an MRP system is to subtract them at the beginning from on-hand inventory. A system based on such a logic is called a "free stock system." The system adds two extra rows in addition to the normal MRP table. The first, "safety stock", indicates the amount of safety stock available in the plan to deal with uncertainties. The second added row, "net requirements", exists to determine when a scheduled receipt is required. Another approach is to use safety stock as a trigger criterion; that is, when the on-hand inventory is expected to drop below the safety stock, an order is placed.

Criteria for Evaluating the Effects of Safety Stocks

The performance of an MRP system can be evaluated by several criteria. To investigate the effects of safety stocks on an MRP system, the system can be measured in terms of inventory investment, customer service level or total costs (Liaw, 1979, Schmitt, 1984); by non-monetary measures such as total number of end item stockouts, number of orders placed (Wemmerlov, 1986); or by measuring the system nervousness (Sridharan and LaForge, 1989).

Chu and Hayya (1988) summarize that three major problems may occur when considering these performance measures. First, total cost is sensitive to the parameters chosen. This can lead to biased results. The second problem is how to define and determine the appropriate service level. The last problem is to select suitable performance measures. In general, that can be a single measure or multiple criteria.

Summary

In this chapter, a literature survey related to the research objectives is presented. Sources, impacts, and resolving methods of uncertainties problems occurring in a physical distribution system and an MRP system are fully discussed. It is important to recognize the nature and impact of various sources of uncertainty occurring in a physical distribution system. A conventional buffering method (safety stock) to resolve uncertainty problems is also discussed.

This survey indicates that most past studies related to uncertainty problems are based on a single source of uncertainty within or outside the system. It is obvious that these studies ignore the possible interactions within several types of uncertainties. Usually the impacts of those interactions cannot be understood by intuition or by results from simplistic models. There is a need to investigate the nature and impacts of various uncertainties in a multi-level distribution system.

Providing safety stocks within the system is proven to be an effective method to protect against uncertainty in a physical distribution system. But there is still no clear guideline available to make a decision for safety stock policy, especially in a multi-echelon environment. Again, there is a need to develop some safety stock policies under different operational environments in a multi-echelon distribution system.

CHAPTER III

RESEARCH METHODOLOGY

First, this chapter presents the model structure used in this study. Then, six experimental factors used in the base experiment and two factors used in the sensitivity analysis experiment are also discussed. Research hypotheses are presented in the third section. The fourth section of this chapter illustrates the performance measures for testing the hypotheses. Experimental design of this study is presented in the last section.

Research Framework

A conceptual model of the research problem is shown in Figure 3.1. It is a multi-echelon distribution system with the replenishment of finished product from an outside vendor and with independent demand occurring at retailers.

Three main sources of uncertainty occur within and/or outside the distribution system; each may be defined as either system uncertainty or environmental uncertainty. Daily demand is the force which initiates the functioning of the channel system. Daily demand occurs at each retailer

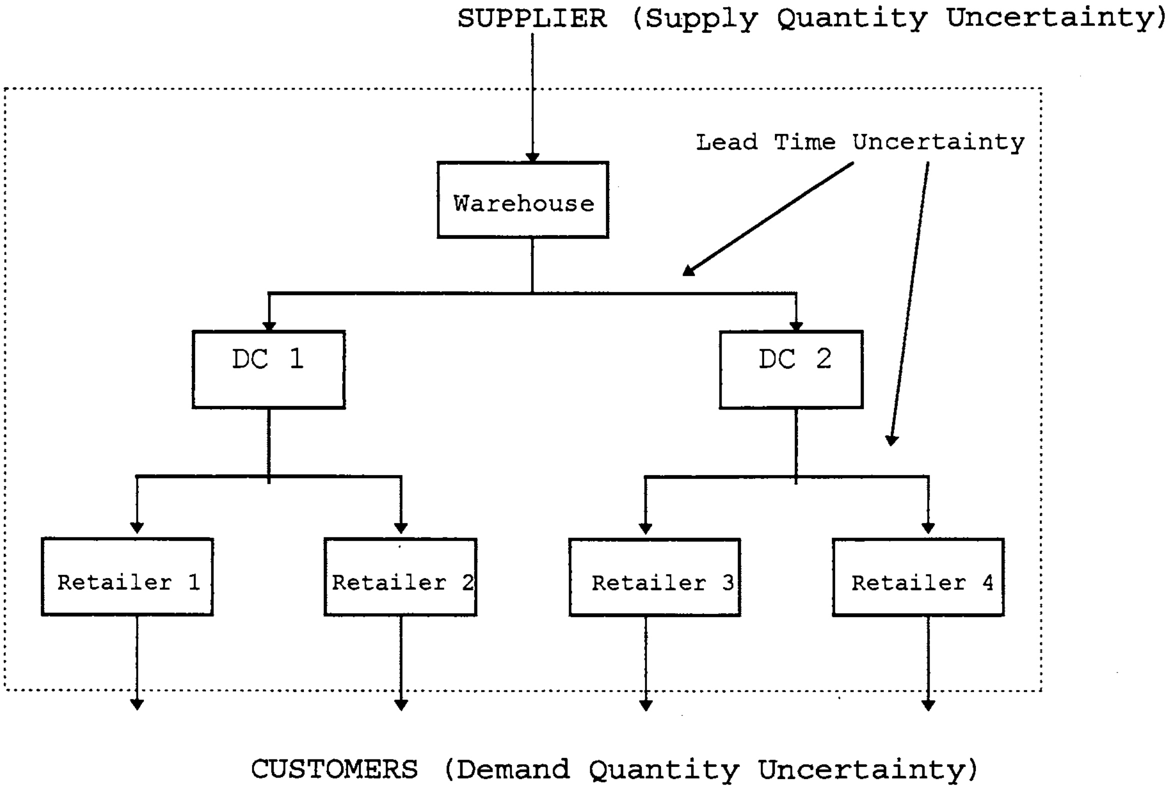


Figure 3.1 A Conceptual Model of the Research Problem

and varies according to a chosen probability distribution. That is known as environmental uncertainty caused by the customer demand uncertainty in quantity. Lead time associated with order processing is defined as the time interval between order placements and order receipts. Transportation lead time is the main component that causes lead time uncertainty within a physical distribution system. Thus, uncertainty in transportation lead time occurring at distribution centers and retailers is regarded as system uncertainty in this study. Another environmental uncertainty discussed in this study is the supply uncertainty, which occurs when the supplier does not ship the planned order quantity to the warehouse.

This research is an exploratory study, investigating the impacts of various types of uncertainty on a multi-echelon distribution system's performance. Every research project has its restrictions and limitations. Several assumptions have been mentioned for the multi-level distribution system in the first chapter. To conduct the research, the following additional assumptions are made about the nature of those decision factors used in this study:

1. There is no backorder allowed in the system.
2. Only demand quantity uncertainty is considered; there are no trend, seasonal, or cyclical patterns in the demand requirements.
3. Only transportation lead time uncertainty is

considered within the distribution system.

4. Only supply quantity uncertainty under shortage condition is studied.
5. A fixed cost structure is used in the base experiment.

Other assumptions, which are not discussed here, are presented in appropriate sections.

Research Design

This research is designed to investigate the impact of various types of uncertainty on a multi-echelon distribution system. Computer simulation is used to model a multi-echelon distribution system which has the assumed environmental conditions and the identified experimental factors to answer the research questions in this study. Among types of research methods, the computer simulation is most appropriate for this study because it provides adequate representation of the system. As discussed in the literature review, analytical formulation of a multi-echelon distribution system has been addressed by several authors (Muckstadt and Thomas, 1980, Schwarz, 1981, Salameh and Schmidt, 1984). Most of the models are developed under simplified environmental conditions and inventory policies. There is no known analytical formulation or simulation model of the problem discussed in this study.

There are two types of simulation experiments, the base experiment and the sensitivity analysis experiments. The base simulation experiments are designed to examine the impact of various types of uncertainties and safety stock policies on a multi-echelon distribution system. Sensitivity analysis experiments are conducted to see how the results obtained in the base experiment are changed; when some factors are changed, which are held to be constants in base experiment. Two factors allowed to alter in the sensitivity analysis experiment are the cost structure of the product and the distribution network. The factors used in the base experiments and the sensitivity analysis experiments are shown in Table 3.1. Detailed descriptions of each factor are given in following sections.

Factors Bearing on the Research

It is important to identify the factors which are important to the research question; these factors are essential to a valid experiment. The main purpose in the base simulation experiments is to investigate the impact of various types of uncertainties on a multi-echelon distribution system under different safety stock policies. Six factors considered in the base simulation experiments are as follows:

FACTOR 1: Customer Demand Uncertainty

The nature of customer demand is a very important factor which may affect the performance of a distribution system. Demand uncertainty may cause stockout or excess inventory in the distribution system. Demand uncertainty is

Table 3.1 Experiment Factors Bearing on the Research

Experimental Factors	Levels
Base Experiment	
1. Demand Quantity Uncertainty	1. Normal Distribution with mean=0, σ_e=15
	2. Normal Distribution with mean=0, σ_e=30
2. Lead Time Uncertainty	1. Uniform Discrete Distribution (C_v=0.47)
	2. Symmetric Discrete Distribution (C_v=0.33)
3. Supply Quantity Uncertainty	1. Normal Distribution with C_v=0.05
	2. Normal Distribution with C_v=0.15
4. Cost Values	1. Inventory Carrying Cost=10% /unit/year; Stockout Cost=10% /unit
	2. Inventory Carrying Cost=30% /unit/year; Stockout Cost=20% /unit
5. Lot-Sizing Rule	1. Lot-For-Lot (L4L)
	2. Economic Order Quantity (EOQ)
6. Safety Stock Policies	8 Different Safety Stock Policies (See Table 3.5)
Sensitivity Analysis Experiment	
Value-added Factors	4 Different Cost Structures (See Table 3.6)
Distribution Network	Base: 1-2-4 (See Figure 3.1) Sensitivity Analysis: 1-4 (See Figure 3.2)

generally modeled by generating forecast errors from a normal distribution with a mean of zero and various standard deviations to achieve differing levels of uncertainty. In this study, the forecast errors are generated in the same way, normally distributed with a mean of zero and standard deviations of 15 and 30. The forecast error generated for each period is added to the forecast demand for that period to achieve the actual demand quantity for that period. This relation is shown as:

$$\text{Actual Demand} = \text{Forecast Demand} + \text{Forecast Error}$$

Forecast demand is generated from a normal distribution with a coefficient of variation (C_V) of 0.20. For those periods where generated forecast demand is less than zero, it is truncated to zero. The coefficient of variation (C_V) is a measure of variability that has been widely used in previous research (Bobko and Whybark, 1985) and the value selected for this study is within the range used by previous studies (Berry, 1972, Wemmerlov, 1982). Although it has been included as a variable factor in previous research, it is held constant in this study to control the number of experimental combinations. The means and standard deviations of forecast demand for each retailer are displayed in Table 3.2.

Table 3.2 Forecast Demand for Each Retailer

	Mean	Standard Deviation
Retailer 1	50	10
Retailer 2	100	20
Retailer 3	150	30
Retailer 4	200	40

FACTOR 2: Lead Time Uncertainty

Lead time uncertainty is modeled by two different discrete probability distributions as shown in Table 3.3. The uniform distribution causes more variability in the lead time than other symmetrical distribution. Grasso and Taylor (1984) use the same lead time distribution to express lead time uncertainty in their study. The same lead time distribution is applied between all channel members. For example, when the uniform distribution is chosen to generate the transportation lead time, the uniform distribution is used to decide the transportation lead time from the warehouse to the distribution centers and from the distribution centers to the retailers. This study only considers lead time uncertainty occurring between the warehouse and distribution centers; and between distribution centers and retailers. The lead time from the outside vendor to the warehouse is assumed fixed, and there is no lead time concerned when the customers purchase products from the retailers.

FACTOR 3: Supply Uncertainty

The specific supply uncertainty examined in this study is caused by order shrinkage from the outside vendor to the warehouse. The supply uncertainty is defined by the coefficient of variation (C_V) of the deviation of "actual receipt" from "planned order". The actual receipt is generated as:

Table 3.3 Lead Time Distributions

Uniform Discrete Distribution	Value (period)	1	2	3	4	5
	Probability	0.2	0.2	0.2	0.2	0.2
Symmetrical Discrete Distribution	Value (period)	1	2	3	4	5
	Probability	0.1	0.1	0.6	0.1	0.1

$$\text{Actual Receipt} = \text{Planned Order}(1-|r|\bullet C_V) \qquad (1)$$

where the planned order is imploded from two distribution centers and $r \sim N(0,1)$ is a standard normal variate. This is because only supply shortage is allowed in the experiment, an absolute value is applied to guarantee only supply shortages occur in the experiment. The presumed supply shortages only condition is realistic in many current industrial operations since few customers will accept larger delivery quantities in these days. Two levels of C_V expressed as uncertainty are 0.05 and 0.15; and when the value of the actual receipt generated from equation (1) is negative, it is assumed to be 0.

When supply shortage occurs, the available inventory in the warehouse cannot meet the demand from two distribution centers. The way that the warehouse replenishes the "planned orders" from the two distribution centers is weighted by the planned order quantities from two distribution centers. For example, the planned order from DC1 is 40 units and the planned order from DC2 is 60 unit. Now warehouse only receives 80 units from the vendor. According to the "allocating method", 32 units are shipped to DC1 and 48 units are shipped to DC2. The same method is used to deal with the allocation problem between distribution centers and retailers.

FACTOR 4: Cost Values

In order to facilitate the inclusion of cost parameter changes into the model, a factor which combines inventory carrying cost and stockout cost is shown in Table 3.4. The cost values are varied over a high and low range. Inventory carrying cost is initially set at a rate of 10% of the dollar value carried at all channel members per year and is varied between 10% and 30%. The stockout cost is initially set at 10% of the dollar value per unit, and will be varied between 10% and 20%. The ordering cost is held constant at 30 times of product's nominal unit cost per order. This is a reasonable setup because it falls within the range of cost structures used in earlier related studies (Collier, 1982, Veral and LaForge, 1985).

FACTOR 5: Lot-sizing Rule

The use of a lot-sizing rule has a significant impact on the performance of a distribution system (Martin, 1993). The lot sizes and order frequencies determined by different lot-sizing rules may affect the variation of inventory carried in the distribution system. Several earlier studies identify the interaction between various types of uncertainties and a lot-sizing rule (Melnyk and Piper, 1985, Wemmerlov, 1989, Minifie and Robert, 1990). Furthermore, Collier (1982) suggests examining the relationship between safety stock policies and lot-sizing rules in an MRP system.

Table 3.4 Cost Values in the Experiment

Cost Component	Low Level Value	High Level Value
Ordering Cost	30	30
Carrying Cost	0.10	0.30
Stockout Cost	0.10	0.20

*The figures shown in the table are the fraction of nominal value of product.

Once the MRP user combines the lot-sizing rule with a safety stock policy, the cumulative effect must be understood. The same principle likely applies in a DRP system.

Two typical lot-sizing rules are applied in this study: lot-for-lot (L4L) and economic order quantity (EOQ). Lot-for-lot, known as a discrete ordering technique, is the simplest and most straightforward of all. It provides period-by-period coverage of net requirements, and the planned-order quantities always equal the quantity being covered. The use of this technique minimizes the inventory carrying cost but also increase the ordering cost.

The EOQ policy is a batch-type ordering technique. The lot size is decided by the equation as follows:

$$Q=\sqrt{\frac{2k\lambda}{h}} \qquad (2)$$

where λ is the forecasted annual demand

k is the ordering cost per order

h is the carrying cost per unit per year

For example, the lot size of retailer 1 is decided by the equation (2) as:

λ = 50 (unit/week)* 52 (week) = 2600 (unit/year)

k = 20 * (product's nominal cost/unit)

h = 0.25 *(product's nominal cost/unit)

$$Q=\sqrt{\frac{2k\lambda}{h}}=\sqrt{\frac{2\cdot 20\cdot 2600}{0.25}}=645\text{ (units)}$$

Usually EOQ ordering techniques cover the net requirements of several periods. Considering the truck-loading problem, which does not prefer the less-than-truck loading, exists in the operation of a distribution system. It is appropriate to apply EOQ ordering technique to meet truck-loading requirement by releasing an order size close to the full truck loading.

FACTOR 6: Safety Stock Policies

Safety stock provides protection against uncertainty occurring within or outside the physical distribution system. This study expands Schwaze's work (1981) and Allen's study (1983) to examine several different ways of allocating safety stocks among all distribution members based on a predetermined safety stock level. Eight different safety stock policies are shown in Table 3.5. Several safety stock policies are discussed as follows: Policy 1 is no buffering, and no safety stock is held at any channel members. Policy 1 may provide a benchmark which can be compared with other safety stock policies with buffering. Policy 2 is a so-called centralized safety stock policy; all the safety stocks are held at the warehouse. Policy 3 is a so-called decentralized safety stock policy; all the safety stocks are held at the retailer level. Furthermore, the

Table 3.5 Safety Stock Policies

Policies	Safety Stock Location and Amount of Safety Stock		
	Warehouse	Distribution Center	Retailer
1	0	0	0
2	1	0	0
3	0	0	1
4	0	1	0
5	1/3	1/3	1/3
6	1/2	1/2	0
7	1/2	0	1/2
8	0	1/2	1/2

Note: The figures are fraction of total safety stock in the system.

amount of safety stocks allocated to each retailer are based on the mean of the forecast demand. For example, the total amount of safety stocks invested in the distribution system is 300 units. Then the amount of safety stocks allocated to each retailer are 30, 60, 90, and 120 respectively based on the mean of forecast demand of each retailer shown in Table 3.2.

Policy 5 is that safety stocks are held at all levels in the distribution system. The same logic is used to allocate safety stocks between distribution centers as used in Policy 3. Again, if the total amount of safety stocks is 300 units. First, 100 units of safety stocks are allocated to each level; 100 units at warehouse, 100 units at two distribution centers, and 100 units at four retailers. Second, the way to allocate 100 units at two distribution centers is based on the mean of gross requirement. The mean of gross requirement of distribution center 1 is calculated by adding the means of forecast demand of retailer 1 and retailer 2, which is 150 units per period. The mean of gross requirement of distribution center 2 is calculated by the same way, which is 350 units per period. Then, 30 units of safety stocks is allocated at distribution center 1, and 70 units of safety stocks is allocated at distribution center 2. Finally, the same logic used in Policy 3 is applied to allocate safety stocks among retailers; 10 units allocated to retailer 1, 20 units allocated to retailer 2, 30 units allocated to retailer 3, and 40 units allocated to retailer 4.

Based upon previous studies, some people advocate placing safety stock near final users to protect against demand uncertainty, and at the warehouse higher level to protect against supply uncertainty (Moore, 1973, and Orlicky, 1975). Another view is to place safety stocks at all levels (Liaw, 1979, Chu, 1984).

The purpose of allocating safety stocks in the distribution system in different ways is to check the performance of different safety stock policies under various operating conditions.

Factors Bearing on the Sensitivity Analysis Experiments

The value-added factor is viewed as the transportation cost incurred when the product is shipped from the warehouse to lower echelon channel members in a multi-echelon distribution system. The purpose of the sensitivity analysis experiments is to examine the performance sensitivity of the factors held constant in the base experiments. Therefore, in the sensitivity analysis experiments, different combinations of the value-added factor are used to test the performance sensitivity caused by changing the value-added factor. A similar value-added approach is used by Collier (1982) and Ho (1992) to determine the costs incurred at each level in a distribution network. In their study, three levels of value-added factor

(0.05, 0.1, 0.2) are randomly chosen to determine item costs by the following equation:

$$C_{j+1} = C_j * (1+\alpha) \qquad (3)$$

Where:

C_j = the nominal unit cost of product at the jth level
α = the value-added factor, randomly selected from 0.05, 0.1, and 0.2.

It is assumed that the nominal unit cost of product at the warehouse is $1. If the value-added factor chosen is 0.05 when product is shipped from warehouse to the distribution centers, then the nominal unit cost of product at the distribution center is $1.05. Once the nominal value of product is changed, the inventory carrying cost, stockout cost and ordering cost are also affected. This is because all of cost components are calculated by the product's nominal value as defined previously. Table 3.6 presents four combinations of the cost structure used in the base and validation experiments. Different cost structures may stand for different products or different marketing channels. For example, the cost structure of a discount store like Wal-Mart is different from that of brand name store like Safeway supermarket.

Another factor considered in the sensitivity analysis experiment is to allow the distribution network to change as shown in Figure 3.2. Different products may be distributed by a different distribution network. In the sensitivity

Table 3.6 Cost Structure

	Channel Member*	Base Experiment		Validation Experiment					
		C1		C2		C3		C4	
Level		V/A**	Cost	V/A	Cost	V/A	Cost	V/A	Cost
1	W		1.0		1.0		1.0		1.0
		0.1		0.2		0.3		0.4	
2	DC1-DC2		1.1		1.2		1.3		1.4
		0.1		0.2		0.3		0.4	
3	R1-R4		1.21		1.44		1.69		1.96

* For channel member, W = warehouse; DC = distribution center; and R = retailer.

** V/A represents value-added factor.

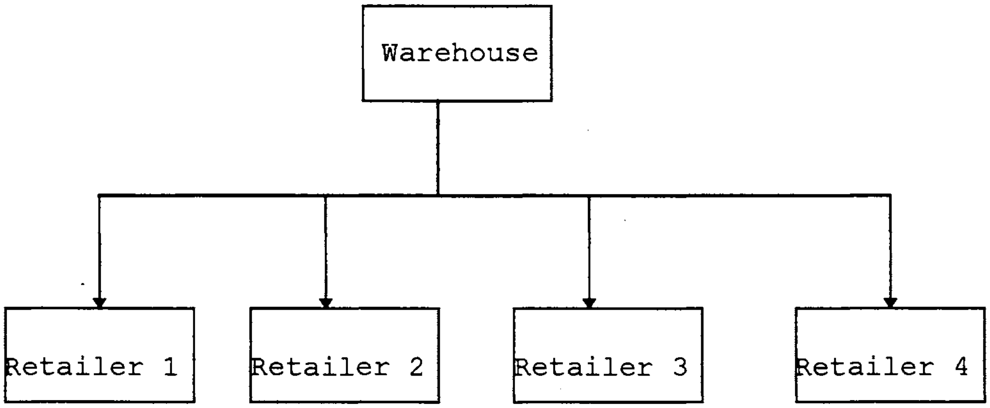


Figure 3.2 Distribution Network in Sensitivity Analysis

analysis experiment, products are shipped directly from warehouse to the retailers. This is because the geographic relationships between the warehouse and retailers are the same as a three-echelon distribution network, the same transportation mode is used to ship products. Therefore, the transportation lead time from warehouse to retailers is the sum of the original lead time from warehouse to distribution centers plus the original lead time from distribution centers to retailers.

The lead time distributions used in this sensitivity analysis experiment is modified Table 3.3 by changing lead time values from (1,2,3,4,5) to (2,4,6,8,10).

System Performance Measures

In general, the goal is to design and operate a physical distribution system to minimize total cost, and evaluate the performance of each channel member. One performance measure of the system is to examine the cost performance in terms of the sum of ordering cost, inventory carrying cost and stockout cost. To evaluate the performance of each channel member, three non-monetary performance measures are also applied at warehouse, distribution centers, and retailers:

- The Mean Service Level
- The Average Stockout Unit Per Period
- The Average Inventory Level

Total Related Cost

Three components which may affect the inventory plan in a physical distribution system are ordering cost, inventory carrying cost and stockout cost. The total related cost (TRC) is calculated for the whole simulation period. Ordering cost includes all the costs to release an order. Inventory carrying costs include a number of cost components, which vary with the quantity of inventory, and can be categorized into the following groups: (1) capital costs, (2) inventory service costs, (3) storage space costs, and (4) inventory risk costs (Lambert and Stock, 1993). The inventory carrying costs generally represent one of the highest costs in the physical distribution system. La Londe and Lambert (1975) present a methodology designed to provide managers with a practical framework for determining the costs of carrying inventory. Usually, the costs range from 12% to 35% of product value.

Different inventory carrying costs may occur at different locations in the physical distribution system. The main reason for using different inventory carrying costs is the transportation value added to products when products are shipped from one channel member to another. The effect of the value-added factor is examined in the sensitivity analysis experiment. Stockout costs include all of those costs which occur directly or indirectly as a consequence of an out-of-stock condition at all inventory locations. Usually, an expected value is used to include all consequences of stockout and their penalties. An example of calculating stockout cost in terms of the percentage of a product's nominal value is shown as:

Outcomes of stockout	Probability	cost/unit
Losing the customer	0.05	50%
Waiting for products	0.30	5%
Finding a substitute from the same company	0.25	10%
Finding a substitute from other companies	0.20	25%
Not purchasing	0.20	5%

The expected value of stockout cost per unit is :

[(0.05*50%)+(0.30*5%)+(0.25*10%)+(0.20*25%)+(0.20*5%)]

= 12.5%(per unit)

Different levels stockout costs are used to present different impacts on the system's performance in the base experiment. Furthermore, different stockout costs are applied at all inventory locations by considering a value-added factor in the sensitivity analysis experiments. Finally, the total related cost (TRC) function is defined as:

$$TRC = \sum_i \sum_j \sum_k O_{ijk} + \sum_i \sum_j \sum_k C_{ijk} + \sum_i \sum_j \sum_k S_{ijk} \qquad (4)$$

where O_{ijk} = ordering cost of channel level(i), channel member(j) at period(k)

C_{ijk} = inventory carrying cost of channel level(i), channel member(j) at period(k)

S_{ijk} = Stockout cost of channel level(i), channel member(j) at period(k)

i = 1,2,3 (1=warehouse, 2=distribution center, 3=retailer)

j = 1 when i=1 (warehouse)

= 1,2 when i=2 (1=distribution center 1; 2=distribution center 2)

= 1,2,3,4 when i=3 (1=retailer 1; 2=retailer 2; 3=retalier 3; 4=retailer 4)

k = 1,..., n (n periods)

The Mean Service Level

The mean service level measures the ability of the physical distribution system to satisfy the demand from outside customers or other channel members in the system. It is the percentage of total demand which is satisfied by available inventory. This proportion is calculated as the sum of the minimum number of product units in each time period which is either available in inventory or demanded, divided by the total product demand. For example, during one simulation run, the total amount of products calculated by the above method is 875 units and the total demand is 1000 units. Then the mean service level is calculated as:

$$\text{Mean Service Level} = \frac{875}{1000} = 87.5\%$$

Thus, a mean service level of 1.0 indicates that all product demands are satisfied. The mean service level is recorded for each channel member in the system.

The Average Stockout Units Per Period

When the available inventory amount can not meet current demand, a shortage occurs. This is known as a stockout. The stockout is calculated as:

stockout units = max [actual demand - (on-hand inventory + in-transit),0]

The records are kept for each channel member as an individual performance measure. Then, the average stockout units per period is calculated as the sum of the stockout units of each period, divided by the total number of periods in one simulation experiment.

The Average Inventory Level

The average inventory level for each period is calculated as the average of beginning inventory and ending inventory. The average inventory level of each simulation experiment is calculated as the sum of average inventory of each period, divided by the total number of periods in one simulation experiment. Again, the average inventory level is recorded for each channel level.

Research Hypothesis

The main purpose of this research is to investigate the impact of demand uncertainty, transportation lead time uncertainty and supply uncertainty on a multi-echelon distribution system's performance and then to evaluate the effects of various safety stock policies under different operating conditions. Furthermore, the impacts of changing cost structure and distribution network on a multi-echelon distribution system are examined.

To achieve the research objectives defined previously, the formal hypotheses statements are presented. The first six hypotheses are about the main effects of experimental factors used in this study on the specified performance criterion. The next four hypotheses are about the interactions between the safety stock policies and three types of uncertainty, and the interaction between the safety stock policies and different lot-sizing rules. These hypotheses are used to test whether the relative effect of the safety stock policies differ when the level of three types of uncertainty are varied and the lot-sizing rules are changed. The hypotheses are stated in detail as follows:

Hypotheses on Total Related Cost

1: There is no significant difference in distribution system performance as measured by the total related cost for the whole system among different levels of demand uncertainty.

2: There is no significant difference in distribution system performance as measured by the total related cost for the whole distribution system among different levels of transportation lead time uncertainty.

3: There is no significant difference in distribution system performance as measured by the total related cost for the whole distribution system among different levels of supply uncertainty.

4: There is no significant difference in distribution system performance as measured by the total related cost for the whole distribution system among different safety stock policies.

5: There is no significant difference in distribution system performance as measured by the total related cost for the whole distribution system when different lot-sizing rules are used.

6: There is no significant difference in distribution system performance as measured by the total related cost for the whole system among different cost values of inventory carrying cost, stockout cost, and ordering cost.

7: There is no significant difference in distribution system performance as measured by the total related cost for the whole system under different safety stock policies when different lot-sizing rules are used.

8: There is no significant difference in distribution system performance as measured by the total related cost for the whole system under different levels of demand uncertainty when different safety stock policies are used.

9: There is no significant difference in distribution system performance as measured by the total related cost for the whole system under different levels of transportation lead time uncertainty when different safety stock policies are used.

10:There is no significant difference in distribution system performance as measured by the total related cost for the whole system under different levels of supply uncertainty when different safety stock policies are used.

Hypotheses on Average Stockout Units

11:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members among different levels of demand uncertainty.

12:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members among different levels of transportation lead time uncertainty.

13:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members among different levels of supply uncertainty.

14:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members among different safety stock policies.

15:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members when different lot-sizing rules are used.

16:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members among different cost values of inventory carrying cost, stockout cost, and ordering cost.

17:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members under different safety stock policies when different lot-sizing rules are used.

18:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members under different levels of demand uncertainty when different safety stock policies are used.

19:There is no significant difference in distribution system performance as measured by the average stockout units at each channel members under different levels of transportation lead time uncertainty when different safety stock policies are used.

20:There is no significant difference in distribution system performance as measured the average stockout units at each channel members under different levels of supply uncertainty when different safety stock policies are used.

Hypotheses on Average Inventory Level

21:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members among different levels of demand uncertainty.

22:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members among different levels of transportation lead time uncertainty.

23:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members among different levels of supply uncertainty.

24:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members among different safety stock policies.

25:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members when different lot-sizing rules are used.

26:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members among different cost values of inventory carrying cost, stockout cost, ordering cost.

27:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members under different safety stock policies when different lot-sizing rules are used.

28:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members under different levels of demand uncertainty when different safety stock policies are used.

29:There is no significant difference in distribution system performance as measured by the average inventory level at each channel members under different levels of transportation lead time uncertainty when different safety stock policies are used.

30:There is no significant difference in distribution system performance as measured the average inventory level at each channel members under different levels of supply uncertainty when different safety stock policies are used.

Hypotheses on Mean Service Level

31:There is no significant difference in distribution system performance as measured by the mean service level at each channel members among different levels of demand uncertainty.

32:There is no significant difference in distribution system performance as measured by the mean service level at each channel members among different levels of transportation lead time uncertainty.

33:There is no significant difference in distribution system performance as measured by the mean service level at each channel members among different levels of supply uncertainty.

34:There is no significant difference in distribution system performance as measured by the mean service level at each channel members among different safety stock policies.

35:There is no significant difference in distribution system performance as measured by the mean service level at each channel members when different lot-sizing rules are used.

36:There is no significant difference in distribution system performance as measured by the mean service level at each channel members among different cost values of inventory carrying cost, stockout cost, ordering cost.

37:There is no significant difference in distribution system performance as measured by the mean service level at each channel members under different safety stock policies when different lot-sizing rules are used.

38:There is no significant difference in distribution system performance as measured by the mean service level at each channel members under different levels of demand uncertainty when different safety stock policies are used.

39:There is no significant difference in distribution system performance as measured by the mean service level at each channel members under different levels of transportation lead time uncertainty when different safety stock policies are used.

40:There is no significant difference in distribution system performance as measured the mean service level at each channel members under different levels of supply uncertainty when different safety stock policies are used.

Experimental Design

The main objective of this study is to examine the impact of three different types of uncertainties on a multi-echelon distribution system under various safety stock policies. The simulation models are written in the FORTRAN programming language. A full factorial design is used in the analysis and the evaluation of the research hypotheses. A summary of the experimental factors and their number of levels in the base experiments is shown in Table 3.7.

There are 256 experimental conditions in the base experiments. Five replications are made for each

Table 3.7 Summary of Experimental Factors Used in the Base Experiment and Their Levels

Factors	Levels
Demand quantity uncertainty	2
Lead time uncertainty	2
Supply quantity uncertainty	2
Cost value	2
Lot-sizing rule	2
Safety stock policy	8
Replications	5
Total observations	1280

experimental condition. A similar number of replications is used in previous research (Carlson, Krop and Juker, 1983, Grasso and Taylor III, 1984, Sridharn and LaForce, 1989). The random number generator used in this study is a linear congruential generator (LCG), introduced by Lehmer (1951). This random number generator provides an accurate approximation to the true continuous U(0,1) distribution. Furthermore, the demand forecast, the forecast error terms and the supply uncertainty are generated from normal distributions using the polar method as described in Law and Kelton (1991).

The MINITAB package is used in the statistical analysis of the results. Separately ANOVA procedures are used to determine the effects of the experimental variables on total related cost (TRC) of the whole distribution system, and mean service level, average stock units, and average inventory level for each channel members in the distribution system.

CHAPTER IV

SIMULATION MODEL

Simulation is the tool used to answer the research questions in this study. The first part of this chapter presents the flowcharts for the simulation programs of the multi-echelon distribution system and illustrates the logic of operating the DRP system. Then, several statistical issues in simulation are addressed. The last section of this chapter illustrates the procedures used to verify and to validate the simulation model.

Formulation of the Simulation Model

The simulation programs are written in the FORTRAN programming language as shown in Appendix A. The main program's flowchart of the multi-echelon distribution system is shown in Figure 4.1. First, the levels of experimental factors as shown in Table 3.1 are specified in the beginning of every simulation run. These experimental factors include demand uncertainty, supply uncertainty, lead time uncertainty, cost values and lot-sizing rule. Once they are specified, 40 simulation runs are executed with five replications for each sof the eight afety stock policies under each specific experimental condition. A macroscopic view of the simulation experiment is shown in Figure 4.2.

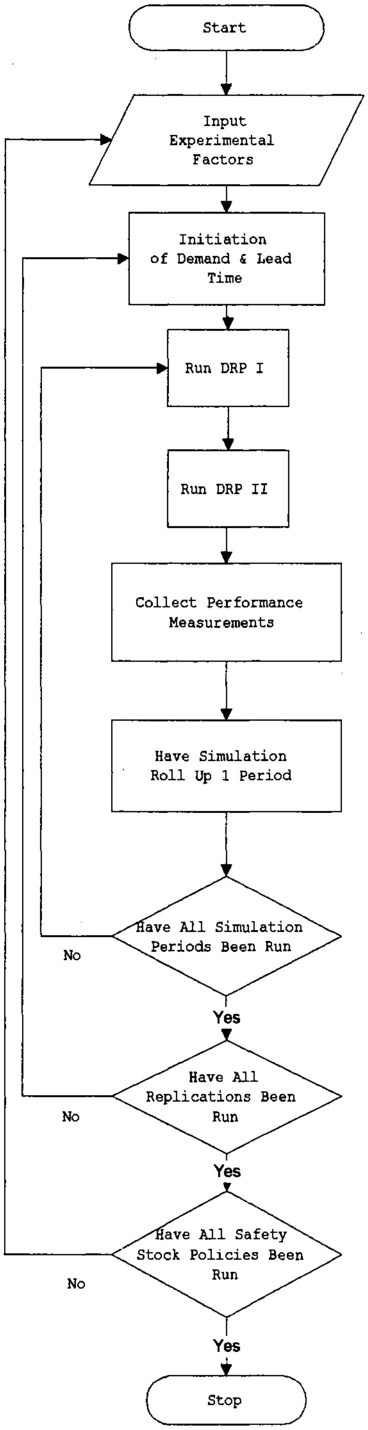
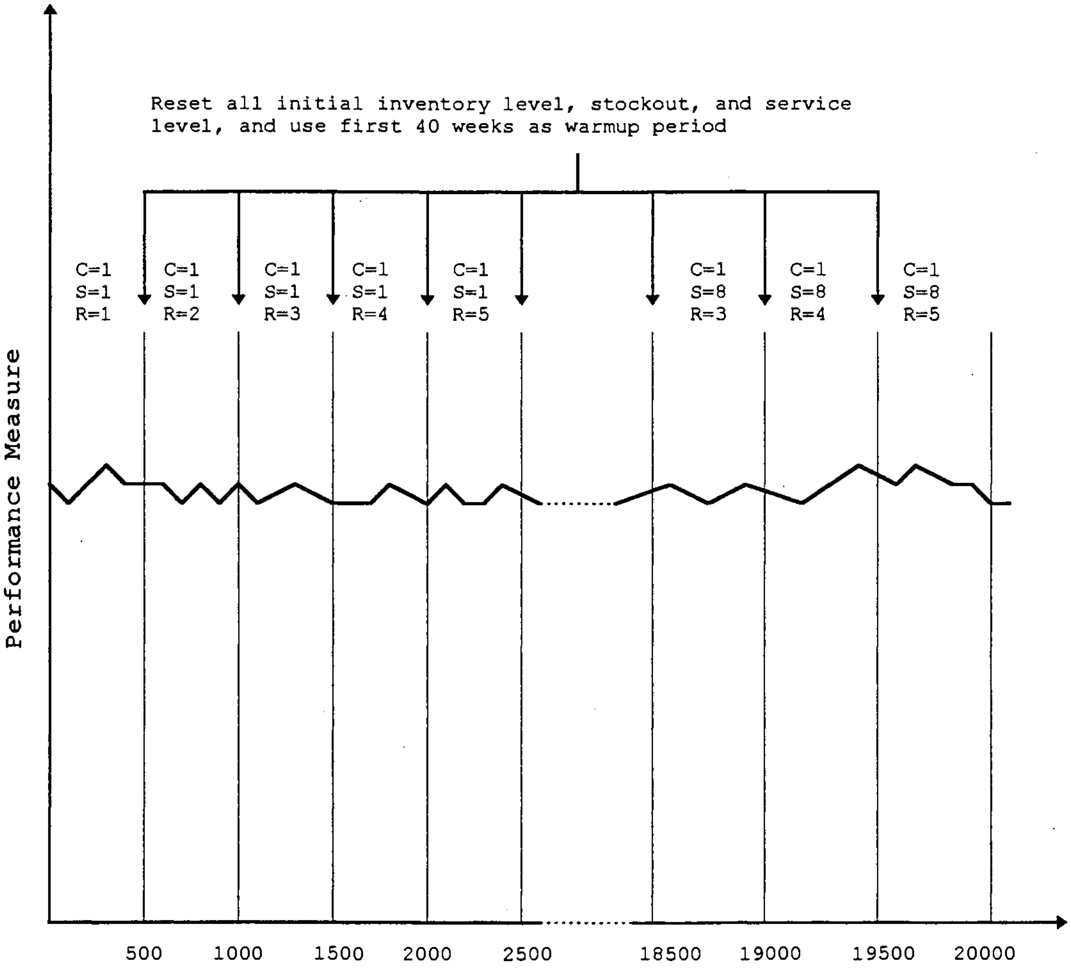


Figure 4.1 Main Program Flowchart



Simulation Time

C: Experimental Factor Combination
S: Safety Stock Policy
R: Replication

Figure 4.2 A Macroscopic View of the Simulation Experiment

As observed in Figure 4.2, the batch sampling is used to collect data for evaluating the performance of various safety stock policies without reinitialization the random number seed. In turn, this may cause more variabilty in the simulation output data. Future research should consider applying common random number streams to each safety stock policy to reduce the variances of the output random variable by reinitialization (Law and Kelton, 1991).

As shown in Figure 4.2, after initializating inventory level, stockout, and service level, the forecast and actual requirements for 500 periods at retailers are generated. The actual supply rates from vendor to warehouse and the actual lead time taken to ship products within channel members are also generated. The first 40 periods of each 500 period block are used as warmup data which is discarded.

The DRP I module shown in Figure 4.3 is used to explain how the DRP information flow works in the multi-echelon distribution system. The DRP records for the first 12 periods of each channel are also shown in Table 4.1 to illustrate an example of DRP logic.

Table 4.1 is the initial DRP schedule of a three-echelon distribution system, used to demonstrate the information flow and scheduling mechanism of DRP. There are four retailers (R_j), two distribution centers (DC_j), and one warehouse (W) in this distribution system. A basic DRP record is shown in Table 1.2, and a more detailed description of DRP records is explained as follows:

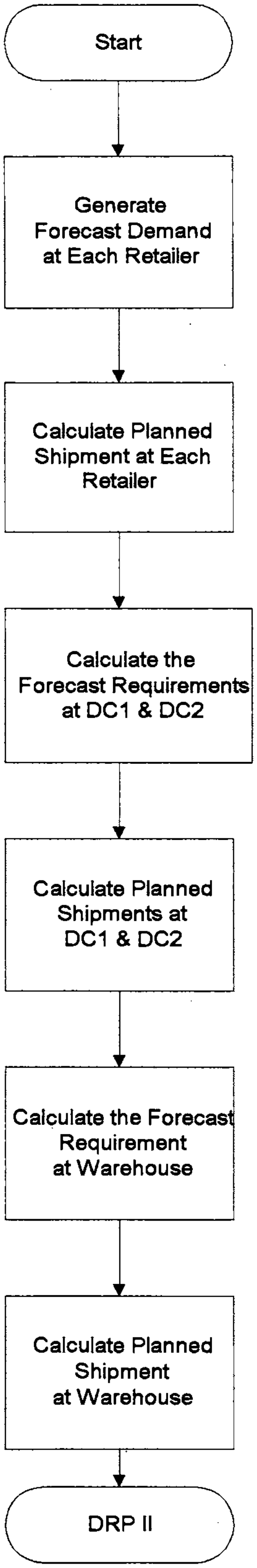


Figure 4.3 DRP I: DRP Information Flowchart

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		47	58	44	46	30	38	56	37	67	48	33	41
In-Transit		47	58	44									
P.A.B.	10	10	10	10	10	10	10	10	10	10	10	10	10
Planned Receipt					46	30	38	56	37	67	48	33	41
Planned Shipment		46	30	38	56	37	67	48	33	41			

R1
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 10

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		135	107	105	116	97	90	129	105	95	95	98	105
In-Transit		135	107	105									
P.A.B.	20	20	20	20	20	20	20	20	20	20	20	20	20
Planned Receipt					116	97	90	129	105	95	95	98	105
Planned Shipment		116	97	90	129	105	95	95	98	105			

R2
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 20

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		118	151	169	154	94	166	130	185	183	108	119	150
In-Transit		118	151	169									
P.A.B.	30	30	30	30	30	30	30	30	30	30	30	30	30
Planned Receipt					154	94	166	130	185	183	108	119	150
Planned Shipment		154	94	166	130	185	183	108	119	150			

R3
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 30

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		267	263	199	168	199	219	194	203	192	225	176	193
In-Transit		267	263	199									
P.A.B.	40	40	40	40	40	40	40	40	40	40	40	40	40
Planned Receipt					168	199	219	194	203	192	225	176	193
Planned Shipment		168	199	219	194	203	192	225	176	193			

R4
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 40

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		162	127	128	185	142	162	157	131	146			
In-Transit		162	127	128									
P.A.B.	30	30	30	30	30	30	30	30	30	30			
Planned Receipt					185	142	162	157	131	146			
Planned Shipment		185	142	162	157	131	146						

DC1
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety stock: 30

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		322	293	385	324	388	375	333	295	343			
In-Transit		322	293	385									
P.A.B.	70	70	70	70	70	70	70	70	70	70			
Planned Receipt					324	388	375	333	295	343			
Planned Shipment		324	388	375	333	295	343						

DC2
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 70

Period		1	2	3	4	5	6	7	8	9	10	11	12
Forecast Requirement		509	530	537	490	426	489						
In-Transit		509	530	537									
P.A.B.	100	100	100	100	100	100	100						
Planned Receipt					490	426	489						
Planned Shipment		490	426	489									

W
Planned Lead Time: 3 periods
Lot Sizing Rule: Lot-for-Lot
Safety Stock: 100

Table 4.1 An Example of DRP Table at Each Channel Member

Forecast Requirement: The expected demand for the product occurs in each time period. At retailers, the forecast requirements are generated from specific distributions. At distribution centers and the warehouse, the forecast requirements are calculated from the lower level's planned shipment. In Table 4.1, the forecast requirement for DC_1 is 162 in week 1, which is calculated by adding the planned shipment of R_1 in week 1 (46) to the planned shipment of R_2 in week 1 (116). The forecast requirement for W in week 1 (509) is calculated by the same method, adding the planned shipment of DC_1 in week 1 (185) to the planned shipment of DC_2 in week 1 (324).

In-Transit: This is the open order scheduled to be received by the warehouse, distribution centers or retailers in the beginning of each time period. One assumption made is that the in-transit quantities in the first three periods are equal to forecast requirements in the first three periods considered.

Projected Available Balance (PAB): The expected on-hand inventory of a channel member at the end of each time period, and the amount is calculated as follows:

$$\text{P.A.B.}_{(t)} = \text{MAX}(\text{P.A.B.}_{(t-1)} + \text{Planned Receipt}_{(t)} + \text{In-Transit}_{(t)} - \text{Forecast Requirement}_{(t)}\ ,\ 0)$$

As shown in Table 4.1, the projected available balance of retailer 2 in week 4 is calculated as: MAX(20+116-116,0)=20.

