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THE EFFECT OF ALTERNATIVE BUFFERING TECHNIQUES TO PROTECT A MULTI-PRODUCT, MULTI-STAGE PRODUCTION INVENTORY SYSTEM AGAINST SUPPLY-UNCERTAINTY

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THE EFFECT OF ALTERNATIVE BUFFERING TECHNIQUES TO PROTECT A MULTI-PRODUCT, MULTI-STAGE PRODUCTION INVENTORY SYSTEM AGAINST SUPPLY UNCERTAINTY.

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

Business Administration

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ABSTRACT

This research has been an experimental investigation of some of the operational aspects of a hypothetical multiproduct, multistage production inventory system operating in a supply uncertainty environment.

The main objective of this study was to explore the relative effect of different multilevel buffering strategies on system performance in order to establish some guidelines for choosing among different buffering techniques when buffering the system against different conditions of supply uncertainty. Several performance criteria, including holding cost, inventory cost, total cost, number of shortages, number of stockouts, service level and buffering cost effectiveness, were used to evaluate system performance.

The independent variables investigated include: buffering strategy (6 strategies), type of supply uncertainty (4 levels), and degree of supply uncertainty (4 levels). Five replications were generated for each of the 96 cells in the three-factor, full factorial experimental design. The main effect for each factor and the interaction effect for different combinations were considered.

Results show that performance of the production system is significantly influenced by the "buffering strategy" factor, although the relative impact of the six buffering strategies is dependent on the performance measure considered. The study also shows that both uncertainty type (quantity and timing) and uncertainty level (high and low) have significant impact on system performance. Moreover, interaction between buffering strategy and either uncertainty type or uncertainty level, were also found to be important in several cases. Overall, this research provides empirical evidence that both supply uncertainty type and level are significant decision variables regarding the selection of an appropriate buffering strategy.

CHAPTER ONE

INTRODUCTION

When manufacturing a complicated product, it is often a problem to get the appropriate number of materials made (or purchased) and ready at the right time to assemble into the end or final product.

Materials Requirements Planning (MRP) has been introduced as a means of approaching this problem. Such a system (sometimes called "time phased requirements planning") embodies a logic designed expressly for companies with assembled products whose parts and raw materials have a demand that is, for the most part, dependent upon the demand for the finished goods. When demand for items is derived from plans to make certain products, as it is in the case of raw materials, parts, and subassemblies which are used in producing a finished product, those items are said to have dependent demand. Conversely, demand for a finished product is independent in the sense that it cannot be based on demand for some higher-level item. MRP is a set of procedures and decision rules designed to determine requirements of inventoried items, as to both quantity and timing, on all levels below the end product. Most of the developmental work on MRP was done by Joseph Orlicky, Oliver Wright, and George Plossl (34, 47, 59) and through the support of the American Production and Inventory Control Society (46). Today these methods are widely used in computer based production and inventory planning and control systems associated with hierarchial, multistage production process (18).

Description of the Problem

As an explosion-based system, MRP derives the demand for dependent items from a master production schedule that projects finished goods production into the future. The exploding process is simply a multiplication of the number of end items by the quantity of each component required to produce a single end item. The explosion identifies what components are required, as well as how many, to produce a given number of end items as specified in the master production schedule. Because the master schedule reflects the planned production of finished goods, the MRP system, ideally, must determine only the true and exact requirements of inventory component items. Though it is possible to operate a requirements planning system on the basis of no buffering or safety stock, uncertainty from various sources typically requires the use of some buffering strategy to avoid disruption of the production process.

There are at least two types of uncertainty with which the MRP system must be able to cope: demand uncertainty and supply uncertainty. Demand uncertainty occurs when the master schedule is increased or decreased to reflect changes in the quantity and/or timing of customer orders or other factors affecting production requirements. This will cause changes in lower level items' requirements. The second source of uncertainty is supply uncertainty which originates from variations in the supply schedule. The time required for processing and filling component orders by an internal supplier is variable because of such factors as delays and breakdowns. In addition, the actual quantity delivered from production is variable because of scrap losses or shortages of lower level materials. Outside purchases are also subject to supply uncertainty. Orders from vendors are subject to uncertainty because of variability in both production and transportation times.