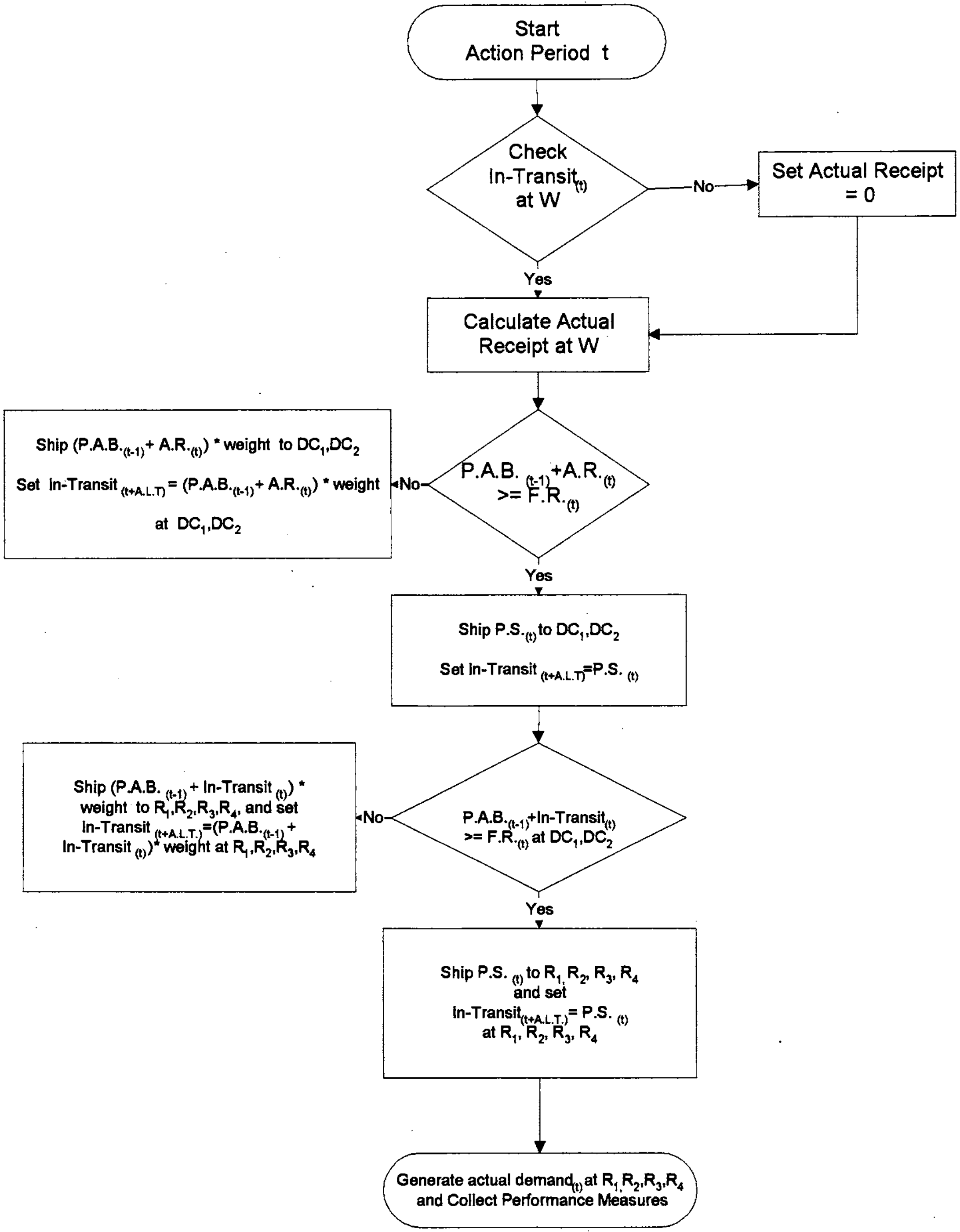
Net Requirement: This is the projected quantity needed in each time period to prevent a stockout. The net requirement is calculated as follows:

$N.R._{(t)} = MAX(\text{Forecast Requirement}_{(t)} + \text{Safety Stock}_{(t)} - (P.A.B._{(t-1)} + \text{In-Transit}_{(t)}), 0)$

Planned Receipt: This indicates the planed receipt in the beginning of each time period, and the quantity of the planned receipt is decided by lot-sizing rules. In this study, only lot-for-lot (L4L) and economic order quantity (EOQ) are applied to calculate the planned receipt quantity. The planned receipt is equal to net requirement when L4L is used. And, the planned receipt is calculated by the EOQ formula when EOQ is applied to be the lot-sizing rule.

Planned Shipment: This indicates a planned order to be released in the beginning of each time period. The planned shipment is calculated by offsetting the lead time for the planned receipt in each time period.

The DRP II module shown in Figure 4.4 is used to explain the physical flow and inventory replenishment method in the multi-echelon distribution system. At first, the actual receipt in the action period at the warehouse is calculated by considering supply uncertainty, and then checking whether the available inventory at the warehouse is enough to replenish the demand from two distribution centers. If the available inventory is more than the requirement, then the exact quantity required is shipped to



A.R. : Actual Receipt
Weight: Determined by Order Quantity

Figure 4.4 DRP II: DRP Physical Flow

the two distribution centers. If the available inventory is less than the requirement, the warehouse is allowed to replenish the order partially. The quantities shipped to the two distribution centers are weighted by the order quantities. For instance, let 100 units be required by two distribution centers at in the beginning of period t, 30 units from DC_1 and 70 units from DC_2. Let there be only 80 units available at the warehouse. According to the weightedmethod, 24 units are shipped to DC_1, and 56 units are shipped to DC_2.

The transportation time is generated from specific probability distributions to determine the shipping time actually taken from the warehouse to the distribution centers. The same method applied at the warehouse is used to determine the shipping quantity and transportation time from distribution centers to retailers. The "Status Update" and "Data Collection" are two main activities in the "Collect Performance Measurement" event as shown in Figure 4.1. These activities are simply the actions to advance the simulation in time by changing the ending stock status to beginning status, advancing shipments in transit, and recording period fill rates, stockouts, and inventory levels of all channel members.

In summary, the simulation occurs as a repeated sequence of four events in a period: (1) demand forecast at retailers, (2) inventory review and ordering at all channel members, (3) inventory replenishment at all channel members, and (4) collection and update of performance measurements. The simulation at a specific configuration of the experimental condition operates for a specific number of time periods and then calculates an average of the periods' performance.

Statistical Issues in Simulation

Three important issues are considered in this study when conducting the simulation experiment. These are: (1) the model initialization and steady state conditions, (2) the determination of the run length, and (3) the determination of the number of replications.

To facilitate the system reaching a steady state condition, two assumptions are made regarding the initial conditions. First, the on-hand inventory in the beginning at each channel member is equal to its safety stock level. Second, the in-transit quantities of the first three periods are equal to the forecast requirements at each channel member. A pilot run is made to determine the warm-up period at which a steady state is reached. The pilot run use the L4L rule with high demand uncertainty, high lead time uncertainty, and high supply uncertainty. The main reason to have the pilot run under high uncertainty is to ensure that the warm-up period found in the pilot run exceeds those warm-up periods found using other experimental conditions.

Initially, the simulation is run for 500 periods, and the method used to find the warm-up period is based on

Welch's procedure (1981, 1983). Its specific goal is to determine a time index l such that $E(Y_i) \approx v$ for $i > l$, where l is the warm-up period, $E(Y_i)$ is the process mean at period i, and v is the steady state mean of the system. The statistic collected in the pilot run is the moving average of total related cost with window size w equals 30 (61 averaged observations) based on 5 replications as shown in Figure 4.5.

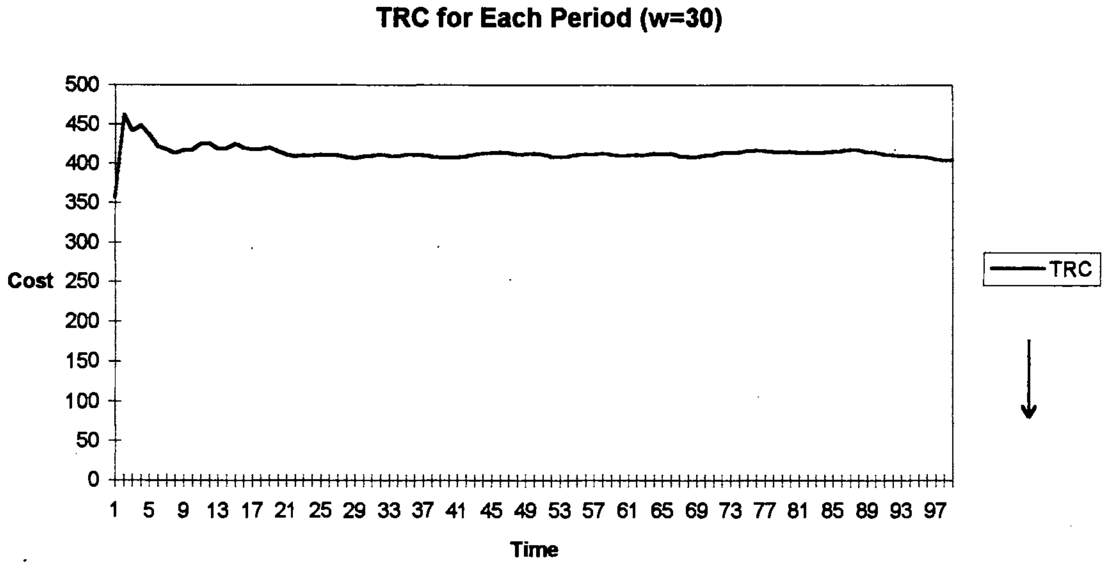


Figure 4.5 Moving Averages for TRC of the System

reaches a stead state within 30 to 40 periods, so a truncation point is determined to be 40 periods in this study.

There is no explicit rule to determine the run length of the simulation experiment. However, a larger run length is used to avoid those biased observations. Based on rule of thumb, the simulation run length is at least ten times that of warmup period. Therefore, the simulation is run for 40 periods initially, and all statistics on cost, inventory, and stockout are cleared. Then, each experimental condition is simulated for an additional 400 periods. For example, each experimental condition is run until the 440 periods are completed.

Neter and Wesserman (1974) suggest that planning of sample size can be determined by controlling the desired confidence intervals. The following equation is used to determine the necessary sample size.

$$n = \frac{t^2 s^2}{d^2}$$

where n = sample size

$t_{\alpha/2,\ n-1}$ = tabulated t value for the desired confidence level from pilot run

d = the half-width of the desired confidence interval

s = the estimate of the standard deviation from pilot runs

Five replications are made based on initial conditions and the run length specified above. The results show s is equal to 3.46 and $t_{0.025,\ 4}$ is equal to 2.776 for the TRC at the 0.05 level of significance. The half-width of the desired confidence interval is set to be 4.22, which is 1% of the average of the pilot run. The number of replications are decided by the above equation, the result is calculated as follows:

$$n = \frac{(2.776)^2(3.46)^2}{4.22^2} = 5.18$$

Based on the result, the closest integer is five. The same numbers of replications are adopted in other similar studies (Blackburn et al., 1986; Whybark and Wemmerlov, 1984). Therefore, five replications are used to collect data for all experimental conditions in this study.

Model Verification and Validation

Verification refers to the comparison of the conceptual model to the computer code used to implement the concept. Many common sense suggestions about model verification are given by Banks and Carson (1984). Two approaches are used to verify the simulation model in this study. One approach is the use of trace. A detailed computer output which gives the value of every variable in a DRP table for the first 24 iterations is compared with the results from manual simulation. The results show the value of variables in a

DRP table from the computer program are exactly the same as the results from manual simulation. Thus, the program of the simulation model can represent the conceptual model in this study.

Another approach suggested by Banks and Carson is a close and thorough examination of the module output for reasonableness under a variety of settings of the input parameters. All the uncertainties are removed from the model. Forecast requirements at retailers 1, 2, 3, and 4 are equal to 50, 100, 150, and 200, respectively. The transportation lead time from warehouse to distribution centers and from distribution centers to retailers are equal to 3 weeks. And, the vendor ships the amount of product which the warehouse requests. The results from the module output are as expected; no stockout occurs at any channel member, and the Projected Available Balance is equal to the safety stock level.

Validation is determining whether a simulation is an accurate representation of the system under study (Law and Kelton, 1991). An idealistic goal in validation is to ensure that a model is developed which can actually be used by a decision maker to make the same decision that would be made if it were feasible and cost-effective to experiment with the system itself (Law and Kelton, 1991).

A three-step approach is proposed by Naylor and Finger (1967) for validating a simulation model:

Step 1: Develop a model with high face validity.

Step 2: Test the assumptions of the model empirically.

Step 3: Determine how representative the simulation output data are.

It is generally impossible to validate a simulation model completely. Two aspects are checked to validate the simulation model used in this study. First, the assumptions of the input distributions are tested. Two distributions are examined here. One is the forecast demand which occurs at retailer 1 and the other is the uniform lead time distribution. As shown in Table 4.2, the results show that the observed forecast demand at retailer 1 is fitted to a normal distribution with mean (49.798) and variance (105.2066). And, the lead time distribution is fitted to a uniform distribution with mean (2.96) and variance (1.98). Both results are very close to theoretical values.

Table 4.2 Empirical and Theoretical Mean and Variance of Two Input Distributions

	Normal Distribution	Uniform Distribution
Empirical Mean	49.796	2.96
Empirical Variance	105.207	1.980
Theoretical Mean	50	3
Theoretical Variance	100	2.083

Second, a sensitivity analysis is conducted to determine if the simulation model output changes reasonably when the value of an input parameter is changed, or when a safety stock policy is changed. It is found that the multi-echelon distribution system with safety stock at all levels ($139.28/period) performs better than the one without safety stock ($392.91/period) in terms of the mean total related cost of the distribution system. Furthermore, the mean total related cost for a system with low demand uncertainty ($401.86/period) is lower than the system with high demand uncertainty ($449.99/period). It can be concluded the simulation model can represent the system under study. The results of the simulation are presented and discussed in the next section.

CHAPTER V

RESULTS

In the following sections the results of the Analysis of Variance for total related cost of the entire distribution system, and the stockout, inventory level, and service level for each channel member are presented, respectively. Finally, a summary of the results for all performance criteria is shown in the last section.

Results for Total Related Costs Analysis

As shown in Table 5.1, Analysis of Variance (ANOVA) is performed on the total related cost obtained from the simulation. The total related cost (TRC) is defined as the sum of inventory carrying cost, stockout cost and order cost incurred at each channel member. Mean TRC, averaged over the whole simulation, is used as an aggregate performance measure for the distribution system. The analysis consists of 1280 data points, with five replications for each of the 256 experimental conditions. The ANOVA results for the main effects and the interactions of safety stock policy with all other effects are shown in Table 5.1. The results lead to the rejection of hypotheses 1, 2, 3, 4, 5, 6, 7, 8, and 9, but there is not enough evidence to reject hypothesis 10 at the 5% significant level. All the hypotheses are

Table 5.1 ANOVA Results for Mean TRC

Analysis of Variance for Mean TRC

Source	DF	SS	MS	F	P
L.R.	1	68009305	68009305	3861.23	0.000
D.U.	1	741339	741339	42.09	0.000
L.T.	1	976612	976612	55.45	0.000
S.U.	1	190273	190273	10.80	0.001
C.V.	1	17290525	17290525	981.67	0.000
S.S.	7	89474673	12782096	725.70	0.000
L.R.*D.U.	1	746969	746969	42.41	0.000
L.R.*L.T.	1	937886	937886	53.25	0.000
L.R.*S.U.	1	111200	111200	6.31	0.012
L.R.*C.V.	1	12717110	12717110	722.01	0.000
L.R.*S.S.	7	88853765	12693395	720.67	0.000
D.U.*L.T.	1	120085	120085	6.82	0.009
D.U.*S.U.	1	10064	10064	0.57	0.450
D.U.*C.V.	1	33140	33140	1.88	0.170
D.U.*S.S.	7	602613	86088	4.89	0.000
L.T.*S.U.	1	81546	81546	4.63	0.032
L.T.*C.V.	1	69235	69235	3.93	0.048
L.T.*S.S.	7	550186	78598	4.46	0.000
S.U.*C.V.	1	15223	15223	0.86	0.353
S.U.*S.S.	7	205550	29364	1.67	0.113
C.V.*S.S.	7	4582729	654676	37.17	0.000
L.R.*D.U.*L.T.	1	122227	122227	6.94	0.009
L.R.*D.U.*S.U.	1	10671	10671	0.61	0.437
L.R.*D.U.*C.V.	1	33211	33211	1.89	0.170
L.R.*D.U.*S.S.	7	610100	87157	4.95	0.000
L.R.*L.T.*S.U.	1	60518	60518	3.44	0.064
L.R.*L.T.*C.V.	1	97731	97731	5.55	0.019
L.R.*L.T.*S.S.	7	612172	87453	4.97	0.000
L.R.*S.U.*C.V.	1	22869	22869	1.30	0.255
L.R.*S.U.*S.S.	7	146206	20887	1.19	0.308
L.R.*C.V.*S.S.	7	4208280	601183	34.13	0.000
D.U.*L.T.*S.U.	1	15272	15272	0.87	0.352
D.U.*L.T.*C.V.	1	37192	37192	2.11	0.147
D.U.*L.T.*S.S.	7	481162	68737	3.90	0.000
D.U.*S.U.*C.V.	1	758	758	0.04	0.836
D.U.*S.U.*S.S.	7	161497	23071	1.31	0.242
D.U.*C.V.*S.S.	7	501867	71695	4.07	0.000
L.T.*S.U.*C.V.	1	12594	12594	0.72	0.398
L.T.*S.U.*S.S.	7	215366	30767	1.75	0.095
L.T.*C.V.*S.S.	7	589526	84218	4.78	0.000
S.U.*C.V.*S.S.	7	104194	14885	0.85	0.550
L.R.*D.U.*L.T.*S.U.	1	14737	14737	0.84	0.361
L.R.*D.U.*L.T.*C.V.	1	36942	36942	2.10	0.148
L.R.*D.U.*L.T.*S.S.	7	484535	69219	3.93	0.000
L.R.*D.U.*S.U.*C.V.	1	812	812	0.05	0.830
L.R.*D.U.*S.U.*S.S.	7	160404	22915	1.30	0.246
L.R.*D.U.*C.V.*S.S.	7	501098	71585	4.06	0.000
L.R.*L.T.*S.U.*C.V.	1	15711	15711	0.89	0.345
L.R.*L.T.*S.U.*S.S.	7	197993	28285	1.61	0.130
L.R.*L.T.*C.V.*S.S.	7	562664	80381	4.56	0.000
L.R.*S.U.*C.V.*S.S.	7	114542	16363	0.93	0.483
D.U.*L.T.*S.U.*C.V.	1	20458	20458	1.16	0.281
D.U.*L.T.*S.U.*S.S.	7	127166	18167	1.03	0.407
D.U.*L.T.*C.V.*S.S.	7	712933	101848	5.78	0.000
D.U.*S.U.*C.V.*S.S.	7	152693	21813	1.24	0.279
L.T.*S.U.*C.V.*S.S.	7	151815	21688	1.23	0.282
L.R.*D.U.*L.T.*S.U.*C.V.	1	20645	20645	1.17	0.279
L.R.*D.U.*L.T.*S.U.*S.S.	7	127712	18245	1.04	0.404
L.R.*D.U.*L.T.*C.V.*S.S.	7	712765	101824	5.78	0.000
L.R.*D.U.*S.U.*C.V.*S.S.	7	153110	21873	1.24	0.277
L.R.*L.T.*S.U.*C.V.*S.S.	7	155174	22168	1.26	0.268
D.U.*L.T.*S.U.*C.V.*S.S.	7	148835	21262	1.21	0.296
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	148917	21274	1.21	0.295
Error	1024	18036102	17613		
Total	1279	317121207			

shown in Chapter Three. The analysis of significant main effects and the interactions of safety stock policy with lot-sizing rule, demand uncertainty, and transportation lead time uncertainty are addressed below.

Main Effects

Six main experimental factors are considered in this study. These are: lot-sizing rule (L.R.), demand uncertainty (D.U.), lead time uncertainty (L.T.), supply uncertainty (S.U.), cost value (C.V.), and safety stock policy (S.S.). A plot of main effects for mean TRC is presented in Figure 5.1, and the mean TRC for each main effect at each level is shown in Table 5.2. Visual examination of the experimental results in Figure 5.1 shows that economic order quantity (EOQ) yields much higher mean TRC than lot-for-lot (L4L).

The negative results of the three sources of uncertainties are expected. The mean TRC is higher when demand uncertainty increases. This is mainly because more stockouts occur at all channel members. The mean TRC increases 14% when transportation lead time follows a discrete uniform distribution. This is because a great number of purchased products are received early as well as late. As the supply shortage increases, the mean TRC also increases. This is because the supply shortage incurred at the warehouse may cause stockouts at all channel members.

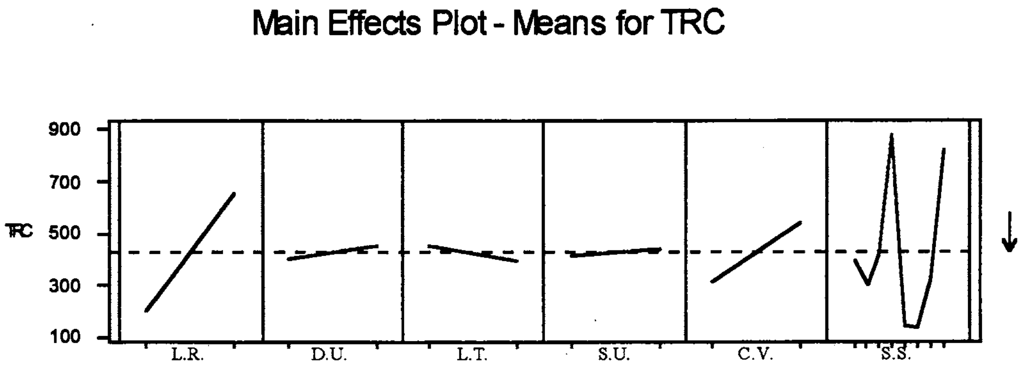


Figure 5.1 Main Effects Plot for Mean TRC

Table 5.2 Mean TRC of Each Main Effect at Each Level of the System

```
              Means

L.R.          N         TRC
1           640      195.42
2           640      656.43

D.U.          N         TRC
1           640      401.86
2           640      449.99

L.T.          N         TRC
1           640      453.55
2           640      398.31

S.U.          N         TRC
1           640      413.73
2           640      438.12

C.V.          N         TRC
1           640      309.70
2           640      542.15

S.S.          N         TRC
1           160      392.91
2           160      296.96
3           160      420.44
4           160      881.20
5           160      139.58
6           160      135.14
7           160      319.82
8           160      821.38
```

As shown in Figure 5.2, the best safety stock policy is policy 6 in terms of the mean TRC, and policy 5 is the second best. Policy 6 allocates safety stocks at the warehouse and two distribution centers to absorb the uncertainties incurred in the system. Policy 5 allocates safety stocks evenly among three levels to deal with uncertainties. Policies 4 and 8 result in much higher mean TRC than other safety stock policies. This is mainly caused by allocating no safety stock at the warehouse. Once the stockout occurs at distribution centers or retailers, the warehouse can not replenish the stock in time.

Finally, as the cost value of inventory carrying cost increases, the mean TRC also increases. To examine the interactions between main effects, the mean TRC averaged over five replications are presented in Table 5.3.

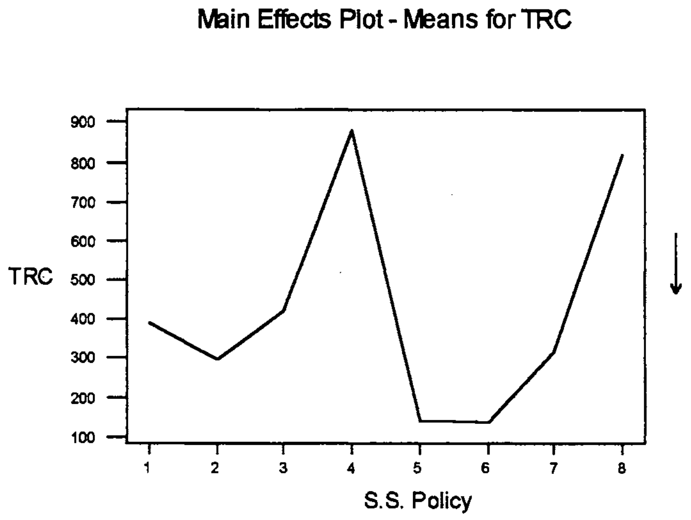


Figure 5.2 Mean TRC Plot as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	173.82	173.02	198.58	166.91	173.62	168.01	183.96	175.72	173.96	172.87	198.23	166.94	173.57	168.42	183.96	175.45
		EOQ	325.60	76.03	188.86	1559.14	58.69	60.55	193.59	1492.94	256.49	279.44	321.70	1581.39	65.66	61.75	109.93	1426.22
	CV=High	L4L	206.78	207.63	250.83	194.72	205.02	196.76	224.67	207.04	207.10	207.49	250.28	195.07	205.14	197.48	224.85	206.83
		EOQ	820.26	631.01	985.05	1828.21	123.39	120.65	878.93	1668.95	1009.28	729.49	1075.79	1810.71	132.07	123.44	835.29	1712.47
S.U.=High	CV=Low	L4L	175.27	173.04	204.06	170.92	175.49	168.48	184.62	183.65	175.30	172.92	203.72	170.88	175.42	168.80	184.61	183.19
		EOQ	201.45	88.43	252.85	1590.36	67.13	60.32	77.20	1436.93	487.21	197.31	531.96	1423.05	68.50	66.72	193.46	1561.21
	CV=High	L4L	208.78	207.20	260.11	201.24	207.89	197.12	225.35	221.11	208.94	207.09	259.55	201.34	207.94	197.72	225.51	220.51
		EOQ	927.39	627.59	999.23	1842.70	136.68	131.44	765.63	1618.26	1008.38	892.32	1123.32	1797.05	145.04	140.07	777.05	1732.68
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	173.53	173.26	195.92	170.30	172.34	170.46	181.95	177.75	173.75	173.51	194.93	170.37	172.43	170.60	181.88	176.99
		EOQ	259.04	60.92	151.05	810.13	51.30	48.94	63.08	313.13	178.55	160.22	174.61	1092.66	50.91	50.79	156.53	1483.11
	CV=High	L4L	199.19	200.48	239.55	192.66	195.96	192.73	214.33	204.41	199.65	200.89	237.94	193.10	196.43	193.44	214.34	203.51
		EOQ	755.67	551.59	761.53	1829.62	101.67	100.03	578.22	1508.60	955.31	598.40	991.35	1692.51	105.91	107.52	833.55	1515.38
S.U.=High	CV=Low	L4L	177.75	173.12	205.16	180.95	177.80	172.19	184.14	191.29	177.63	173.36	204.18	179.71	177.25	172.00	183.86	190.19
		EOQ	208.63	65.10	104.02	1358.73	52.01	51.98	69.99	829.91	451.10	174.26	294.09	1428.49	52.56	53.56	110.04	1422.49
	CV=High	L4L	206.72	199.82	256.53	212.40	205.52	195.51	217.94	229.85	206.58	200.22	254.90	210.34	204.89	195.56	217.55	228.20
		EOQ	704.95	812.95	727.12	1800.89	106.32	103.77	467.96	1681.06	978.97	541.84	1157.08	1774.91	121.88	117.69	890.26	1704.97

Table 5.3 Experimental Results for Mean TRC per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The interaction of lot-sizing rules and safety stock policies has a significant effect on TRC. As shown in Table 5.4, the effect of the safety stock policies is significantly influenced by the lot-sizing rules used in terms of the mean TRC.

Table 5.4 Mean TRC for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. / L.R.	1	2	3	4	5	6	7	8
L4L	190.3	188.5	225.9	186.1	189.2	182.8	202.1	198.5
EOQ	595.5	405.4	615.0	1576.3	90.0	87.5	437.5	1444.3

When L4L is used to calculate the planned order quantity, most safety stock policies result in a lower mean TRC than when EOQ is used, except for policies 5 and 6 as displayed in Figure 5.3 and Table 5.4. Though L4L may result in higher ordering cost than EOQ, it can be justified by the lower mean inventory level and less stockouts.

Furthermore, L4L is less sensitive to the changes in safety stock policies used, but EOQ presents dramatically different results under various safety stock policies. For instance, safety stock policies 4 and 8 result in extremely high mean TRC when EOQ is applied, and policies 5 and 6 perform under EOQ even better than L4L does. There is no safety stock kept at the warehouse using safety stock policies 4 and 8, all the safety stocks are allocated at distribution centers or retailers. When EOQ is used, due to the built-in safety stock associated with EOQ, it helps to absorb the uncertainty. But once a shortage occurs at the distribution centers or retailers, there is a delay before the inventory can be replenished by the vendor. That may deteriorate the system performance by increasing stockouts at all channel members. On the other hand, policies 5 and 6 prevent the stockout problem by keeping safety stock at the warehouse. That means the safety stock policy should be considered along with the lot-sizing rule to achieve the best system performance.

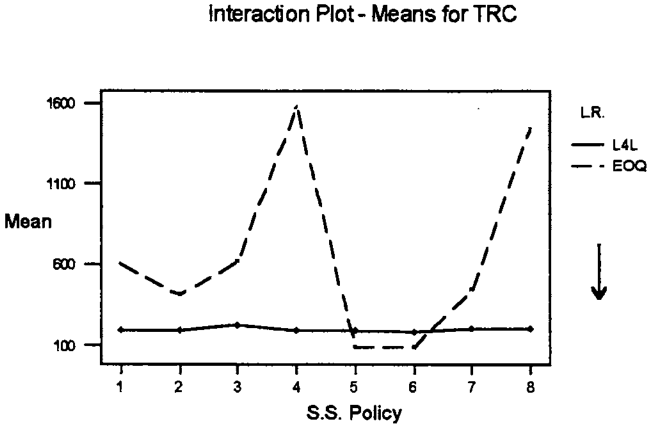


Figure 5.3 Mean TRC Plot as a Function of Lot-sizing Rule and Safety Stock Policy

Interaction of Demand Uncertainty and Safety Stock Policy

As shown in Table 5.5 and Figure 5.4, when the demand uncertainty increases, the mean TRC increases for most safety stock policies. Good safety stock policies such as 5 and 6 are less sensitive to changes in demand uncertainty, and policies 1, 2, 3, 7 and 8 result in higher mean TRC under high demand uncertainty.

Table 5.5 Mean TRC for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. D.U.	1	2	3	4	5	6	7	8
Low	357.80	276.32	373.78	881.87	138.18	133.68	294.47	758.79
High	428.01	317.60	467.10	880.53	140.98	136.60	345.17	883.96

The interaction of demand uncertainty and safety stock policy is displayed below in Figure 5.4, which is a plot of Table 5.5. As demand uncertainty increases at retailers, the mean TRC also increases under most safety stock policies. Safety Stock policy 8 results in much higher TRC when demand uncertainty increases. The change in cost, when uncertainty is increased, is mainly caused by an increase in stockout cost at all channel members.

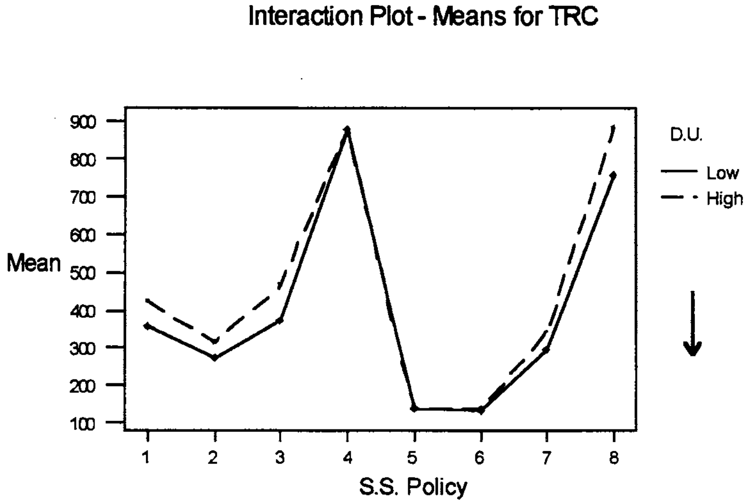


Figure 5.4 Mean TRC Plot as a Function of Demand Uncertainty and Safety Stock Policy

Interaction of Lead Time Uncertainty and Safety Stock Policy

When the transportation lead time distribution varies from a symmetric discrete distribution with low variation to a discrete uniform distribution with high variation, the mean TRC increases under all safety stock policies. The interaction of these two factors for mean TRC is displayed in Table 5.6.

Table 5.6 Mean TRC for Lead Time Uncertainty and Safety Stock Policy (n=80)

S.S. / L.U.	1	2	3	4	5	6	7	8
Low	375.44	278.75	384.37	831.11	134.07	131.15	297.85	753.80
High	410.38	315.18	456.51	931.29	145.08	139.23	341.79	888.95

The lead time uncertainty may cause a stockout when the actual lead time is longer than planned lead time. It can also cause extra inventory carrying cost when products arrive early. That explains why mean TRC increases under high transportation lead time variations. As shown in Figure 5.5, safety stock policies 5 and 6 are less sensitive to the changes in transportation lead time.

Results for Stockout Analysis

Stockout is one of the three non-monetary performance measures used in this study. The warehouse, distribution

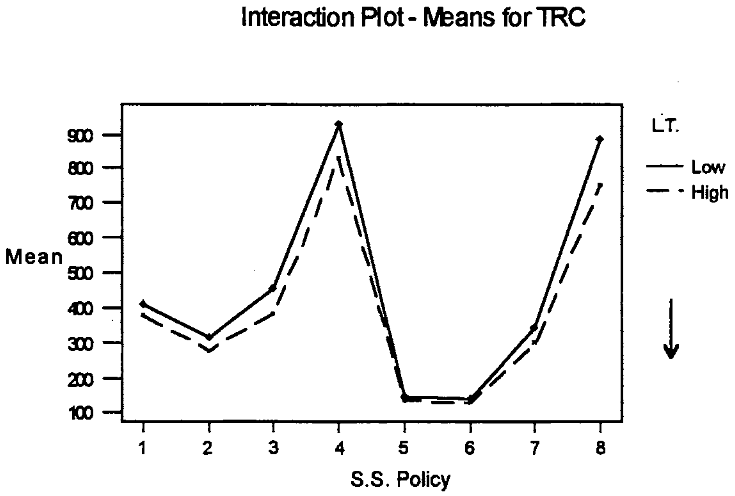


Figure 5.5 Mean TRC Plot as a Function of Lead Time Uncertainty and Safety Stock Policy

centers, and retailers are either owned or fully controlled by the same company. Under this condition, only the stockouts occurring at retailers are of major concern to the company. However, if each channel member in the distribution system is operated by different owners, the performance of each channel member plays the same important role for each owner. Three non-monetary performance measures: average stockout units per period, mean inventory level, and mean service level, are presented for each channel member in this study to provide more information to meet different distribution organizations' needs.

Stockout at Warehouse (SOW)

ANOVA is performed on the average stockout units obtained from the simulation. The analysis consists of 1280 data points, with five replications for each of the 256 experimental conditions. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.7. The results lead to the rejection of all hypotheses. All the main effects and the interactions of safety stock policy with all other main effects, which are significant at the 5% level, are addressed below.

Main Effects

A plot of main effects for average SOW is presented in Figure 5.6; the average SOW for each main effect at each level is shown in Table 5.8. Visual examination of the experimental results in Figure 5.6 shows that EOQ yields much higher average SOW than L4L. It is mainly because the warehouse fails to respond to the operating uncertainty in time when EOQ is applied. In this study, since transportation lead time uncertainty occurs between channel members, a shipping delay can cause demand shortage over several periods when using EOQ as the lot-sizing rule. The stockout problem caused by transportation lead time uncertainty does not affect the system as much as when the L4L lot-sizing rule is applied. This is because the order is replenished once an order is released.

Table 5.7 ANOVA Results for Average SOW

Analysis of Variance for Average SOW

Source	DF	SS	MS	F	P
L.R.	1	300934981	300934981	3213.36	0.000
D.U.	1	984521	984521	10.51	0.001
L.T.	1	2786436	2786436	29.75	0.000
S.U.	1	879870	879870	9.40	0.002
C.V.	1	13324007	13324007	142.27	0.000
S.S.	7	840517657	120073951	1282.14	0.000
L.R.*D.U.	1	1028019	1028019	10.98	0.001
L.R.*L.T.	1	3586879	3586879	38.30	0.000
L.R.*S.U.	1	312414	312414	3.34	0.068
L.R.*C.V.	1	13324007	13324007	142.27	0.000
L.R.*S.S.	7	806218239	115174034	1229.82	0.000
D.U.*L.T.	1	969325	969325	10.35	0.001
D.U.*S.U.	1	107527	107527	1.15	0.284
D.U.*C.V.	1	990311	990311	10.57	0.001
D.U.*S.S.	7	5268096	752585	8.04	0.000
L.T.*S.U.	1	680700	680700	7.27	0.007
L.T.*C.V.	1	2119647	2119647	22.63	0.000
L.T.*S.S.	7	7773168	1110453	11.86	0.000
S.U.*C.V.	1	248301	248301	2.65	0.104
S.U.*S.S.	7	1666175	238025	2.54	0.014
C.V.*S.S.	7	38836315	5548045	59.24	0.000
L.R.*D.U.*L.T.	1	999612	999612	10.67	0.001
L.R.*D.U.*S.U.	1	101477	101477	1.08	0.298
L.R.*D.U.*C.V.	1	990311	990311	10.57	0.001
L.R.*D.U.*S.S.	7	5309427	758490	8.10	0.000
L.R.*L.T.*S.U.	1	457560	457560	4.89	0.027
L.R.*L.T.*C.V.	1	2119647	2119647	22.63	0.000
L.R.*L.T.*S.S.	7	8924853	1274979	13.61	0.000
L.R.*S.U.*C.V.	1	248301	248301	2.65	0.104
L.R.*S.U.*S.S.	7	934426	133489	1.43	0.191
L.R.*C.V.*S.S.	7	38836315	5548045	59.24	0.000
D.U.*L.T.*S.U.	1	133251	133251	1.42	0.233
D.U.*L.T.*C.V.	1	1181028	1181028	12.61	0.000
D.U.*L.T.*S.S.	7	4230345	604335	6.45	0.000
D.U.*S.U.*C.V.	1	161864	161864	1.73	0.189
D.U.*S.U.*S.S.	7	274384	39198	0.42	0.891
D.U.*C.V.*S.S.	7	4429833	632833	6.76	0.000
L.T.*S.U.*C.V.	1	306677	306677	3.27	0.071
L.T.*S.U.*S.S.	7	2123575	303368	3.24	0.002
L.T.*C.V.*S.S.	7	6166030	880861	9.41	0.000
S.U.*C.V.*S.S.	7	888199	126886	1.35	0.221
L.R.*D.U.*L.T.*S.U.	1	128929	128929	1.38	0.241
L.R.*D.U.*L.T.*C.V.	1	1181028	1181028	12.61	0.000
L.R.*D.U.*L.T.*S.S.	7	4260023	608575	6.50	0.000
L.R.*D.U.*S.U.*C.V.	1	161864	161864	1.73	0.189
L.R.*D.U.*S.U.*S.S.	7	266986	38141	0.41	0.898
L.R.*D.U.*C.V.*S.S.	7	4429833	632833	6.76	0.000
L.R.*L.T.*S.U.*C.V.	1	306677	306677	3.27	0.071
L.R.*L.T.*S.U.*S.S.	7	1778425	254061	2.71	0.009
L.R.*L.T.*C.V.*S.S.	7	6166030	880861	9.41	0.000
L.R.*S.U.*C.V.*S.S.	7	888199	126886	1.35	0.221
D.U.*L.T.*S.U.*C.V.	1	177190	177190	1.89	0.169
D.U.*L.T.*S.U.*S.S.	7	971540	138791	1.48	0.170
D.U.*L.T.*C.V.*S.S.	7	4833685	690526	7.37	0.000
D.U.*S.U.*C.V.*S.S.	7	410970	58710	0.63	0.734
L.T.*S.U.*C.V.*S.S.	7	1414278	202040	2.16	0.036
L.R.*D.U.*L.T.*S.U.*C.V.	1	177190	177190	1.89	0.169
L.R.*D.U.*L.T.*S.U.*S.S.	7	979138	139877	1.49	0.166
L.R.*D.U.*L.T.*C.V.*S.S.	7	4833685	690526	7.37	0.000
L.R.*D.U.*S.U.*C.V.*S.S.	7	410970	58710	0.63	0.734
L.R.*L.T.*S.U.*C.V.*S.S.	7	1414278	202040	2.16	0.036
D.U.*L.T.*S.U.*C.V.*S.S.	7	835369	119338	1.27	0.260
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	835369	119338	1.27	0.260
Error	1024	95898902	93651		
Total	1279	2254134264			

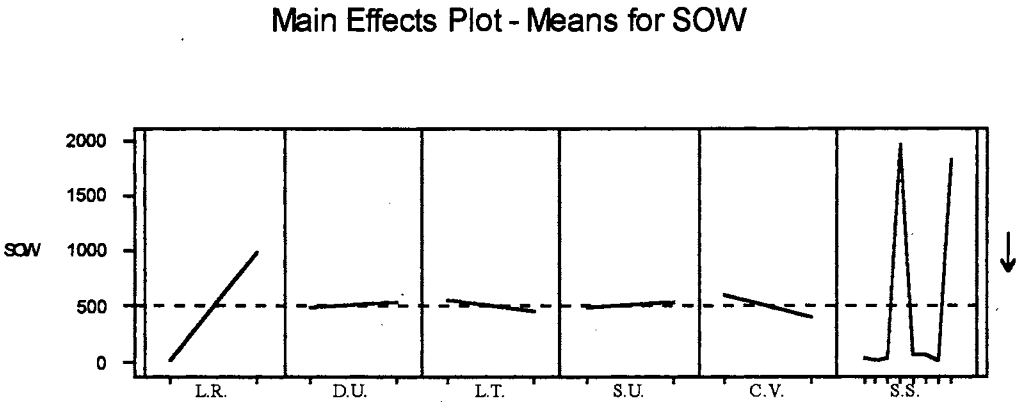


Figure 5.6 Main Effects Plot for Average SOW

Table 5.8 Average Stockout Units per Week of Each Main Effect at Each Level at the Warehouse

Means		
L.R.	N	SOW
1	640	16.58
2	640	986.34
D.U.	N	SOW
1	640	473.73
2	640	529.19
L.T.	N	SOW
1	640	548.12
2	640	454.80
S.U.	N	SOW
1	640	475.24
2	640	527.68
C.V.	N	SOW
1	640	603.49
2	640	399.43
S.S.	N	SOW
1	160	20.7
2	160	13.4
3	160	24.0
4	160	1974.5
5	160	69.1
6	160	61.2
7	160	16.8
8	160	1832.1

The results of the three sources of uncertainties are expected. As demand uncertainty, transportation lead time uncertainty, and supply uncertainty increase, average stockout units also increase at the warehouse.

As shown in Figure 5.7, the best safety stock policy is policy 2 in terms of minimizing average stockout units; policy 7 is the second best. Safety stock policy 2 puts all safety stocks at the warehouse to absorb the supply uncertainties occurring in the system. Safety stock policy 7 distributes safety stocks evenly among the warehouse and the four retailers to deal with uncertainties. The same reason addressed in the TRC analysis explains why safety stock policies 4 and 8 cause high average stockout units at the warehouse. As the cost ratio decreases from 300:1 to 100:1, the average stockout units also decrease at the warehouse. This is mainly because the order frequency by EOQ increases as the cost ratio decreases.

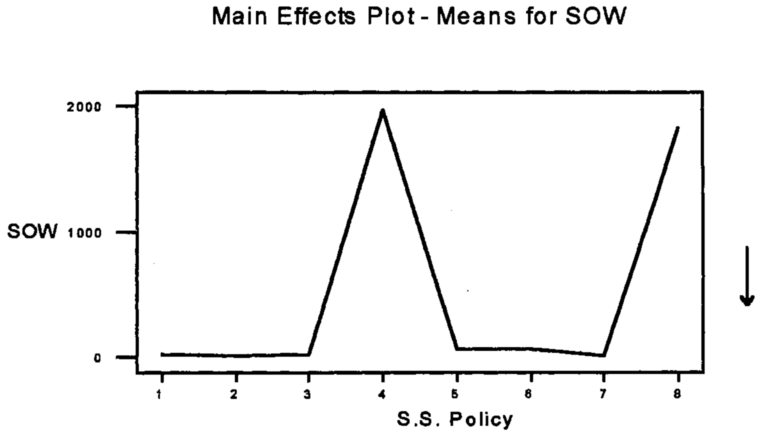


Figure 5.7 Means Plot for SOW per Week as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S.Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	0.39	0.00	3.02	7.76	1.56	0.31	0.00	18.54	0.36	0.00	2.97	7.33	1.51	0.28	0.00	17.78
		EOQ	45.31	26.48	52.87	5440.48	94.31	110.26	33.34	5255.51	59.79	23.59	80.54	5466.79	134.28	123.26	52.11	4994.66
	CV=High	L4L	0.39	0.00	3.02	7.76	1.56	0.31	0.00	18.54	0.36	0.00	2.97	7.33	1.51	0.28	0.00	17.78
		EOQ	15.03	22.73	4.32	3108.48	137.14	130.63	11.48	2913.51	10.82	29.96	4.42	3086.90	162.90	134.50	15.52	2971.92
S.U.=High	CV=Low	L4L	6.82	0.08	17.38	36.13	11.69	3.98	2.25	57.84	6.51	0.07	17.28	34.44	11.33	3.66	2.19	56.29
		EOQ	70.67	31.39	61.58	5473.00	143.47	113.76	48.52	5013.17	47.21	55.89	54.08	4996.44	157.13	157.47	41.91	5424.62
	CV=High	L4L	6.82	0.08	17.38	36.13	11.69	3.98	2.25	57.84	6.51	0.07	17.28	34.44	11.33	3.66	2.19	56.29
		EOQ	11.23	32.34	8.90	3122.22	183.09	167.33	22.90	2824.86	7.99	14.78	1.87	3064.04	201.65	197.26	9.48	2985.56
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	2.95	0.00	7.15	19.66	3.23	0.37	0.03	36.36	2.29	0.00	6.74	15.23	2.68	0.30	0.03	32.81
		EOQ	37.96	15.47	34.35	2966.67	73.79	54.24	26.73	1227.09	66.84	32.24	73.68	3931.18	75.74	76.59	40.52	5135.51
	CV=High	L4L	2.95	0.00	7.15	19.66	3.23	0.37	0.03	36.36	2.29	0.00	6.74	15.23	2.68	0.30	0.03	32.81
		EOQ	21.33	24.07	10.92	3102.55	95.11	92.82	32.63	2633.67	10.11	20.44	6.97	2888.50	112.96	108.68	18.02	2646.53
S.U.=High	CV=Low	L4L	22.71	0.22	32.62	101.16	31.95	13.12	7.62	103.20	21.43	0.19	32.19	88.55	29.30	10.58	7.13	99.83
		EOQ	48.60	28.42	56.12	4774.50	77.87	85.87	32.30	2963.86	59.57	26.53	68.90	5038.35	84.46	86.88	41.40	4958.86
	CV=High	L4L	22.71	0.22	32.62	101.16	31.95	13.12	7.62	103.20	21.43	0.19	32.19	88.55	29.30	10.58	7.13	99.83
		EOQ	12.33	14.90	9.52	3075.93	124.49	112.26	45.61	2894.60	9.64	26.99	1.47	3026.60	166.01	140.86	27.60	2936.38

Table 5.9 Experimental Results for Average SOW per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The interaction of lot-sizing rules and safety stock policies for average SOW is displayed in Table 5.10. As observed in Table 5.10, the interaction of lot-sizing rules and safety stock policies has a significant effect on the average stockout units at the warehouse. The effect of the safety stock policies is significantly influenced by the lot-sizing rules used in terms of average SOW.

Table 5.10 Average SOW per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	7.9	0.1	14.9	38.8	11.7	4.1	2.4	52.8
EOQ	33.4	26.6	33.2	3910.2	126.5	118.3	31.3	3611.3

When L4L is used to calculate the planned order quantity, all safety stock policies result in much lower average stockout units than when EOQ is used. When the lot-sizing rule is changed from L4L to EOQ, there is a considerable impact on safety stock policies 4 and 8. As shown in Figure 5.8 and Table 5.10, the average stockout units increase dramatically for policies 4 and 8 under the EOQ lot-sizing rule. As addressed before, this is because safety stocks at retailers and distribution centers may satisfy few periods of demand. Once the inventories at distribution centers and retailers are depleted, there is no stock available at the warehouse to meet these demands. It takes nine weeks to replenish the stocks from the vendor. It may take longer when the transportation lead time uncertainty between channel members is a concern.

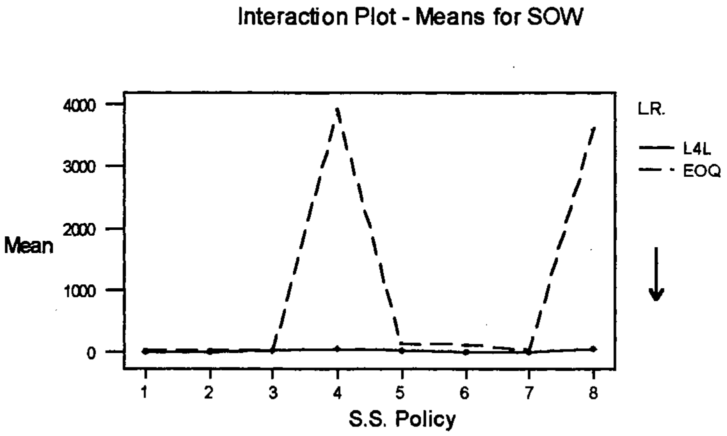


Figure 5.8 Means Plot for SOW per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Interaction of Demand Uncertainty and Safety Stock Policy

When the demand uncertainty increases, the average stockout units at the warehouse increases from 1% to 17% under most safety stock policies. As shown in Table 5.11, when demand uncertainty increases, there is an immense impact when using policy 8.

Table 5.11 Average SOW per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. D.U.	1	2	3	4	5	6	7	8
Low	20.5	12.3	22.4	1962.1	64.1	56.4	17.1	1634.9
High	20.8	14.4	25.1	1981.9	74.0	65.9	16.6	2029.2

As demand uncertainty increases, the forecast demand error also increases. Forecast demand error which occurred at the retailers may affect the accuracy of forecast requirements at the warehouse, and then causes more stockouts as demand uncertainty increases. As displayed in the interaction of demand uncertainty and safety stock policy in Table 5.11 and Figure 5.8, most safety stock policies are less sensitive to the changes in demand uncertainty, except policy 8. As shown in Table 5.9, policy 8 results in higher average SOW when using the EOQ lot-sizing rule with a low cost value. As addressed before, it is because the EOQ lot-sizing rule with safety stock policy 8 can not respond to the demand uncertainty well.

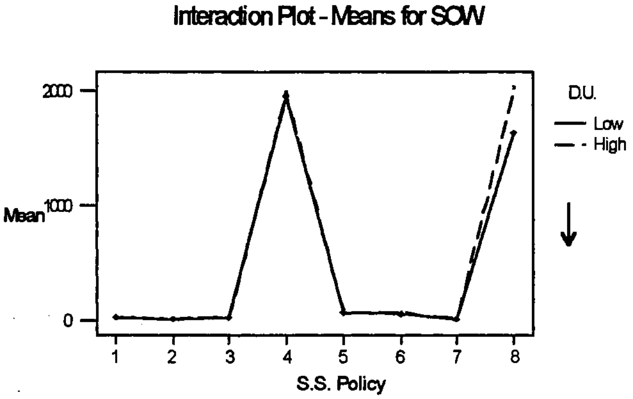


Figure 5.9 Means Plot for SOW per Week as a Function of Demand Uncertainty and Safety Stock Policy

Interaction of Lead Time Uncertainty and Safety Stock Policy

When the transportation lead time distribution changes from a discrete distribution with low variation to a uniform distribution with high variation, the average stockout units increase under most safety stock policies. The average stockout units for the interaction of these two factors is displayed in Table 5.12, and a plot of the interaction of lead time uncertainty and safety stock policy is shown in Figure 5.10.

Table 5.12 Average SOW per Week for Lead Time Uncertainty and Safety Stock Policy (n=80)

S.S. L.T.	1	2	3	4	5	6	7	8
Low	22.8	11.9	26.2	1828.3	59	50.4	18.4	1621.3
High	18.5	14.8	21.9	2120.6	79.1	71.9	15.3	2042.8

The lead time uncertainty may cause stockouts when the actual lead time is longer than the planned lead time. That explains why average stockout units increase under high transportation lead time variations for most safety stock policies. Policies 4 and 8 are more affected by lead time uncertainty than other policies.

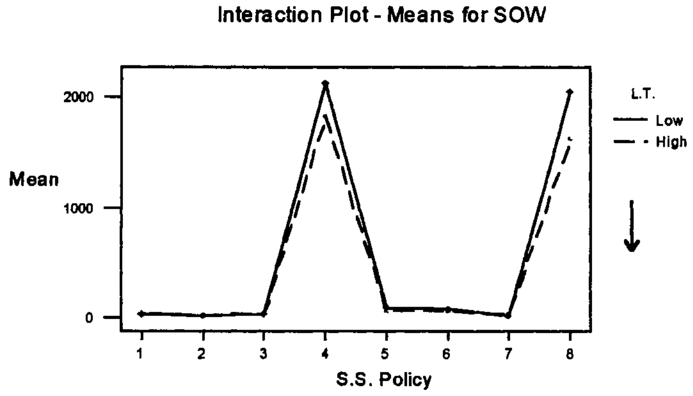


Figure 5.10 Means Plot for SOW per Week as a Function of Lead Time Uncertainty and Safety Stock Policy

Stockout at Distribution Center 1 (SODC1)

ANOVA is performed on the average SODC1 obtained from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.13 and discussed below. The results lead to the rejection of hypotheses 11, 12, 13, 15, 16, 17, and 18 at the 5% level.

Main Effects

A plot of main effects for average SODC1 is presented in Figure 5.11, and the average SODC1 for each main effect at each level is shown in Table 5.14. Visual examination of the experimental results in Figure 5.11 shows that EOQ yields much higher average SODC1 than L4L. The reason is the same as that given for the situation at the warehouse.

The results of three sources of uncertainties are similar to the results at the warehouse. As the demand uncertainty, transportation lead time uncertainty, and supply uncertainty increase, the average SODC1 also increases.

As shown in Figure 5.12, the best safety stock policy is policy 6 in terms of the average SODC1; policy 5 is the second best. Again, safety stock policies 4 and 8 result in higher average SODC1 than other safety stock policies. As the cost value increases, the average SODC1 decreases. This

Table 5.13 ANOVA Results for Average SODC1 per Week

Analysis of Variance for Average SODC1

Source	DF	SS	MS	F	P
L.R.	1	222625235	222625235	1077.86	0.000
D.U.	1	7607622	7607622	36.83	0.000
L.T.	1	4309614	4309614	20.87	0.000
S.U.	1	672132	672132	3.25	0.072
C.V.	1	4058700	4058700	19.65	0.000
S.S.	7	163868641	23409806	113.34	0.000
L.R.*D.U.	1	7800262	7800262	37.77	0.000
L.R.*L.T.	1	4085002	4085002	19.78	0.000
L.R.*S.U.	1	594867	594867	2.88	0.090
L.R.*C.V.	1	4058700	4058700	19.65	0.000
L.R.*S.S.	7	165067328	23581047	114.17	0.000
D.U.*L.T.	1	494583	494583	2.39	0.122
D.U.*S.U.	1	175538	175538	0.85	0.357
D.U.*C.V.	1	1121323	1121323	5.43	0.020
D.U.*S.S.	7	7337875	1048268	5.08	0.000
L.T.*S.U.	1	766967	766967	3.71	0.054
L.T.*C.V.	1	912641	912641	4.42	0.036
L.T.*S.S.	7	2255608	322230	1.56	0.144
S.U.*C.V.	1	231277	231277	1.12	0.290
S.U.*S.S.	7	1366513	195216	0.95	0.470
C.V.*S.S.	7	13483528	1926218	9.33	0.000
L.R.*D.U.*L.T.	1	511620	511620	2.48	0.116
L.R.*D.U.*S.U.	1	177274	177274	0.86	0.354
L.R.*D.U.*C.V.	1	1121323	1121323	5.43	0.020
L.R.*D.U.*S.S.	7	7404805	1057829	5.12	0.000
L.R.*L.T.*S.U.	1	730042	730042	3.53	0.060
L.R.*L.T.*C.V.	1	912641	912641	4.42	0.036
L.R.*L.T.*S.S.	7	2277402	325343	1.58	0.139
L.R.*S.U.*C.V.	1	231277	231277	1.12	0.290
L.R.*S.U.*S.S.	7	1281391	183056	0.89	0.517
L.R.*C.V.*S.S.	7	13483528	1926218	9.33	0.000
D.U.*L.T.*S.U.	1	121059	121059	0.59	0.444
D.U.*L.T.*C.V.	1	119282	119282	0.58	0.447
D.U.*L.T.*S.S.	7	3235183	462169	2.24	0.029
D.U.*S.U.*C.V.	1	20432	20432	0.10	0.753
D.U.*S.U.*S.S.	7	2041111	291587	1.41	0.197
D.U.*C.V.*S.S.	7	2567525	366789	1.78	0.089
L.T.*S.U.*C.V.	1	373294	373294	1.81	0.179
L.T.*S.U.*S.S.	7	977409	139630	0.68	0.693
L.T.*C.V.*S.S.	7	2537867	362552	1.76	0.093
S.U.*C.V.*S.S.	7	735817	105117	0.51	0.828
L.R.*D.U.*L.T.*S.U.	1	122309	122309	0.59	0.442
L.R.*D.U.*L.T.*C.V.	1	119282	119282	0.58	0.447
L.R.*D.U.*L.T.*S.S.	7	3244032	463433	2.24	0.029
L.R.*D.U.*S.U.*C.V.	1	20432	20432	0.10	0.753
L.R.*D.U.*S.U.*S.S.	7	2038613	291230	1.41	0.197
L.R.*D.U.*C.V.*S.S.	7	2567525	366789	1.78	0.089
L.R.*L.T.*S.U.*C.V.	1	373294	373294	1.81	0.179
L.R.*L.T.*S.U.*S.S.	7	984057	140580	0.68	0.689
L.R.*L.T.*C.V.*S.S.	7	2537867	362552	1.76	0.093
L.R.*S.U.*C.V.*S.S.	7	735817	105117	0.51	0.828
D.U.*L.T.*S.U.*C.V.	1	184625	184625	0.89	0.345
D.U.*L.T.*S.U.*S.S.	7	1200470	171496	0.83	0.562
D.U.*L.T.*C.V.*S.S.	7	2532135	361734	1.75	0.094
D.U.*S.U.*C.V.*S.S.	7	1463634	209091	1.01	0.421
L.T.*S.U.*C.V.*S.S.	7	822012	117430	0.57	0.782
L.R.*D.U.*L.T.*S.U.*C.V.	1	184625	184625	0.89	0.345
L.R.*D.U.*L.T.*S.U.*S.S.	7	1198310	171187	0.83	0.563
L.R.*D.U.*L.T.*C.V.*S.S.	7	2532135	361734	1.75	0.094
L.R.*D.U.*S.U.*C.V.*S.S.	7	1463634	209091	1.01	0.421
L.R.*L.T.*S.U.*C.V.*S.S.	7	822012	117430	0.57	0.782
D.U.*L.T.*S.U.*C.V.*S.S.	7	892039	127434	0.62	0.742
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	892039	127434	0.62	0.742
Error	1024	211500129	206543		
Total	1279	892185269			

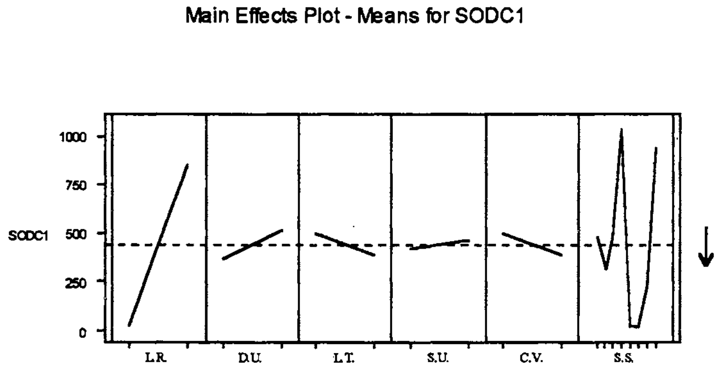


Figure 5.11 Main Effects Plot for Average SODC1

Table 5.14 Average Stockout Units per Week of Each Main Effect at Each Level at Distribution Center 1

Means		
L.R.	N	SODC1
1	640	22.11
2	640	856.20
D.U.	N	SODC1
1	640	362.06
2	640	516.25
L.T.	N	SODC1
1	640	497.18
2	640	381.13
S.U.	N	SODC1
1	640	416.24
2	640	462.07
C.V.	N	SODC1
1	640	495.47
2	640	382.85
S.S.	N	SODC1
1	160	481.6
2	160	312.9
3	160	479.4
4	160	1037.2
5	160	22.3
6	160	18.1
7	160	223.1
8	160	938.6

is mainly because the order frequency increases when using high cost value with EOQ lot-sizing rule. Thus, it can respond to changes in operating condition quickly. As shown in Table 5.15, EOQ with high cost value results in lower average SODC1 than low cost value under most operating conditions.

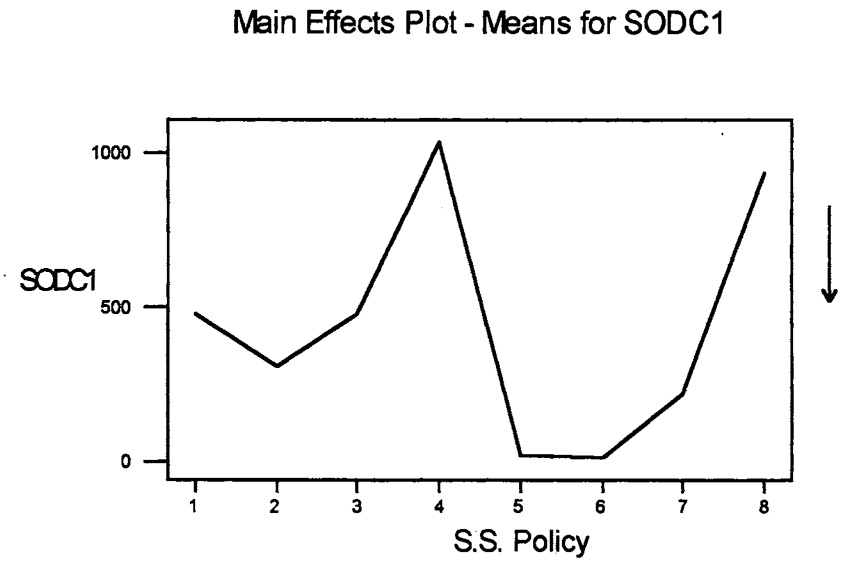


Figure 5.12 Means Plot for SODC1 per Week as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	14.78	14.83	73.88	3.08	16.91	5.94	38.41	20.27	13.99	14.10	71.12	2.65	15.58	5.47	36.94	18.22
		EOQ	1279.59	127.57	123.33	2887.34	24.16	31.56	1023.36	2731.06	1369.08	1693.24	1233.94	2973.70	37.20	30.46	184.52	2616.36
	CV=High	L4L	14.78	14.83	73.88	3.08	16.91	5.94	38.41	20.27	13.99	14.10	71.12	2.65	15.58	5.47	36.94	18.22
		EOQ	344.68	412.98	876.49	1686.39	34.90	35.82	734.21	1455.81	1126.98	981.95	1229.85	1659.78	37.49	39.00	674.05	1490.61
S.U.=High	CV=Low	L4L	15.66	14.83	78.77	3.56	17.84	6.04	38.82	24.89	14.81	14.10	76.13	3.10	16.49	5.54	37.34	22.60
		EOQ	729.56	209.12	669.07	2997.00	39.26	36.23	120.20	2673.17	1989.23	966.94	1687.21	2629.04	32.88	40.28	270.81	2919.39
	CV=High	L4L	15.66	14.83	78.77	3.56	17.84	6.04	38.82	24.89	14.81	14.10	76.13	3.10	16.49	5.54	37.34	22.60
		EOQ	745.97	679.91	1038.35	1705.75	43.01	33.49	449.62	1387.83	995.33	1050.72	1396.36	1646.56	38.06	41.23	136.20	1540.87
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	14.69	13.27	60.50	2.93	13.23	6.83	30.87	16.28	12.92	11.88	54.28	2.21	11.63	5.32	27.55	13.65
		EOQ	893.13	74.89	328.97	1409.16	19.50	22.03	44.60	413.09	702.66	619.06	870.15	1952.67	27.19	23.75	174.27	2777.36
	CV=High	L4L	14.69	13.27	60.50	2.93	13.23	6.83	30.87	16.28	12.92	11.88	54.28	2.21	11.63	5.32	27.55	13.65
		EOQ	616.63	414.46	347.37	1688.98	18.62	22.43	338.64	1299.90	770.38	420.49	919.47	1545.29	26.93	30.52	652.60	1298.08
S.U.=High	CV=Low	L4L	17.82	13.28	71.40	5.87	16.48	7.36	32.96	26.42	15.81	11.88	65.02	4.32	14.15	5.69	29.51	22.60
		EOQ	653.52	117.71	385.43	2481.44	22.57	21.46	69.09	1484.89	1977.45	903.99	1508.84	2600.27	18.07	24.01	375.96	2631.68
	CV=High	L4L	17.82	13.28	71.40	5.87	16.48	7.36	32.96	26.42	15.81	11.88	65.02	4.32	14.15	5.69	29.51	22.60
		EOQ	78.70	725.15	77.27	1647.70	20.48	21.45	267.74	1473.12	898.84	398.07	1546.67	1623.69	28.57	30.40	1078.06	1512.30

Table 5.15 Experimental Results for Average SODC1 per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The interaction of lot-sizing rules and safety stock policies for average SODC1 is displayed in Table 5.16. Thus, the interaction of lot-sizing rules and safety stock policies has a significant effect on the average SODC1. The effect of the safety stock policies is significantly influenced by the lot-sizing rules used.

Table 5.16 Average SODC1 per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	15.1	13.5	68.9	3.5	15.3	6.0	34.1	20.6
EOQ	948.2	612.3	889.9	2070.9	29.3	30.3	402.1	1856.6

As shown in Table 5.16, L4L outperforms EOQ in terms of the average SODC1 under all safety stock policies. And L4L is less sensitive to the safety stock policy used. When lot-sizing is changed from L4L to EOQ, there is an immense impact on safety policies 4 and 8. The average SODC1 increases dramatically for policies 4 and 8 when using the EOQ lot-sizing rule as shown in Figure 5.13. As discussed before, the high average SODC1 for policies 4 and 8 when using EOQ, is due to the stockouts which occurred at the warehouse. In turn, the stockouts at the warehouse affect distribution centers and retailers. On the other hand, policy 4 results in the lowest average SODC1 when L4L is used. That implies the safety stock policy should be considered along with the lot-sizing rule to achieve a better system performance.

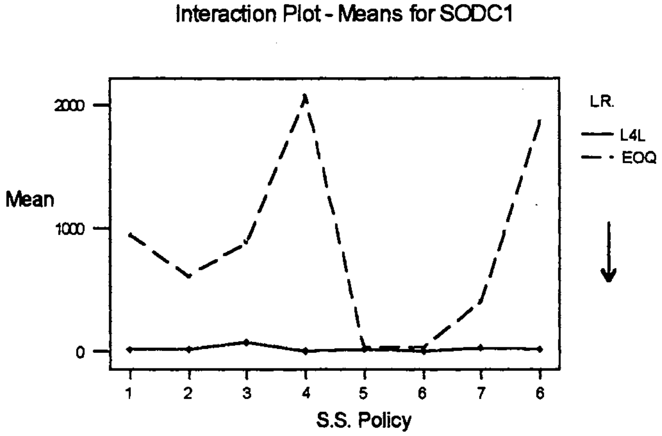


Figure 5.13 Means Plot for SODC1 per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Interaction of Demand Uncertainty and Safety Stock Policy

When the demand uncertainty increases, it affects safety stock policies to a different degree. As shown in Table 5.17 and Figure 5.14, when demand uncertainty increases, there is a severe impact on the average SODC1 for policies 1, 2, 3, and 8.

Table 5.17 Average SODC1 per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. / D.U.	1	2	3	4	5	6	7	8
Low	341.7	179.6	276.0	1033.4	22.0	17.3	208.1	818.4
High	621.6	446.6	682.8	1041.0	22.6	19.0	238.1	1058.8

The reason for this has been explained previously. The change in stockouts, when demand uncertainty increases, is mainly caused by an increase in demand forecast error at the retailers. Compared to the result in SOW, demand uncertainty from customers has more impact on the performance of distribution centers than on the warehouse. This is because distribution centers are closer to the source of uncertainty.

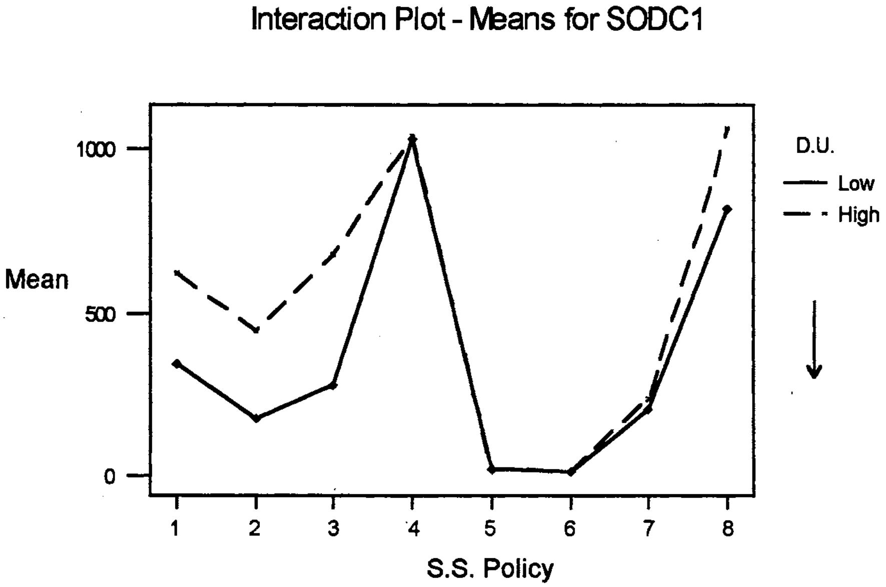


Figure 5.14 Means Plot for SODC1 per Week as a Function of Demand Uncertainty and Safety Stock Policy

Stockout at Retailer 1(SOR1)

ANOVA is performed on the average SOR1 obtained from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.18. The results lead to the rejection of hypotheses 11, 12, 13, 15, 16, 17, and 18 at the 5% level. All the important main effects and interactions are addressed below.

Main Effects

A main effects plot for average SOR1 is presented in Figure 5.15, and the average SOR1 of each main effect at each level is shown in Table 5.19. Visual examination of the experimental results in Figure 5.15 shows that EOQ yields higher average SOR1 than L4L. However, the lot-sizing rules do not make as much difference in terms of average stockout units at the retailers as they do at distribution centers or the warehouse.

The results of three sources of uncertainties at the retailers are the same as at the warehouse and distribution centers. As the demand uncertainty, transportation lead time uncertainty, and supply uncertainty increase, the mean stockout units also increase. As the cost value increases, the average SOR1 also increases. The results of changes in cost value at retailers differ from those at the warehouse and distribution centers. As shown in Figure 5.16, the best safety stock policy is policy 5 in terms of average SOR1; policy 6 is the second best. Policies 4 and 8 result in higher average SOR1 than other policies. To examine the interaction effects, the experimental results for average SOR1 are shown in Table 5.20, and discussed below.

Table 5.18 ANOVA Results for Average SOR1 per Week

```
                    Analysis of Variance for Average SOR1

Source                            DF         SS         MS       F      P
L.R.                               1     4673.0     4673.0   51.45  0.000
D.U.                               1     6031.1     6031.1   66.40  0.000
L.T.                               1     5904.5     5904.5   65.00  0.000
S.U.                               1      331.6      331.6    3.65  0.056
C.V.                               1     2163.4     2163.4   23.82  0.000
S.S.                               7    73488.1    10498.3  115.58  0.000
L.R.*D.U.                          1     2079.0     2079.0   22.89  0.000
L.R.*L.T.                          1       27.9       27.9    0.31  0.580
L.R.*S.U.                          1      120.9      120.9    1.33  0.249
L.R.*C.V.                          1     2163.4     2163.4   23.82  0.000
L.R.*S.S.                          7    75510.5    10787.2  118.76  0.000
D.U.*L.T.                          1      254.1      254.1    2.80  0.095
D.U.*S.U.                          1       59.4       59.4    0.65  0.419
D.U.*C.V.                          1       29.4       29.4    0.32  0.570
D.U.*S.S.                          7     2767.8      395.4    4.35  0.000
L.T.*S.U.                          1      297.7      297.7    3.28  0.071
L.T.*C.V.                          1       91.6       91.6    1.01  0.315
L.T.*S.S.                          7      950.6      135.8    1.50  0.165
S.U.*C.V.                          1       36.3       36.3    0.40  0.527
S.U.*S.S.                          7      691.3       98.8    1.09  0.369
C.V.*S.S.                          7     1815.9      259.4    2.86  0.006
L.R.*D.U.*L.T.                     1       98.3       98.3    1.08  0.298
L.R.*D.U.*S.U.                     1       73.9       73.9    0.81  0.367
L.R.*D.U.*C.V.                     1       29.4       29.4    0.32  0.570
L.R.*D.U.*S.S.                     7     3385.1      483.6    5.32  0.000
L.R.*L.T.*S.U.                     1      197.2      197.2    2.17  0.141
L.R.*L.T.*C.V.                     1       91.6       91.6    1.01  0.315
L.R.*L.T.*S.S.                     7      997.1      142.4    1.57  0.141
L.R.*S.U.*C.V.                     1       36.3       36.3    0.40  0.527
L.R.*S.U.*S.S.                     7      454.9       65.0    0.72  0.659
L.R.*C.V.*S.S.                     7     1815.9      259.4    2.86  0.006
D.U.*L.T.*S.U.                     1      102.5      102.5    1.13  0.288
D.U.*L.T.*C.V.                     1        7.3        7.3    0.08  0.776
D.U.*L.T.*S.S.                     7     1480.8      211.5    2.33  0.023
D.U.*S.U.*C.V.                     1        0.3        0.3    0.00  0.955
D.U.*S.U.*S.S.                     7      724.4      103.5    1.14  0.336
D.U.*C.V.*S.S.                     7     1012.0      144.6    1.59  0.134
L.T.*S.U.*C.V.                     1       71.9       71.9    0.79  0.374
L.T.*S.U.*S.S.                     7      467.1       66.7    0.73  0.643
L.T.*C.V.*S.S.                     7     1011.1      144.4    1.59  0.134
S.U.*C.V.*S.S.                     7      250.7       35.8    0.39  0.906
L.R.*D.U.*L.T.*S.U.                1      116.4      116.4    1.28  0.258
L.R.*D.U.*L.T.*C.V.                1        7.3        7.3    0.08  0.776
L.R.*D.U.*L.T.*S.S.                7     1485.6      212.2    2.34  0.023
L.R.*D.U.*S.U.*C.V.                1        0.3        0.3    0.00  0.955
L.R.*D.U.*S.U.*S.S.                7      727.7      104.0    1.14  0.333
L.R.*D.U.*C.V.*S.S.                7     1012.0      144.6    1.59  0.134
L.R.*L.T.*S.U.*C.V.                1       71.9       71.9    0.79  0.374
L.R.*L.T.*S.U.*S.S.                7      484.9       69.3    0.76  0.619
L.R.*L.T.*C.V.*S.S.                7     1011.1      144.4    1.59  0.134
L.R.*S.U.*C.V.*S.S.                7      250.7       35.8    0.39  0.906
D.U.*L.T.*S.U.*C.V.                1      162.2      162.2    1.79  0.182
D.U.*L.T.*S.U.*S.S.                7      478.2       68.3    0.75  0.628
D.U.*L.T.*C.V.*S.S.                7     1198.0      171.1    1.88  0.069
D.U.*S.U.*C.V.*S.S.                7      429.4       61.3    0.68  0.693
L.T.*S.U.*C.V.*S.S.                7      366.3       52.3    0.58  0.776
L.R.*D.U.*L.T.*S.U.*C.V.           1      162.2      162.2    1.79  0.182
L.R.*D.U.*L.T.*S.U.*S.S.           7      474.7       67.8    0.75  0.632
L.R.*D.U.*L.T.*C.V.*S.S.           7     1198.0      171.1    1.88  0.069
L.R.*D.U.*S.U.*C.V.*S.S.           7      429.4       61.3    0.68  0.693
L.R.*L.T.*S.U.*C.V.*S.S.           7      366.3       52.3    0.58  0.776
D.U.*L.T.*S.U.*C.V.*S.S.           7      413.2       59.0    0.65  0.715
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.      7      413.2       59.0    0.65  0.715
Error                           1024    93013.7       90.8
Total                           1279   296067.7
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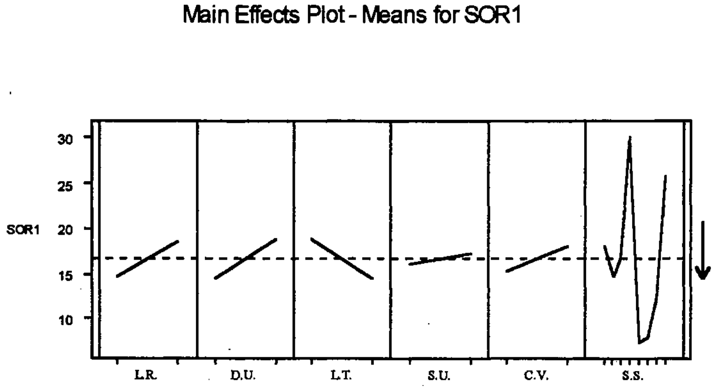

Figure 5.15 Main Effects Plot for Average SOR1

Table 5.19 Average Stockout Units per Week of Each Main Effect at Each Level at Retailer 1

Means		
L.R.	N	SOR1
1	640	14.748
2	640	18.570
D.U.	N	SOR1
1	640	14.488
2	640	18.830
L.T.	N	SOR1
1	640	18.807
2	640	14.511
S.U.	N	SOR1
1	640	16.150
2	640	17.168
C.V.	N	SOR1
1	640	15.359
2	640	17.959
S.S.	N	SOR1
1	160	18.093
2	160	14.619
3	160	16.877
4	160	30.209
5	160	7.291
6	160	7.822
7	160	12.441
8	160	25.921

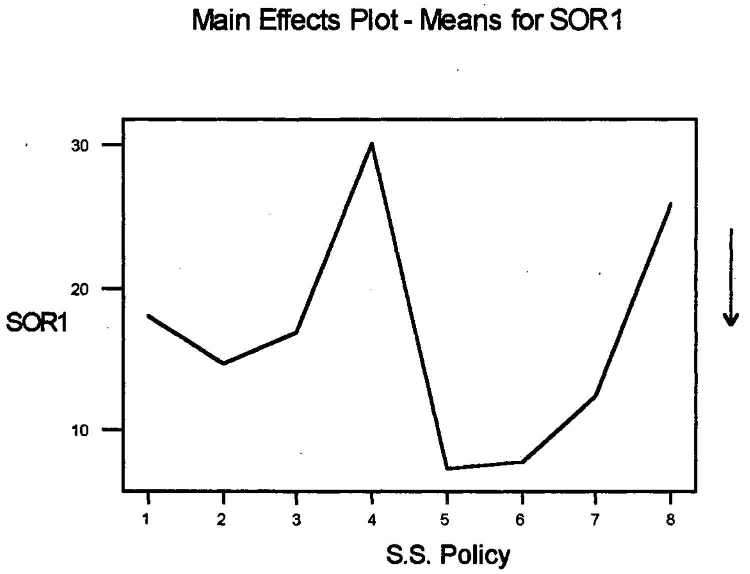

Figure 5.16 Means Plot for SOR1 per Week as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	17.48	17.57	15.52	16.08	14.46	16.06	16.59	13.45	18.62	18.38	16.67	18.12	16.39	17.71	17.87	15.20
		EOQ	21.12	1.66	1.19	47.99	0.57	0.42	16.27	44.65	22.70	28.24	19.41	51.57	0.96	0.44	2.82	43.92
	CV=High	L4L	17.48	17.57	15.52	16.08	14.46	16.06	16.59	13.45	18.62	18.38	16.67	18.12	16.39	17.71	17.87	15.20
		EOQ	9.70	10.44	24.42	48.91	0.99	0.97	20.37	39.47	32.24	28.28	34.92	49.38	1.54	1.38	19.93	42.68
S.U.=High	CV=Low	L4L	17.64	17.57	16.24	16.22	14.60	16.08	16.69	14.06	18.77	18.38	17.36	18.22	16.54	17.70	17.95	15.73
		EOQ	12.14	3.29	9.96	49.84	0.47	0.75	0.92	43.58	33.32	15.24	28.06	44.78	0.89	1.05	3.76	49.64
	CV=High	L4L	17.64	17.57	16.24	16.22	14.60	16.08	16.69	14.06	18.77	18.38	17.36	18.22	16.54	17.70	17.95	15.73
		EOQ	21.08	18.54	28.71	49.27	1.14	1.17	11.70	38.85	28.47	30.12	39.60	49.21	1.49	1.64	3.42	43.73
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	13.52	12.67	10.28	11.63	10.43	11.26	11.87	9.13	15.27	14.14	12.07	14.69	13.04	13.78	13.81	11.72
		EOQ	15.12	1.67	4.35	22.91	0.23	0.26	0.46	5.99	11.97	10.22	13.16	33.20	0.62	0.57	2.55	46.92
	CV=High	L4L	13.52	12.67	10.28	11.63	10.43	11.26	11.87	9.13	15.27	14.14	12.07	14.69	13.04	13.78	13.81	11.72
		EOQ	16.62	11.75	8.49	48.72	0.46	0.56	9.44	36.27	22.15	11.05	26.08	46.07	1.29	1.52	19.34	36.65
S.U.=High	CV=Low	L4L	14.27	12.67	11.78	12.30	10.95	11.40	12.16	10.62	15.81	14.14	13.32	15.09	13.39	13.86	14.02	12.85
		EOQ	11.02	1.13	5.90	41.50	0.48	0.47	1.01	23.77	31.55	14.44	23.73	43.31	0.69	0.73	6.25	44.27
	CV=High	L4L	14.27	12.67	11.78	12.30	10.95	11.40	12.16	10.62	15.81	14.14	13.32	15.09	13.39	13.86	14.02	12.85
		EOQ	1.35	20.38	1.15	47.23	0.46	0.77	6.68	40.81	25.65	10.32	44.43	48.10	1.39	1.87	31.27	42.76

Table 5.20 Experimental Results for Average SOR1 per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The interaction of lot-sizing rules and safety stock policies has a significant effect on the average SOR1. As observed in Table 5.21, the effect of the safety stock policies is significantly influenced by the lot-sizing rules used

Table 5.21 Average SOR1 per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	16.423	15.691	14.155	15.294	13.733	14.733	15.120	12.845
EOQ	19.762	13.548	19.598	45.125	0.854	0.911	9.762	38.997

As shown in Figure 5.17 and Table 5.21, when L4L is used, safety stock policies 1, 3, 4, and 8 perform better than when the EOQ is used. On the other hand, safety stock policies 2, 5, 6, and 7 result in fewer stockouts at retailers when EOQ is applied. This result is different from the results at the warehouse and distribution centers, where L4L outperforms EOQ under all safety stock policies in terms of minimizing average stock units. This result may be explained by the built-in safety stock feature of the EOQ lot-sizing rule which can absorb operating uncertainty along with appropriate safety stock policies.

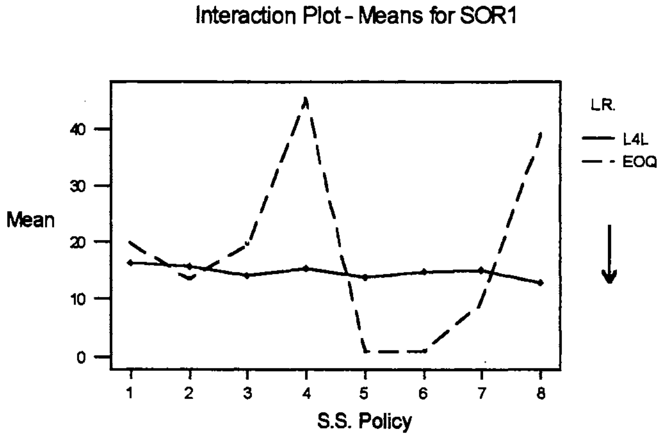

Figure 5.17 Means Plot for SOR1 per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Interaction of Demand Uncertainty and Safety Stock Policy

Although the ranking of the safety stock policies stays the same when the demand uncertainty increases, the magnitude of the increases in average SOR1 is different under various safety stock policies. As shown in Table 5.22, when demand uncertainty increases, safety stock policies 5 and 6 are less sensitive to the changes in the demand uncertainty.

Table 5.22 Average SOR1 per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. D.U.	1	2	3	4	5	6	7	8
Low	14.623	11.865	11.988	29.301	6.606	7.187	11.342	22.994
High	21.562	17.394	21.766	31.117	7.975	8.457	13.540	28.847

The interaction of demand uncertainty and safety stock policy is displayed below in Figure 5.18, which is a plot of Table 5.22. As observed in Figure 5.18, when demand uncertainty is increased, it also results in an increase in average stockout units at retailers. Compared to the result in SOW or SODC1, the safety stock policy used at retailers are more sensitive to the changes in demand uncertainty. This is because the retailer is the closest to the uncertainty source than the warehouse and distribution centers.

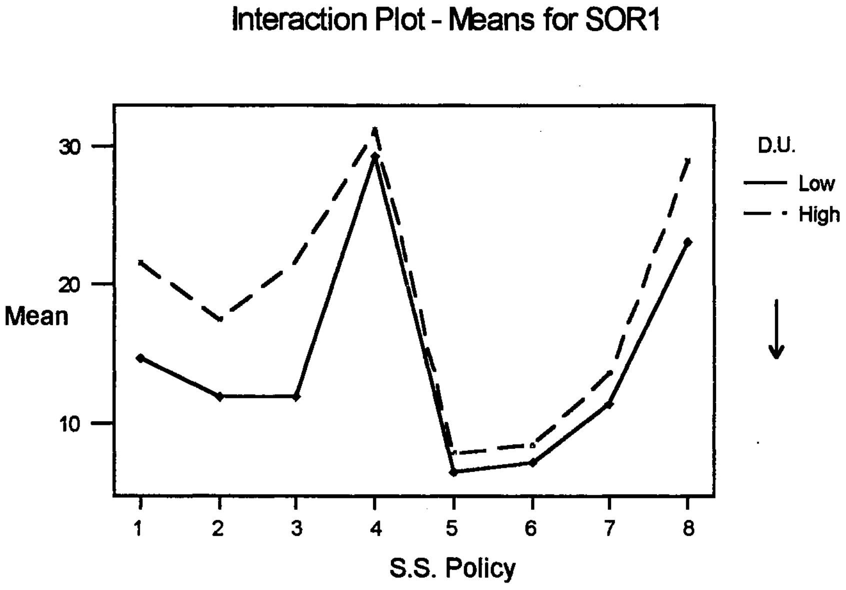

Figure 5.18 Means Plot for SOR1 per Week as a Function of Demand Uncertainty and Safety Stock Policy

Results for Inventory Level Analysis

The inventory type considered in this study is finished goods. The average inventory for each period is calculated as the average of the beginning inventory and the ending inventory. The average inventory level of the whole simulation experiment is calculated as the sum of average inventory of each period, divided by the number of simulation periods. This is one of the three non-monetary performance measures used in this study, and the average inventory level is recorded for each channel member.

Average Inventory Level at Warehouse (INVW)

ANOVA is performed on the mean INVW obtained from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.23. The results lead to the rejection of all hypotheses, except for hypotheses 26 and 30. Hypotheses 21 - 30 are stated in chapter 3. All important effects and interactions are addressed below.

Main Effects

A plot of main effects for average INVW is presented in Figure 5.19. The average INVW of each main effect at each level is shown in Table 5.24. Visual examination of the experimental results in Figure 5.19 shows that EOQ yields much higher average INVW than L4L. As EOQ is used, the average INVW increases because the built-in safety stock feature of the EOQ lot-sizing rule. Unlike L4L which always

Table 5.23 ANOVA Results for Average INVW per Week

Analysis of Variance for Average INVW

Source	DF	SS	MS	F	P
L.R.	1	450699073	450699073	5900.46	0.000
D.U.	1	1683618	1683618	22.04	0.000
L.T.	1	535184	535184	7.01	0.008
S.U.	1	4927621	4927621	64.51	0.000
C.V.	1	43120	43120	0.56	0.453
S.S.	7	360027874	51432553	673.34	0.000
L.R.*D.U.	1	1487079	1487079	19.47	0.000
L.R.*L.T.	1	745978	745978	9.77	0.002
L.R.*S.U.	1	5566	5566	0.07	0.787
L.R.*C.V.	1	43120	43120	0.56	0.453
L.R.*S.S.	7	263163668	37594810	492.18	0.000
D.U.*L.T.	1	5	5	0.00	0.994
D.U.*S.U.	1	55723	55723	0.73	0.393
D.U.*C.V.	1	1751578	1751578	22.93	0.000
D.U.*S.S.	7	3711997	530285	6.94	0.000
L.T.*S.U.	1	242524	242524	3.18	0.075
L.T.*C.V.	1	567910	567910	7.43	0.007
L.T.*S.S.	7	1921198	274457	3.59	0.001
S.U.*C.V.	1	247941	247941	3.25	0.072
S.U.*S.S.	7	615257	87894	1.15	0.329
C.V.*S.S.	7	43536478	6219497	81.42	0.000
L.R.*D.U.*L.T.	1	1477	1477	0.02	0.889
L.R.*D.U.*S.U.	1	61485	61485	0.80	0.370
L.R.*D.U.*C.V.	1	1751578	1751578	22.93	0.000
L.R.*D.U.*S.S.	7	3797334	542476	7.10	0.000
L.R.*L.T.*S.U.	1	244079	244079	3.20	0.074
L.R.*L.T.*C.V.	1	567910	567910	7.43	0.007
L.R.*L.T.*S.S.	7	1394742	199249	2.61	0.011
L.R.*S.U.*C.V.	1	247941	247941	3.25	0.072
L.R.*S.U.*S.S.	7	633096	90442	1.18	0.309
L.R.*C.V.*S.S.	7	43536478	6219497	81.42	0.000
D.U.*L.T.*S.U.	1	114984	114984	1.51	0.220
D.U.*L.T.*C.V.	1	611685	611685	8.01	0.005
D.U.*L.T.*S.S.	7	1128472	161210	2.11	0.040
D.U.*S.U.*C.V.	1	4273	4273	0.06	0.813
D.U.*S.U.*S.S.	7	107488	15355	0.20	0.985
D.U.*C.V.*S.S.	7	1443690	206241	2.70	0.009
L.T.*S.U.*C.V.	1	153355	153355	2.01	0.157
L.T.*S.U.*S.S.	7	178295	25471	0.33	0.939
L.T.*C.V.*S.S.	7	510395	72914	0.95	0.463
S.U.*C.V.*S.S.	7	361505	51644	0.68	0.692
L.R.*D.U.*L.T.*S.U.	1	109141	109141	1.43	0.232
L.R.*D.U.*L.T.*C.V.	1	611685	611685	8.01	0.005
L.R.*D.U.*L.T.*S.S.	7	1141842	163120	2.14	0.038
L.R.*D.U.*S.U.*C.V.	1	4273	4273	0.06	0.813
L.R.*D.U.*S.U.*S.S.	7	106375	15196	0.20	0.986
L.R.*D.U.*C.V.*S.S.	7	1443690	206241	2.70	0.009
L.R.*L.T.*S.U.*C.V.	1	153355	153355	2.01	0.157
L.R.*L.T.*S.U.*S.S.	7	184511	26359	0.35	0.933
L.R.*L.T.*C.V.*S.S.	7	510395	72914	0.95	0.463
L.R.*S.U.*C.V.*S.S.	7	361505	51644	0.68	0.692
D.U.*L.T.*S.U.*C.V.	1	105171	105171	1.38	0.241
D.U.*L.T.*S.U.*S.S.	7	533817	76260	1.00	0.431
D.U.*L.T.*C.V.*S.S.	7	1603417	229060	3.00	0.004
D.U.*S.U.*C.V.*S.S.	7	297003	42429	0.56	0.792
L.T.*S.U.*C.V.*S.S.	7	545717	77960	1.02	0.415
L.R.*D.U.*L.T.*S.U.*C.V.	1	105171	105171	1.38	0.241
L.R.*D.U.*L.T.*S.U.*S.S.	7	537253	76750	1.00	0.426
L.R.*D.U.*L.T.*C.V.*S.S.	7	1603417	229060	3.00	0.004
L.R.*D.U.*S.U.*C.V.*S.S.	7	297003	42429	0.56	0.792
L.R.*L.T.*S.U.*C.V.*S.S.	7	545717	77960	1.02	0.415
D.U.*L.T.*S.U.*C.V.*S.S.	7	303676	43382	0.57	0.782
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	303676	43382	0.57	0.782
Error	1024	78216960	76384		
Total	1279	1282487543			

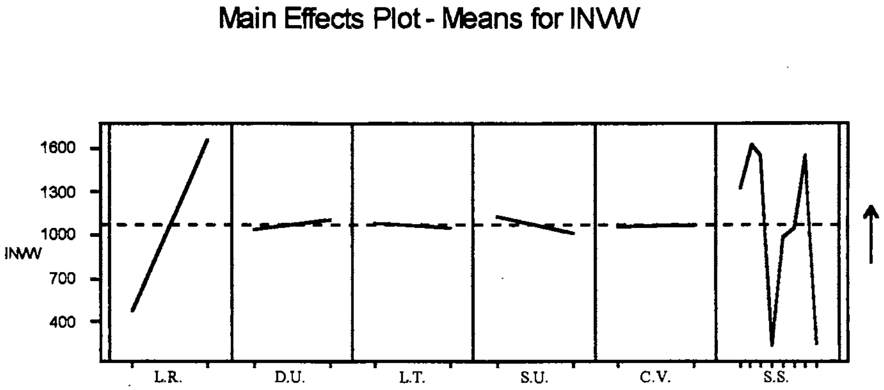

Figure 5.19 Main Effects Plot for Average INVW

Table 5.24 Average Inventory Level per Week of Each Main Effect at Each Level at the Warehouse

Means		
L.R.	N	INVW
1	640	476.0
2	640	1662.8
D.U.	N	INVW
1	640	1033.1
2	640	1105.6
L.T.	N	INVW
1	640	1089.8
2	640	1048.9
S.U.	N	INVW
1	640	1131.4
2	640	1007.3
C.V.	N	INVW
1	640	1063.6
2	640	1075.2
S.S.	N	INVW
1	160	1325.5
2	160	1630.1
3	160	1552.1
4	160	228.7
5	160	984.2
6	160	1044.3
7	160	1551.4
8	160	238.7

orders the exact quantity for the current period's need, the EOQ model chooses the order quantity to minimize the average cost per unit. When EOQ is used as the lot-sizing rule, usually excessive inventories are carried during the order interval.

As the demand uncertainty and transportation lead time uncertainty increase, the mean INVW also increases. It is because high demand forecast error may cause excess inventory at the warehouse. Transportation lead time within the distribution system may also cause excessive stocks held at the warehouse. When an order is delivered to distribution centers or retailers early, the open orders at the warehouse have to be held longer. The result of supply uncertainty is expected: as supply uncertainty increases the average INVW decreases. This is mainly because the supply shortage from vendor increases. However, the cost value factor is not significant at the 5 % level in this case.

As shown in Figure 5.20, the best safety stock policy is policy 2 in terms of the average INVW; policy 7 is the second best. Policies 4 and 8 result in lower average INVW. It is consistent with the results found in the average SOW analysis previously. To examine the interaction effects, the experimental results are shown in Table 5.25 and discussed below.

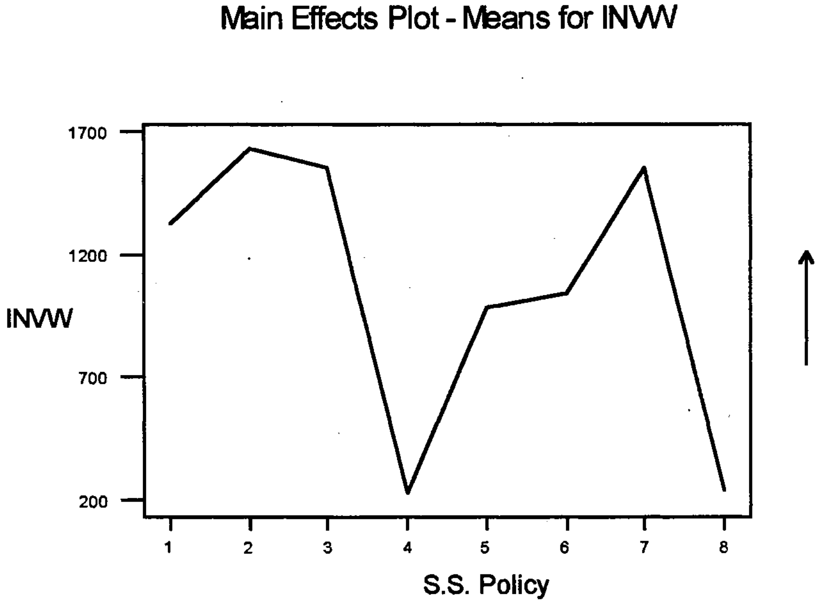

Figure 5.20 Means Plot for INVW as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	552.67	870.67	486.76	467.07	559.92	648.59	656.34	393.50	554.41	871.88	487.47	471.33	562.43	652.11	657.06	396.99
		EOQ	1964.90	2546.79	1968.06	3.81	1974.74	2026.07	2472.70	38.88	2168.46	2702.60	1943.00	0.94	2011.41	2001.73	2434.47	106.70
	CV=High	L4L	552.67	870.67	486.76	467.07	559.92	648.59	656.34	393.50	554.41	871.88	487.47	471.33	562.43	652.11	657.06	396.99
		EOQ	2482.47	2372.35	3664.29	7.85	1114.71	1195.89	2629.61	40.82	2744.37	2515.37	3845.49	9.76	1127.06	1180.30	2935.54	28.70
S.U.=High	CV=Low	L4L	431.90	752.28	387.18	345.00	428.59	518.90	525.72	287.29	433.55	753.66	387.43	348.95	430.72	522.63	526.34	288.89
		EOQ	1486.43	2505.09	2030.72	0.00	1916.89	1826.21	2196.47	69.86	2193.25	2551.46	2063.25	100.20	1879.66	1804.77	2376.59	4.36
	CV=High	L4L	431.90	752.28	387.18	345.00	428.59	518.90	525.72	287.29	433.55	753.66	387.43	348.95	430.72	522.63	526.34	288.89
		EOQ	2270.00	2259.89	3241.95	5.71	964.56	1019.18	2454.26	55.19	2631.17	3438.76	3581.50	16.80	941.02	1017.36	2991.94	25.67
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	444.66	766.80	399.05	372.73	470.17	550.44	564.75	330.71	451.95	773.43	401.66	388.07	478.33	561.44	569.05	337.70
		EOQ	2074.69	2561.63	2205.79	580.13	2005.65	2205.36	2467.92	1125.75	2174.26	2781.48	2003.11	435.15	1973.33	2131.53	2619.77	68.84
	CV=High	L4L	444.66	766.80	399.05	372.73	470.17	550.44	564.75	330.71	451.95	773.43	401.66	388.07	478.33	561.44	569.05	337.70
		EOQ	1999.24	2116.26	2774.61	7.34	1182.24	1202.71	2276.75	152.03	3180.93	2235.36	3877.84	64.94	1192.69	1190.20	3277.06	116.33
S.U.=High	CV=Low	L4L	328.35	627.75	309.25	256.74	342.41	409.51	426.30	249.55	332.58	635.24	310.61	266.62	348.45	419.55	429.22	251.47
		EOQ	1631.79	2372.20	1722.04	160.95	1983.17	1958.99	2335.86	533.40	1596.99	2589.74	1668.59	59.35	1941.19	1904.70	2319.86	109.75
	CV=High	L4L	328.35	627.75	309.25	256.74	342.41	409.51	426.30	249.55	332.58	635.24	310.61	266.62	348.45	419.55	429.22	251.47
		EOQ	2091.64	2323.27	2807.56	11.46	1053.91	1104.54	2026.02	52.58	2665.59	2188.07	3931.03	19.83	990.22	1081.62	3119.88	36.01

Table 5.25 Experimental Results for Average INVW per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The average inventory level for the interaction of lot-sizing rules and safety stock policies is displayed in Table 5.26. As shown in Table 5.26, the interaction of lot-sizing rules and safety stock policies has a significant effect on the average inventory level at the warehouse.

Table 5.26 Average INVW per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	441.3	756.5	396.2	364.6	452.6	535.4	544.3	317.0
EOQ	2209.8	2503.8	2708.1	92.8	1515.8	1553.2	2558.4	160.3

Furthermore, L4L results in lower average INVW than EOQ, and is less sensitive to the changes of the safety stock policy. When lot-sizing is changed from L4L to EOQ, there is an immense impact on safety stock policies 4 and 8. As shown in Figure 5.21, the mean inventory level drops dramatically for policies 4 and 8 under the EOQ lot-sizing rule. Other safety stock policies result in a higher average inventory level at the warehouse under the EOQ rule. This is consistent with previous results discussed in "stockout analysis". Policies 4 and 8 result in low mean inventory levels, which cause the stockouts at the warehouse.

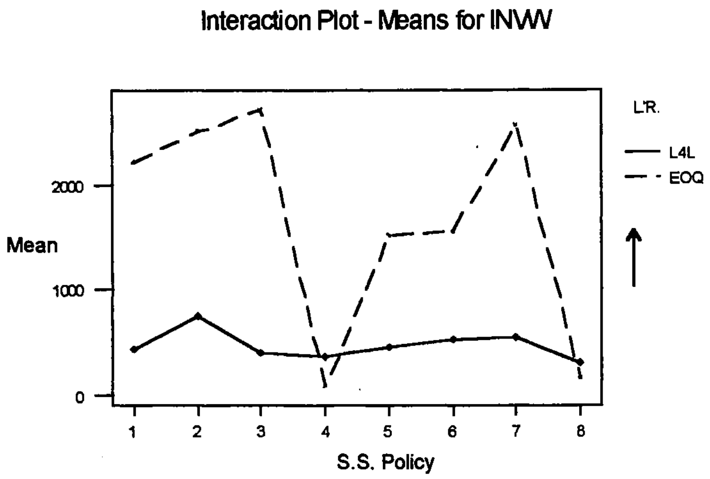

Figure 5.21 Means Plot for INVW per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Interaction of Demand Uncertainty and Safety Stock Policy

The mean inventory levels for demand uncertainty and safety stock policy are shown in Table 5.27. As observed in Table 5.27, when the demand uncertainty increases, the average inventory level at the warehouse increases under safety stock policies 1, 2, 3, and 7.

Table 5.27 Average INVW per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. / D.U.	1	2	3	4	5	6	7	8
Low	1219.8	1568.3	1473.7	228.8	987.4	1049.6	1450.4	286.9
High	1431.2	1692.0	1630.5	228.6	981.0	1039.0	1652.4	190.4

The interaction of demand uncertainty and safety stock policy is shown in Figure 5.22. As shown in Figure 5.22, the average INVW under policies 4, 5, 6, and 8 are not affected by demand uncertainty. As discussed before, policies 5 and 6 are the two best safety stock policies in terms of the average SOW. It is believed that safety stocks can absorb demand uncertainty when they are put in the right place. As shown in Table 5.25, demand uncertainty has different effects on policies 4 and 8 under various operating conditions. Safety stock policies 4 and 8 are less sensitive to the changes in demand uncertainty when the L4L rule is applied.

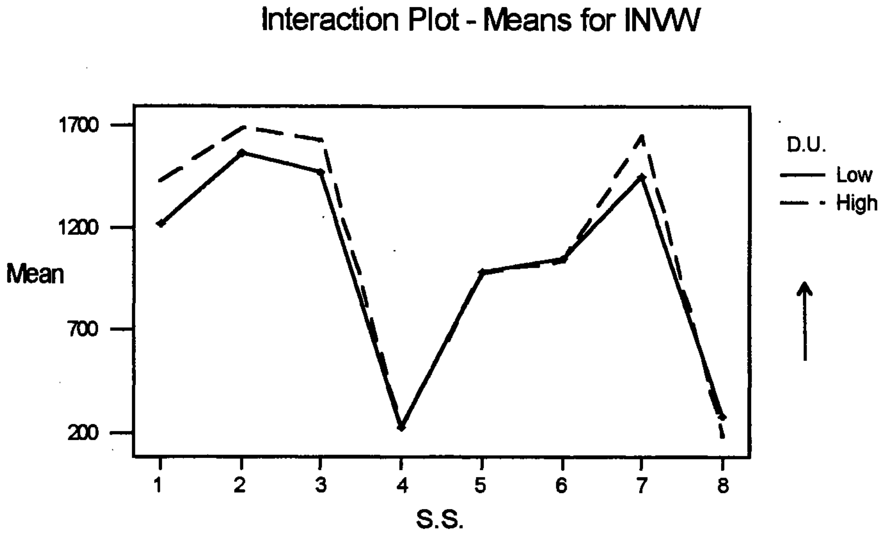

Figure 5.22 Means Plot for INVW per Week as a Function of Demand Uncertainty and Safety Stock Policy

Interaction of Lead Time Uncertainty and Safety Stock Policy

The average INVW for the interaction of the lead time uncertainty and safety stock policies is displayed in Table 5.28 and Figure 5.23. When the transportation lead time variations increase, the average INVW increases under most safety stock policies. As addressed before, this is mainly due to the early arrival of the order at distribution centers or retailers. Thus, excessive stocks have to be kept at the warehouse longer.

Table 5.28 Average INVW per Week for Lead Time Uncertainty and Safety Stock Policy (n=80)

S.S. / L.T.	1	2	3	4	5	6	7	8
Low	1283.1	1548.4	1489.5	244.2	975.1	1041.3	1526.4	283.3
High	1367.9	1711.8	1614.7	213.1	973.3	1047.2	1576.4	194.0

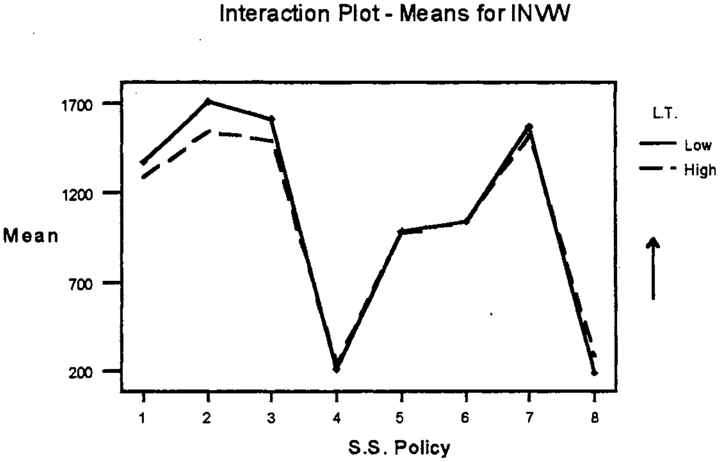

Figure 5.23 Means Plot for INVW per Week as a Function of Lead Time Uncertainty and Safety Stock Policy

Average Inventory Level at Distribution Center 1(INVDC1)

ANOVA is performed on the mean INVDC1 obtained from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.29. The results lead to the rejection of all hypotheses 21-30, except for hypothesis 30 at the 5% level. All the important main effects and interactions are addressed below.

Main Effects

A plot of main effects for average INVDC1 is presented in Figure 5.24, and the average INVDC1 of each main effect at each level is shown in Table 5.30. Visual examination of the experimental results in Figure 5.24 shows that EOQ yields a much higher average INVDC1 than L4L. The reason is the same as given for the situation at the warehouse.

As the demand uncertainty and transportation lead time uncertainty increase, the average INVDC1 decreases. This is consistent with the results from the average SODC1 analysis. As expected, when the supply shortage from the vendor increases, the average INVDC1 decreases. Furthermore, when the cost ratio decreases, the order quantity decided by the EOQ lot-sizing rule also decreases. This may cause lower average INVDC1 under low cost ratio.

Table 5.29 ANOVA Results for Average INVDC1 per Week