The problem of uncertainty is studied in detail in the classical inventory literature. A substantial body of knowledge exists on the use of safety stock as a buffering strategy in statistical inventory management system (Economic Lot Size/Reorder Point Systems) (for example see: 8, 26, 33, 54). In a very comprehensive article, Tersine (36) outlined the procedures available for developing safety stock levels under conditions of known and unknown stockout cost for discrete and continuous distributions of usage during lead time. These procedures are designed mainly for independent demand items with the assumption that demand is constant. Most dependent demand items in a multiechelon inventory structure exhibit "lumpy" demand patterns. This lumpiness occurs because most manufacturing is in lots and all items needed to produce the lots are usually withdrawn from inventory at the same time, not unit by unit. A major assumption upon which conventional inventory control models are based (constant demand) is violated, thus such inventory systems are not readily applicable in these cases. If one attempts to adapt the use of this type of system by employing average demand rate, unexpected stockouts of components occur because of the lumped nature of the requirements, which upsets assembly schedules.

On the other hand, there has been little research on how to protect manufactured parts, subassemblies, or final assemblies against demand and supply uncertainties in a production system using MRP technique. In 1975, New (41) reported that there has been little reference to the problem of setting safety stock levels in MRP systems. After about eight years, it seems that this is still the case especially if the problem of different buffering strategies is considered.

Most of the research in this area has been limited to the use of safety stocks as the only technique available to protect the production process against uncertainty. This type of research might be considered as an extension of the classical inventory analysis, using mostly mathematical and statistical techniques. Researchers have not considered some of the other buffering alternatives that might be used in an MRP system to protect against uncertainty. New (41) introduced three methods available to protect the system against both supply and demand uncertainty. These are fixed quantity buffer, safety lead time, and increased master schedule. Whybark and Williams (58) mentioned that to protect the part against uncertainty, several alternatives are available, varying from inventory oriented buffering techniques to frequent replanning with sufficient capacity and flexibility to accommodate the new plans. In their study, however, they restricted their attention to evaluating two inventory oriented buffering techniques: safety lead time and safety stock.

Another major shortcoming in this area of research is that only demand uncertainty has received much attention (for example see: 4, 11, 19, 35, 39, 42). The use of some demand forecasting techniques was always introduced as a way of reducing demand uncertainty (21, 42). The effect of end-item demand variability and uncertainty on the production system performance and lot size selection has also been mentioned in the literature (11, 12). On the other hand, supply uncertainty has not received an equal research effort and study in spite of the fact that supply uncertainty is anticipated to be a common factor in the future. Buffa (9) expresses it as follows:

> ".... materials will become more and more scarce. Good operations management may be the result of managing with scarce or uncertain supply ....
>
> .... If the environment were to change so that uncertainty of supply were a common factor, then the focus of operations management would also need to change."

The need for a comprehensive study of this problem has frequently been mentioned. In a rather comprehensive survey of the problem, New (41) reported that little guidance has been offered to the manager in selecting a buffering procedure appropriate to his operating environment. In 1976, Whybark and Williams (59) stated that a systematic study to provide guidelines for the use of safety stock or safety lead time is required. Therefore, the theme of this research is to study the effect of different multilevel (joint) buffering techniques when used to protect a multistate production-inventory system against quantity and timing supply uncertainty in an MRP system. A joint buffering strategy as used in this study is a combination of different buffering techniques (safety stock and safety lead time) applied to different levels of the product structure. A joint uncertainty, on the other hand, will indicate a combination of different types (quantity, timing) and levels (high, low) of supply uncertainty applied to different levels of product structure. This study will attempt to accomplish two objectives:

(1) Provide some insights into the behavior of a production-inventory system facing different conditions of supply uncertainty when using different buffering strategies. Therefore, exploring the relative effect of different joint (multilevel) buffering strategies on the performance of a production-inventory system will be possible.