```
                    Analysis of Variance for Average INVDC1

Source                            DF        SS         MS       F      P
L.R.                               1  47276037   47276037 1957.75  0.000
D.U.                               1    840707     840707   34.81  0.000
L.T.                               1    366503     366503   15.18  0.000
S.U.                               1    179091     179091    7.42  0.007
C.V.                               1   8687229    8687229  359.75  0.000
S.S.                               7  34182922    4883275  202.22  0.000
L.R.*D.U.                          1   1010608    1010608   41.85  0.000
L.R.*L.T.                          1    967015     967015   40.05  0.000
L.R.*S.U.                          1     76452      76452    3.17  0.075
L.R.*C.V.                          1   8687229    8687229  359.75  0.000
L.R.*S.S.                          7  35479013    5068430  209.89  0.000
D.U.*L.T.                          1    171314     171314    7.09  0.008
D.U.*S.U.                          1     17002      17002    0.70  0.402
D.U.*C.V.                          1    121956     121956    5.05  0.025
D.U.*S.S.                          7    899369     128481    5.32  0.000
L.T.*S.U.                          1     85993      85993    3.56  0.059
L.T.*C.V.                          1    136854     136854    5.67  0.017
L.T.*S.S.                          7    504374      72053    2.98  0.004
S.U.*C.V.                          1     33552      33552    1.39  0.239
S.U.*S.S.                          7    191186      27312    1.13  0.341
C.V.*S.S.                          7   1796406     256629   10.63  0.000
L.R.*D.U.*L.T.                     1    205680     205680    8.52  0.004
L.R.*D.U.*S.U.                     1     17203      17203    0.71  0.399
L.R.*D.U.*C.V.                     1    121956     121956    5.05  0.025
L.R.*D.U.*S.S.                     7    871989     124570    5.16  0.000
L.R.*L.T.*S.U.                     1     57130      57130    2.37  0.124
L.R.*L.T.*C.V.                     1    136854     136854    5.67  0.017
L.R.*L.T.*S.S.                     7    510667      72952    3.02  0.004
L.R.*S.U.*C.V.                     1     33552      33552    1.39  0.239
L.R.*S.U.*S.S.                     7    129103      18443    0.76  0.618
L.R.*C.V.*S.S.                     7   1796406     256629   10.63  0.000
D.U.*L.T.*S.U.                     1      8852       8852    0.37  0.545
D.U.*L.T.*C.V.                     1     76055      76055    3.15  0.076
D.U.*L.T.*S.S.                     7    454565      64938    2.69  0.009
D.U.*S.U.*C.V.                     1        22         22    0.00  0.976
D.U.*S.U.*S.S.                     7    250587      35798    1.48  0.170
D.U.*C.V.*S.S.                     7    367534      52505    2.17  0.034
L.T.*S.U.*C.V.                     1     34410      34410    1.42  0.233
L.T.*S.U.*S.S.                     7    134099      19157    0.79  0.593
L.T.*C.V.*S.S.                     7    375122      53589    2.22  0.031
S.U.*C.V.*S.S.                     7    110825      15832    0.66  0.710
L.R.*D.U.*L.T.*S.U.                1      9065       9065    0.38  0.540
L.R.*D.U.*L.T.*C.V.                1     76055      76055    3.15  0.076
L.R.*D.U.*L.T.*S.S.                7    447660      63951    2.65  0.010
L.R.*D.U.*S.U.*C.V.                1        22         22    0.00  0.976
L.R.*D.U.*S.U.*S.S.                7    249647      35664    1.48  0.172
L.R.*D.U.*C.V.*S.S.                7    367534      52505    2.17  0.034
L.R.*L.T.*S.U.*C.V.                1     34410      34410    1.42  0.233
L.R.*L.T.*S.U.*S.S.                7    118644      16949    0.70  0.671
L.R.*L.T.*C.V.*S.S.                7    375122      53589    2.22  0.031
L.R.*S.U.*C.V.*S.S.                7    110825      15832    0.66  0.710
D.U.*L.T.*S.U.*C.V.                1     28551      28551    1.18  0.277
D.U.*L.T.*S.U.*S.S.                7    158082      22583    0.94  0.478
D.U.*L.T.*C.V.*S.S.                7    332695      47528    1.97  0.056
D.U.*S.U.*C.V.*S.S.                7    154681      22097    0.92  0.494
L.T.*S.U.*C.V.*S.S.                7    111845      15978    0.66  0.705
L.R.*D.U.*L.T.*S.U.*C.V.           1     28551      28551    1.18  0.277
L.R.*D.U.*L.T.*S.U.*S.S.           7    157508      22501    0.93  0.481
L.R.*D.U.*L.T.*C.V.*S.S.           7    332695      47528    1.97  0.056
L.R.*D.U.*S.U.*C.V.*S.S.           7    154681      22097    0.92  0.494
L.R.*L.T.*S.U.*C.V.*S.S.           7    111845      15978    0.66  0.705
D.U.*L.T.*S.U.*C.V.*S.S.           7    135997      19428    0.80  0.584
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.      7    135997      19428    0.80  0.584
Error                           1024  24727718      24148
Total                           1279 175763257
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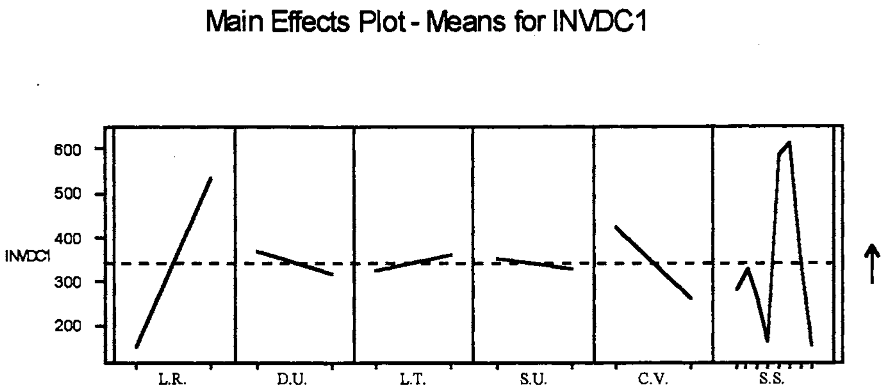

Figure 5.24 Main Effects Plot for Average INVDC1

Table 5.30 Average Inventroy Level per Week of Each Main Effect at Each Level at Distribution Center 1

Means		
L.R.	N	INVDC1
1	640	149.91
2	640	534.28
D.U.	N	INVDC1
1	640	367.72
2	640	316.46
L.T.	N	INVDC1
1	640	325.17
2	640	359.01
S.U.	N	INVDC1
1	640	353.92
2	640	330.26
C.V.	N	INVDC1
1	640	424.47
2	640	259.71
S.S.	N	INVDC1
1	160	282.38
2	160	329.39
3	160	263.66
4	160	160.69
5	160	586.26
6	160	616.03
7	160	346.43
8	160	151.89

As shown in Figure 5.25, the best safety stock policy is policy 6 in terms of the average INVDC1; policy 5 is the second best. Policies 4 and 8 result in much lower average INVDC1 than other policies. This is consistent with the previous stockout analysis at the distribution center 1. To examine the interactions, the average inventory level over five replications is presented in Table 5.31 and discussed below.

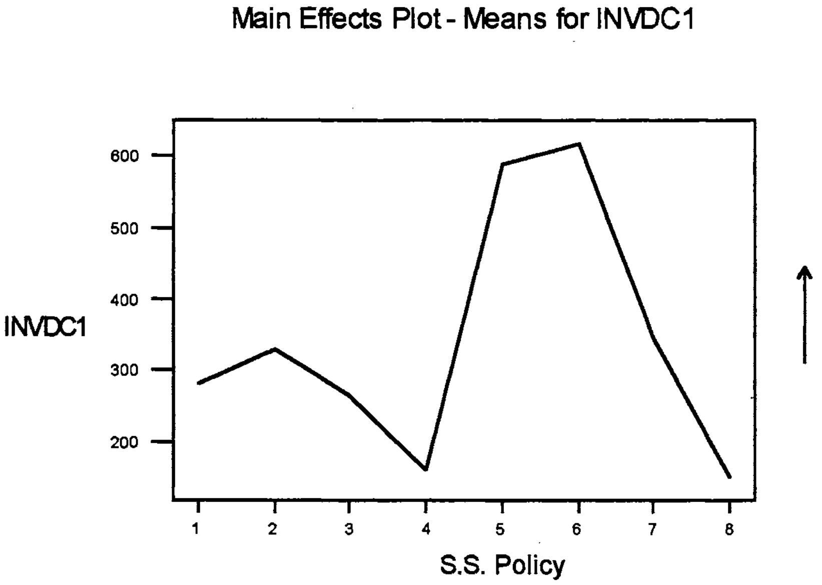

Figure 5.25 Means Plot for INVDC1 per Week as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	149.31	151.40	82.50	263.10	165.53	206.04	111.98	163.62	151.20	153.19	84.39	266.08	169.19	208.99	114.02	168.39
		EOQ	468.62	779.37	813.38	20.44	1297.67	1359.83	495.12	52.68	426.68	316.22	498.69	0.75	1378.40	1337.62	855.94	114.64
	CV=High	L4L	149.31	151.40	82.50	263.10	165.53	206.04	111.98	163.62	151.20	153.19	84.39	266.08	169.19	208.99	114.02	168.39
		EOQ	481.94	403.35	285.13	5.47	724.28	814.48	305.86	44.52	183.50	260.68	153.17	13.12	773.80	806.46	319.13	34.58
S.U.=High	CV=Low	L4L	145.28	151.39	76.82	253.84	161.19	204.50	111.08	148.18	147.44	153.19	78.33	257.00	164.85	207.62	113.16	152.35
		EOQ	608.40	765.14	676.27	0.00	1185.27	1273.63	795.09	89.73	262.00	553.90	285.10	82.34	1297.90	1394.79	777.15	23.75
	CV=High	L4L	145.28	151.39	76.82	253.84	161.19	204.50	111.08	148.18	147.44	153.19	78.33	257.00	164.85	207.62	113.16	152.35
		EOQ	354.60	320.52	196.79	1.68	770.50	795.71	381.73	51.97	212.50	219.98	140.86	13.18	708.89	754.24	510.75	21.67
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	127.73	128.77	86.72	222.07	145.27	175.25	106.03	139.64	133.74	134.14	92.29	232.77	152.51	183.72	110.35	148.36
		EOQ	574.57	929.83	881.98	504.00	1306.08	1247.94	969.85	1019.27	708.75	625.27	586.07	352.03	1326.76	1217.49	762.41	94.45
	CV=High	L4L	127.73	128.77	86.72	222.07	145.27	175.25	106.03	139.64	133.74	134.14	92.29	232.77	152.51	183.72	110.35	148.36
		EOQ	380.16	452.98	489.38	2.70	750.72	786.68	450.13	109.52	363.24	444.68	287.10	50.67	731.42	768.03	335.22	110.35
S.U.=High	CV=Low	L4L	117.97	128.65	77.90	193.70	134.60	170.97	102.05	114.95	123.79	134.05	82.11	206.93	142.45	180.37	106.56	122.60
		EOQ	706.34	809.06	778.08	170.79	1306.93	1290.71	957.93	579.25	262.73	588.87	401.58	99.08	1205.37	1320.59	756.65	111.39
	CV=High	L4L	117.97	128.65	77.90	193.70	134.60	170.97	102.05	114.95	123.79	134.05	82.11	206.93	142.45	180.37	106.56	122.60
		EOQ	570.65	380.43	587.77	10.17	775.20	725.94	459.04	48.85	278.56	420.58	53.61	24.63	750.09	743.94	203.32	37.80

Table 5.31 Experimental Results for Average INVDC1 per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

The interaction of lot-sizing rules and safety stock policies has a significant effect on average INVDC1. The effect of the safety stock policies is significantly influenced by the lot-sizing rules used. As shown in Table 5.32, L4L is less sensitive to the safety stock policy used at distribution center 1. EOQ results in different average INVDC1 under various safety stock policies. The reason for this has been addressed in the previous stockout analysis. As observed in Figure 5.26, EOQ results in higher average INVDC1 than L4L under most safety stock policies except for policy 4. This is because the warehouse can not replenish the stock at distribution center 1 when EOQ is used along with policy 4.

Table 5.32 Average INVDC1 per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	137.1	141.8	82.6	236.9	154.4	192.2	109.4	144.8
EOQ	427.7	516.9	444.7	84.7	1018.1	1039.9	583.5	159.0

Interaction of Demand Uncertainty and Safety Stock Policy

When the demand uncertainty increases, it affects safety stock policies to a different degree. As shown in Table 5.33, when demand uncertainty increases, there is a

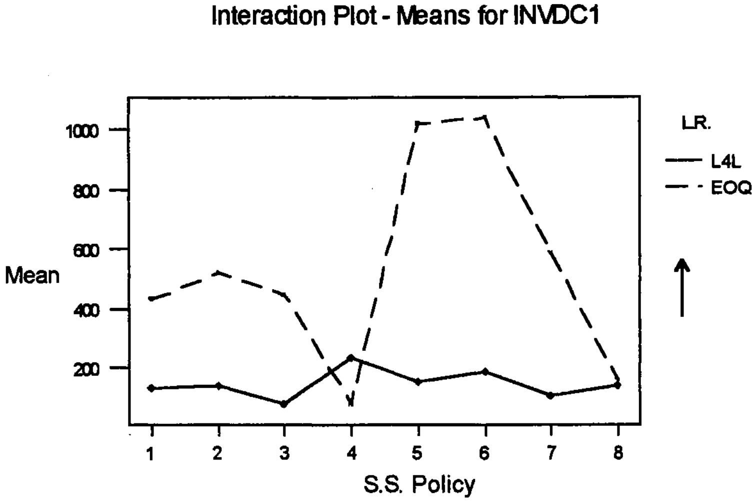

Figure 5.26 Means Plot for INVDC1 per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Table 5.33 Mean INVDC1 per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. D.U.	1	2	3	4	5	6	7	8
Low	326.62	372.59	334.79	161.29	583.11	613.03	354.81	195.54
High	238.14	286.21	192.53	160.09	589.41	619.04	338.05	108.25

severe impact on policies 1, 2, 3, and 8. However, policies 5 and 6 are not much affected by demand uncertainty

The same reason used in stockout analysis at distribution center 1 may explain the interaction between the demand uncertainty and safety stock policies at distribution center 1. The change in the average inventory level is due to the increase in demand forecast error at retailers. In turn, that results in lower average inventory level at distribution center 1 when demand uncertainty increases. The interaction of demand uncertainty and safety stock policy is displayed in Figure 5.27. Compared to the results obtained from INVW, demand uncertainty from customers has more impact on the performance of distribution center 1 than on the warehouse. There is an opposite change at the warehouse when demand uncertainty changes. This is because distribution centers are affected more directly by the demand uncertainty than the warehouse.

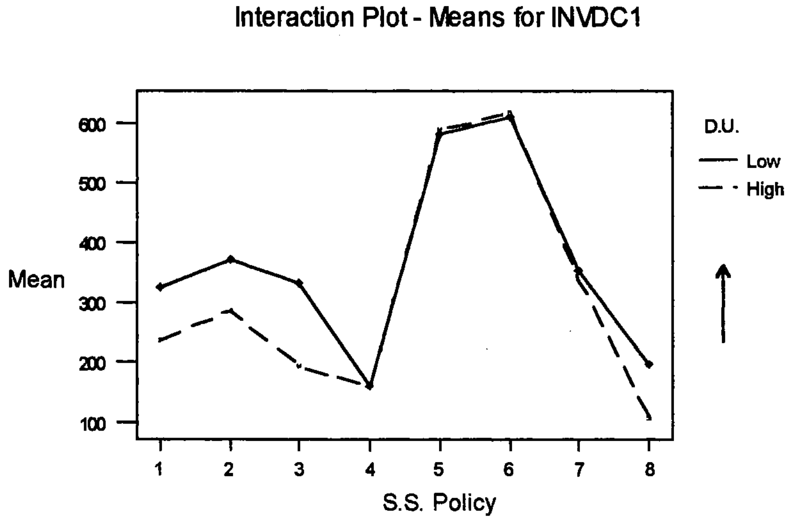

Figure 5.27 Means Plot for INVDC1 per Week as a Function of Demand Uncertainty and Safety Stock Policy

Interaction of Lead Time Uncertainty and Safety Stock Policy

When the transportation lead time distribution varies from a symmetric discrete distribution with low variation to a discrete uniform distribution with high variation, the average INVDC1 decreases under most safety stock policies, except for policies 5 and 6. The average inventory level for the interaction of these two factors is displayed in Table 5.34 and Figure 5.28. As shown in Table 5.34, policy 8 under the EOQ lot-sizing rule results in much lower average INVDC1 when lead time uncertainty is increased.

Table 5.34 Average INVDC1 per Week for Lead Time uncertainty and Safety Stock Policy (n=80)

S.S. L.T.	1	2	3	4	5	6	7	8
Low	303.22	356.43	296.47	182.81	581.39	595.12	359.03	197.62
High	261.54	302.34	230.84	138.56	591.14	636.94	333.83	106.16

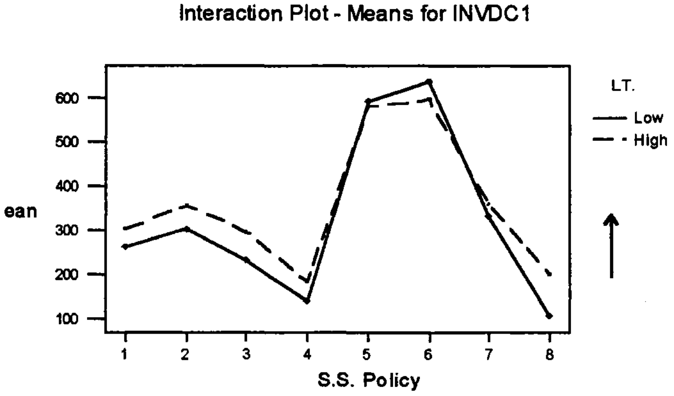

Figure 5.28 Means Plot for INVDC1 per Week of Lead Time Uncertainty and Safety Stock Policy

Average Inventory at Retailer 1(INVR1)

ANOVA is performed on the average INVR1 obtained from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other main effects are shown in Table 5.35. The results lead to the rejection of all hypotheses 21-30 except for hypotheses 23 and 30 at the 5% level. All the important main effects and interactions are addressed below.

Main Effects

A plot of main effects for average INVR1 is presented in Figure 5.29; the average INVR1 of each main effect at each level is shown in Table 5.36. As observed in the experimental results in Figure 5.29, EOQ yields a much higher average INVR1 than L4L. This is because when EOQ is used to calculate the planned order, the built-in safety stock feature of EOQ may carry excessive stocks until the next order point.

As the demand uncertainty and transportation lead time uncertainty increase, the average INVR1 decreases. This is because the demand forecast error becomes worse when demand uncertainty increases. This is especially true when the actual demand exceeds the forecast demand. That may cause lower average INVR1 due to stockouts. On the other hand, when actual demand is less than forecast demand, all the DRP system must do is to adjust the next period's planned order

Table 5.35 ANOVA Results for Average INVR1 per Week

```
                  Analysis of Variance for Average INVR1

Source                            DF        SS          MS         F       P
L.R.                               1  35104309    35104309   2711.32   0.000
D.U.                               1    444783      444783     34.35   0.000
L.T.                               1     94666       94666      7.31   0.007
S.U.                               1     29507       29507      2.28   0.131
C.V.                               1   4928079     4928079    380.63   0.000
S.S.                               7  10499684     1499955    115.85   0.000
L.R.*D.U.                          1    618240      618240     47.75   0.000
L.R.*L.T.                          1     73071       73071      5.64   0.018
L.R.*S.U.                          1     24048       24048      1.86   0.173
L.R.*C.V.                          1   4928079     4928079    380.63   0.000
L.R.*S.S.                          7  10629875     1518554    117.29   0.000
D.U.*L.T.                          1     29103       29103      2.25   0.134
D.U.*S.U.                          1      3329        3329      0.26   0.612
D.U.*C.V.                          1     86190       86190      6.66   0.010
D.U.*S.S.                          7    391752       55965      4.32   0.000
L.T.*S.U.                          1     28658       28658      2.21   0.137
L.T.*C.V.                          1     34334       34334      2.65   0.104
L.T.*S.S.                          7    275209       39316      3.04   0.004
S.U.*C.V.                          1     11765       11765      0.91   0.341
S.U.*S.S.                          7     72512       10359      0.80   0.587
C.V.*S.S.                          7    703415      100488      7.76   0.000
L.R.*D.U.*L.T.                     1     35162       35162      2.72   0.100
L.R.*D.U.*S.U.                     1      3400        3400      0.26   0.608
L.R.*D.U.*C.V.                     1     86190       86190      6.66   0.010
L.R.*D.U.*S.S.                     7    400415       57202      4.42   0.000
L.R.*L.T.*S.U.                     1     26496       26496      2.05   0.153
L.R.*L.T.*C.V.                     1     34334       34334      2.65   0.104
L.R.*L.T.*S.S.                     7    274554       39222      3.03   0.004
L.R.*S.U.*C.V.                     1     11765       11765      0.91   0.341
L.R.*S.U.*S.S.                     7     65379        9340      0.72   0.654
L.R.*C.V.*S.S.                     7    703415      100488      7.76   0.000
D.U.*L.T.*S.U.                     1     12150       12150      0.94   0.333
D.U.*L.T.*C.V.                     1      6567        6567      0.51   0.477
D.U.*L.T.*S.S.                     7    221610       31659      2.45   0.017
D.U.*S.U.*C.V.                     1       355         355      0.03   0.868
D.U.*S.U.*S.S.                     7    113718       16245      1.25   0.270
D.U.*C.V.*S.S.                     7    131211       18744      1.45   0.183
L.T.*S.U.*C.V.                     1      9977        9977      0.77   0.380
L.T.*S.U.*S.S.                     7     41362        5909      0.46   0.866
L.T.*C.V.*S.S.                     7    176191       25170      1.94   0.060
S.U.*C.V.*S.S.                     7     37366        5338      0.41   0.895
L.R.*D.U.*L.T.*S.U.                1     12293       12293      0.95   0.330
L.R.*D.U.*L.T.*C.V.                1      6567        6567      0.51   0.477
L.R.*D.U.*L.T.*S.S.                7    220537       31505      2.43   0.018
L.R.*D.U.*S.U.*C.V.                1       355         355      0.03   0.868
L.R.*D.U.*S.U.*S.S.                7    113795       16256      1.26   0.269
L.R.*D.U.*C.V.*S.S.                7    131211       18744      1.45   0.183
L.R.*L.T.*S.U.*C.V.                1      9977        9977      0.77   0.380
L.R.*L.T.*S.U.*S.S.                7     42080        6011      0.46   0.861
L.R.*L.T.*C.V.*S.S.                7    176191       25170      1.94   0.060
L.R.*S.U.*C.V.*S.S.                7     37366        5338      0.41   0.895
D.U.*L.T.*S.U.*C.V.                1      9199        9199      0.71   0.399
D.U.*L.T.*S.U.*S.S.                7     60379        8626      0.67   0.701
D.U.*L.T.*C.V.*S.S.                7    150696       21528      1.66   0.114
D.U.*S.U.*C.V.*S.S.                7     72202       10315      0.80   0.590
L.T.*S.U.*C.V.*S.S.                7     55542        7935      0.61   0.746
L.R.*D.U.*L.T.*S.U.*C.V.           1      9199        9199      0.71   0.399
L.R.*D.U.*L.T.*S.U.*S.S.           7     60316        8617      0.67   0.701
L.R.*D.U.*L.T.*C.V.*S.S.           7    150696       21528      1.66   0.114
L.R.*D.U.*S.U.*C.V.*S.S.           7     72202       10315      0.80   0.590
L.R.*L.T.*S.U.*C.V.*S.S.           7     55542        7935      0.61   0.746
D.U.*L.T.*S.U.*C.V.*S.S.           7     74326       10618      0.82   0.571
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.      7     74326       10618      0.82   0.571
Error                           1024  13258052       12947
Total                           1279  86255272
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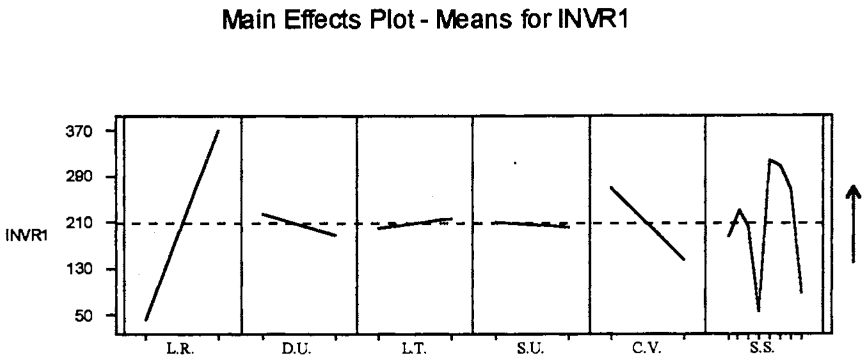

Figure 5.29 Main Effects Plot for Average INVR1

Table 5.36 Average Inventory Level per Week of Each Main Effect at Each Level at Retailer 1

	Means	
L.R.	N	INVR1
1	640	41.21
2	640	372.43
D.U.	N	INVR1
1	640	225.46
2	640	188.18
L.T.	N	INVR1
1	640	198.22
2	640	215.42
S.U.	N	INVR1
1	640	211.62
2	640	202.02
C.V.	N	INVR1
1	640	268.87
2	640	144.77
S.S.	N	INVR1
1	160	186.35
2	160	229.63
3	160	201.81
4	160	53.88
5	160	319.63
6	160	310.13
7	160	266.12
8	160	87.01

to offset the excessive inventories. This may explain why the average INVR1 decreases when demand uncertainty increases. When the actual transportation lead time takes longer than 3 weeks, the on-hand inventories will be depleted. This explains how high lead time variations result in lower mean INVR1. As addressed in the analysis of average INVDC1, when the cost value increases, the average INVR1 also decreases.

According to Figure 5.30, the best safety stock policy in terms of the mean INVR1 is policy 5; policy 6 is the second best. Policies 4 and 8 still result in lower mean INVR1 than other safety stock policies. The same reason given at the warehouse may explain the performance of these safety stock policies. To examine the interactions, the average inventory level over five replications is given in Table 5.37 and discussed below.

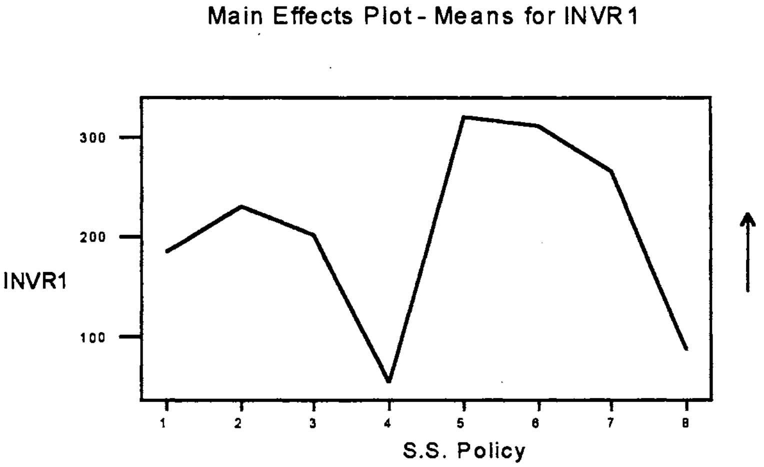

Figure 5.30 Means Plot for INVR1 per Week as a Function of Safety Stock Policy

			L.T.=Low															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	32.35	30.89	42.70	36.08	41.07	35.86	37.52	44.26	38.38	36.96	48.25	41.36	46.38	41.15	42.69	51.38
		EOQ	403.99	731.39	692.58	31.84	815.56	779.35	562.10	74.91	373.37	317.78	440.48	3.05	768.24	741.45	702.71	86.72
	CV=High	L4L	32.35	30.89	42.70	36.08	41.07	35.86	37.52	44.26	38.38	36.96	48.25	41.36	46.38	41.15	42.69	51.38
		EOQ	334.32	335.54	226.24	8.72	467.92	413.19	287.10	70.01	151.37	184.55	127.48	15.57	457.84	448.16	293.52	48.98
S.U.=High	CV=Low	L4L	32.07	30.89	41.09	35.85	40.74	35.79	37.32	42.43	38.13	36.97	46.65	41.17	45.92	41.13	42.52	49.49
		EOQ	570.86	668.17	554.89	10.04	761.60	712.72	737.88	92.13	260.25	502.10	309.41	106.75	769.68	795.95	649.57	12.80
	CV=High	L4L	32.07	30.89	41.09	35.85	40.74	35.79	37.32	42.43	38.13	36.97	46.65	41.17	45.92	41.13	42.52	49.49
		EOQ	246.35	263.25	200.14	5.98	473.47	446.47	330.68	70.77	185.63	168.56	92.82	17.24	443.46	457.09	446.79	41.80
			L.T.=High															
			D.U.=Low								D.U.=High							
			S.S.Policy								S.S. Policy							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
S.U.=Low	CV=Low	L4L	32.95	33.21	47.11	35.89	40.95	36.66	40.09	46.21	40.49	41.12	55.52	42.81	47.93	44.29	47.21	54.08
		EOQ	492.53	661.21	628.91	356.11	739.51	722.04	739.99	633.00	505.32	563.10	500.52	232.37	698.05	674.94	646.59	55.42
	CV=High	L4L	32.95	33.21	47.11	35.89	40.95	36.66	40.09	46.21	40.49	41.12	55.52	42.81	47.93	44.29	47.21	54.08
		EOQ	244.97	302.22	344.04	8.95	423.16	438.17	336.69	99.75	227.23	332.40	193.20	39.86	430.09	411.65	244.21	97.73
S.U.=High	CV=Low	L4L	31.73	33.20	43.29	34.90	39.89	36.45	39.52	43.14	39.40	41.12	52.00	42.07	46.99	44.14	46.68	51.22
		EOQ	539.76	696.30	599.95	121.55	728.83	704.36	731.32	418.33	263.44	509.54	345.92	104.07	712.09	692.65	617.28	102.18
	CV=High	L4L	31.73	33.20	43.29	34.90	39.89	36.45	39.52	43.14	39.40	41.12	52.00	42.07	46.99	44.14	46.68	51.22
		EOQ	401.87	232.95	406.07	17.58	428.65	429.00	362.00	64.91	190.99	310.33	42.03	24.22	410.17	426.08	160.23	50.60

Table 5.37 Experimental Results for Average INVR1 per Week

Interaction of Lot-Sizing Rule and Safety Stock Policy

As observed in Table 5.38 and Figure 5.31, the interaction of lot-sizing rules and safety stock policies are obviously significant. Furthermore, L4L is very insensitive to the safety stock policies used at the retailer 1. However, EOQ results in different mean INVR1 under various safety stock policies.

As observed in Table 5.37, EOQ results in higher mean INVR1 than L4L under most operating conditions. It can be explained by the built-in safety stock associated with EOQ. Thus, excessive stocks will be carried until the next order point.

Table 5.38 Mean INVR1 per Week for Lot-sizing Rule and Safety Stock Policy (n=80)

S.S. L.R.	1	2	3	4	5	6	7	8
L4L	35.69	35.54	47.08	38.77	43.73	39.44	41.69	47.78
EOQ	337.01	423.71	356.54	68.99	595.52	580.83	490.54	126.25

Interaction of Demand Uncertainty and Safety Stock Policy

Although the ranking of the safety stock policies stays the same when the demand uncertainty increases, the magnitude of the decreases in the average inventory levels are different under various safety stock policies. As shown in Table 5.39 and Figure 5.32, policies 4, 5, and 6 are less sensitive to the changes in demand uncertainty.

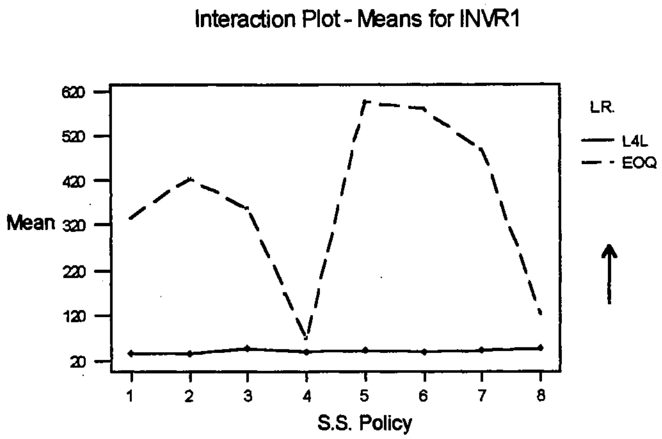

Figure 5.31 Means Plot for INVR1 per Week as a Function of Lot-sizing Rule and Safety Stock Policy

Table 5.39 Average SOR1 per Week for Demand Uncertainty and Safety Stock Policy (n=80)

S.S. / D.U.	1	2	3	4	5	6	7	8
Low	218.30	259.21	250.08	52.89	322.75	308.43	274.79	117.24
High	154.40	200.04	153.54	54.57	316.50	311.84	257.44	56.79

The interaction of demand uncertainty and safety stock policy is displayed in Figure 5.32. As observed in Figure 5.32, when demand uncertainty increases, it results in a decrease of average INVR1 under most safety stock policies. Compared to the results in average INVDC1, the interaction between these two factors at the retailer 1 follows the same pattern as distribution center 1. The same reason given in the mean INVDC1 analysis may explain why average INVR1 decreases when demand uncertainty increases.

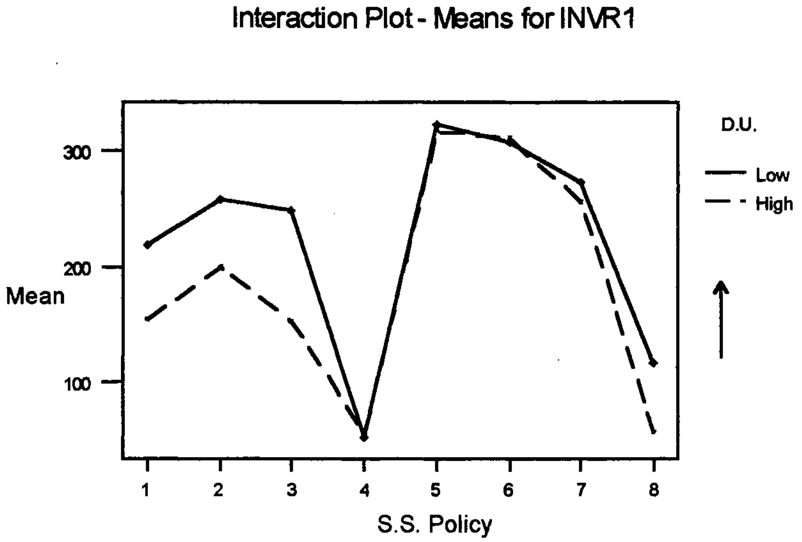

Figure 5.32 Means Plot for INVR1 per Week as a Function of Demand Uncertainty and Safety Stock Policy

Interaction of Lead Time Uncertainty and Safety Stock Policy

Average INVR1 for the interaction of lead time uncertainty and safety stock policy is displayed in Table 5.40 and Figure 5.33. When the transportation lead time distribution changes from a symmetric discrete distribution with low variation to a discrete uniform distribution with high variation, the average INVR1 decreases under most safety stock policies. The pattern is the same as at the distribution centers. This is because lead time uncertainty occurs both at the distribution centers and at the retailers.

Table 5.40 Average INVR1 per Week for Lead Time Uncertainty and Safety Stock Policy (n=80)

S.S. L.T.	1	2	3	4	5	6	7	8
Low	197.20	244.08	216.03	76.00	307.63	301.37	261.58	119.45
High	175.50	215.17	187.59	31.76	331.62	318.87	270.65	54.58

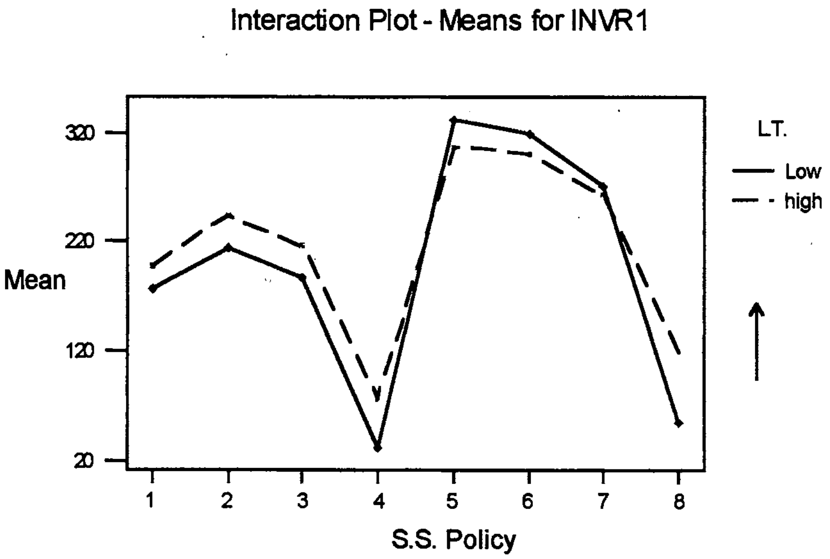

Figure 5.33 Means Plot for INVR1 per Week as a Function of Lead Time Uncertainty and Safety Stock Policy

Results for Service Level Analysis

The mean service level measures the ability of the physical distribution system to satisfy the demand from outside customers or other channel members in the system. The mean service level is the percentage of the total demand which is satisfied by available inventory at each channel member. It is calculated as the sum of the minimum number of product units in each time period which is either available in inventory or demanded, divided by the total demand.

The simulation results for the mean service level at the warehouse, distribution centers and retailers are the same as those for average stockout units. This is because these two performance measures are essentially the same. They describe the same thing from two different viewpoints. The higher the mean service level, the lower the average stockout units. Only a brief discussion of the simulation results for all channel members is provided below. The analysis of the results is given previously in the stockout analysis. All the main effects, important two-way interaction plots, and ANOVA table are listed in Appendix B.

Mean Service Level at Warehouse(SERW)

All main effects are significant at the 5% level. As demand uncertainty, transportation lead time uncertainty, and supply uncertainty increase, the mean SERW decreases. When the cost value increases, the mean SERW also decreases.

The best safety stock policy is policy 2 in terms of the mean SERW; the second best policy is policy 7. The results are the same as stockout analysis.

L4L always generates higher mean SERW than EOQ. The mean SERW drops below 10% under policies 4 and 8, when EOQ is used. When lead time uncertainty increases, all safety stock policies result in lower mean SERW. This is because only supply shortage is considered. Thus, all safety stock policies result in lower mean service level when supply uncertainty increases.

Mean Service Level at Distribution Center 1(SERDC1)

All main effects are significant at the 5% level. As demand uncertainty, transportation lead time uncertainty, supply uncertainty and cost value increase, the mean SERDC1 decreases. The best safety stock policy is policy 6 in terms of the mean SERDC1. Policy 6 puts safety stocks at the warehouse and two distribution centers. The second best policy is policy 5, which puts safety stocks at all channel members.

L4L outperforms EOQ in terms of the mean SERDC1. The mean SERDC1 under policies 5 and 6 is not much affected by the lot-sizing rule used. When lead time uncertainty increases, all safety stock policies result in lower mean SERDC1. Again, this is because only supply shortage is considered in this study. All safety stock policies result in lower mean service level when supply uncertainty increases.

Mean Service Level at Retailer 1(SERR1)

All main effects are significant at the 5% level, except for supply uncertainty. As demand uncertainty, transportation lead time uncertainty and cost value increase, the mean SERR1 decreases. The best safety stock policy is policy 5 in terms of the mean SERR1; the second best policy is policy 6, which allocates safety stocks at the warehouse and at two distribution centers.

L4L doesn't always generate higher service levels than EOQ in this case. While safety stock policies 1, 3, 4 and 8 result in a higher mean service level under L4L, safety stock policies 2, 5, 6 and 7 have better performance in terms of mean SERR1 when EOQ is used. Furthermore, all safety stock policies result in lower mean SERR1 under high demand variations.

Discussion of Results

The purpose of this study is to examine the impact of selected main effects and the interactions of safety stock policy with those selected main factors on various performance measures in a multi-echelon distribution system. Based on the previous discussion, a summary of experimental results in the base experiment is presented in Table 5.41. As shown in Table 5.41, six main effects, four two-way interactions, and the best safety stock policy are listed for each channel member under all performance measures. A follow-up discussion of the main effects and interaction analysis are based on the summary.

Table 5.41 Summary of Experimental Results in the Base Experiment

	TRC	Stockout Unit			Inventory Level			Service Level		
		W	DC	R	W	DC	R	W	DC	R
L.R.	+	+	+	+	+	+	+	+	+	+
D.U.	+	+	+	+	+	+	+	+	+	+
L.T.	+	+	+	+	+	+	+	+	+	+
S.U.	+	+	-	-	+	+	-	+	+	-
C.V.	+	+	+	+	-	+	+	+	+	+
S.S.	+	+	+	+	+	+	+	+	+	+
L.R.*S.S.	+	+	+	+	+	+	+	+	+	+
D.U.*S.S.	+	+	+	+	+	+	+	-	+	+
L.T.*S.S.	+	+	-	-	+	+	+	+	-	-
S.U.*S.S.	-	+	-	-	-	-	-	+	-	-
Best S.S.	6	2	6	5	2	6	5	2	6	5
Second Best	5	7	5	6	3	5	6	7	5	6
Best L.R.	L4L	L4L	L4L	L4L	L4L	L4L	L4L	L4L	L4L	L4L

+ Significant at the 5% Level
- Not Significant at the 5% Level

Lot-Sizing Rule

The lot-sizing rules used at each channel member results in significantly different values in all performance measures. The EOQ lot-sizing rule results in higher mean TRC than L4L. Although L4L results in higher ordering cost than EOQ, it can be justified by lower stockout cost and lower inventory carrying cost as shown in Table 5.42. The L4L rule also performs better than EOQ in terms of the average stockout units and the mean service level at all channel members.

Although lot-sizing rules have a significant effect on all channel members, the magnitude of effect on each channel member is different. When average stockout units are considered, the lot-sizing rule used to decide the planned order quantity has a larger effect at the warehouse and distribution centers than at the retailers. The average stockout units under the two lot-sizing rules for all channel members are shown in Table 5.42. When the EOQ lot-sizing rule is used, the average stockout units increase at all channel members mainly due to the interaction of transportation lead time uncertainty and safety stock policies. As shown in Figure 5.34, the EOQ lot-sizing rule

Table 5.42 Average Stockout Units, Average Inventory Level, and Mean Service Level for All Channel Members under Two Lot-sizing Rules

	Lot-sizing Rule	Warehouse	Distribution Center 1	Retailer 1
Average Stockout Unit	L4L	16.58	22.11	14.748
	EOQ	986.34	856.20	18.57
Average Inventory Level	L4L	476.0	149.91	41.21
	EOQ	1662.8	534.28	372.43
Mean Service Level	L4L	0.961	0.847	0.70
	EOQ	0.659	0.411	0.63

is more sensitive to the changes in lead time uncertainty in terms of the average SOW.

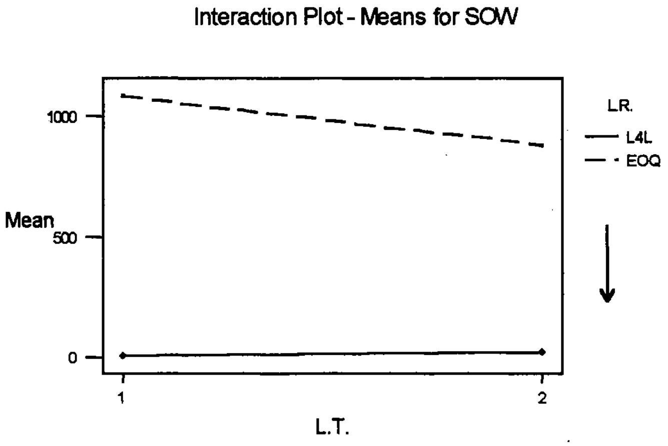

Figure 5.34 Means Plot for SOW per Week as a Function of Lot-Sizing Rule and Lead Time Uncertainty

Demand Uncertainty

While the nature of customer demand is an important factor which affects the performance of the whole distribution system, it affects individual channel members to a different degree. The system performance deteriorates in terms of mean TRC when the demand uncertainty increases. As shown in Table 5.43, demand uncertainty has less effect on the warehouse than on distribution centers and retailers in terms of the three non-monetary performance measures. For instance, as the demand uncertainty increases, the average SOW increases 12%, the average SODC1 increases 42%, and the average SOR1 increases 30%. This is because the

Table 5.43 Average Stockout Units, Average Inventory Level, and Mean Service Level for All Channel Members under Two Levels of Demand Uncertainty

	Demand Uncertainty	Warehouse	Distribution Center 1	Retailer 1
Average Stockout Unit	Low	473.73	362.06	14.48
	High	529.19	516.25	18.83
Average Inventory Level	Low	1033.1	367.72	225.46
	High	1105.6	316.46	188.18
Mean Service Level	Low	0.818	0.658	0.710
	High	0.803	0.602	0.626

demand uncertainty has a more direct influence on retailers and distribution centers.

Demand uncertainty has different effects on each channel member in terms of average inventory level. When the demand uncertainty increases, the average INVW will increase and average INVDC1, average INVR1 will decrease. Furthermore, the mean service level decreases at all channel members when the demand uncertainty increases. This is consistent with the result found by Bregman (1989): the demand uncertainty has a significant effect on customer service.

Lead Time Uncertainty

As shown in Table 5.41, the transportation lead time uncertainty has significant effects on all channel members under each performance measure. The mean TRC is higher when transportation lead time follows a uniform discrete distribution rather than a symmetric discrete distribution, since a greater number of products are received early as well as late. Both the stockout cost and inventory carrying cost may increase when the transportation lead time variations increase. Similar results are found by Grasso and Taylor III (1984). In their study, the mean total cost is the highest under a uniform discrete distribution in a multi-echelon MRP system.

Again, the lead time uncertainty has different effects on each channel member in terms of average stockout units, average inventory level, and mean service level as shown in Table 5.44. For example, when the transportation lead time uncertainty increases, average SOW increases 17%, and average SODC1, SOR1 increase 23%. In this study, lead time

Table 5.44 Average Stockout Units, Average Inventory Level, and Mean Service Level for All Channel Members under Two Levels of Lead Time Uncertainty

	Lead Time Uncertainty	Warehouse	Distribution Center 1	Retailer 1
Average Stockout Unit	Low	548.12	497.18	18.81
	High	454.80	381.13	14.51
Average Inventory Level	Low	1089.80	325.17	198.22
	High	1048.90	359.01	215.42
Mean Service Level	Low	0.807	0.600	0.625
	High	0.814	0.659	0.711

uncertainty occurs only at distribution centers and retailers. For this reason, lead time uncertainty has less effect on the warehouse than distribution centers and retailers in terms of the three non-monetary performance measures.

Supply Uncertainty

The supply uncertainty does not have a consistent effect on all channel members as observed in Table 5.41. In this study, the supply uncertainty only occurs when product is shipped from an outside vendor to the warehouse. That explains why supply uncertainty always has a significant effect at the warehouse on all non-monetary performance measures.

In this study, only a supply shortage at the warehouse is of concern. When supply uncertainty increases, the mean TRC increases 6%. This is because the frequent supply shortage at the warehouse may cause more stockouts at all channel members. Furthermore, the warehouse is more sensitive to the changes of supply uncertainty as shown in Table 5.45. The average inventory level at the warehouse drops 11%, which is the highest of all channel members, when supply uncertainty increases.

Table 5.45 Average Stockout Units, Average Inventory Level, and Mean Service Level for All Channel Members under Two Levels of Supply Uncertainty

	Supply Uncertainty	Warehouse	Distribution Center 1	Retailer 1
Average Stockout Unit	Low	475.24	416.24	16.15
	High	527.68	462.07	17.17
Average Inventory Level	Low	1131.40	353.92	211.62
	High	1007.30	330.26	202.02
Mean Service Level	Low	0.828	0.641	0.678
	High	0.793	0.618	0.658

Cost Value

The cost values of inventory carrying cost, stockout cost, and ordering cost have a significant effect at all channel members in all performance measures. In this study, when the cost value increases, only inventory carrying cost is changed from 0.1 unit price/year to 0.3 unit price/year. The mean TRC increases 75% when the cost value increases. It is mainly caused by an increase of inventory carrying cost. As shown in Table 5.46, when cost value increases, the average stockout units decrease at the warehouse and distribution centers. However, the average stockout units increase at retailers when the cost value increases. As observed in Table 5.20, it is possible because the cost ration drops from 300:1 to 100:1, thus the planned order quantity determined by the EOQ is decreased. Furthermore, the built-in safety stock provided by EOQ is not enough to absorb the operating uncertainty.

Table 5.46 Average Stockout Units, Average Inventory Level, and Mean Service Level for All Channel Members under Two Levels of Cost Value

	Cost Value	Warehouse	Distribution Center 1	Retailer 1
Average Stockout Unit	Low	603.49	495.47	15.36
	High	399.43	382.85	17.96
Average Inventory Level	Low	1063.60	424.47	268.87
	High	1075.20	259.71	144.77
Mean Service Level	Low	0.817	0.644	0.694
	High	0.813	0.615	0.642

Safety Stock Policy

The way of allocating safety stock in a multi-echelon distribution system has a significant effect on all performance measures. Different safety stock policies may be preferred by different channel members based on various performance measures as displayed in Table 5.41. Generally speaking, policies 5 and 6 are good safety stock policies, which satisfy most performance criteria. Policy 5 suggests putting safety stock at all channel members, and policy 6 allocates safety stock for the warehouse and two distribution centers. This result contradicts the simulation results by Allen (1983). He suggests that all safety stock be kept at field facilities in order to obtain the highest fill rate. It is a "so-called" decentralized policy. He also describes a "fair-share" policy which allocates safety stock for field facilities and the central facility. The performance of a "fair-share" policy is very close to a decentralized policy. Allen only considers a two-level distribution system under different operating conditions. However, the result found by Chakravarty and Shtub (1986) is consistent with this study. They suggest keeping safety stock at the central distribution center to achieve the same level of system service at lower cost.

Policy 2 advocates putting all safety stock at the warehouse. The safety stock allocated for the warehouse is used to deal with various uncertainties. This is the best policy when only the various performance measures are considered at the warehouse. The centralized system is also favored by Schwarz (1981) in his study.

Policies 4 and 8 are found to be the two worst safety stock policies under all performance criteria. Policy 4 suggests putting all safety stock at two distribution centers. Policy 8 allocates safety stock for distribution centers and retailers. Policies 4 and 8 perform much worse when the EOQ lot-sizing rule is applied. They yield the highest mean TRC, highest average stockout units and lowest mean service level. This is because safety stocks at retailers and distribution centers may satisfy a few periods of demand. Once the inventories at distribution centers and retailers are depleted, it takes nine weeks to replenish the stocks; this does not even consider transportation lead time uncertainty.

The mean TRC plot and values under revised safety stock policies are displayed in Figure 5.35 and Table 5.44. A follow-up analysis is made to examine the pattern of safety stock policies 4 and 8, which yield a high mean TRC. A set of revised safety stock policies as shown in Table 5.43 is modified from the safety stock policies shown in Table 3.5, and are used to calculate the TRC. The operating condition for this follow-up analysis is applying the EOQ lot-sizing rule with low demand and low supply uncertainties. Policies 1, 3, 4 and 8 show the same pattern. All the policies do not put any safety stock at the warehouse and yield higher mean TRC than other safety stock policies.

Table 5.47 Revised and Original Safety Stock Policies

S.S. Policy	Revised (W, DC, R)	Original (W, DC, R)
1	(0,0.7,0.3)	(0,0,0)
2	(1,0,0)	(1,0,0)
3	(0,0.3,0.7)	(0,0,1)
4	(0,1,0)	(0,1,0)
5	(1/3,1/3,1/3)	(1/3,1/3,1/3)
6	(1/2,1/2,0)	(1/2,1/2,0)
7	(1/2,0,1/2)	(1/2,0,1/2)
8	(0,1/2,1/2)	(0,1/2,1/2)

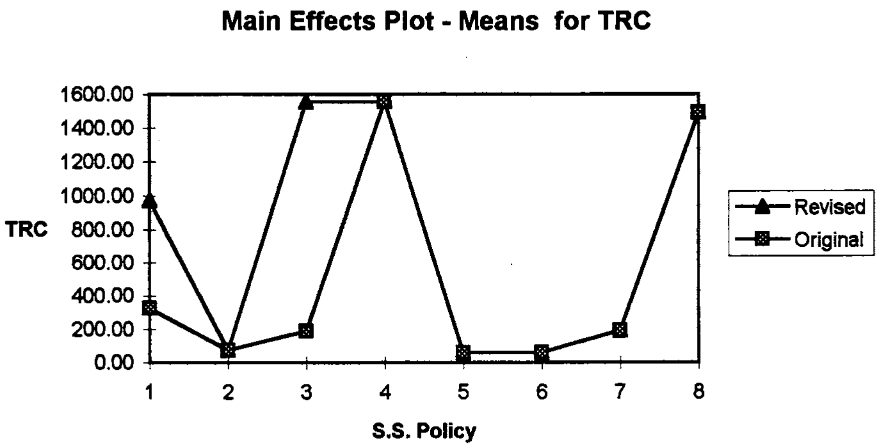

Figure 5.35 Mean TRC per Week Plot under Revised and Original Safety Stock Policies

Table 5.48 Mean TRC per Week for Each Revised and Original Safety Stock Policy

S.S. Policy	1	2	3	4	5	6	7	8
TRC(Revised)	970.85	76.03	1555.47	1559.14	58.69	60.55	193.59	1492.94
TRC(Original)	325.06	76.03	188.86	1559.14	58.69	60.55	193.59	1492.94

Furthermore, an extended study is conducted to examine the pattern of safety stock policy 5, which is a "so-called" fair-share policy by allocating safety stock at all channel members. As observed in Table 5.49, three new safety stock policies are used to examine the impact due to changing the quantity of safety stock at all channel members in the distribution system. The operating condition is the same as the previous follow-up analysis. It is found that the mean TRC increases when the quantity of safety stock at the retailers increases. This implies that increased safety stock at the retailers may deteriorate the system performance. This is because more stock occurs at all channel members when more safety stock put at retailers.

Table 5.49 Mean TRC for Revised and Original Safety stock Policy 5

S.S. Policy	(W, DC, R)	TRC
5	(1/3,1/3,1/3)	58.69
5-1	(3/7,3/7,1/7)	55.90
5-2	(2/7,2/7,3/7)	60.46
5-3	(1/7,1/7,5/7)	61.36

In summary, the way of allocating safety stock in the distribution system has a great effect on mean TRC. Allocating safety stock for the warehouse yields better performance in terms of mean TRC and all three non-monetary performance measures.

Interaction Analysis

The interactions between safety stock policy and lot-sizing rule, demand uncertainty, transportation lead time uncertainty, and supply uncertainty are examined in this study. As shown in Table 5.41, most of the interactions are significant at the 5% level for all performance measures, except for the interaction between supply uncertainty and safety stock policy.

There is a strong interaction between lot-sizing rule and safety stock policy. In general, L4L is less sensitive to the safety stock policy used than EOQ. This is because L4L can respond to the changes in operating conditions more effectively due to the order frequency. L4L provides period-by-period coverage of net requirements, and it allows the channel members to respond to various uncertainties. Although the lot-sizing rules result in different values in all performance measures under most safety stock policies, the lot-sizing rules affect the safety stock policies to a different degree. Safety stock policies 5 and 6 are not affected by the lot-sizing rule in terms of all performance measures. However, the performance of safety stock policies 4 and 8 deteriorates when the EOQ lot-sizing rule is used. That means the safety stock policy should be considered along with the lot-sizing rule in order to achieve the best system performance.

The effects from demand uncertainty, lead time uncertainty, and supply uncertainty on safety stock policies are different. As observed in Figure 5.36, safety stock policies 5 and 6 exhibit the least sensitivity to the changes in operating conditions. This is because the safety stock policies absorb the operating uncertainty effectively. Furthermore, policy 8 is the most sensitive to the changes in operating conditions. The mean TRC of policy 8 drops to 550 in LHL, and goes up to 965 in LLH. LHL represents an operating condition in which there is a low level of demand uncertainty, a high level of transportation lead time distribution, and a low level of supply shortage.

As shown in Figure 5.36, safety stock policies 5 and 6 outperform other policies in all operating conditions, and policies 4 and 8 perform poorly in all operating conditions. However, the preference of policies 1, 2, 3, and 7 are different in various operating conditions. Furthermore, in LHL all policies result in the lowest mean TRC; in HLH most policies present the highest mean TRC, except for policies 4 and 8. This can be explained by the added effect of the sources of uncertainties considered in this study. Furthermore, it does appear that demand uncertainty and supply uncertainty have a strong impact on mean TRC under a low variation transportation lead time distribution. The overriding impact of lead time variations may explain this fact. One extreme lead time deviation can measurably increase the stockout or inventory level; an extremely large demand will be offset by an extremely small demand over the

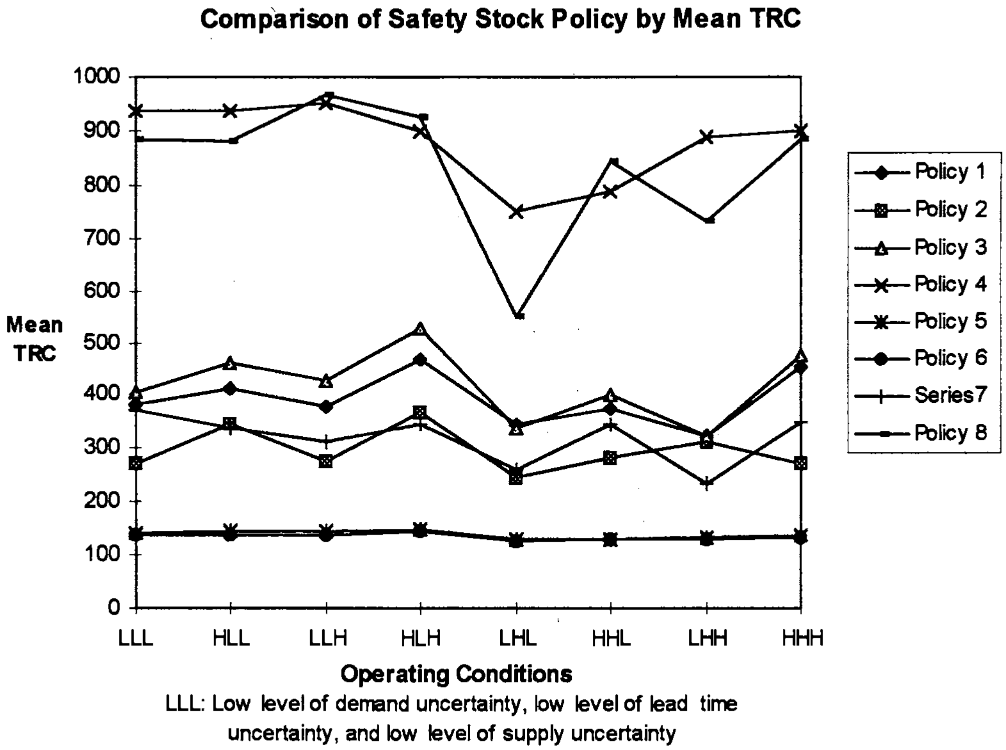

Figure 5.36 Comparison of Safety Stock Policy by Mean TRC

transportation lead time period. The effects of demand variation and supply uncertainty on mean TRC are overridden by lead time variation.

The interaction between cost value and safety stock policy is significant at the 5% level. As shown in Table 5.3, safety stock policies 5 and 6 are less sensitive to changes of the cost value in terms of mean TRC. Furthermore, L4L is not much affected by the cost value in terms of the mean TRC. As the cost value changes, that will only affect the order quantity decided by the EOQ rule. Thus, EOQ is sensitive to the safety stock policy used. As shown in Figure 5.3, EOQ presents very close results to L4L in terms of mean TRC under safety stock policies 5 and 6. That may explain why safety stock policies 5 and 6 are not affected much by the cost value in terms of mean TRC.

This chapter describes the impact of selected main effects and interactions of safety stock policy with those main effects on the performance in a multi-echelon distribution system. Further study of altering the value-added factor and changing the distribution network is presented in the next chapter.

CHAPTER VI

SENSITIVITY ANALYSIS

Based on the results of the base experiments, a further study of two factors used in the base experiments is conducted. The first factor involves the value-added factor used between channel members. The value-added factor is the transportation cost incurred when the product is shipped from one higher echelon channel member to the lower echelon members in a multi-echelon distribution system. Rather than fixing the value-added factors, four different sets of value-added factors are used in the sensitivity analysis experiment.

Another factor considered in the sensitivity analysis is the structure of distribution networks. Two levels of distribution network are investigated in the sensitivity analysis. The distribution centers are removed from the network. Products are shipped directly from warehouse to retailers. The results of two experiments of sensitivity analysis are described below.

Experimental Procedure

In the base experiments, the value-added factor and distribution network are fixed as described previously. In the experiments for sensitivity analysis, several experimental conditions are changed to conduct a valid experiment. The detailed experimental procedures for two sets of sensitivity analysis experiments are described as follows:

Changing Value-Added Factor

The purpose of this experiment for sensitivity analysis is to examine the performance of the value-added factor held constant in the base experiment. The value-added factor is the transportation cost incurred between channel members. In the base experiment, the value-added factor is fixed at (0.1, 0.1), which is within the value range used by Collier (1982) in his study. That means the nominal unit cost of product increases 10 percent when product is shipped from the warehouse to distribution centers or from the distribution centers to retailers. As shown in Table 3.6, four different combinations of the value-added factor are used to test the performance sensitivity.

In the sensitivity analysis, both cost value and supply uncertainty are held at the low levels and are held constant to obtain a manageable experimental design. A summary of experimental factors used in this sensitivity analysis is shown in Table 6.1. Runs are replicated five times with a run length of 400 weeks and a warm-up period of 40 weeks.

Table 6.1 Summary of Experimental Factors Used in a Changing Value-added Factors Sensitivity Analysis

Factors	Levels
Cost Value	Fixed
Supply Uncertainty	Fixed
Lot-Sizing Rule	2
Demand Uncertainty	2
Lead Time Uncertainty	2
Safety Stock Policy	8
Value-added Factors	4
Replications	5
Total Observations	1280

Changing Distribution Network

The purpose of this experiment for sensitivity analysis is to examine the performance sensitivity caused by changing the distribution network. In the sensitivity analysis, the products are shipped directly from the warehouse to the retailers. The distribution network is changed from a three-level distribution system to a two-level distribution system as displayed in Figure 3.2.

Supply uncertainty, cost value, and value-added factors are held at the low levels. To keep the same mean transportation lead time from the warehouse to retailers as in the base experiment, the lead time distributions are modified as shown in Table 6.2. Only four different safety stock policies, as shown in Table 6.3, are applied in this sensitivity analysis when the structure of distribution network is changed. A summary of experimental factors used in the experiment of changing distribution network is shown in Table 6.4.

Table 6.2 Lead Time Distributions Used in Distribution Network Sensitivity Analysis

Uniform Discrete Distribution	Value (period)	2	4	6	8	10
	Probability	0.2	0.2	0.2	0.2	0.2
Symmetrical Discrete Distribution	Value (period)	2	4	6	8	10
	Probability	0.1	0.1	0.6	0.1	0.1

Table 6.3 Safety Stock Policies Used in Distribution Network Sensitivity Analysis

Safety Stock Policy	(W, R)
1	(0, 0)
2	(1, 0)
3	(0, 1)
4	(1/2, 1/2)

Table 6.4 Summary of Experimental Factors Used in a Changing Distribution Network Sensitivity Analysis

Factors	Levels
Cost Value	Fixed
Supply Uncertainty	Fixed
Lot-Sizing Rule	2
Demand Uncertainty	2
Lead Time Uncertainty	2
Safety Stock Policy	4
Value-added Factors	Fixed
Replications	5
Total Observations	160

Results for Changing Value-Added Factor

In this sensitivity analysis, only mean TRC of the distribution system is examined. The three non-monetary performance measures are not affected by changing the value-added factor.

ANOVA is performed on the mean TRC obtained from the simulation. The analysis consists of 1280 data points, with five replications for each of the 256 experimental conditions. The ANOVA results for the main factors and the interactions of safety stock policy with all other main factors are shown in Table 6.5. All main effects and important interactions are significant at the 5% level, and are addressed below.

Table 6.5 ANOVA Results for Mean TRC When Changing the Value-added Factor

Analysis of Variance for TRC

Source	DF	SS	MS	F	P
L.R.	1	19184916	19184916	617.28	0.000
D.U.	1	1172576	1172576	37.73	0.000
L.T.	1	3401546	3401546	109.45	0.000
V.A.	3	1410829	470276	15.13	0.000
S.S.	7	85021488	12145927	390.80	0.000
L.R.*D.U.	1	1174034	1174034	37.77	0.000
L.R.*L.T.	1	3395033	3395033	109.24	0.000
L.R.*V.A.	3	17346	5782	0.19	0.906
L.R.*S.S.	7	86699699	12385671	398.51	0.000
D.U.*L.T.	1	790639	790639	25.44	0.000
D.U.*V.A.	3	7149	2383	0.08	0.973
D.U.*S.S.	7	3302605	471801	15.18	0.000
L.T.*V.A.	3	21501	7167	0.23	0.875
L.T.*S.S.	7	5362736	766105	24.65	0.000
V.A.*S.S.	21	382642	18221	0.59	0.930
L.R.*D.U.*L.T.	1	791783	791783	25.48	0.000
L.R.*D.U.*V.A.	3	7048	2349	0.08	0.973
L.R.*D.U.*S.S.	7	3316048	473721	15.24	0.000
L.R.*L.T.*V.A.	3	20370	6790	0.22	0.884
L.R.*L.T.*S.S.	7	5489002	784143	25.23	0.000
L.R.*V.A.*S.S.	21	399496	19024	0.61	0.912
D.U.*L.T.*V.A.	3	3899	1300	0.04	0.989
D.U.*L.T.*S.S.	7	4273384	610483	19.64	0.000
D.U.*V.A.*S.S.	21	19148	912	0.03	1.000
L.T.*V.A.*S.S.	21	26363	1255	0.04	1.000
L.R.*D.U.*L.T.*V.A.	3	3874	1291	0.04	0.989
L.R.*D.U.*L.T.*S.S.	7	4279044	611292	19.67	0.000
L.R.*D.U.*V.A.*S.S.	21	19252	917	0.03	1.000
L.R.*L.T.*V.A.*S.S.	21	27166	1294	0.04	1.000
D.U.*L.T.*V.A.*S.S.	21	23385	1114	0.04	1.000
L.R.*D.U.*L.T.*V.A.*S.S.	21	23422	1115	0.04	1.000
Error	1024	31825652	31080		
Total	1279	261893077			

Main Effects

A plot of main effects for the mean TRC is presented in Figure 6.1, and the mean TRC of each main effect at each level is shown in Table 6.6. Visual examination of the experimental results in Figure 6.1 shows that EOQ yields much higher mean TRC than L4L. The results of two sources of uncertainties are consistent with the results from the base experiment.

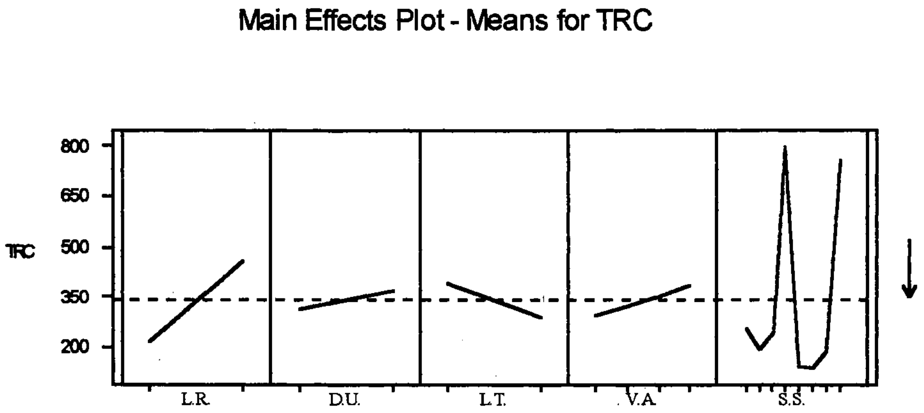

Figure 6.1 Main Effects Plot for Mean TRC When Changing the Value-added Factor

Table 6.6 Mean TRC of Each Main Effect at Each Level When Changing the Value-added Factor

```
               Means

L.R.         N        TRC
1          640     215.51
2          640     460.36

D.U.         N        TRC
1          640     307.67
2          640     368.20

L.T.         N        TRC
1          640     389.48
2          640     286.38

V.A.         N        TRC
1          320     294.06
2          320     322.43
3          320     352.11
4          320     383.13

S.S.         N        TRC
1          160     254.23
2          160     189.70
3          160     240.88
4          160     799.10
5          160     138.19
6          160     135.41
7          160     187.55
8          160     758.39
```

As the demand uncertainty and transportation lead time uncertainty increase, the mean TRC also increases. The forecast demand error incurred at the retailers may cause either stockout or excessive stock at all channel members. Furthermore, the lead time uncertainty may cause an order to arrive early as well as late. That explains why the mean TRC increases under high demand uncertainty and high transportation lead time variations. The effect on the mean TRC is significant when value-added factors are changed. The higher the value-added factors, the higher the mean TRC.

As shown in Figure 6.2 and Table 6.6, the best safety stock policy in terms of the mean TRC is policy 6; policy 5 is the second best safety stock policy for all levels of the added-value factor.

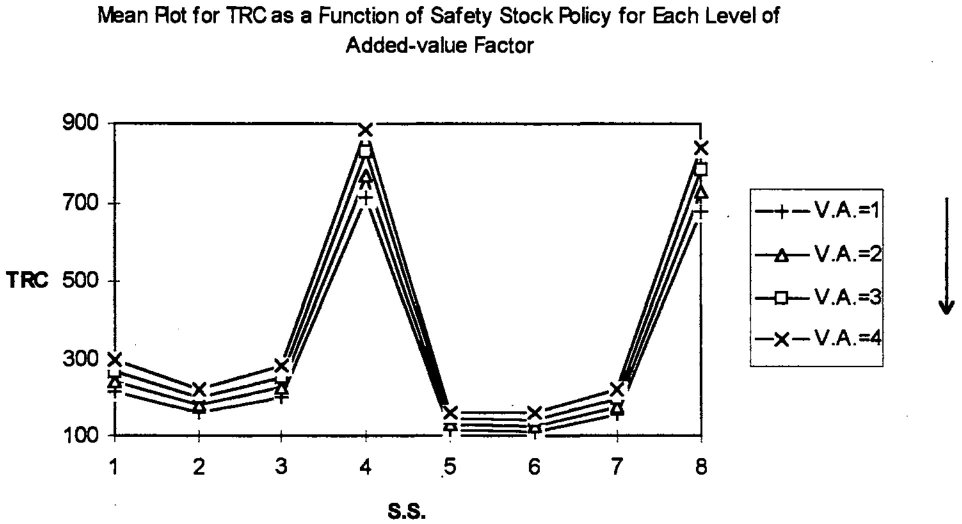

Figure 6.2 Means Plot for TRC as a Function of Safety Stock Policy When Changing the Value-added Factor

		S.S. Policy	D.U.=Low								D.U.=High							
			1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
VA=1	LT=Low	L4L	173.82	173.02	198.58	166.91	173.62	168.01	183.96	175.72	173.96	172.87	198.23	166.94	173.57	168.42	183.96	175.45
		EOQ	325.60	76.03	188.86	1559.14	58.69	60.55	193.59	1492.94	256.49	279.44	321.70	1581.39	65.66	61.75	109.93	1426.22
	LT=High	L4L	173.53	173.26	195.92	170.30	172.34	170.46	181.95	177.75	173.75	173.51	194.93	170.37	172.43	170.60	181.88	176.99
		EOQ	259.04	60.92	151.05	810.13	51.30	48.94	63.08	313.13	178.55	160.22	174.61	1092.66	50.91	50.79	156.53	1483.11
VA=2	LT=Low	L4L	198.45	197.47	225.84	190.35	197.97	191.65	209.69	200.01	198.62	197.32	225.46	190.41	197.93	192.13	209.70	199.75
		EOQ	360.11	84.28	208.68	1666.53	64.54	66.43	214.25	1595.29	283.61	309.33	355.34	1690.89	71.79	67.60	121.47	1524.33
	LT=High	L4L	197.89	197.56	222.58	193.89	196.37	194.33	207.24	202.00	198.19	197.88	221.50	194.08	196.52	194.52	207.20	201.20
		EOQ	286.52	67.64	167.08	864.76	56.54	54.05	69.91	333.78	197.21	177.19	192.84	1166.85	56.07	55.89	173.00	1585.76
VA=3	LT=Low	L4L	224.87	223.70	254.96	215.49	224.06	217.00	237.24	226.03	225.07	223.55	254.55	215.58	224.05	217.57	237.26	225.77
		EOQ	395.58	92.91	229.12	1776.44	70.71	72.64	2235.57	1700.04	311.55	340.12	389.93	1802.95	78.26	73.77	133.47	1624.75
	LT=High	L4L	224.01	223.62	251.04	219.19	222.12	219.91	234.29	227.95	224.39	224.00	249.87	219.49	222.33	220.16	234.30	227.13
		EOQ	314.82	74.69	183.66	920.75	62.08	59.46	77.08	355.05	216.47	194.72	211.68	1242.84	61.54	61.29	190.02	1690.82
VA=4	LT=Low	L4L	253.07	251.70	285.92	242.34	251.91	244.07	266.60	253.78	253.31	251.54	285.48	242.47	251.91	244.73	266.64	253.53
		EOQ	432.03	101.92	250.17	1888.87	77.20	79.18	257.56	1807.20	340.31	371.81	425.45	1917.58	85.06	80.27	145.91	1727.49
	LT=High	L4L	251.88	251.42	281.30	246.18	249.58	247.21	263.12	255.63	252.36	251.88	280.03	246.62	249.86	247.53	263.19	254.77
		EOQ	343.92	82.08	200.77	978.10	67.93	65.17	84.58	376.95	236.35	212.83	231.13	1320.62	67.30	66.98	207.59	1798.31

Table 6.7 Experimental Results for Mean TRC When Changing the Value-added Factor

Important Two-Way Interactions

Three two-way interactions are of concern in the sensitivity analysis. As shown in Table 6.7, the interactions between lot-sizing rule and safety stock policy, demand uncertainty and safety stock policy, and lead time uncertainty and safety stock policy, are all significant.

The results of these three two-way interactions are consistent with the mean TRC analysis in the base experiment. The interaction of lot-sizing rules and safety stock policies has a significant effect on mean TRC. The effect of the safety stock policies is significantly influenced by the lot-sizing rules used. When L4L is used, safety stock policies 1, 3, 4, and 8 yield a lower mean TRC than EOQ does. Policies 2, 5, 6, and 7, however, perform better under the EOQ rule. The mean TRC for the interaction of lot-sizing rule and safety stock policy at each level with value-added factor is shown in Table 6.8. The plot for interaction effects between the lot-sizing rules and safety stock policies when value-added factor is at level 1 is shown in Figure 6.3. The means plot of TRC as a function of lot-sizing rule and safety stock policy is similar under various levels of the value-added factor.

According to Table 6.9, when demand uncertainty increases, the mean TRC increases under all safety stock policies.

Table 6.8 Mean TRC for Lot-sizing Rule and Safety Stock Policy at each level of Value-added Factor

	V.A. =1		V.A. =2		V.A. =3		V.A. =4	
S.S. Policy	L4L	EOQ	L4L	EOQ	L4L	EOQ	L4L	EOQ
1	173.8	254.9	198.3	281.9	224.6	309.6	252.7	338.2
2	173.2	144.2	197.6	159.6	223.7	175.6	251.6	192.2
3	196.9	209.1	223.8	231.0	252.6	253.6	283.2	276.9
4	168.6	1260.8	192.2	1347.3	217.4	1435.7	244.4	1526.3
5	173.0	56.6	197.2	62.2	223.1	68.1	250.8	74.4
6	169.4	55.5	193.2	61	218.7	66.8	245.9	72.9
7	182.9	130.8	208.5	144.7	235.8	159.0	264.9	173.9
8	176.5	1178.9	200.7	1259.8	226.7	1342.7	254.4	1427.5

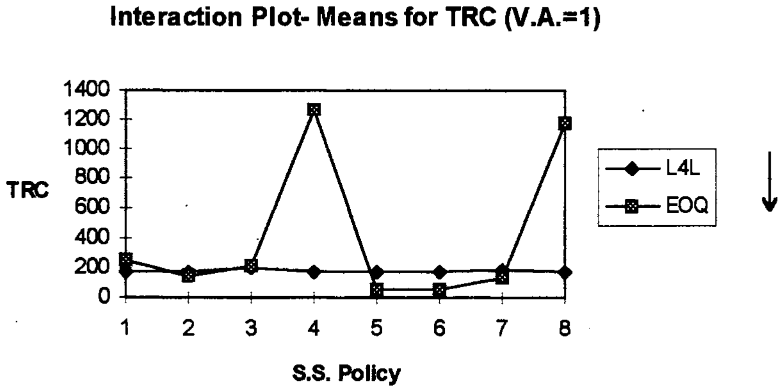

Figure 6.3 Means Plot for TRC as a Function of Lot-sizing Rule and Safety Stock Policy When Changing the Value-added Factor (V.A.=1)

Table 6.9 Mean TRC for Demand Uncertainty and Safety Stock Policy at each level of Value-added Factor

	V.A. =1		V.A. =2		V.A. =3		V.A. =4-	
S.S. Policy	D.U.=Low	D.U.=High	D.U.=Low	D.U.=High	D.U.=Low	D.U.=High	D.U.=Low	D.U.=High
1	233.0	195.7	260.7	219.3	289.8	244.4	320.2	270.6
2	120.8	196.5	136.7	220.4	153.7	245.6	1741.8	272.0
3	183.6	222.4	206.0	248.8	229.7	276.5	254.5	305.5
4	676.6	752.8	728.9	810.6	783.0	870.2	838.9	931.8
5	114.0	115.6	128.9	130.6	144.7	146.5	161.7	163.5
6	112.0	112.9	126.6	127.5	142.3	143.2	158.9	159.9
7	155.6	158.1	175.3	177.8	196.0	198.8	218.0	220.8
8	539.9	815.4	582.8	877.8	627.3	942.1	673.4	1008.5

Although the ranking of the safety stock policies stays the same under both demand uncertainty levels, the magnitude of the increase in mean TRC is different. As shown in Figure 6.4, safety stock policies 5, 6, and 7 are less sensitive to the changes in demand uncertainty. Furthermore, there is a great effect on safety stock policy 8, when demand uncertainty increases. This is because a good safety stock policy can absorb the demand uncertainty.

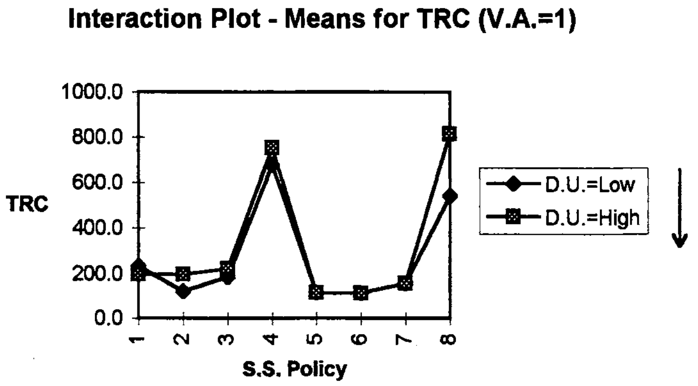

Figure 6.4 Means Plot for TRC as a Function of Demand Uncertainty and Safety Stock Policy When Changing the Value-added Factor (V.A.=1)

When the transportation lead time distribution changes from a symmetric discrete distribution with low variation to a uniform discrete distribution with high variation, the mean TRC increases under all safety stock policies to a different degree. Safety stock policies 5, 6, and 7 are not much affected by the lead time uncertainty. The performance of safety stock policies 4 and 8 becomes much worse when transportation lead time uncertainty increases. The mean TRC for the interaction of lead time uncertainty and safety stock policy at each level of value-added factor is shown in Table 6.10. As shown in Figure 6.5, the interaction of these two factors is consistent with the result in the base experiment.

Table 6.10 Mean TRC for Lead Time Uncertainty and Safety Stock Policy at each level of the Value-added Factor

	V.A.=1		V.A.=2		V.A.=3		V.A.=4	
S.S. Policy	L.T.=Low	L.T.=High	L.T.=Low	L.T.=High	L.T.=Low	L.T.=High	L.T.=Low	L.T.=High
1	232.5	196.2	260.2	220.0	289.3	244.9	319.7	271.1
2	175.3	142.0	197.1	160.1	220.1	179.3	244.2	199.6
3	226.8	179.1	253.8	201.0	282.1	224.1	311.8	248.3
4	868.6	560.9	934.5	604.9	1002.6	650.6	1072.8	697.9
5	117.9	111.7	133.1	126.4	149.3	142.0	166.5	158.7
6	114.7	110.2	129.5	124.7	145.2	140.2	162.1	156.7
7	167.9	145.9	188.8	164.3	210.9	183.9	234.2	204.6
8	817.6	537.7	879.8	580.7	944.1	625.2	1010.5	671.4

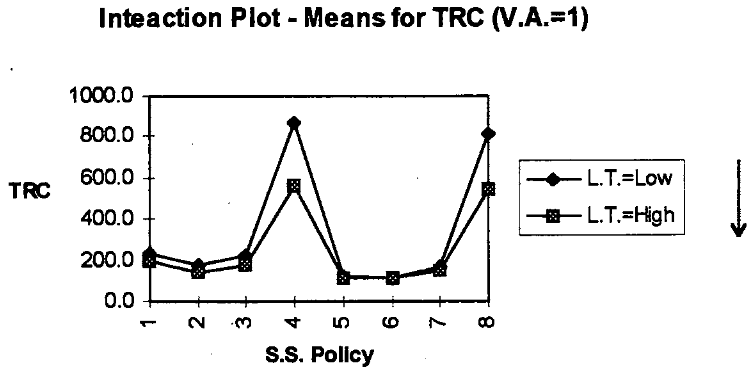

Figure 6.5 Means Plot for TRC as a Function of Lead Time Uncertainty and Safety Stock Policy When Changing Value-added Factor (V.A.=1)

Results for Changing Distribution Network

Based on experimental results from the sensitivity analysis, there is an effect on all performance measures when the distribution network is changed. In this sensitivity analysis, the mean TRC of the distribution system and the mean service level for each channel member are discussed. The results of average stockout units and average inventory level are shown in Appendix C.

Total Related Cost Analysis

ANOVA is performed on the mean TRC obtained from the simulation. The analysis consists of 160 data points, including five replications for each of the 32 experimental conditions. The ANOVA results for the main factors and the interactions of safety stock policy with all other main factors are shown in Table 6.11. The results show that lot-sizing rule, lead time uncertainty and safety stock policy are significant at the 5% level. And, the interaction between lot-sizing rule and safety stock policy is significant.

Table 6.11 ANOVA Results for Mean TRC When Changing Distribution Network