(2) Establish some guidelines for choosing among different buffering techniques when buffering the system against different combinations of supply uncertainty types and levels.

Scope and Limitations of this Research

This study is intended to provide new information concerning the applicability of joint buffering strategies in a multistage production-inventory system using MRP. Moreover, this study will contribute to the current body of knowledge by assessing the effects of various factors on the performance of a multiechelon production-inventory system. These are: (1) multilevel (joint) buffering strategies, (2) degree of supply uncertainty, and (3) type of supply uncertainty. The main effect for each factor and the interaction effect for different combinations will be considered for various system performance measures.

To protect the system against uncertainty, several alternatives are available as mentioned above. In this research only two inventory oriented buffering techniques, safety stock and safety lead time, are considered. Uncertainty of supply will be the only source of risk considered. Limiting the scope of this study in this manner allows concentration on the influence of different types and levels of supply uncertainty on the buffering strategies.

In this study, the literature most relevant to this research is reviewed in Chapter II. Methodological and technical aspects of the study are pointed out and attempts are made to resolve these issues in Chapter III. The main purpose of the chapter is to describe the simulation system that is used and the procedures that incorporate risk into the system at each inventory level. The statements of hypotheses and the procedures used to test these hypotheses are also provided. The results of these statistical tests are presented in Chapter IV. Analysis and discussion of the results are also included.

Chapter V summarizes the major results of these investigations and draws conclusions concerning the impact of system variables, the overall efficiency of buffering strategies, and the most appropriate strategy to buffer the system against supply uncertainty. Finally, a suggestion is made to extend the current research to more system variables.

CHAPTER II

REVIEW OF THE LITERATURE

There has been little empirical research on how to protect manufactured parts, components, subassemblies, or final assemblies against demand and supply uncertainties.

MRP advocates do not agree whether safety stock should be used in MRP. Those who oppose the use of safety stock in MRP argue that because MRP systems adapt to changing conditions that affect demand and lead times, safety stock will not actually be used under the vast majority of circumstances in MRP (23). Orlicky (43, p. 79) argues that an item safety stock forces the MRP system to overstate requirements which is undesirable and sometimes leads to distorted timing when the safety stock causes the net requirement to be pulled forward in time. This overstated requirement or false timing tends to cause confusion, unnecessary expense, and loss of credibility in the MRP system. Wight (59, p. 34) stated that an objective of MRP is to plan priorities effectively and safety stock tends to dilute priorities. Their message is clear: safety stock should have very limited role in MRP systems, appearing only at the finished product level or for items whose demand is not strictly derived from production schedules. Peterson and Silver (45, p. 474) also believe that it is more effective to avoid shortages and excess inventories through the adjustment of production lead times, these adjustments being accomplished by expediting or, more generally, shifting priorities of shop orders.

Outright elimination of any buffering policy for dependent demand items may not be the final answer in MRP. New (41) indicated that operating an MRP system on the basis of zero buffer stocks might cause some problems because of variations caused by uncertainty of demand and uncertainty of supply, both in terms of time and quantity, in the system. He also added that correction of actual stock errors elsewhere in the system as another cause of these variations. Stressing supply uncertainty, Buffa (10, p. 334) mentioned that buffer stock is required to absorb variations in supply schedule. He indicated that the time required for processing orders through an intermittent system is variable because of such factors as delays and breakdowns. Moreover, the actual quantity delivered from production is variable because of the scrap. Orlicky (43, p. 80) himself did not rule out completely the possibility of using safety stock under an MRP system. He stated that there is justification for carrying some safety stock of an item where the resupply performance is erratic and uncontrollable.

If timing and quantity supply uncertainty is inevitable for some items under MRP system, the question becomes: What is the best way to buffer the system against this uncertainty?