```
                    Analysis of Variance for TRC

Source                   DF        SS          MS       F      P
L.R.                      1   135158.4   135158.4 1496.62  0.000
D.U.                      1        0.6        0.6    0.01  0.936
L.T.                      1     1124.8     1124.8   12.46  0.001
S.S.                      3    15962.6     5320.9   58.92  0.000
L.R.*D.U.                 1        2.1        2.1    0.02  0.879
L.R.*L.T.                 1      672.0      672.0    7.44  0.007
L.R.*S.S.                 3     2936.5      978.8   10.84  0.000
D.U.*L.T.                 1      160.5      160.5    1.78  0.185
D.U.*S.S.                 3      257.7       85.9    0.95  0.418
L.T.*S.S.                 3      636.9      212.3    2.35  0.075
L.R.*D.U.*L.T.            1      167.2      167.2    1.85  0.176
L.R.*D.U.*S.S.            3      252.1       84.0    0.93  0.428
L.R.*L.T.*S.S.            3      357.4      119.1    1.32  0.271
D.U.*L.T.*S.S.            3      349.7      116.6    1.29  0.280
L.R.*D.U.*L.T.*S.S.       3      383.9      128.0    1.42  0.241
Error                   128    11559.6       90.3
Total                   159   169981.9
```

Main Effects

A plot of main effects for the mean TRC is presented in Figure 6.6, and the mean TRC of each main effect at each level is shown in Table 6.12. Visual examination of the experimental results in Figure 6.6 shows that EOQ yields much higher mean TRC than L4L. The results of two sources of uncertainties are different from the results observed in the base experiment. The mean TRC is not affected by demand uncertainty when the distribution network is changed. It may be explained by the change in distribution network. The warehouse can work closely with retailers to absorb the demand uncertainty. The transportation lead time variations have significant effect on mean TRC when the distribution network is changed. The lead time uncertainty still exists between the warehouse and retailers. As addressed in the base experiment, higher transportation lead time variations may cause more stockouts or excessive inventories, and increases the mean TRC of the distribution system.

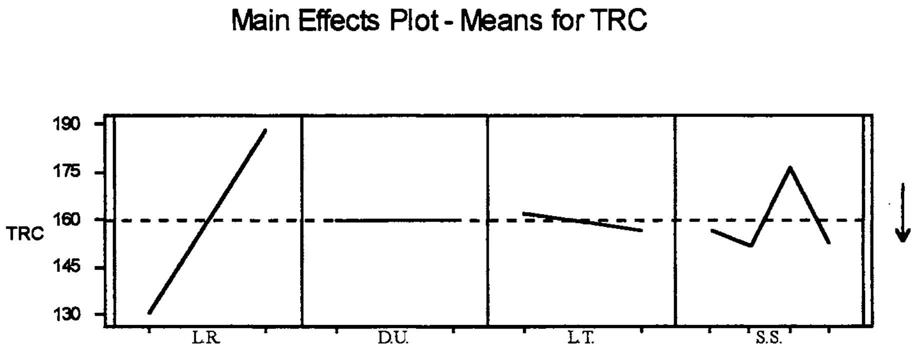

Figure 6.6 Main Effects Plot for TRC When Changing Distribution Network

Table 6.12 Mean TRC of Each Main Effect at Each Level When Changing Distribution Network

	Means	
L.R.	N	TRC
1	80	130.43
2	80	188.55
D.U.	N	TRC
1	80	159.55
2	80	159.43
L.T.	N	TRC
1	80	162.14
2	80	156.84
S.S.	N	TRC
1	40	156.65
2	40	151.84
3	40	176.51
4	40	152.96

As shown in Figure 6.7, the best safety stock policy is policy 2 in terms of the mean TRC; policy 4 is the second best safety stock policy. There is only one warehouse and four retailers in the distribution system used in the sensitivity analysis. As shown in Table 6.3, safety stock policy 2 suggests putting all safety stocks at the warehouse, and policy 4 allocates safety stocks for the warehouse and retailers. The results are consistent with the results in the base experiment. The best safety stock policies in terms of the mean TRC in the base experiment are either keeping safety stock evenly at the warehouse, distribution centers and retailers (policy 5) or allocating safety stock for the warehouse and two distribution centers (policy 6). Furthermore, safety stock policy 3 is about 16% higher than other policies in terms of mean TRC. Safety stock policy 3 keeps all the safety stock at retailers only. As explained in the base experiment, it may cause more stockout at the warehouse. Once the inventories at retailers are depleted, there is no stock at the warehouse to replenish the demand immediately.

To examine the main effects and interaction effects, the mean TRC and three non-monetary performance measures averaged over five replications are presented in Table 6.13 and discussed below.

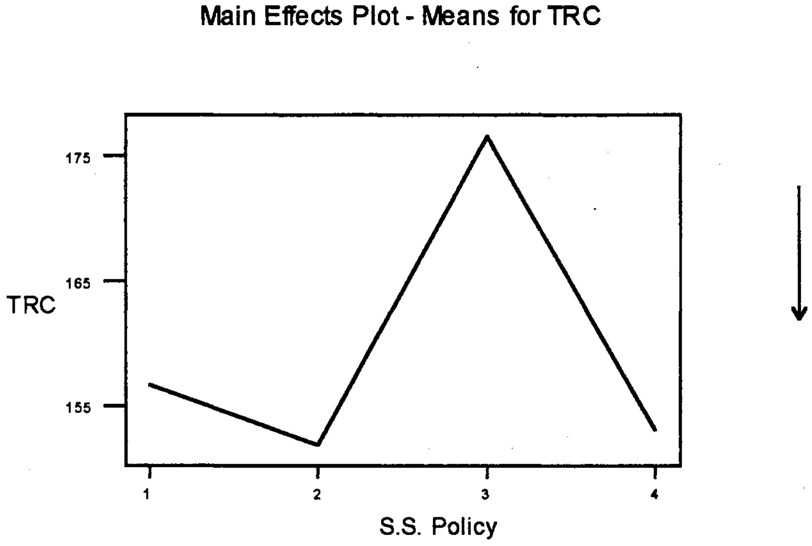

Figure 6.7 Means Plot for TRC as a Function of Safety Stock Policy When Changing Distribution Network

			D.U. = Low				D.U.= High			
		S.S. Policy	1	2	3	4	1	2	3	4
TRC	LT=Low	L4L	123.34	120.91	156.26	123.3	123.05	121.28	156.34	123.41
		EOQ	196.4	183.06	216.36	185.99	193.68	182.82	200.05	187.68
	LT=High	L4L	123.85	121.08	153.36	120.88	123.85	121.7	152.73	121.15
		EOQ	175.63	184.69	186.59	181.11	193.13	179.15	188.92	180.14
SOW	LT=Low	L4L	9.79	0	248.44	41.14	8.04	0	247.24	39.17
		EOQ	253.54	82.15	535.94	78.94	268.81	81.63	283.92	93.97
	LT=High	L4L	13.48	0	255.33	17.21	11.58	0	247.24	39.17
		EOQ	52.14	43.02	113.82	45.39	240.83	43.02	146.88	41.81
INVW	LT=Low	L4L	266.32	536.98	185.63	256.12	311.98	539.15	185.63	258.61
		EOQ	1137.72	2337.29	1233.04	2207.91	1091.75	2277.33	1119.61	2221.95
	LT=High	L4L	258.85	519.56	207.87	290.68	262.61	531.24	207.99	300.39
		EOQ	1632.01	2246.61	1587.01	2145.36	1394.1	2247.72	1642.14	2205.2
SERW	LT=Low	L4L	0.97	1	0.6	0.91	0.98	1	0.6	0.91
		EOQ	0.61	0.83	0.54	0.84	0.59	0.83	0.59	0.81
	LT=High	L4L	0.97	1	0.62	0.96	0.97	1	0.63	0.97
		EOQ	0.88	0.9	0.79	0.9	0.63	0.9	0.75	0.91
SOR1	LT=Low	L4L	14.99	14.19	12.81	10.65	16.1	15.17	13.65	11.87
		EOQ	1.88	0.44	3.39	0.7	3.13	0.83	1.43	1.08
	LT=High	L4L	9.97	9.06	8.55	6.3	11.96	11.22	9.97	8.52
		EOQ	0.76	0.39	0.37	0.3	2.04	0.83	2.1	0.52
INVR1	LT=Low	L4L	42.58	46.91	48.37	62.02	51.37	56.6	57.96	70.96
		EOQ	871.86	1164.97	877.95	1021.22	850.88	1028.45	821.61	967.29
	LT=High	L4L	45.22	48.96	50.47	63.24	54.91	61.16	62.1	73.53
		EOQ	788.38	840.9	812.52	851.33	795.27	862.91	876.77	828.24
SERR1	LT=Low	L4L	0.7	0.72	0.74	0.79	0.68	0.7	0.73	0.76
		EOQ	0.96	0.99	0.93	0.99	0.94	0.98	0.97	0.98
	LT=High	L4L	0.8	0.82	0.83	0.87	0.76	0.78	0.8	0.83
		EOQ	0.98	0.99	0.99	0.99	0.96	0.98	0.96	0.99

Table 6.13 Summary of Experimental Results for TRC, SOW, INVW, SERW, SOR1, INVR1, and SERR1 When Changing Distribution Network

Important Two-way Interactions

Two two-way interactions are of concern in the sensitivity analysis. As shown in Table 6.8, the interaction between lot-sizing rules and safety stock policies, as well as the interaction between the lead time uncertainty and safety stock policies, is significant. The results are consistent with the previous results from the mean TRC analysis in the base experiment.

The interaction plot between the lot-sizing rule and safety stock policy is shown in Figure 6.8. As shown in Figure 6.8, the L4L lot-sizing rule outperforms the EOQ rule under all safety stock policies. This is because stockout costs do not decrease enough to justify the increased inventory carrying costs when the EOQ rule is applied. Furthermore, the EOQ lot-sizing rule is less sensitive to the safety stock policy used in terms of the mean TRC.

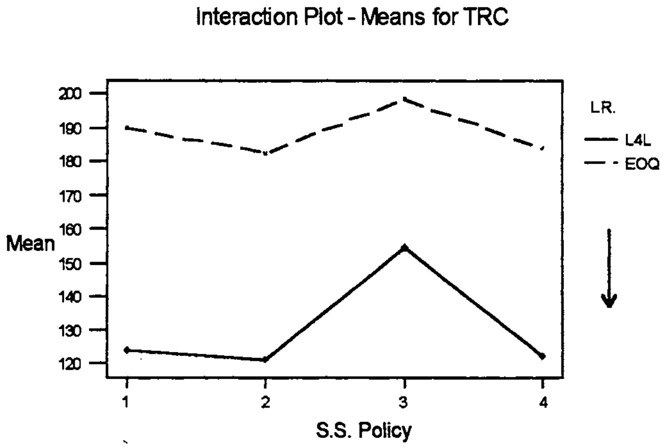

Figure 6.8 Means Plot for TRC as a Function of Lot-sizing Rule and Safety Stock Policy When Changing Distribution Network

When the transportation lead time distribution varies from a symmetric discrete distribution with low variation to a uniform discrete distribution with high variation, the mean TRC increases under most safety stock policies. However, safety stock policy 2 is not affected much by lead time uncertainty. This is because when all safety stocks are allocated at the warehouse, the lead time variations have been absorbed. The interaction of these two factors is shown in Figure 6.9.

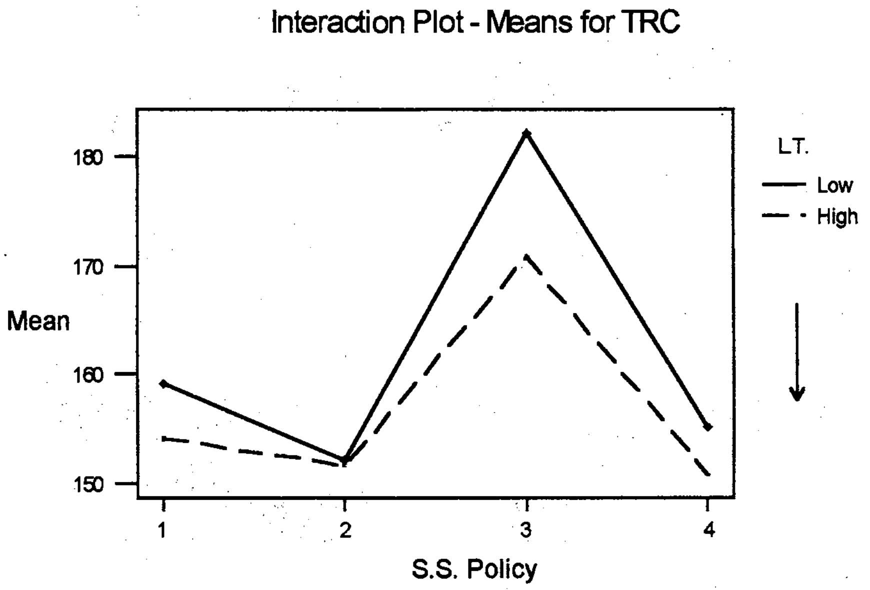

Figure 6.9 Means Plot for TRC as a Function of Lead Time Uncertainty and Safety Stock Policy When Changing Distribution Network

Mean Service Level Analysis at Warehouse (SERW)

ANOVA is performed on the mean SERW from the simulation. The ANOVA results for the main factors and the interactions of safety stock policy with all other main factors are shown in Table 6.14. The results show that lot-sizing rule, lead time uncertainty and safety stock policy are significant at the 5% level. And, the interaction between lot-sizing rule and safety stock policy is also significant.

Table 6.14 ANOVA Results for Mean SERW per Week When Changing Distribution Network

```
                  Analysis of Variance for Mean SERW

Source                 DF        SS         MS        F       P
L.R.                    1   0.50400    0.50400   120.09   0.000
D.U.                    1   0.01321    0.01321     3.15   0.078
L.T.                    1   0.21199    0.21199    50.51   0.000
S.S.                    3   2.13860    0.71287   169.86   0.000
L.R.*D.U.               1   0.01735    0.01735     4.13   0.044
L.R.*L.T.               1   0.11385    0.11385    27.13   0.000
L.R.*S.S.               3   0.61276    0.20425    48.67   0.000
D.U.*L.T.               1   0.01556    0.01556     3.71   0.056
D.U.*S.S.               3   0.03022    0.01007     2.40   0.071
L.T.*S.S.               3   0.02563    0.00854     2.04   0.112
L.R.*D.U.*L.T.          1   0.01768    0.01768     4.21   0.042
L.R.*D.U.*S.S.          3   0.03031    0.01010     2.41   0.070
L.R.*L.T.*S.S.          3   0.03773    0.01258     3.00   0.033
D.U.*L.T.*S.S.          3   0.02837    0.00946     2.25   0.085
L.R.*D.U.*L.T.*S.S.     3   0.03049    0.01016     2.42   0.069
Error                 128   0.53720    0.00420
Total                 159   4.36496
```

Main Effects

A plot of main effects for the mean SERW is presented in Figure 6.10, and the mean service level of each main effect at each level is shown in Table 6.15. Visual examination of experimental results in Figure 6.10 shows that L4L yields a much higher mean SERW than the EOQ does.

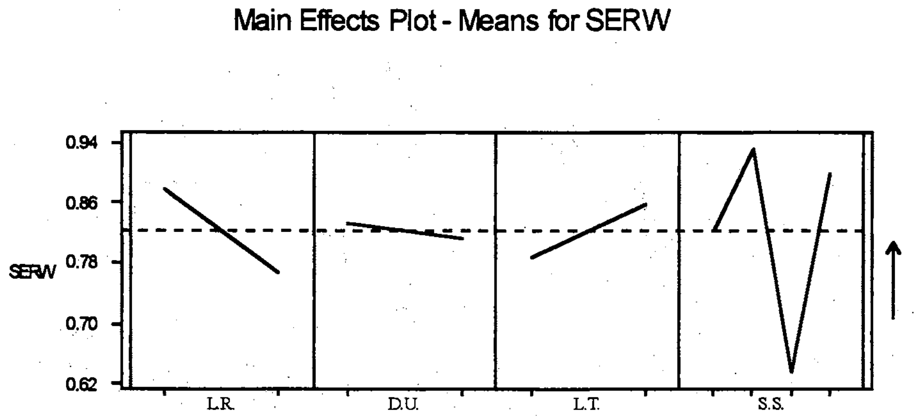

Figure 6.10 Main Effects Plot for Mean SERW When Changing Distribution Network

Table 6.15 Mean Service Level per Week at the Warehouse of Each Main Effect at Each Level When Changing Distribution Network

Means

L.R.	N	SERW
1	80	0.87940
2	80	0.76715
D.U.	N	SERW
1	80	0.83236
2	80	0.81419
L.T.	N	SERW
1	80	0.78688
2	80	0.85967
S.S.	N	SERW
1	40	0.82490
2	40	0.93307
3	40	0.63490
4	40	0.90022

The results of two sources of uncertainties are consistent with the results in the base experiment. Although the mean SERW is not affected by demand uncertainty statistically, the mean SERW still decreases when demand uncertainty increases. However, the lead time uncertainty has the similar effect on mean SERW as in the base experiment. As the transportation lead time uncertainty increases, the mean SERW decreases. The negative effect on the mean SERW is mainly caused by an increased number of stockout units at the warehouse when transportation lead time increases.

As shown in Figure 6.11, the best safety stock policy is policy 2 in terms of the mean SERW (93%), and policy 4 is the second best (90%). All safety stocks are either allocated for the warehouse or kept at the warehouse and retailers to achieve the highest mean SERW. The mean SERW drops to 63% when policy 3 is applied. This is mainly because policy 3 causes more stockouts at the warehouse.

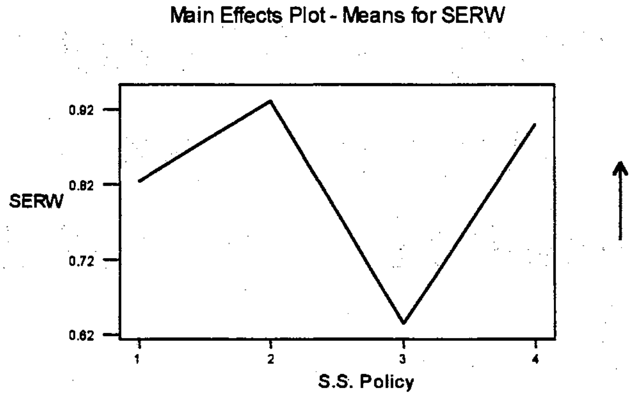

Figure 6.11 Means Plot for SERW as a Function of Safety Stock Policy When Changing Distribution Network

Important Two-Way Interactions

As shown in Table 6.13, the interaction between lot-sizing rule and safety stock policy is significant. The L4L lot-sizing rule outperforms the EOQ rule under all safety stock policies except policy 3. As observed in Table 6.13, EOQ outperforms L4L in terms of the mean SERW under policy 3 with low transportation lead time variation. This can be explained by the built-in safety stock feature of EOQ that performs effectively under low lead time uncertainty. The interaction plot between lot-sizing rule and safety stock policy is shown in Figure 6.12.

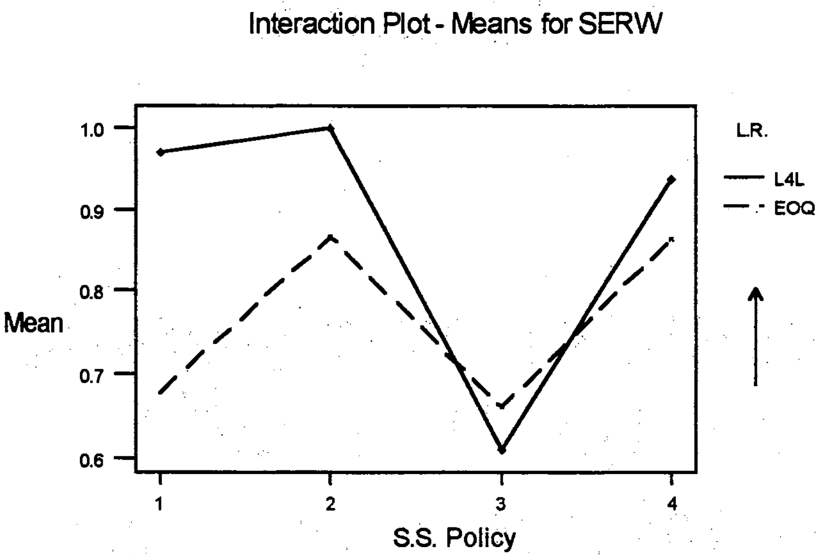

Figure 6.12 Means Plot for SERW as a Function of Lot-sizing Rule and Safety Stock Policy When Changing Distribution Network

Mean Service Level Analysis at Retailer 1 (SERR1)

ANOVA is performed on the mean SERR1 from the simulation. The ANOVA results for the main effects and the interactions of safety stock policy with all other factors are shown in Table 6.16. The results show that lot-sizing rule, lead time uncertainty, demand uncertainty, and safety stock policy are significant at the 5% level in terms of the mean SERR1. Also, the interaction between lot-sizing rules and safety stock policies is significant. All the important main effects and interactions are addressed below.

Table 6.16 ANOVA Results for Mean SERR1 per Week When Changing Distribution Network

```
                   Analysis of Variance for Mean SERR1

Source                 DF        SS          MS        F       P
L.R.                    1   1.693734    1.693734  2776.47  0.000
D.U.                    1   0.016402    0.016402    26.89  0.000
L.T.                    1   0.095942    0.095942   157.27  0.000
S.S.                    3   0.058633    0.019544    32.04  0.000
L.R.*D.U.               1   0.003960    0.003960     6.49  0.012
L.R.*L.T.               1   0.051768    0.051768    84.86  0.000
L.R.*S.S.               3   0.028155    0.009385    15.38  0.000
D.U.*L.T.               1   0.003534    0.003534     5.79  0.018
D.U.*S.S.               3   0.001421    0.000474     0.78  0.509
L.T.*S.S.               3   0.001227    0.000409     0.67  0.572
L.R.*D.U.*L.T.          1   0.000020    0.000020     0.03  0.858
L.R.*D.U.*S.S.          3   0.000600    0.000200     0.33  0.805
L.R.*L.T.*S.S.          3   0.001332    0.000444     0.73  0.537
D.U.*L.T.*S.S.          3   0.002661    0.000887     1.45  0.230
L.R.*D.U.*L.T.*S.S.     3   0.003858    0.001286     2.11  0.102
Error                 128   0.078084    0.000610
Total                 159   2.041330
```

Main Effects

A main effects plot for mean SERR1 is presented in Figure 6.13, and the mean SERR1 of each main effect at each level is shown in Table 6.17. Visual examination of the

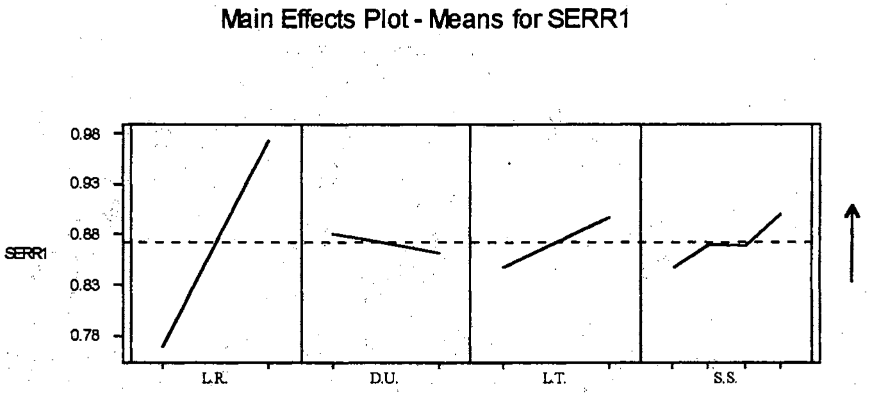

Figure 6.13 Main Effects Plot for SERR1 When Changing Distribution Network

Table 6.17 Mean Service Level per Week at Retailer 1 of Each Main Effect at Each Level When Changing Distribution Network

Means		
L.R.	N	SERR1
1	80	0.76842
2	80	0.97420
D.U.	N	SERR1
1	80	0.88144
2	80	0.86119
L.T.	N	SERR1
1	80	0.84682
2	80	0.89580
S.S.	N	SERR1
1	40	0.84720
2	40	0.86965
3	40	0.86762
4	40	0.90077

experimental results in Figure 6.13 shows that EOQ yields much higher mean SERR1 than L4L does. The mean SERR1 decreases when demand uncertainty increases. It is explained by the forecast error incurred at retailers. The extremely high forecast error may cause stockout at retailers. Furthermore, as the transportation lead time uncertainty increases, the mean SERR1 decreases. If the actual delivery time becomes much longer than the planned lead time, it may cause a stockout at the retailers, and deteriorate the mean SERR1.

As shown in Figure 6.14, the best safety stock policy is policy 4 in terms of the mean SERR1. Safety stocks are allocated for the warehouse and retailers to achieve the highest mean service level for retailers. This is consistent with the result observed in the base experiment. Safety stocks are kept with each channel member (policy 5) to achieve highest mean SERR1 in the base experiment. As observed in Table 6.13, safety stock policy 1 results in lower mean SERR1 under most operating conditions when no safety stock is applied in the distribution system.

Important Two-Way Interactions

As shown in Table 6.16 and Figure 6.15, the interaction between the lot-sizing rule and safety stock policy is significant. It is shown that the EOQ rule outperforms the L4L rule under all safety stock policies.

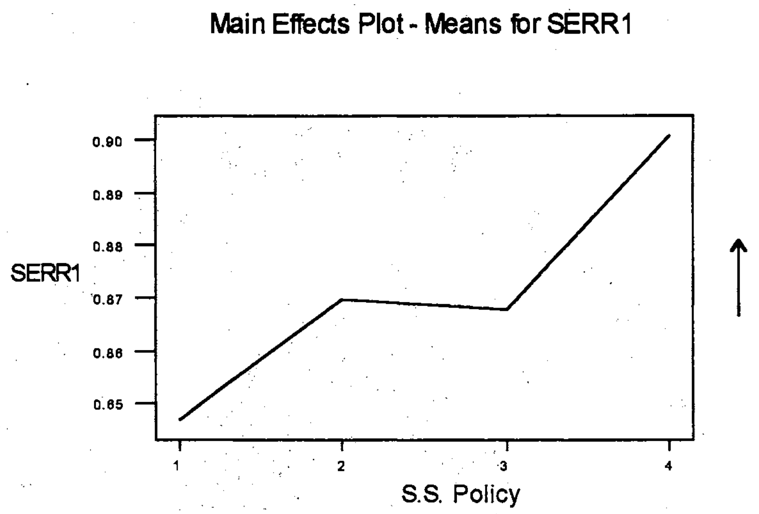

Figure 6.14 Means Plot for SERR1 as a Function of Safety Stock Policy When Changing Distribution Network

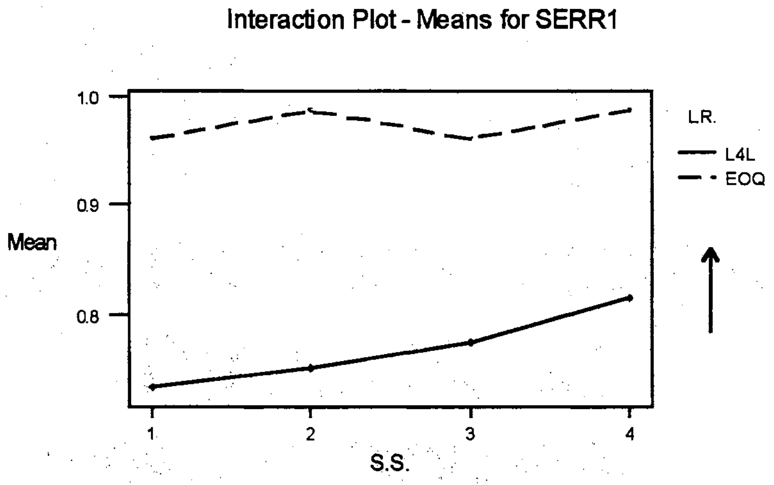

Figure 6.15 Means Plot for SERR1 as a Function of Lot-sizing Rule and Safety Stock Policy When Changing Distribution Network

Discussion of Results in Sensitivity Analysis

Two constant factors in the base experiments are varied in the sensitivity analysis to examine their effects on mean TRC, average stockout units, mean inventory level, and mean service level. Based on previous discussion, a summary of experimental results in the sensitivity analysis experiment is presented in Table 6.18. The results of the sensitivity analysis are consistent with the conclusion drawn from the base experiment when the value-added factors are changed. As addressed before, different value-added factors may stand for different products or different marketing channels. That means the results drawn from the base experiment can be generalized for different products or different marketing channels.

Lot-sizing rule, demand uncertainty and lead time uncertainty have similar effects on the mean TRC of the distribution system under different value-added factors. These results support the conclusions drawn in the base experiment. The best stock policy is still policy 6 in terms of the mean TRC. Safety stock policies 5 and 6 are less sensitive to the changes in lot-sizing rule, demand uncertainty, or lead time uncertainty. Safety stock policy appears to be an effective way to reduce the mean TRC by dampening the effects caused by operating uncertainty.

The results changes in the structure of the distribution network as seen in the sensitivity analysis also confirm most of the conclusions drawn in the base experiment. However, both the demand uncertainty and lead time uncertainty have less effect on the mean TRC when the distribution network is changed. This is because the warehouse may respond to the changes in operating conditions effectively in a two-level distribution network.

Table 6.18 Summary of Experimental Results in the Sensitivity Analysis Experiment

	Value-added Factor	Distribution Network						
Source	TRC	TRC	Stockout Unit		Inventory Level		Service Level	
			W	R	W	R	W	R
L.R.	+	+	+	+	+	+	+	+
D.U.	+	-	-	+	-	-	-	+
L.T.	+	+	+	+	+	+	+	+
S.U.	fixed	fixed	fixed	fixed	fixed	fixed	fixed	fixed
C.V.	fixed	fixed	fixed	fixed	fixed	fixed	fixed	fixed
S.S.	+	+	+	+	+	+	+	+
L.R.*S.S.	+	+	+	+	+	+	+	+
D.U.*S.S.	+	-	-	-	-	-	-	-
L.T.*S.S.	+	-	-	-	+	+	-	-
S.U.*S.S.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Best S.S.	6	2	2	4	2	2	2	4
Second Best S.S.	5	4	4	2	4	4	4	2
Best L.R.	L4L	L4L	L4L	EOQ	L4L	L4L	L4L	EOQ

$^{+}$ Significant at the 5% Level
$^{-}$ Insignificant at the 5% Level

Most of the results of the sensitivity analysis at retailers due to a change in the distribution network structure are consistent with the conclusions drawn from the base experiment in terms of the mean service level. Retailers are still highly affected by the change in demand variations than the warehouse. This is mainly because retailers are closer to the source of uncertainty. As observed in Table 6.13, lead time uncertainty has a significant effect on retailer 1 in terms of three non-monetary performance measures. It would be worthwhile to investigate the use of the EOQ lot-sizing rule at the retailers. The EOQ rule yields fewer stockouts and a much higher mean service level than L4L at retailers. This is because the built-in safety stock feature of the EOQ lot-sizing rule works more effectively in the two-level distribution network.

The next chapter provides a summary of the study, discusses the practical implications of the findings, and outlines directions for future research.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The purpose of this research is first to evaluate the impact of three different sources and types of uncertainties in terms of total related cost, average stockout units, mean inventory level and mean service level in a multi-echelon distribution system. The three uncertainties considered are: (1) demand uncertainty from the outside customers, (2) transportation lead time uncertainty within the distribution system, and (3) supply uncertainty from the outside vendor.

The polices for allocating safety stocks are then evaluated in a multi-echelon distribution system. Current studies have partially addressed these problems, but do not provide detailed cross comparison of various types of uncertainties. Most of the efforts in past research related to the safety stock problem in a multi-echelon distribution system are based on a reorder point system or other inventory control methods. This pilot study is to find a more effective safety stock policy in a multi-echelon distribution system under the operation of DRP.

In the preceding chapters, the types and effects of uncertainty are discussed, the research methodology is described, and the results of the simulation data analysis are presented. A summary of major findings of this chapter and contributions of this study are presented in the first two sections. Finally, the directions for further research are suggested.

Summary of Major Findings

This objectives of this study are to explore two research issues: (1) the impact of various operating conditions on the performance of a multi-echelon distribution system; and (2) the effectiveness of alternative safety stock policies. Based on the simulation results analyses in Chapters Five and Six, the following conclusions are reached:

1. The effect of demand uncertainty, transportation lead time uncertainty, and supply uncertainty on DRP system performance is significant. The impact of these uncertainties on a distribution system are demonstrated in terms of mean TRC of the whole system, and the average stockout units, average inventory level and mean service level of each channel member. The effect of these uncertainties does not stop with one channel member. Thus, the impact occurring at one channel member will adversely affect the performance of the other channel members in the distribution system.

In general, demand uncertainty from the outside customer and lead time uncertainty within the distribution system creates a more serious impact in terms of three non-monetary performance measures at the retailer and distribution center levels. This impact creates stockouts in the distribution system, which, in turn, causes a low mean service level at the retailers and distribution centers. The lead time uncertainty impacts the retailers and distribution centers more directly. This is consistent with the findings of Wagenheim and Spen (1975), and Allen (1983). The impact from supply uncertainty is caused by the supply shortage at the warehouse. However, the effect will prevail to distribution centers and retailers.

2. It is found that there are significant interactions among the experimental factors. This suggests that these factors should be examined together, rather than individually. To make sure that the best safety stock policy is used in a multi-echelon distribution system, all operating conditions have to be examined at the same time. As shown in Table 5.2, the L4L rule outperforms the EOQ rule in terms of mean TRC; the best safety stock policy is policy 6.

All the conclusions drawn above are based on performance in general. Ignoring the interaction between lot-sizing rule and safety stock policy in this case may be misleading. Based on the mean TRC shown in Table 5.3, the best operating condition is to apply the EOQ rule under safety stock policy 6. This result holds true under various operating conditions, except when high supply uncertainty, low lead time uncertainty, high demand uncertainty, and low cost value are applied.

3. When non-monetary performance measures are examined for each channel member, distribution centers and retailers show very similar results. These results indicate that the operating condition in terms of main effects in this experiment have similar effects on DRP system performance at these two channel members.

4. In general, the L4L rule outperforms the EOQ rule under most operating conditions. The same conclusions are found by Melnyk and Pipier (1985), and Minifie and Davis (1986). When the interaction between the lot-sizing rule and safety stock policy is observed, the L4L is robust in terms of all performance measures under all safety stock policies.

5. When investigating the impact of a changing distribution network on the performance of the distribution system, it is found that changes in the structure of the distribution network have an effect on the distribution system. When the non-monetary performance measures are considered at the retailer level, the EOQ rule is better than L4L. It is believed that there are some interaction effects which exist between the lot-sizing rule and other experimental factors in this study. In the base experiment, the performance of the EOQ rule is deteriorated in all performance measures when the lead time uncertainty increases. When the distribution network is changed from three levels to two levels, it can be viewed as a way to mitigate lead time uncertainty. This is because lead time

uncertainty only occurs at the warehouse and retailers. In turn, it makes the built-in safety stock feature of EOQ work effectively in the two-level distribution network.

6. Good safety stock policies are less sensitive to the changes in operating uncertainty. Effective safety stock policies allocate safety stock at the warehouse and distribution centers, or put safety stocks at all channel members. Safety stocks provide protection against various sources of uncertainty in this study. Safety stocks at the warehouse can protect against supply shortages caused by the order shipping delays from the vendor occurring at distribution centers. Safety stocks at distribution centers can absorb the order shrinkage caused by supply uncertainty, lead time uncertainty at distribution centers and retailers, or demand uncertainty at the retailers. The same function of safety stock is applied at the retailer level.

These findings are consistent with the results in Salameh and Schmidt (1984). They reserve the safety stocks at the first two levels in a multi-level inventory system. Liaw (1979) evaluates several safety stock policies in an MRP system. Furthermore, Liaw indicates that holding safety stock at an inventory stage with more significant uncertainty may generate better return on inventory.

In the experiment for sensitivity analysis, it is found that allocating safety stock for the warehouse can always yield better performance than allocating no safety stock.

Similar results are found by Chakravarty and Shtub (1986) in a two-echelon distribution simulation study.

Contributions of this Study

This research is one step closer to real life settings than previous research in this area. First, it considers the stochastic nature of demand, transportation lead time, and supply simultaneously in a multi-echelon distribution system. Secondly, this study evaluates the system performance under a rolling schedule with the DRP inventory control method. Most of the related research is based on a reorder point system or other inventory control methods. Therefore, the safety stock policy is evaluated under operating conditions incorporating more of the complexities faced in a real-life distribution system.

The results of this study can provide decision rules that specify which policies are used under various operating conditions. The results also provide practical guidelines for the practitioners as follows:

(1) The EOQ rule should not be used at the warehouse level and distribution center level in a multi-echelon distribution system. The EOQ rule, when used at the warehouse level, yields the worst performance under most operating conditions in this study. The EOQ rule, however, can be applied at the retailer level with an appropriate safety stock policy. For example, safety stock policies 5

and 6 result in the lowest average stockout units when EOQ is used at retailer 1.

(2) The transportation lead time uncertainty that exists within the warehouse, distribution centers, and retailers should be reduced. Two probability distributions to describe transportation lead time uncertainty are examined in this study. The symmetrical discrete distribution yields better performance than the uniform discrete distribution due to tighter lead time variability.

(3) When allocating safety stocks within the distribution system, it is more prudent to keep safety stock at the top level (warehouse). The simulation results indicate that safety stock policies with safety stock at the warehouse (S.S. Policies 2, 5, 6, and 7) are better than those policies with no safety stock at the warehouse.

(4) The aggregate performance measure (TRC) should be examined with non-monetary measures when evaluating system performance. The mean TRC of the distribution system is sensitive to changes in the values of cost parameters. That may lead to a wrong decision based on the single TRC performance measure.

To academicians, this research provides a methodology to evaluate the safety stock policy in a multi-echelon distribution system under the operation of DRP. Furthermore, the results offer an opportunity to illustrate the impact of various sources of uncertainties on a multi-echelon distribution system. Demand uncertainty, transportation lead time uncertainty, and supply uncertainty affect the whole distribution system and each channel member to a different degree. The relationships between safety stock policy and other experimental factors are also discussed in this study. Although the interaction between safety stock policy and lot-sizing rule is significant, some policies (5 and 6) are not affected much by the lot-sizing rule.

To practitioners, this study provides a guideline for conducting an effective safety stock policy in a multi-echelon distribution under DRP's operation. Allocating all safety stock for the warehouse (policy 2) is the best way to minimize the stockouts at the warehouse. And keeping safety stock at each channel member (policy 5) or at the warehouse and distribution centers are the two best policies for reducing the mean TRC for the distribution system.

Directions for Future Study

It is important to recognize that this study considers only a limited variety of operating environments. However, some of the assumptions made in this study may limit the generalization of its findings. Specifically, backorders are not allowed, and capacity is assumed to be unrestricted. Only shortage from supply side uncertainty is considered in this study. Removing the above restrictions would make it possible to extend the current study. The behavior of system performance measure under more complex operating conditions may provide direction for future research.

Another avenue for future research is to evaluate the performance of such buffering methods as safety lead time or safety capacity in a multi-echelon distribution system. The result from using other buffering methods could be compared with the results of using the safety stock method alone.

In this study, the same lot-sizing rule is applied globally at every channel member in the distribution system. The results of this study show L4L performs better at the warehouse and distribution centers, but EOQ may be more appropriately applied at retailers. It is worth investigating the behavior of a mixed lot-sizing rule. That allows one to use a different lot-sizing rule for different channel members in the distribution system.

An effective safety stock policy is suggested to achieve high performance of the distribution system. This study only examines eight fixed types of safety stock policies. Further development of the safety stock policy to allocate safety stock within channel members is suggested for future study.

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APPENDICES

APPENDIX A

FORTRAN PROGRAMS FOR CHAPTER IV

```
      PROGRAM INIT11
*************************************************************************
*     THIS IS A PROGRAM WITH 5 REPS, 8 SAFETY STOCK POLICIES,          *
*     USING L4L WITH WARMUP PERIOD 40 WEEKS(THREE LEVELS)               *
*************************************************************************
      INTEGER FDR(4,500)
      INTEGER ADR(4,500)
      INTEGER LTR(4,500),LTDC(2,500),ARW(500)
      REAL ARRATE(500)
      REAL AVGINV(3,4,500)
      REAL VAW,VADC,VAR
      REAL CC,SC,OC
      REAL CV
      REAL TRC(500),TRCW(500),TRCDC(2,500),TRCR(4,500),TRCSUM,
     +     CAVTRC(500)
      REAL INSUMW,INSUMD(2),INSUMR(4)
      REAL CAVGW(500),CAVGD(2,500),CAVGR(4,500)
      REAL CAVGRW(500),CAVGRD(2,500),CAVGRR(4,500)
      REAL SERVW(500),SERVD(2,500),SERVR(4,500)
      REAL SOSUMW,SOSUMD(2),SOSUMR(4)
      REAL GRSUMW,GRSUMD(2),GRSUMR(4)
      REAL CAVSOW(500),CAVSOD(2,500),CAVSOR(4,500)
      REAL SOW(8,5),INVW(8,5),SERW(8,5),SODC1(8,5),INVDC1(8,5)
      REAL SERDC1(8,5),SODC2(8,5),INVDC2(8,5),SERDC2(8,5),SOR1(8,5)
      REAL INVR1(8,5),SERR1(8,5),SOR2(8,5),INVR2(8,5),SERR2(8,5)
      REAL SOR3(8,5),INVR3(8,5),SERR3(8,5),SOR4(8,5),INVR4(8,5)
      REAL SERR4(8,5),TRCSYSTEM(8,5)
      INTEGER SO(3,4,500)
      INTEGER GR(3,4,500),TRANSIT(3,4,500),PAB(3,4,0:500)
      INTEGER NR(3,4,500),PR(3,4,500),PS(3,4,500)
      INTEGER SS(3,4)
      DATA VAW/1.0/,VADC/1.1/,VAR/1.21/
      DATA CC/0.002/,SC/0.1/,OC/30.0/
      DATA CV/0.05/
C
C INPUT SAFETY STOCK POLICY
      DO 1 S=1,8
      IF(S.EQ.1) GOTO 201
      IF(S.EQ.2) GOTO 202
      IF(S.EQ.3) GOTO 203
      IF(S.EQ.4) GOTO 204
      IF(S.EQ.5) GOTO 205
      IF(S.EQ.6) GOTO 206
      IF(S.EQ.7) GOTO 207
      IF(S.EQ.8) GOTO 208
  201 SS(1,1)=0
      SS(1,2)=0
      SS(1,3)=0
      SS(1,4)=0
      SS(2,1)=0
      SS(2,2)=0
      SS(3,1)=0
      GOTO 333
```

```
 202   SS(1,1)=0
       SS(1,2)=0
       SS(1,3)=0
       SS(1,4)=0
       SS(2,1)=0
       SS(2,2)=0
       SS(3,1)=300
       GOTO 333
 203   SS(1,1)=30
       SS(1,2)=60
       SS(1,3)=90
       SS(1,4)=120
       SS(2,1)=0
       SS(2,2)=0
       SS(3,1)=0
       GOTO 333
 204   SS(1,1)=0
       SS(1,2)=0
       SS(1,3)=0
       SS(1,4)=0
       SS(2,1)=90
       SS(2,2)=210
       SS(3,1)=0
       GOTO 333
 205   SS(1,1)=10
       SS(1,2)=20
       SS(1,3)=30
       SS(1,4)=40
       SS(2,1)=30
       SS(2,2)=70
       SS(3,1)=100
       GOTO 333
 206   SS(1,1)=0
       SS(1,2)=0
       SS(1,3)=0
       SS(1,4)=0
       SS(2,1)=45
       SS(2,2)=105
       SS(3,1)=150
       GOTO 333
 207   SS(1,1)=15
       SS(1,2)=30
       SS(1,3)=45
       SS(1,4)=60
       SS(2,1)=0
       SS(2,2)=0
       SS(3,1)=150
       GOTO 333
 208   SS(1,1)=15
       SS(1,2)=30
       SS(1,3)=45
       SS(1,4)=60
       SS(2,1)=45
       SS(2,2)=105
       SS(3,1)=0
C
 333   DO 2 K=1,5
       DO 101 P=1,3
       DO 102 J=1,4
       DO 103 Q=1,500
```

```
        GR(P,J,Q)=0
        TRANSIT(P,J,Q)=0
        PAB(P,J,Q)=0
        NR(P,J,Q)=0
        PR(P,J,Q)=0
        PS(P,J,Q)=0
  103 CONTINUE
  102 CONTINUE
  101 CONTINUE
      INSUMW=0.0
      INSUMD(1)=0.0
      INSUMD(2)=0.0
      INSUMR(1)=0.0
      INSUMR(2)=0.0
      INSUMR(3)=0.0
      INSUMR(4)=0.0
C
      SOSUMW=0.0
      SOSUMD(1)=0.0
      SOSUMD(2)=0.0
      SOSUMR(1)=0.0
      SOSUMR(2)=0.0
      SOSUMR(3)=0.0
      SOSUMR(4)=0.0
C
      GRSUMW=0.0
      GRSUMD(1)=0.0
      GRSUMD(2)=0.0
      GRSUMR(1)=0.0
      GRSUMR(2)=0.0
      GRSUMR(3)=0.0
      GRSUMR(4)=0.0
C
      TRCSUM=0.0
C
      DO 5 T=1,500
      FDR(1,T)=NINT(XNORMAL()*10)+50
      FDR(2,T)=NINT(XNORMAL()*20)+100
      FDR(3,T)=NINT(XNORMAL()*30)+150
      FDR(4,T)=NINT(XNORMAL()*40)+200
      ADR(1,T)=MAX(FDR(1,T)+NINT(XNORMAL()*30),0)
      ADR(2,T)=MAX(FDR(2,T)+NINT(XNORMAL()*30),0)
      ADR(3,T)=MAX(FDR(3,T)+NINT(XNORMAL()*30),0)
      ADR(4,T)=MAX(FDR(4,T)+NINT(XNORMAL()*30),0)
      ARRATE(T)=MAX(1-ABS(XNORMAL( ))*CV,0.0)
      LTDC(1,T)=LT2()
      LTDC(2,T)=LT2()
      LTR(1,T)=LT2()
      LTR(2,T)=LT2()
      LTR(3,T)=LT2()
      LTR(4,T)=LT2()
    5 CONTINUE
************************************************************
*               THIS PART IS DRP I (INFORMATION FLOW)      *
************************************************************
C INPUT FORECAST REQUIREMENT FOR R1,R2,R3,R4
C
      DO 15 T=1,500
      GR(1,1,T)=FDR(1,T)
      GR(1,2,T)=FDR(2,T)
```

```
      GR(1,3,T)=FDR(3,T)
      GR(1,4,T)=FDR(4,T)
   15 CONTINUE
C INPUT FIRST THREE IN-TRANSIT AT R1,R2,R3,R4
      DO 22 T=1,3
      TRANSIT(1,1,T)=FDR(1,T)
      TRANSIT(1,2,T)=FDR(2,T)
      TRANSIT(1,3,T)=FDR(3,T)
      TRANSIT(1,4,T)=FDR(4,T)
   22 CONTINUE
C CALCULATE NET REQUIREMENT FOR R1,R2,R3,R4
      DO 13 L=1,450
      DO 23 J=1,4
      PAB(1,J,0)=SS(1,J)
      DO 33 T=L,L+11
      IF(T.LE.L+2) THEN
       NR(1,J,T)=0
       PR(1,J,T)=NR(1,J,T)
       PAB(1,J,T)=MAX(PAB(1,J,T-1)+TRANSIT(1,J,T)-GR(1,J,T),0)
      ELSE
       NR(1,J,T)=MAX(GR(1,J,T)+SS(1,J)-PAB(1,J,T-1)-TRANSIT(1,J,T),0)
       PR(1,J,T)=NR(1,J,T)
       PAB(1,J,T)=MAX(PAB(1,J,T-1)+PR(1,J,T)+TRANSIT(1,J,T)-GR(1,J,T),0)
       PS(1,J,T-3)=PR(1,J,T)
       END IF
   33 CONTINUE
   23 CONTINUE
C CALCULATE THE FORECAST REQUIREMENT AT DC1,DC2
      DO 41 T=L,L+8
      GR(2,1,T)=PS(1,1,T)+PS(1,2,T)
      GR(2,2,T)=PS(1,3,T)+PS(1,4,T)
   41 CONTINUE
C CALCULATE NET REQUIREMENT FOR DC1,DC2
      IF(L.GT.1) GOTO 10
      DO 42 J=1,2
      TRANSIT(2,J,1)=GR(2,J,1)
      TRANSIT(2,J,2)=GR(2,J,2)
      TRANSIT(2,J,3)=GR(2,J,3)
      PAB(2,J,0)=SS(2,J)
   42 CONTINUE
   10 DO 43 J=1,2
      DO 44 T=L,L+8
      IF(T.LE.L+2) THEN
       NR(2,J,T)=0
       PR(2,J,T)=NR(2,J,T)
       PAB(2,J,T)=MAX(PAB(2,J,T-1)+TRANSIT(2,J,T)-GR(2,J,T),0)
      ELSE
       NR(2,J,T)=MAX(GR(2,J,T)+SS(2,J)-PAB(2,J,T-1)-TRANSIT(2,J,T),0)
       PR(2,J,T)=NR(2,J,T)
       PAB(2,J,T)=MAX(PAB(2,J,T-1)+PR(2,J,T)+TRANSIT(2,J,T)-GR(2,J,T),0)
       PS(2,J,T-3)=PR(2,J,T)
       END IF
   44 CONTINUE
   43 CONTINUE
C CALCULATE THE FORECAST REQUIREMENT AT W
      DO 51 T=L,L+5
      GR(3,1,T)=PS(2,1,T)+PS(2,2,T)
   51 CONTINUE
C CALCULATE NET REQUIREMENT FOR W
      IF(L.GT.1) GOTO 20
```

```
      TRANSIT(3,1,1)=GR(3,1,1)
      TRANSIT(3,1,2)=GR(3,1,2)
      TRANSIT(3,1,3)=GR(3,1,3)
      PAB(3,1,0)=SS(3,1)
   20 DO 52 T=L,L+5
      IF(T.LE.L+2) THEN
       NR(3,1,T)=0
       PR(3,1,T)=NR(3,1,T)
       PAB(3,1,T)=MAX(PAB(3,1,T-1)+TRANSIT(3,1,T)-GR(3,1,T),0)
      ELSE
       NR(3,1,T)=MAX(GR(3,1,T)+SS(3,1)-PAB(3,1,T-1)-TRANSIT(3,1,T),0)
       PR(3,1,T)=NR(3,1,T)
       PAB(3,1,T)=MAX(PAB(3,1,T-1)+PR(3,1,T)+TRANSIT(3,1,T)-GR(3,1,T),0)
       PS(3,1,T-3)=PR(3,1,T)
       END IF
   52 CONTINUE
*************************************************************
*             THIS PART IS DRP II (PHYSICAL FLOW)           *
*************************************************************
C CALCULATE THE ACTUAL RECEIPT FROM VENDOR AT WAREHOUSE &
C ACTUAL SHIPMENT TO DC1,DC2
      ARW(L)=NINT(TRANSIT(3,1,L)*ARRATE(L))
      IF ((PAB(3,1,L-1)+ARW(L)).GE.GR(3,1,L)) THEN
       TRANSIT(2,1,L+LTDC(1,L))=PS(2,1,L)+TRANSIT(2,1,L+LTDC(1,L))
         TRANSIT(2,2,L+LTDC(2,L))=PS(2,2,L)+TRANSIT(2,2,L+LTDC(2,L))
      ELSE
       TRANSIT(2,1,L+LTDC(1,L))=NINT((PAB(3,1,L-1)+ARW(L))*(PS(2,1,L)/
     + REAL(PS(2,1,L)+PS(2,2,L))))+TRANSIT(2,1,L+LTDC(1,L))
       TRANSIT(2,2,L+LTDC(2,L))=PAB(3,1,L-1)+ARW(L)-NINT((PAB(3,1,L-1)
     + +ARW(L))*(PS(2,1,L)/REAL(PS(2,1,L)+PS(2,2,L))))+TRANSIT(2,2,L+
     + LTDC(2,L))
      END IF
C CALCULATE THE ACTUAL SHIPMENT FROM DC1 TO R1,R2
      IF ((PAB(2,1,L-1)+TRANSIT(2,1,L)).GE.GR(2,1,L)) THEN
       TRANSIT(1,1,L+LTR(1,L))=PS(1,1,L)+TRANSIT(1,1,L+LTR(1,L))
         TRANSIT(1,2,L+LTR(2,L))=PS(1,2,L)+TRANSIT(1,2,L+LTR(2,L))
      ELSE
       TRANSIT(1,1,L+LTR(1,L))=NINT((PAB(2,1,L-1)+TRANSIT(2,1,L))
     + *(PS(1,1,L)/REAL(PS(1,1,L)+PS(1,2,L))))+TRANSIT(1,1,L+LTR(1,L))
       TRANSIT(1,2,L+LTR(2,L))=PAB(2,1,L-1)+TRANSIT(2,1,L)-
     + NINT((PAB(2,1,L-1)+TRANSIT(2,1,L)+PR(2,1,L))
     + *(PS(1,1,L)/REAL(PS(1,1,L)+PS(1,2,L))))+TRANSIT(1,2,L+LTR(2,L))
      END IF
C CALCULATE THE ACTUAL SHIPMENT FROM DC2 TO R3,R4
      IF ((PAB(2,2,L-1)+TRANSIT(2,2,L)).GE.GR(2,2,L)) THEN
       TRANSIT(1,3,L+LTR(3,L))=PS(1,3,L)+TRANSIT(1,3,L+LTR(3,L))
         TRANSIT(1,4,L+LTR(4,L))=PS(1,4,L)+TRANSIT(1,4,L+LTR(4,L))
      ELSE
       TRANSIT(1,3,L+LTR(3,L))=NINT((PAB(2,2,L-1)+TRANSIT(2,2,L))
     + *(PS(1,3,L)/REAL(PS(1,3,L)+PS(1,4,L))))+TRANSIT(1,3,L+LTR(3,L))
      TRANSIT(1,4,L+LTR(4,L))=PAB(2,2,L-1)+TRANSIT(2,2,L)-
     +  NINT((PAB(2,2,L-1)+TRANSIT(2,2,L)+PR(2,2,L))
     + *(PS(1,3,L)/REAL(PS(1,3,L)+PS(1,4,L))))+TRANSIT(1,4,L+LTR(4,L))
      END IF
C
C UPDATE THE PORJECTED AVAILABLE BALANCE AT R1,R2,R3,R4,DC1,DC2,W
C & IN-TRANSIT AT W
C
      PAB(1,1,L)=MAX((PAB(1,1,L-1)+TRANSIT(1,1,L)-ADR(1,L)),0)
      PAB(1,2,L)=MAX((PAB(1,2,L-1)+TRANSIT(1,2,L)-ADR(2,L)),0)
```

```
      PAB(1,3,L)=MAX((PAB(1,3,L-1)+TRANSIT(1,3,L)-ADR(3,L)),0)
      PAB(1,4,L)=MAX((PAB(1,4,L-1)+TRANSIT(1,4,L)-ADR(4,L)),0)
      PAB(2,1,L)=MAX((PAB(2,1,L-1)+TRANSIT(2,1,L)-GR(2,1,L)),0)
      PAB(2,2,L)=MAX((PAB(2,2,L-1)+TRANSIT(2,2,L)-GR(2,2,L)),0)
      PAB(3,1,L)=MAX((PAB(3,1,L-1)+ARW(L)-GR(3,1,L)),0)
      TRANSIT(3,1,L+3)=PS(3,1,L)
************************************************************************
*     THIS PART IS STAT: COLLECT THE PERFORMANCE MEASURE               *
************************************************************************
C CALCULATE THE AVERAGE INVENTORY ,STOCKOUT AND SERVICE LEVEL AT W
C
      IF(L.LE.40) GOTO 13
      SO(3,1,L)=MAX(GR(3,1,L)-(PAB(3,1,L-1)+ARW(L)),0)
      SOSUMW=SOSUMW+SO(3,1,L)
      CAVSOW(L)=SOSUMW/(L-40)
C
      AVGINV(3,1,L)=((PAB(3,1,L-1)+ARW(L))+MAX(PAB(3,1,L-1)+ARW(L)-
     +               GR(3,1,L),0))/2.0
      INSUMW=INSUMW+AVGINV(3,1,L)
      CAVGW(L)=INSUMW/(L-40)
      GRSUMW=GRSUMW+GR(3,1,L)
      CAVGRW(L)=GRSUMW/(L-40)
      SERVW(L)=1-(CAVSOW(L)/CAVGRW(L))
C CALCULATE THE AVERAGE INVENTORY AND STOCKOUT AT DC1,DC2
C
      DO 61 J=1,2
      SO(2,J,L)=MAX(GR(2,J,L)-(PAB(2,J,L-1)+TRANSIT(2,J,L)),0)
      SOSUMD(J)=SOSUMD(J)+SO(2,J,L)
      CAVSOD(J,L)=SOSUMD(J)/(L-40)
      AVGINV(2,J,L)=((PAB(2,J,L-1)+TRANSIT(2,J,L))+MAX(PAB(2,J,L-1)+
     +              TRANSIT(2,J,L)-GR(2,J,L),0))/2.0
      INSUMD(J)=INSUMD(J)+AVGINV(2,J,L)
      CAVGD(J,L)=INSUMD(J)/(L-40)
      GRSUMD(J)=GRSUMD(J)+GR(2,J,L)
      CAVGRD(J,L)=GRSUMD(J)/(L-40)
      SERVD(J,L)=1-(CAVSOD(J,L)/CAVGRD(J,L))
   61 CONTINUE
C CALCULATE THE AVERAGE INVENTORY AND STOCKOUT AT R1,R2,R3,R4
      DO 62 J=1,4
      SO(1,J,L)=MAX(ADR(J,L)-(PAB(1,J,L-1)+TRANSIT(1,J,L)),0)
      SOSUMR(J)=SOSUMR(J)+SO(1,J,L)
      CAVSOR(J,L)=SOSUMR(J)/(L-40)
      AVGINV(1,J,L)=((PAB(1,J,L-1)+TRANSIT(1,J,L))+MAX(PAB(1,J,L-1)+
     +              TRANSIT(1,J,L)-ADR(1,L),0))/2.0
      INSUMR(J)=INSUMR(J)+AVGINV(1,J,L)
      CAVGR(J,L)=INSUMR(J)/(L-40)
      GRSUMR(J)=GRSUMR(J)+GR(1,J,L)
      CAVGRR(J,L)=GRSUMR(J)/(L-40)
      SERVR(J,L)=1-(CAVSOR(J,L)/CAVGRR(J,L))
   62 CONTINUE
C
C UPDATE THE PORJECTED AVAILABLE BALANCE AT R1,R2,R3,R4,DC1,DC2,W
C & IN-TRANSIT AT W
C
      PAB(1,1,L)=MAX((PAB(1,1,L-1)+TRANSIT(1,1,L)-ADR(1,L)),0)
      PAB(1,2,L)=MAX((PAB(1,2,L-1)+TRANSIT(1,2,L)-ADR(2,L)),0)
      PAB(1,3,L)=MAX((PAB(1,3,L-1)+TRANSIT(1,3,L)-ADR(3,L)),0)
      PAB(1,4,L)=MAX((PAB(1,4,L-1)+TRANSIT(1,4,L)-ADR(4,L)),0)
      PAB(2,1,L)=MAX((PAB(2,1,L-1)+TRANSIT(2,1,L)-GR(2,1,L)),0)
      PAB(2,2,L)=MAX((PAB(2,2,L-1)+TRANSIT(2,2,L)-GR(2,2,L)),0)
```

```
      PAB(3,1,L)=MAX((PAB(3,1,L-1)+ARW(L)-GR(3,1,L)),0)
      TRANSIT(3,1,L+3)=PS(3,1,L)
C
C CALCULATE THE TOTAL RELATED COST AT PERIOD T
C
C TOTAL COST AT W
      IF (PS(3,1,L).GT.0) THEN
       OC=20.0
      ELSE
       OC=0.0
      END IF
      TRCW(L)=(SO(3,1,L)*SC+AVGINV(3,1,L)*CC+OC)*VAW
C
C TOTAL COST AT DC
      DO 72 J=1,2
      IF (PS(2,J,L).GT.0) THEN
       OC=20.0
      ELSE
       OC=0.0
      END IF
      TRCDC(J,L)=(SO(2,J,L)*SC+AVGINV(2,J,L)*CC+OC)*VADC
   72 CONTINUE
C
C TOTAL COST AT R
      DO 73 J=1,4
      IF (PS(1,J,L).GT.0) THEN
       OC=20.0
      ELSE
       OC=0.0
      END IF
      TRCR(J,L)=(SO(1,J,L)*SC+AVGINV(1,J,L)*CC+OC)*VAR
   73 CONTINUE
C
C TOTAL COST FOR THE WHOLE SYSTEM
      TRC(L)=(TRCW(L)+TRCDC(1,L)+TRCDC(2,L)+TRCR(1,L)+TRCR(2,L)+
     +        TRCR(3,L)+TRCR(4,L))
      TRCSUM=TRCSUM+TRC(L)
      CAVTRC(L)=TRCSUM/(L-40)
   13 CONTINUE
C
C  SUMMARY REPORT AT W,DC,R FOR EACH REP IN EACH PERFORMANCE MEASURE:
C  AVG STOCKOUT, AVG INVENTORY AND SERVICE LEVEL
C
      SOW(S,K)=CAVSOW(440)
      INVW(S,K)=CAVGW(440)
      SERW(S,K)=SERVW(440)
C FOR DC
      SODC1(S,K)=CAVSOD(1,440)
      INVDC1(S,K)=CAVGD(1,440)
      SERDC1(S,K)=SERVD(1,440)
      SODC2(S,K)=CAVSOD(2,440)
      INVDC2(S,K)=CAVGD(2,440)
      SERDC2(S,K)=SERVD(2,440)
C FOR R
      SOR1(S,K)=CAVSOR(1,440)
      INVR1(S,K)=CAVGR(1,440)
      SERR1(S,K)=SERVR(1,440)
      SOR2(S,K)=CAVSOR(2,440)
      INVR2(S,K)=CAVGR(2,440)
      SERR2(S,K)=SERVR(2,440)
```

```
      SOR3(S,K)=CAVSOR(3,440)
      INVR3(S,K)=CAVGR(3,440)
      SERR3(S,K)=SERVR(3,440)
      SOR4(S,K)=CAVSOR(4,440)
      INVR4(S,K)=CAVGR(4,440)
      SERR4(S,K)=SERVR(4,440)
      TRCSYSTEM(S,K)=CAVTRC(440)
    2 CONTINUE
    1 CONTINUE
*******************************************************************
*     SUMMARY REPORT                                              *
*******************************************************************
      OPEN(UNIT=2,FILE='SET16-6.DAT',STATUS='NEW')
      WRITE(2,894)((TRCSYSTEM(S,K),SOW(S,K),INVW(S,K),SERW(S,K),
     +SODC1(S,K),INVDC1(S,K),SERDC1(S,K),SODC2(S,K),INVDC2(S,K),
     +SERDC2(S,K),SOR1(S,K),INVR1(S,K),SERR1(S,K),SOR2(S,K),INVR2(S,K)
     +,SERR2(S,K),SOR3(S,K),INVR3(S,K),SERR3(S,K),SOR4(S,K),INVR4(S,K)
     +,SERR4(S,K),K=1,5),S=1,8)
      CLOSE(2)
  894 FORMAT(1X,22F8.3)
      END
C
      FUNCTION RAND( )
      SAVE SEED
      INTEGER SEED,C1,C2,C3
      PARAMETER (C1=29,C2=217,C3=2**22)
      REAL RAND
      DATA SEED/1/
      SEED=MOD(SEED*C1+C2,C3)
      RAND=REAL(SEED)/C3
      END
C
C
      FUNCTION XNORMAL()
      REAL U1,U2,V1,V2,W
   10 U1=RAND( )
      U2=RAND( )
      V1=2*U1-1
      V2=2*U2-1
      W=(V1*V1)+(V2*V2)
      IF (W.GT.1) GOTO 10
      XNORMAL=(-2*LOG(W)/W)**0.5*V2
      END
C
      FUNCTION LT1( )
      REAL X
      X=RAND()
      IF(X.LE.0.2) THEN
      LT1=1
      ELSE IF(X.LE.0.4) THEN
      LT1=2
      ELSE IF(X.LE.0.6) THEN
      LT1=3
      ELSE IF(X.LE.0.8) THEN
      LT1=4
      ELSE IF(X.LE.1.0) THEN
      LT1=5
      END IF
      END
C
```

```
C
      FUNCTION LT2( )
      REAL X
      X=RAND()
      IF(X.LE.0.1) THEN
      LT2=1
      ELSE IF(X.LE.0.2) THEN
      LT2=2
      ELSE IF(X.LE.0.8) THEN
      LT2=3
      ELSE IF(X.LE.0.9) THEN
      LT2=4
      ELSE IF(X.LE.1.0) THEN
      LT2=5
      END IF
      END
```

```
      PROGRAM INIT3
************************************************************************
*     THIS IS A PROGRAM WITH 5 REPS, 4 SAFETY STOCK POLICIES,          *
*     USING L4L WITH WARMUP PERIOD 40 WEEKS ( TWO LEVELS)              *
************************************************************************
      INTEGER FDR(4,500)
      INTEGER ADR(4,500)
      INTEGER LTR(4,500),ARW(500)
      REAL ARRATE(500)
      REAL AVGINV(2,4,500)
      REAL VAW,VAR
      REAL CC,SC,OC
      REAL CV
      REAL TRC(500),TRCW(500),TRCR(4,500),TRCSUM,
     +     CAVTRC(500)
      REAL INSUMW,INSUMR(4)
      REAL CAVGW(500),CAVGR(4,500)
      REAL CAVGRW(500),CAVGRR(4,500)
      REAL SERVW(500),SERVR(4,500)
      REAL SOSUMW,SOSUMR(4)
      REAL GRSUMW,GRSUMR(4)
      REAL CAVSOW(500),CAVSOR(4,500)
      REAL SOW(4,5),INVW(4,5),SERW(4,5)
      REAL SOR1(4,5)
      REAL INVR1(4,5),SERR1(4,5),SOR2(4,5),INVR2(4,5),SERR2(4,5)
      REAL SOR3(4,5),INVR3(4,5),SERR3(4,5),SOR4(4,5),INVR4(4,5)
      REAL SERR4(4,5),TRCSYSTEM(4,5)
      INTEGER SO(2,4,500)
      INTEGER GR(2,4,500),TRANSIT(2,4,500),PAB(2,4,0:500)
      INTEGER NR(2,4,500),PR(2,4,500),PS(2,4,500)
      INTEGER SS(2,4)
      DATA VAW/1.0/,VAR/1.21/
      DATA CC/0.002/,SC/0.1/,OC/30.0/
      DATA CV/0.05/
C
C INPUT SAFETY STOCK POLICY
      DO 1 S=1,4
      IF(S.EQ.1) GOTO 201
      IF(S.EQ.2) GOTO 202
      IF(S.EQ.3) GOTO 203
      IF(S.EQ.4) GOTO 204
  201 SS(1,1)=0
      SS(1,2)=0
      SS(1,3)=0
      SS(1,4)=0
      SS(2,1)=0
      GOTO 333
 202  SS(1,1)=0
      SS(1,2)=0
      SS(1,3)=0
      SS(1,4)=0
      SS(2,1)=300
      GOTO 333
 203  SS(1,1)=30
      SS(1,2)=60
      SS(1,3)=90
      SS(1,4)=120
      SS(2,1)=0
      GOTO 333
```

```
 204  SS(1,1)=15
      SS(1,2)=30
      SS(1,3)=45
      SS(1,4)=60
      SS(2,1)=150
C
 333  DO 2 K=1,5
      DO 101 P=1,2
      DO 102 J=1,4
      DO 103 Q=1,500
       GR(P,J,Q)=0
       TRANSIT(P,J,Q)=0
       PAB(P,J,Q)=0
       NR(P,J,Q)=0
       PR(P,J,Q)=0
       PS(P,J,Q)=0
  103 CONTINUE
  102 CONTINUE
  101 CONTINUE
      INSUMW=0.0
      INSUMR(1)=0.0
      INSUMR(2)=0.0
      INSUMR(3)=0.0
      INSUMR(4)=0.0
C
      SOSUMW=0.0
      SOSUMR(1)=0.0
      SOSUMR(2)=0.0
      SOSUMR(3)=0.0
      SOSUMR(4)=0.0
C
      GRSUMW=0.0
      GRSUMR(1)=0.0
      GRSUMR(2)=0.0
      GRSUMR(3)=0.0
      GRSUMR(4)=0.0
C
      TRCSUM=0.0
C
      DO 5 T=1,500
      FDR(1,T)=NINT(XNORMAL()*10)+50
      FDR(2,T)=NINT(XNORMAL()*20)+100
      FDR(3,T)=NINT(XNORMAL()*30)+150
      FDR(4,T)=NINT(XNORMAL()*40)+200
      ADR(1,T)=MAX(FDR(1,T)+NINT(XNORMAL()*30),0)
      ADR(2,T)=MAX(FDR(2,T)+NINT(XNORMAL()*30),0)
      ADR(3,T)=MAX(FDR(3,T)+NINT(XNORMAL()*30),0)
      ADR(4,T)=MAX(FDR(4,T)+NINT(XNORMAL()*30),0)
      ARRATE(T)=MAX(1-ABS(XNORMAL( ))*CV,0.0)
      LTR(1,T)=LT2()
      LTR(2,T)=LT2()
      LTR(3,T)=LT2()
      LTR(4,T)=LT2()
    5 CONTINUE
**************************************************************
*             THIS PART IS DRP I (INFORMATION FLOW)          *
**************************************************************
C INPUT FORECAST REQUIREMENT FOR R1,R2,R3,R4
C
      DO 15 T=1,500
```

```
      GR(1,1,T)=FDR(1,T)
      GR(1,2,T)=FDR(2,T)
      GR(1,3,T)=FDR(3,T)
      GR(1,4,T)=FDR(4,T)
   15 CONTINUE
C INPUT FIRST SIX IN-TRANSIT AT R1,R2,R3,R4
      DO 22 T=1,6
      TRANSIT(1,1,T)=FDR(1,T)
      TRANSIT(1,2,T)=FDR(2,T)
      TRANSIT(1,3,T)=FDR(3,T)
      TRANSIT(1,4,T)=FDR(4,T)
   22 CONTINUE
C CALCULATE NET REQUIREMENT FOR R1,R2,R3,R4
      DO 13 L=1,450
      DO 23 J=1,4
      PAB(1,J,0)=SS(1,J)
      DO 33 T=L,L+11
      IF(T.LE.L+5) THEN
       NR(1,J,T)=0
       PR(1,J,T)=NR(1,J,T)
       PAB(1,J,T)=MAX(PAB(1,J,T-1)+TRANSIT(1,J,T)-GR(1,J,T),0)
      ELSE
       NR(1,J,T)=MAX(GR(1,J,T)+SS(1,J)-PAB(1,J,T-1)-TRANSIT(1,J,T),0)
       PR(1,J,T)=NR(1,J,T)
       PAB(1,J,T)=MAX(PAB(1,J,T-1)+PR(1,J,T)+TRANSIT(1,J,T)-GR(1,J,T),0)
       PS(1,J,T-6)=PR(1,J,T)
       END IF
   33 CONTINUE
   23 CONTINUE
C CALCULATE THE FORECAST REQUIREMENT AT W
      DO 51 T=L,L+5
      GR(2,1,T)=PS(1,1,T)+PS(1,2,T)+PS(1,3,T)+PS(1,4,T)
   51 CONTINUE
C CALCULATE NET REQUIREMENT FOR W
      IF(L.GT.1) GOTO 20
      TRANSIT(2,1,1)=GR(2,1,1)
      TRANSIT(2,1,2)=GR(2,1,2)
      TRANSIT(2,1,3)=GR(2,1,3)
      PAB(2,1,0)=SS(2,1)
   20 DO 52 T=L,L+5
      IF(T.LE.L+2) THEN
       NR(2,1,T)=0
       PR(2,1,T)=NR(2,1,T)
       PAB(2,1,T)=MAX(PAB(2,1,T-1)+TRANSIT(2,1,T)-GR(2,1,T),0)
      ELSE
       NR(2,1,T)=MAX(GR(2,1,T)+SS(2,1)-PAB(2,1,T-1)-TRANSIT(2,1,T),0)
       PR(2,1,T)=NR(2,1,T)
       PAB(2,1,T)=MAX(PAB(2,1,T-1)+PR(2,1,T)+TRANSIT(2,1,T)-GR(2,1,T),0)
       PS(2,1,T-3)=PR(2,1,T)
       END IF
   52 CONTINUE
*************************************************************
*             THIS PART IS DRP II (PHYSICAL FLOW)           *
*************************************************************
C CALCULATE THE ACTUAL RECEIPT FROM VENDOR AT WAREHOUSE &
C ACTUAL SHIPMENT TO R1,R2,R3,R4,
      ARW(L)=NINT(TRANSIT(2,1,L)*ARRATE(L))
      IF ((PAB(2,1,L-1)+ARW(L)).GE.GR(2,1,L)) THEN
       TRANSIT(1,1,L+LTR(1,L))=PS(1,1,L)+TRANSIT(1,1,L+LTR(1,L))
       TRANSIT(1,2,L+LTR(2,L))=PS(1,2,L)+TRANSIT(1,2,L+LTR(2,L))
```

```
       TRANSIT(1,3,L+LTR(3,L))=PS(1,3,L)+TRANSIT(1,3,L+LTR(3,L))
       TRANSIT(1,4,L+LTR(4,L))=PS(1,4,L)+TRANSIT(1,4,L+LTR(4,L))
      ELSE
       TRANSIT(1,1,L+LTR(1,L))=NINT((PAB(2,1,L-1)+ARW(L))*
     + (PS(1,1,L)/(GR(2,1,L)*1.0)))+TRANSIT(1,1,L+LTR(1,L))
       TRANSIT(1,2,L+LTR(2,L))=NINT((PAB(2,1,L-1)+ARW(L))*
     + (PS(1,2,L)/(GR(2,1,L)*1.0)))+TRANSIT(1,2,L+LTR(2,L))
       TRANSIT(1,3,L+LTR(3,L))=NINT((PAB(2,1,L-1)+ARW(L))*
     + (PS(1,3,L)/(GR(2,1,L)*1.0)))+TRANSIT(1,3,L+LTR(3,L))
       TRANSIT(1,4,L+LTR(4,L))=NINT((PAB(2,1,L-1)+ARW(L))*
     + (PS(1,4,L)/(GR(2,1,L)*1.0)))+TRANSIT(1,4,L+LTR(4,L))
      END IF
C
C UPDATE THE PORJECTED AVAILABLE BALANCE AT R1,R2,R3,R4,W
C & IN-TRANSIT AT W
C
      PAB(1,1,L)=MAX((PAB(1,1,L-1)+TRANSIT(1,1,L)-ADR(1,L)),0)
      PAB(1,2,L)=MAX((PAB(1,2,L-1)+TRANSIT(1,2,L)-ADR(2,L)),0)
      PAB(1,3,L)=MAX((PAB(1,3,L-1)+TRANSIT(1,3,L)-ADR(3,L)),0)
      PAB(1,4,L)=MAX((PAB(1,4,L-1)+TRANSIT(1,4,L)-ADR(4,L)),0)
      PAB(2,1,L)=MAX((PAB(2,1,L-1)+ARW(L)-GR(2,1,L)),0)
      TRANSIT(2,1,L+3)=PS(2,1,L)
**********************************************************************
*     THIS PART IS STAT: COLLECT THE PERFORMANCE MEASURE             *
**********************************************************************
C CALCULATE THE AVERAGE INVENTORY ,STOCKOUT AND SERVICE LEVEL AT W
C
      IF(L.LE.40) GOTO 13
      SO(2,1,L)=MAX(GR(2,1,L)-(PAB(2,1,L-1)+ARW(L)),0)
      SOSUMW=SOSUMW+SO(2,1,L)
      CAVSOW(L)=SOSUMW/(L-40)
C
      AVGINV(2,1,L)=((PAB(2,1,L-1)+ARW(L))+MAX(PAB(2,1,L-1)+ARW(L)-
     +               GR(2,1,L),0))/2.0
      INSUMW=INSUMW+AVGINV(2,1,L)
      CAVGW(L)=INSUMW/(L-40)
      GRSUMW=GRSUMW+GR(2,1,L)
      CAVGRW(L)=GRSUMW/(L-40)
      SERVW(L)=1-(CAVSOW(L)/CAVGRW(L))
C CALCULATE THE AVERAGE INVENTORY AND STOCKOUT AT R1,R2,R3,R4
      DO 62 J=1,4
      SO(1,J,L)=MAX(ADR(J,L)-(PAB(1,J,L-1)+TRANSIT(1,J,L)),0)
      SOSUMR(J)=SOSUMR(J)+SO(1,J,L)
      CAVSOR(J,L)=SOSUMR(J)/(L-40)
      AVGINV(1,J,L)=((PAB(1,J,L-1)+TRANSIT(1,J,L))+MAX(PAB(1,J,L-1)+
     +              TRANSIT(1,J,L)-ADR(1,L),0))/2.0
      INSUMR(J)=INSUMR(J)+AVGINV(1,J,L)
      CAVGR(J,L)=INSUMR(J)/(L-40)
      GRSUMR(J)=GRSUMR(J)+GR(1,J,L)
      CAVGRR(J,L)=GRSUMR(J)/(L-40)
      SERVR(J,L)=1-(CAVSOR(J,L)/CAVGRR(J,L))
   62 CONTINUE
C
C UPDATE THE PORJECTED AVAILABLE BALANCE AT R1,R2,R3,R4,W
C & IN-TRANSIT AT W
C
      PAB(1,1,L)=MAX((PAB(1,1,L-1)+TRANSIT(1,1,L)-ADR(1,L)),0)
      PAB(1,2,L)=MAX((PAB(1,2,L-1)+TRANSIT(1,2,L)-ADR(2,L)),0)
      PAB(1,3,L)=MAX((PAB(1,3,L-1)+TRANSIT(1,3,L)-ADR(3,L)),0)
      PAB(1,4,L)=MAX((PAB(1,4,L-1)+TRANSIT(1,4,L)-ADR(4,L)),0)
```

```
      PAB(2,1,L)=MAX((PAB(2,1,L-1)+ARW(L)-GR(2,1,L)),0)
      TRANSIT(2,1,L+3)=PS(2,1,L)
C
C CALCULATE THE TOTAL RELATED COST AT PERIOD T
C
C TOTAL COST AT W
      IF (PS(2,1,L).GT.0) THEN
       OC=20.0
      ELSE
       OC=0.0
      END IF
      TRCW(L)=(SO(2,1,L)*SC+AVGINV(2,1,L)*CC+OC)*VAW
C
C TOTAL COST AT R
      DO 73 J=1,4
      IF (PS(1,J,L).GT.0) THEN
       OC=20.0
      ELSE
       OC=0.0
      END IF
      TRCR(J,L)=(SO(1,J,L)*SC+AVGINV(1,J,L)*CC+OC)*VAR
   73 CONTINUE
C
C TOTAL COST FOR THE WHOLE SYSTEM
      TRC(L)=(TRCW(L)+TRCR(1,L)+TRCR(2,L)+TRCR(3,L)+TRCR(4,L))
      TRCSUM=TRCSUM+TRC(L)
      CAVTRC(L)=TRCSUM/(L-40)
   13 CONTINUE
C
C  SUMMARY REPORT AT W,R FOR EACH REP IN EACH PERFORMANCE MEASURE:
C  AVG STOCKOUT, AVG INVENTORY AND SERVICE LEVEL
C
      SOW(S,K)=CAVSOW(440)
      INVW(S,K)=CAVGW(440)
      SERW(S,K)=SERVW(440)
C FOR R
      SOR1(S,K)=CAVSOR(1,440)
      INVR1(S,K)=CAVGR(1,440)
      SERR1(S,K)=SERVR(1,440)
      SOR2(S,K)=CAVSOR(2,440)
      INVR2(S,K)=CAVGR(2,440)
      SERR2(S,K)=SERVR(2,440)
      SOR3(S,K)=CAVSOR(3,440)
      INVR3(S,K)=CAVGR(3,440)
      SERR3(S,K)=SERVR(3,440)
      SOR4(S,K)=CAVSOR(4,440)
      INVR4(S,K)=CAVGR(4,440)
      SERR4(S,K)=SERVR(4,440)
      TRCSYSTEM(S,K)=CAVTRC(440)
    2 CONTINUE
    1 CONTINUE
*****************************************************************
*     SUMMARY REPORT                                            *
*****************************************************************
      OPEN(UNIT=2,FILE='SET4-7.DAT',STATUS='NEW')
      WRITE(2,894)((TRCSYSTEM(S,K),SOW(S,K),INVW(S,K),SERW(S,K)
     +,SOR1(S,K),INVR1(S,K),SERR1(S,K),SOR2(S,K),INVR2(S,K)
     +,SERR2(S,K),SOR3(S,K),INVR3(S,K),SERR3(S,K),SOR4(S,K),INVR4(S,K)
     +,SERR4(S,K),K=1,5),S=1,4)
      CLOSE(2)
```

```
  894 FORMAT(1X,16F8.3)
      END
C
C
      FUNCTION RAND( )
      SAVE SEED
      INTEGER SEED,C1,C2,C3
      PARAMETER (C1=29,C2=217,C3=2**18)
      REAL RAND
      DATA SEED/1/
      SEED=MOD(SEED*C1+C2,C3)
      RAND=REAL(SEED)/C3
      END
C
C
      FUNCTION XNORMAL()
      REAL U1,U2,V1,V2,W
   10 U1=RAND( )
      U2=RAND( )
      V1=2*U1-1
      V2=2*U2-1
      W=(V1*V1)+(V2*V2)
      IF (W.GT.1) GOTO 10
      XNORMAL=(-2*LOG(W)/W)**0.5*V2
      END
C
C
      FUNCTION LT1( )
      REAL X
      X=RAND()
      IF(X.LE.0.2) THEN
      LT1=2
      ELSE IF(X.LE.0.4) THEN
      LT1=4
      ELSE IF(X.LE.0.6) THEN
      LT1=6
      ELSE IF(X.LE.0.8) THEN
      LT1=8
      ELSE IF(X.LE.1.0) THEN
      LT1=10
      END IF
      END
C
C
      FUNCTION LT2( )
      REAL X
      X=RAND()
      IF(X.LE.0.1) THEN
      LT2=2
      ELSE IF(X.LE.0.2) THEN
      LT2=4
      ELSE IF(X.LE.0.8) THEN
      LT2=6
      ELSE IF(X.LE.0.9) THEN
      LT2=8
      ELSE IF(X.LE.1.0) THEN
      LT2=10
      END IF
      END
```

APPENDIX B.

RESULTS OF SERVICE LEVEL ANALYSIS IN THE BASE EXPERIMENT

Table B1. ANOVA Results for Mean SERW per Week

Analysis of Variance for Mean SERW

Source	DF	SS	MS	F	P
L.R.	1	29.1910	29.1910	7589.26	0.000
D.U.	1	0.0711	0.0711	18.49	0.000
L.T.	1	0.0187	0.0187	4.87	0.028
S.U.	1	0.3959	0.3959	102.93	0.000
C.V.	1	0.0639	0.0639	16.62	0.000
S.S.	7	50.2795	7.1828	1867.42	0.000
L.R.*D.U.	1	0.0945	0.0945	24.56	0.000
L.R.*L.T.	1	0.3133	0.3133	81.45	0.000
L.R.*S.U.	1	0.0512	0.0512	13.32	0.000
L.R.*C.V.	1	0.0639	0.0639	16.62	0.000
L.R.*S.S.	7	33.4791	4.7827	1243.44	0.000
D.U.*L.T.	1	0.0212	0.0212	5.50	0.019
D.U.*S.U.	1	0.0077	0.0077	2.00	0.158
D.U.*C.V.	1	0.0127	0.0127	3.29	0.070
D.U.*S.S.	7	0.0412	0.0059	1.53	0.154
L.T.*S.U.	1	0.0301	0.0301	7.82	0.005
L.T.*C.V.	1	0.0281	0.0281	7.31	0.007
L.T.*S.S.	7	0.0587	0.0084	2.18	0.034
S.U.*C.V.	1	0.0039	0.0039	1.01	0.315
S.U.*S.S.	7	0.1747	0.0250	6.49	0.000
C.V.*S.S.	7	0.0622	0.0089	2.31	0.024
L.R.*D.U.*L.T.	1	0.0299	0.0299	7.78	0.005
L.R.*D.U.*S.U.	1	0.0052	0.0052	1.36	0.243
L.R.*D.U.*C.V.	1	0.0127	0.0127	3.29	0.070
L.R.*D.U.*S.S.	7	0.0409	0.0058	1.52	0.157
L.R.*L.T.*S.U.	1	0.0091	0.0091	2.35	0.125
L.R.*L.T.*C.V.	1	0.0281	0.0281	7.31	0.007
L.R.*L.T.*S.S.	7	0.1372	0.0196	5.09	0.000
L.R.*S.U.*C.V.	1	0.0039	0.0039	1.01	0.315
L.R.*S.U.*S.S.	7	0.0953	0.0136	3.54	0.001
L.R.*C.V.*S.S.	7	0.0622	0.0089	2.31	0.024
D.U.*L.T.*S.U.	1	0.0000	0.0000	0.01	0.931
D.U.*L.T.*C.V.	1	0.0017	0.0017	0.45	0.501
D.U.*L.T.*S.S.	7	0.0515	0.0074	1.91	0.064
D.U.*S.U.*C.V.	1	0.0004	0.0004	0.11	0.740
D.U.*S.U.*S.S.	7	0.0251	0.0036	0.93	0.481
D.U.*C.V.*S.S.	7	0.0494	0.0071	1.84	0.077
L.T.*S.U.*C.V.	1	0.0027	0.0027	0.70	0.402
L.T.*S.U.*S.S.	7	0.0676	0.0097	2.51	0.015
L.T.*C.V.*S.S.	7	0.0408	0.0058	1.52	0.158
S.U.*C.V.*S.S.	7	0.0144	0.0021	0.54	0.807
L.R.*D.U.*L.T.*S.U.	1	0.0002	0.0002	0.05	0.820
L.R.*D.U.*L.T.*C.V.	1	0.0017	0.0017	0.45	0.501
L.R.*D.U.*L.T.*S.S.	7	0.0539	0.0077	2.00	0.052
L.R.*D.U.*S.U.*C.V.	1	0.0004	0.0004	0.11	0.740
L.R.*D.U.*S.U.*S.S.	7	0.0266	0.0038	0.99	0.438
L.R.*D.U.*C.V.*S.S.	7	0.0494	0.0071	1.84	0.077
L.R.*L.T.*S.U.*C.V.	1	0.0027	0.0027	0.70	0.402
L.R.*L.T.*S.U.*S.S.	7	0.0291	0.0042	1.08	0.373
L.R.*L.T.*C.V.*S.S.	7	0.0408	0.0058	1.52	0.158
L.R.*S.U.*C.V.*S.S.	7	0.0144	0.0021	0.54	0.807
D.U.*L.T.*S.U.*C.V.	1	0.0122	0.0122	3.17	0.075
D.U.*L.T.*S.U.*S.S.	7	0.0176	0.0025	0.65	0.711
D.U.*L.T.*C.V.*S.S.	7	0.0714	0.0102	2.65	0.010
D.U.*S.U.*C.V.*S.S.	7	0.0235	0.0034	0.87	0.528
L.T.*S.U.*C.V.*S.S.	7	0.0395	0.0056	1.47	0.175
L.R.*D.U.*L.T.*S.U.*C.V.	1	0.0122	0.0122	3.17	0.075
L.R.*D.U.*L.T.*S.U.*S.S.	7	0.0178	0.0025	0.66	0.706
L.R.*D.U.*L.T.*C.V.*S.S.	7	0.0714	0.0102	2.65	0.010
L.R.*D.U.*S.U.*C.V.*S.S.	7	0.0235	0.0034	0.87	0.528
L.R.*L.T.*S.U.*C.V.*S.S.	7	0.0395	0.0056	1.47	0.175
D.U.*L.T.*S.U.*C.V.*S.S.	7	0.0073	0.0010	0.27	0.965
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	0.0073	0.0010	0.27	0.965
Error	1024	3.9387	0.003		
Total	1279	119.6421			

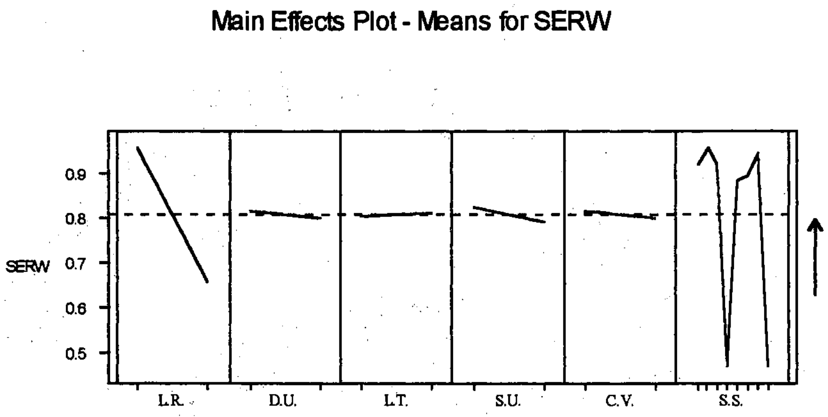

Figure B1. Main Effects Plot for Mean SERW

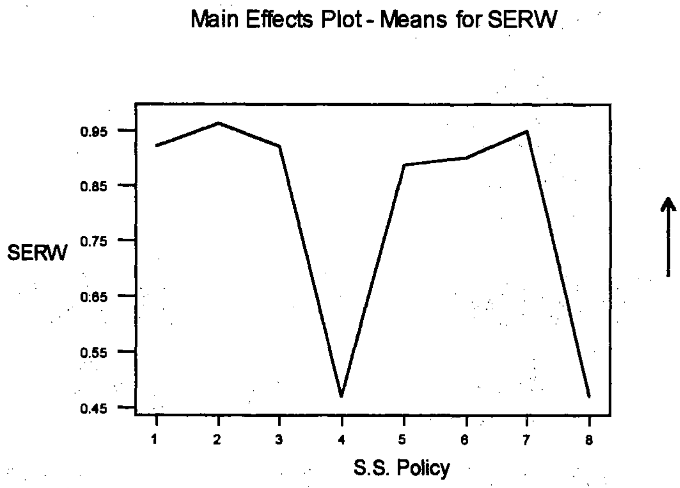

Figure B2. Means Plot for SERW as a Function of Safety Stock Policy

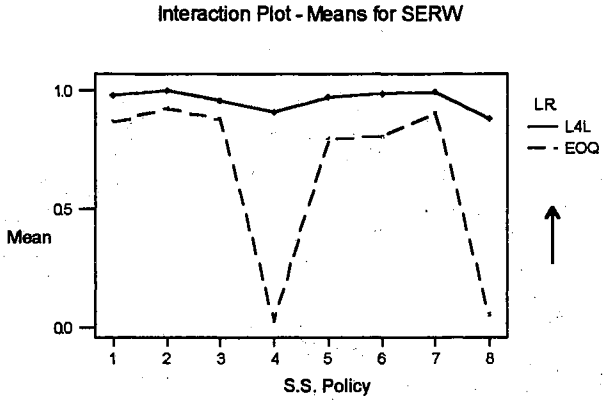

Figure B3. Means Plot for SERW as a Fuction of Lot-sizing Rule and Safety Stock Policy

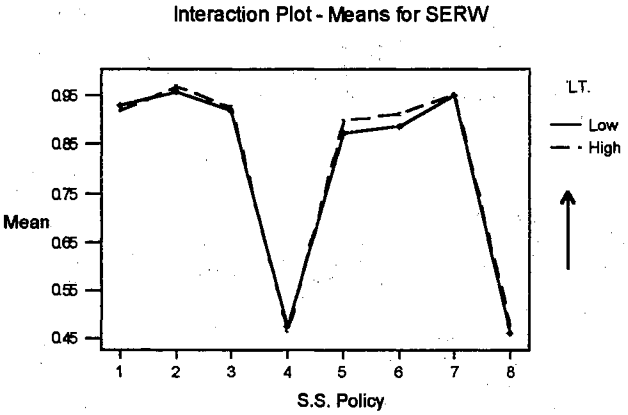

Figure B4. Means Plot for SERW as a Function of Lead Time Uncertainty and Safety Stock Policy

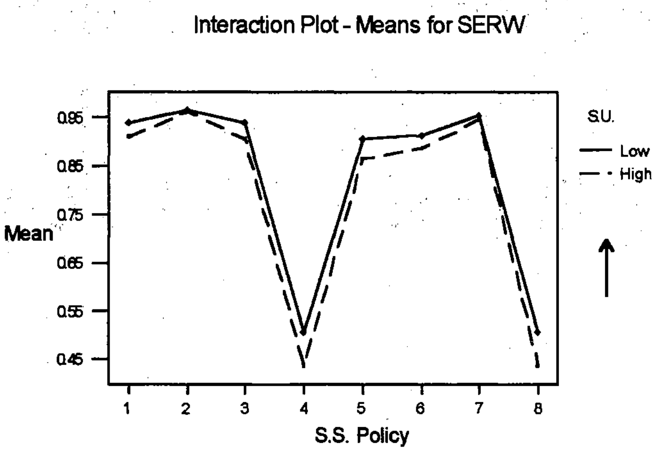

Figure B5. Means Plot for SERW as a Function of Supply Uncertainty and Safety Stock Policy

Table B2. ANOVA Results for Mean SERDC1 per Week

Analysis of Variance for Mean SERDC1

Source	DF	SS	MS	F	P
L.R.	1	60.7026	60.7026	2980.26	0.000
D.U.	1	0.9934	0.9934	48.77	0.000
L.T.	1	1.1182	1.1182	54.90	0.000
S.U.	1	0.1710	0.1710	8.40	0.004
C.V.	1	0.2639	0.2639	12.96	0.000
S.S.	7	30.6892	4.3842	215.25	0.000
L.R.*D.U.	1	1.3954	1.3954	68.51	0.000
L.R.*L.T.	1	0.2942	0.2942	14.44	0.000
L.R.*S.U.	1	0.0137	0.0137	0.67	0.412
L.R.*C.V.	1	0.2639	0.2639	12.96	0.000
L.R.*S.S.	7	27.5642	3.9377	193.33	0.000
D.U.*L.T.	1	0.1661	0.1661	8.15	0.004
D.U.*S.U.	1	0.0186	0.0186	0.91	0.339
D.U.*C.V.	1	0.0602	0.0602	2.96	0.086
D.U.*S.S.	7	0.7914	0.1131	5.55	0.000
L.T.*S.U.	1	0.0820	0.0820	4.03	0.045
L.T.*C.V.	1	0.0252	0.0252	1.23	0.267
L.T.*S.S.	7	0.1568	0.0224	1.10	0.361
S.U.*C.V.	1	0.0119	0.0119	0.58	0.445
S.U.*S.S.	7	0.1125	0.0161	0.79	0.597
C.V.*S.S.	7	0.2323	0.0332	1.63	0.123
L.R.*D.U.*L.T.	1	0.2184	0.2184	10.72	0.001
L.R.*D.U.*S.U.	1	0.0218	0.0218	1.07	0.301
L.R.*D.U.*C.V.	1	0.0602	0.0602	2.96	0.086
L.R.*D.U.*S.S.	7	0.8374	0.1196	5.87	0.000
L.R.*L.T.*S.U.	1	0.0243	0.0243	1.19	0.275
L.R.*L.T.*C.V.	1	0.0252	0.0252	1.23	0.267
L.R.*L.T.*S.S.	7	0.1448	0.0207	1.02	0.418
L.R.*S.U.*C.V.	1	0.0119	0.0119	0.58	0.445
L.R.*S.U.*S.S.	7	0.0695	0.0099	0.49	0.844
L.R.*C.V.*S.S.	7	0.2323	0.0332	1.63	0.123
D.U.*L.T.*S.U.	1	0.0309	0.0309	1.52	0.218
D.U.*L.T.*C.V.	1	0.0013	0.0013	0.07	0.799
D.U.*L.T.*S.S.	7	0.2932	0.0419	2.06	0.046
D.U.*S.U.*C.V.	1	0.0007	0.0007	0.03	0.852
D.U.*S.U.*S.S.	7	0.1999	0.0286	1.40	0.201
D.U.*C.V.*S.S.	7	0.2410	0.0344	1.69	0.108
L.T.*S.U.*C.V.	1	0.0170	0.0170	0.83	0.361
L.T.*S.U.*S.S.	7	0.1243	0.0178	0.87	0.528
L.T.*C.V.*S.S.	7	0.2603	0.0372	1.83	0.079
S.U.*C.V.*S.S.	7	0.0467	0.0067	0.33	0.942
L.R.*D.U.*L.T.*S.U.	1	0.0342	0.0342	1.68	0.196
L.R.*D.U.*L.T.*C.V.	1	0.0013	0.0013	0.07	0.799
L.R.*D.U.*L.T.*S.S.	7	0.3116	0.0445	2.19	0.033
L.R.*D.U.*S.U.*C.V.	1	0.0007	0.0007	0.03	0.852
L.R.*D.U.*S.U.*S.S.	7	0.1942	0.0277	1.36	0.218
L.R.*D.U.*C.V.*S.S.	7	0.2410	0.0344	1.69	0.108
L.R.*L.T.*S.U.*C.V.	1	0.0170	0.0170	0.83	0.361
L.R.*L.T.*S.U.*S.S.	7	0.1195	0.0171	0.84	0.556
L.R.*L.T.*C.V.*S.S.	7	0.2603	0.0372	1.83	0.079
L.R.*S.U.*C.V.*S.S.	7	0.0467	0.0067	0.33	0.942
D.U.*L.T.*S.U.*C.V.	1	0.0618	0.0618	3.04	0.082
D.U.*L.T.*S.U.*S.S.	7	0.1883	0.0269	1.32	0.237
D.U.*L.T.*C.V.*S.S.	7	0.1616	0.0231	1.13	0.339
D.U.*S.U.*C.V.*S.S.	7	0.1238	0.0177	0.87	0.531
L.T.*S.U.*C.V.*S.S.	7	0.0630	0.0090	0.44	0.876
L.R.*D.U.*L.T.*S.U.*C.V.	1	0.0618	0.0618	3.04	0.082
L.R.*D.U.*L.T.*S.U.*S.S.	7	0.1826	0.0261	1.28	0.256
L.R.*D.U.*L.T.*C.V.*S.S.	7	0.1616	0.0231	1.13	0.339
L.R.*D.U.*S.U.*C.V.*S.S.	7	0.1238	0.0177	0.87	0.531
L.R.*L.T.*S.U.*C.V.*S.S.	7	0.0630	0.0090	0.44	0.876
D.U.*L.T.*S.U.*C.V.*S.S.	7	0.0530	0.0076	0.37	0.919
L.R.*D.U.*L.T.*S.U.*C.V.*S.S.	7	0.0530	0.0076	0.37	0.919
Error	1024	20.8571	0.0204		
Total	1279	151.3686			

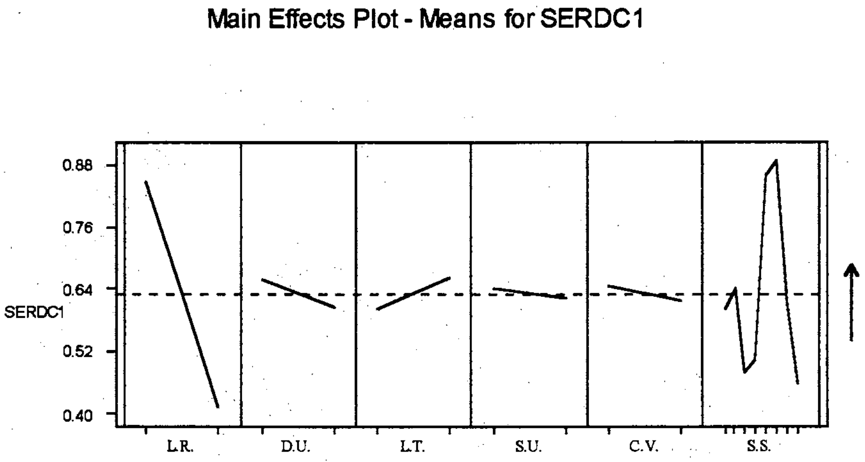

Figure B6. Main Effects Plot for Mean SERDC1

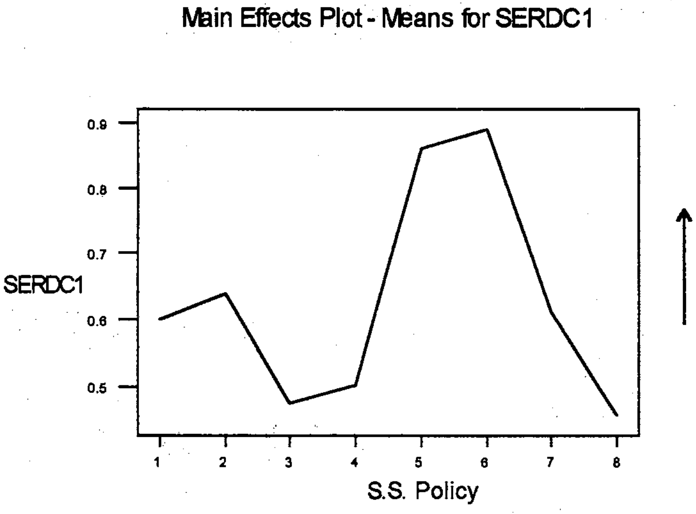

Figure B7. Means Plot for SERDC1 as a Function of Safety Stock Policy

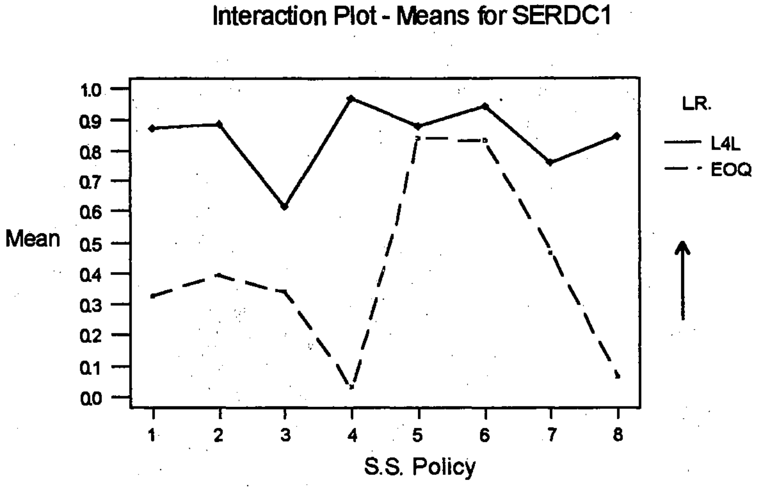

Figure B8. Means Plot for SERDC1 as a Function of Lot-sizing Rule and Safety Stock Policy

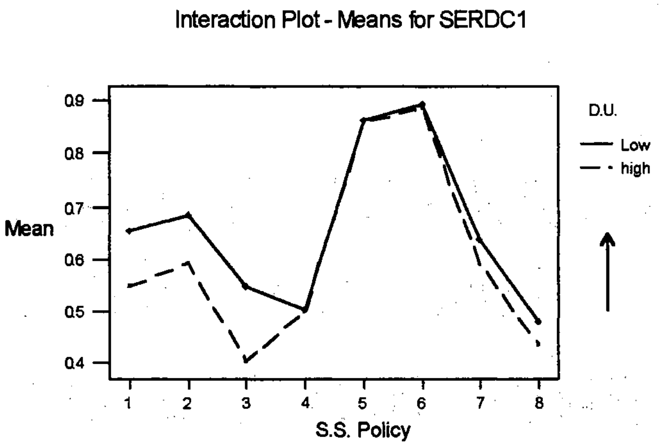

Figure B9. Means Plot for SERDC1 as a Function of Lead Time Uncertainty and Safety Stock Policy

Table B3. ANOVA Results for Mean SERR1 per Week

```
                Analysis of Variance for Mean SERR1

 Source                                DF         SS         MS       F       P
 L.R.                                   1    1.72563    1.72563   48.42   0.000
 D.U.                                   1    2.31523    2.31523   64.96   0.000
 L.T.                                   1    2.33210    2.33210   65.43   0.000
 S.U.                                   1    0.13534    0.13534    3.80   0.052
 C.V.                                   1    0.85140    0.85140   23.89   0.000
 S.S.                                   7   28.66195    4.09456  114.88   0.000
 L.R.*D.U.                              1    0.77333    0.77333   21.70   0.000
 L.R.*L.T.                              1    0.00910    0.00910    0.26   0.614
 L.R.*S.U.                              1    0.04963    0.04963    1.39   0.238
 L.R.*C.V.                              1    0.85140    0.85140   23.89   0.000
 L.R.*S.S.                              7   29.63416    4.23345  118.78   0.000
 D.U.*L.T.                              1    0.10253    0.10253    2.88   0.090
 D.U.*S.U.                              1    0.02413    0.02413    0.68   0.411
 D.U.*C.V.                              1    0.01268    0.01268    0.36   0.551
 D.U.*S.S.                              7    1.11152    0.15879    4.46   0.000
 L.T.*S.U.                              1    0.11598    0.11598    3.25   0.072
 L.T.*C.V.                              1    0.03640    0.03640    1.02   0.312
 L.T.*S.S.                              7    0.37419    0.05346    1.50   0.163
 S.U.*C.V.                              1    0.01518    0.01518    0.43   0.514
 S.U.*S.S.                              7    0.27136    0.03877    1.09   0.369
 C.V.*S.S.                              7    0.68860    0.09837    2.76   0.008
 L.R.*D.U.*L.T.                         1    0.04023    0.04023    1.13   0.288
 L.R.*D.U.*S.U.                         1    0.03009    0.03009    0.84   0.358
 L.R.*D.U.*C.V.                         1    0.01268    0.01268    0.36   0.551
 L.R.*D.U.*S.S.                         7    1.36096    0.19442    5.46   0.000
 L.R.*L.T.*S.U.                         1    0.07601    0.07601    2.13   0.144
 L.R.*L.T.*C.V.                         1    0.03640    0.03640    1.02   0.312
 L.R.*L.T.*S.S.                         7    0.39283    0.05612    1.57   0.139
 L.R.*S.U.*C.V.                         1    0.01518    0.01518    0.43   0.514
 L.R.*S.U.*S.S.                         7    0.17788    0.02541    0.71   0.661
 L.R.*C.V.*S.S.                         7    0.68860    0.09837    2.76   0.008
 D.U.*L.T.*S.U.                         1    0.03987    0.03987    1.12   0.290
 D.U.*L.T.*C.V.                         1    0.00316    0.00316    0.09   0.766
 D.U.*L.T.*S.S.                         7    0.58556    0.08365    2.35   0.022
 D.U.*S.U.*C.V.                         1    0.00023    0.00023    0.01   0.935
 D.U.*S.U.*S.S.                         7    0.28689    0.04098    1.15   0.329
 D.U.*C.V.*S.S.                         7    0.39005    0.05572    1.56   0.143
 L.T.*S.U.*C.V.                         1    0.02867    0.02867    0.80   0.370
 L.T.*S.U.*S.S.                         7    0.18024    0.02575    0.72   0.653
 L.T.*C.V.*S.S.                         7    0.39805    0.05686    1.60   0.133
 S.U.*C.V.*S.S.                         7    0.10277    0.01468    0.41   0.895
 L.R.*D.U.*L.T.*S.U.                    1    0.04541    0.04541    1.27   0.259
 L.R.*D.U.*L.T.*C.V.                    1    0.00316    0.00316    0.09   0.766
 L.R.*D.U.*L.T.*S.S.                    7    0.58575    0.08368    2.35   0.022
 L.R.*D.U.*S.U.*C.V.                    1    0.00023    0.00023    0.01   0.935
 L.R.*D.U.*S.U.*S.S.                    7    0.28768    0.04110    1.15   0.327
 L.R.*D.U.*C.V.*S.S.                    7    0.39005    0.05572    1.56   0.143
 L.R.*L.T.*S.U.*C.V.                    1    0.02867    0.02867    0.80   0.370
 L.R.*L.T.*S.U.*S.S.                    7    0.18775    0.02682    0.75   0.627
 L.R.*L.T.*C.V.*S.S.                    7    0.39805    0.05686    1.60   0.133
 L.R.*S.U.*C.V.*S.S.                    7    0.10277    0.01468    0.41   0.895
 D.U.*L.T.*S.U.*C.V.                    1    0.06472    0.06472    1.82   0.178
 D.U.*L.T.*S.U.*S.S.                    7    0.18935    0.02705    0.76   0.622
 D.U.*L.T.*C.V.*S.S.                    7    0.48140    0.06877    1.93   0.062
 D.U.*S.U.*C.V.*S.S.                    7    0.16752    0.02393    0.67   0.696
 L.T.*S.U.*C.V.*S.S.                    7    0.13842    0.01977    0.55   0.793
 L.R.*D.U.*L.T.*S.U.*C.V.               1    0.06472    0.06472    1.82   0.178
 L.R.*D.U.*L.T.*S.U.*S.S.               7    0.18722    0.02675    0.75   0.629
 L.R.*D.U.*L.T.*C.V.*S.S.               7    0.48140    0.06877    1.93   0.062
 L.R.*D.U.*S.U.*C.V.*S.S.               7    0.16752    0.02393    0.67   0.696
 L.R.*L.T.*S.U.*C.V.*S.S.               7    0.13842    0.01977    0.55   0.793
 D.U.*L.T.*S.U.*C.V.*S.S.               7    0.16004    0.02286    0.64   0.722
 L.R.*D.U.*L.T.*S.U.*C.V.*S.S.          7    0.16004    0.02286    0.64   0.722
Error                                1024   36.49640    0.03564
Total                                1279  115.86491
```

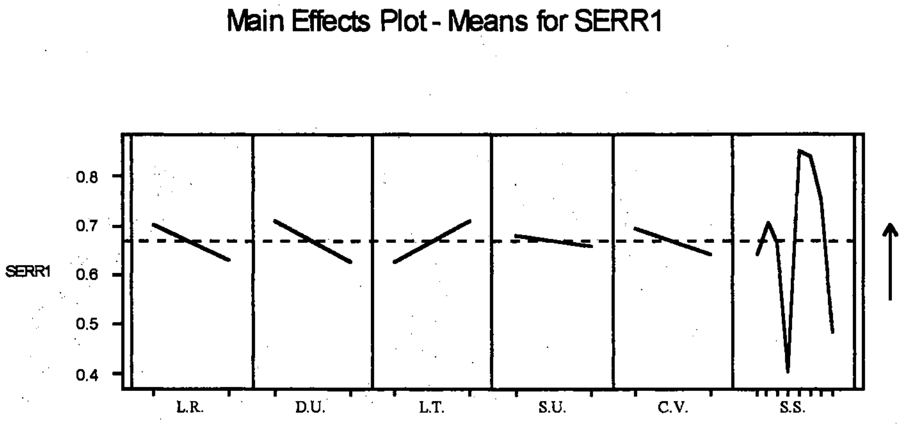

Figure B10. Main Effects Plot for Mean SERR1

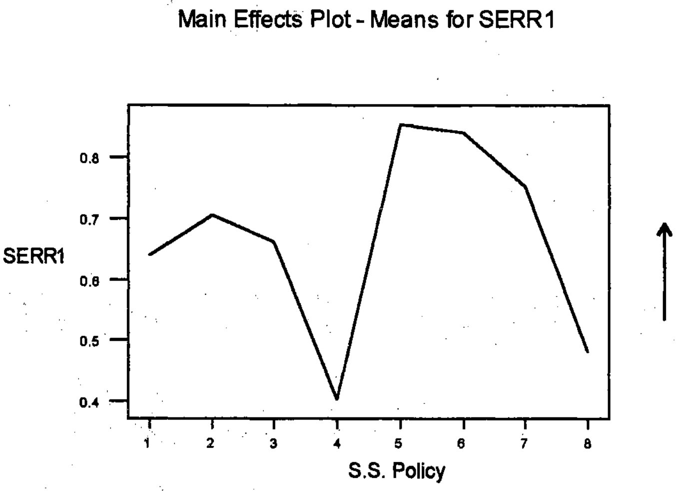

Figure B11. Means Plot for SERR1 as a Function of Safety Stock Policy

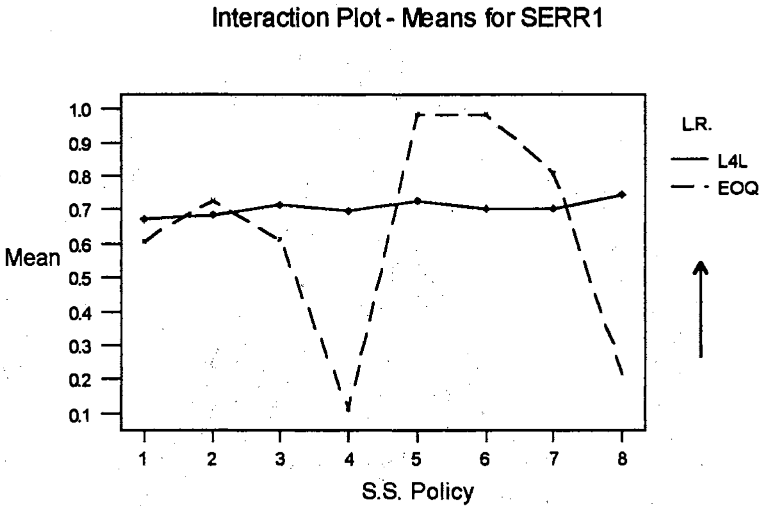

Figure B12. Means Plot for SERR1 as a Function of Lot-sizing Rule and Safety Stock Policy

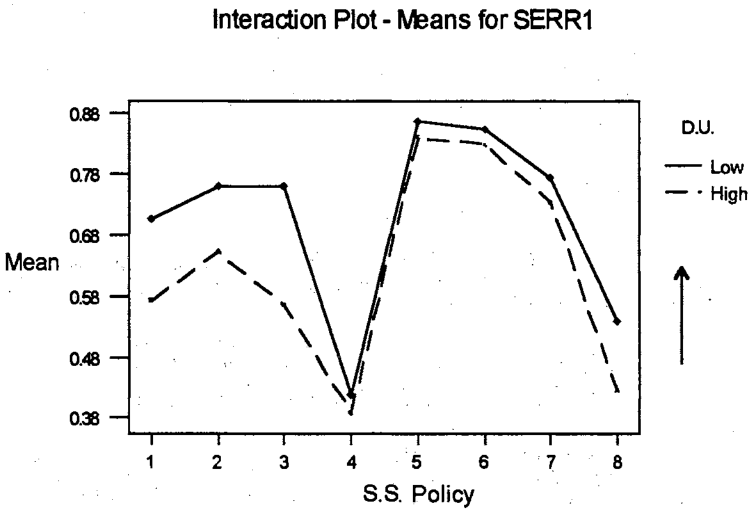

Figure B13. Means Plot for SERR1 as a Function of Demand Uncertainty and Safety Stock Policy

APPENDIX C.

RESULTS OF STOCKOUT ANALYSIS AND INVENTORY LEVEL ANALYSIS WHEN CHANGING DISTRIBUTION NETWORK

Table C1. ANOVA Results for Average SOW When Changing Distribution Network

```
               Analysis of Variance for Average SOW

Source                     DF          SS          MS         F        P
L.R.                        1      252464      252464     14.89    0.000
D.U.                        1           1           1      0.00    0.993
L.T.                        1      145476      145476      8.58    0.004
S.S.                        3     1340682      446894     26.35    0.000
L.R.*D.U.                   1         169         169      0.01    0.921
L.R.*L.T.                   1      125143      125143      7.38    0.008
L.R.*S.S.                   3      178099       59366      3.50    0.017
D.U.*L.T.                   1       32107       32107      1.89    0.171
D.U.*S.S.                   3       52069       17356      1.02    0.385
L.T.*S.S.                   3       76337       25446      1.50    0.218
L.R.*D.U.*L.T.              1       34502       34502      2.03    0.156
L.R.*D.U.*S.S.              3       48736       16245      0.96    0.415
L.R.*L.T.*S.S.              3       99623       33208      1.96    0.124
D.U.*L.T.*S.S.              3       42917       14306      0.84    0.472
L.R.*D.U.*L.T.*S.S.         3       46169       15390      0.91    0.439
Error                     128     2170703       16959
Total                     159     4645199
```

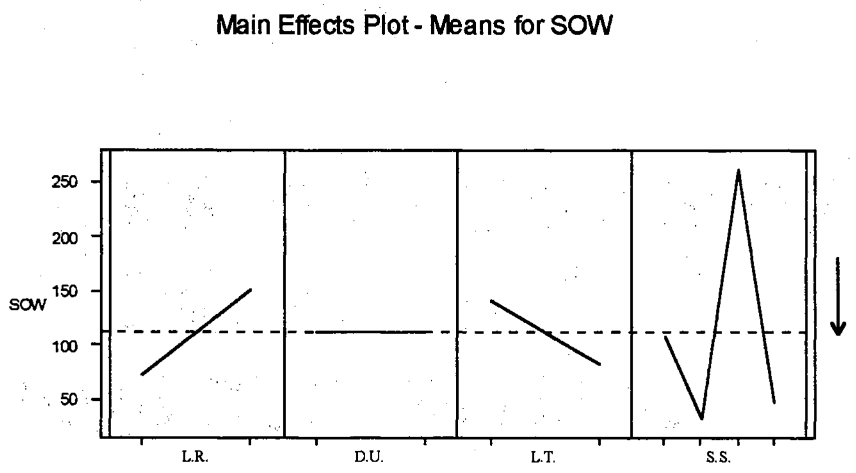

Figure C1. Main Effects Plot for Average SOW When Changing Distribution Network

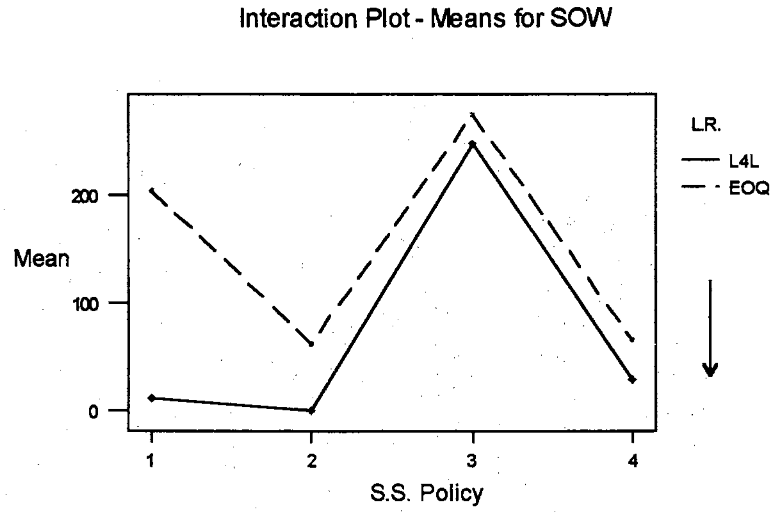

Figure C2. Means Plot for SOW as a Function of Lot-Sizing Rule and Safety Stock Policy When Changing Distribution Network

Table C2. ANOVA Results for Average SOR1 When Changing Distribution Network

```
             Analysis of Variance for Average SOR1

Source                  DF        SS         MS       F       P
L.R.                     1   4229.27    4229.27 2851.69   0.000
D.U.                     1     40.88      40.88   27.57   0.000
L.T.                     1    240.41     240.41  162.10   0.000
S.S.                     3    140.10      46.70   31.49   0.000
L.R.*D.U.                1      9.83       9.83    6.63   0.011
L.R.*L.T.                1    129.69     129.69   87.45   0.000
L.R.*S.S.                3     68.19      22.73   15.33   0.000
D.U.*L.T.                1      8.88       8.88    5.99   0.016
D.U.*S.S.                3      3.50       1.17    0.79   0.503
L.T.*S.S.                3      2.86       0.95    0.64   0.589
L.R.*D.U.*L.T.           1      0.03       0.03    0.02   0.886
L.R.*D.U.*S.S.           3      1.62       0.54    0.36   0.780
L.R.*L.T.*S.S.           3      3.20       1.07    0.72   0.543
D.U.*L.T.*S.S.           3      6.45       2.15    1.45   0.231
L.R.*D.U.*L.T.*S.S.      3      9.52       3.17    2.14   0.098
Error                  128    189.83       1.48
Total                  159   5084.27
```

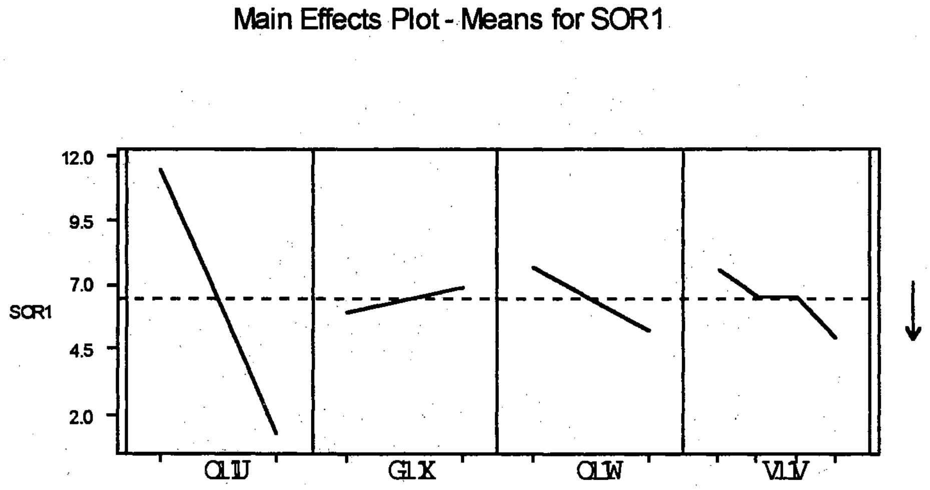

Figure C3. Main Effects Plot for Average SOR1 When Changing Distribution Network

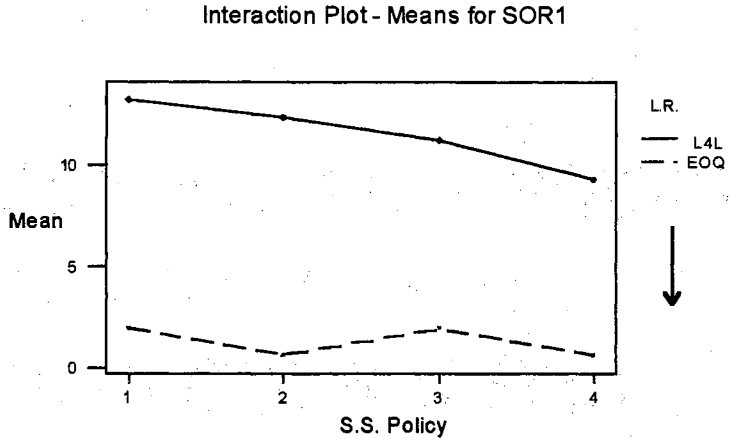

Figure C4. Means Plot for SOR1 as a Function of Lot-Sizing Rule and Safety Stock Policy When Changing Distribution Network

Table C3. ANOVA Results for Average INVW When Changing Distribution Network

```
                    Analysis of Variance for Average INVW

Source                     DF         SS          MS        F        P
L.R.                        1   86627390    86627390  7815.19    0.000
D.U.                        1      25490       25490     2.30    0.132
L.T.                        1     328678      328678    29.65    0.000
S.S.                        3   11992676     3997559   360.64    0.000
L.R.*D.U.                   1      33618       33618     3.03    0.084
L.R.*L.T.                   1     257311      257311    23.21    0.000
L.R.*S.S.                   3    5420900     1806967   163.02    0.000
D.U.*L.T.                   1          2           2     0.00    0.989
D.U.*S.S.                   3      46432       15477     1.40    0.247
L.T.*S.S.                   3     483781      161260    14.55    0.000
L.R.*D.U.*L.T.              1        288         288     0.03    0.872
L.R.*D.U.*S.S.              3      40837       13612     1.23    0.302
L.R.*L.T.*S.S.              3     500897      166966    15.06    0.000
D.U.*L.T.*S.S.              3      29611        9870     0.89    0.448
L.R.*D.U.*L.T.*S.S.         3      28401        9467     0.85    0.467
Error                     128    1418815       11084
Total                     159  107235125
```

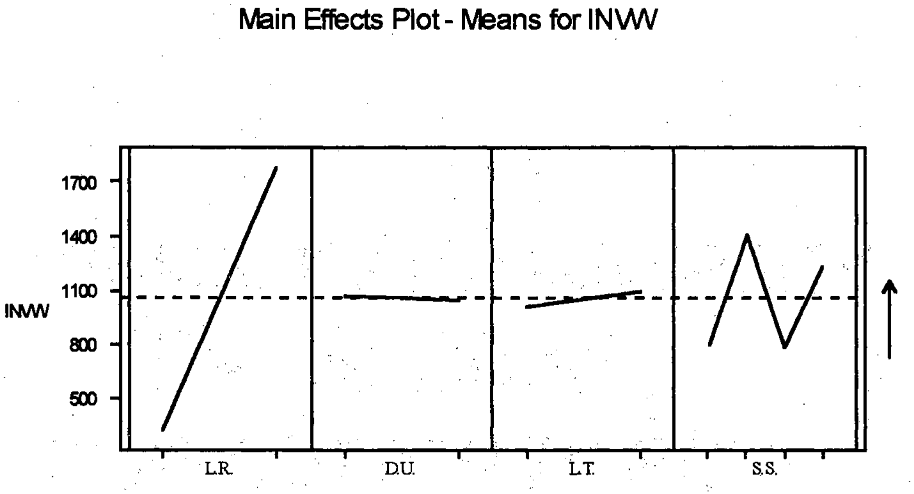

Figure C5. Main Effects Plot for Average INVW When Changing Distribution Network

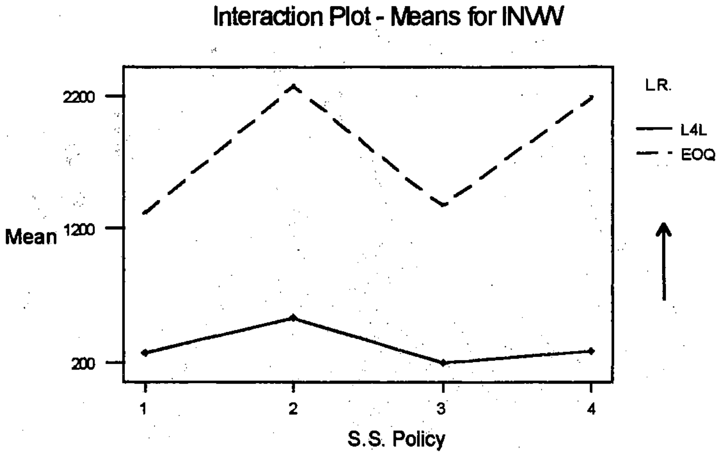

Figure C6. Means Plot for INVW as a Function of Lot-Sizing Rule and Safety Stock Policy When Changing Distribution Network

Table C4. ANOVA Results for Average INVR1 When Changing Distribution Network

```
                Analysis of Variance for Average INVR1

Source                DF        SS          MS        F       P
L.R.                   1  27852608    27852608  5350.47   0.000
D.U.                   1      2701        2701     0.52   0.473
L.T.                   1    137474      137474    26.41   0.000
S.S.                   3    154659       51553     9.90   0.000
L.R.*D.U.              1     13273       13273     2.55   0.113
L.R.*L.T.              1    151694      151694    29.14   0.000
L.R.*S.S.              3    129185       43062     8.27   0.000
D.U.*L.T.              1     17195       17195     3.30   0.071
D.U.*S.S.              3      4903        1634     0.31   0.815
L.T.*S.S.              3     77630       25877     4.97   0.003
L.R.*D.U.*L.T.         1     15647       15647     3.01   0.085
L.R.*D.U.*S.S.         3      5232        1744     0.34   0.800
L.R.*L.T.*S.S.         3     77240       25747     4.95   0.003
D.U.*L.T.*S.S.         3      7619        2540     0.49   0.691
L.R.*D.U.*L.T.*S.S.    3      7402        2467     0.47   0.701
Error                128    666322        5206
Total                159  29320783
```

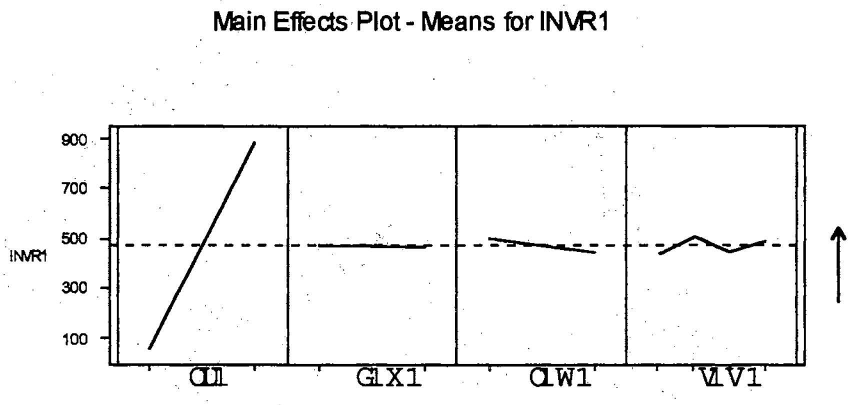

Figure C7. Main Effects Plot for Average INVR1 When Changing Distribution Network

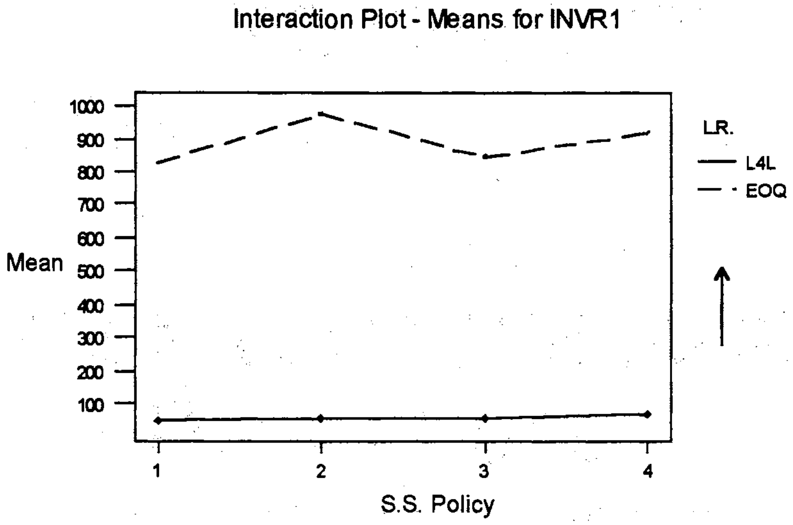

Figure C8. Means Plot for INVR1 as a Function of Lot-Sizing Rule and Safety Stock Policy When Changing Distribution Network

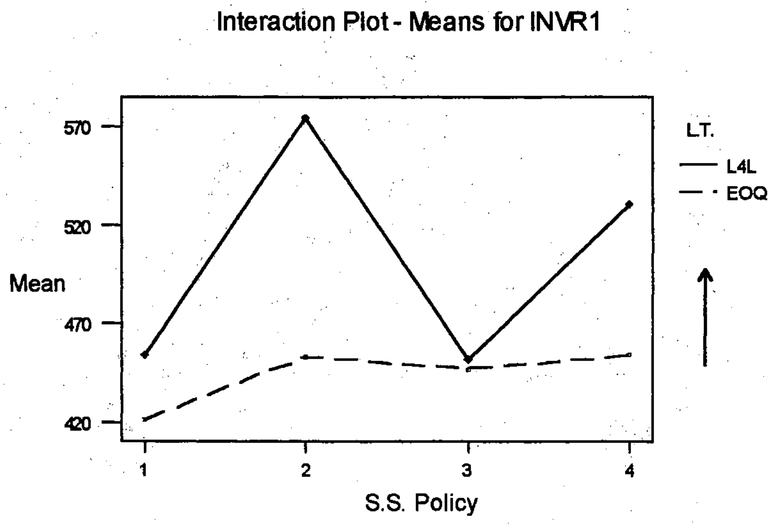

Figure C9. Means Plot for INVR1 as a Function of Lead Time Uncertainty and Safety Stock Policy When Changing Distribution Network

VITA

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