Safety stock is commonly used in the case of stock replenishment (independent demand systems) as a way of absorbing variations in demand and lead time. Under these systems, the reorder level is set to cover normal usage during the supply lead time plus the safety stock. Safety stock is computed on the basis of a demand distribution during the supply lead time for the item in question and the desired service level (see 8, 17, 25, 33, 61). Hadley and Whitin (26) in an early work, discussed most procedures available for developing safety stocks under conditions of known and unknown stockout cost for discrete and continuous demand distributions. These procedures are designed mainly for independent demand items.

As with the stock replenishment system, Plossl and Wight (59) stated that safety stocks are necessary also in material requirements planning to protect against demand variations for the end products and supply variations for components. They have discussed the available procedures and pointed to the need for more theoretical work to be done on developing a rational basis for setting safety stock levels.

Moore (39) discussed the use of safety stock with MRP. He explained the similarity between MRP and the two basic systems of inventory replenishment, fixed order and periodic ordering, to justify using the same methods in establishing safety stocks in both MRP and the other inventory systems. However, for an end-item with independent demand, under MRP, safety stock calculations must consider the cumulative lead time (CLT) for the item if its components are manufactured or purchased in discrete quantities dictated by higher level use. Failing to do so, as he said, will cause customer service to fall short of the desired goal, or priority changes, and/or emergency orders will be caused when the user attempts to replenish the safety stock at less than the cumulative lead time. His suggested system is simple: Calculate safety stock according to the maximum usage during the cumulative lead time and a desired service level, use safety stock to satisfy the surge in demand, replenish the safety stock at the cumulative lead time for the item.

Eichert (19) addressed the problem of demand uncertainty under MRP systems in a very special way. He suggested that most unplanned demand and master schedule errors may be treated as an independent requirement. These "other requirements" are field failures, non-productive demand, shop failures, rejected materials, vendor shortages, change notices, engineering changes, data errors, and pull-ins. He introduced a technique which may be applied as part of a material requirement planning system to account for these requirements. Field failure, non-productive demands, and pull-ins can be included in the master schedule by separate forecasts for each. Shop failures, rejected material, and vendor shortages can be predicted by determining the failure, rejection, or shortage rates for parts or vendors. On the other hand he recognized the difficulties of attacking change notices, engineering changes, and data errors. This practical approach of a separate forecast for each "other requirement", protects the system against uncertainty through the application of statistical inventory techniques to unexpected requirements.

New (41) pioneered the research on introducing safety factors into requirements plans. He discussed three methods available to protect the system against both supply and demand uncertainty. These are: fixed quantity buffers, safety times, and increased master production schedule. He pointed out some of the pitfalls associated with these methods. Fixed quantity buffer requires the implementation of a fairly complex system of checks to insure that buffer stock usage and replenishment are planned correctly. On the other hand, safety time as a buffer inflates both the length of the planning horizon required and the total composite lead time for a multi-level assembly. As for increasing the requirements forecasts used in the master schedule in terms of "scrap" or "yield loss" allowances, he indicated that it is superfluous when used at the finished item stage. Part of the reason for the buffer stock is to absorb such variation in production yield. Using these allowances for lower level components is also fairly critical to the performance of the system.

In an effort to offer some guidance in selecting an appropriate procedure, he concluded that particular procedures are appropriate only under specific circumstances. The safety time system is recommended on sparse schedules--lumpy demand--where production is infrequent, and also at the raw material level when items are purchased from outside the company. When using safety time, the projected stock vary widely from period to period. Therefore, when production is infrequent the safety time system adjusts much more quickly to scheduled production than would a fixed quantity buffer stock. Using the latter system under these circumstances means that the buffer quantity held all the time when only few orders per year will be made. On the other hand, using buffer stock at the finished item stage is appropriate. Using safety time in this case with its projected stock variations represents an uncertain level of "safety cover" for the schedule over time. Moreover, he suggested that combinations of methods be used under different circumstances. A safety time system may be used for raw materials and a fixed buffer for intermediate items in a company manufacturing for "call-off" schedules, while a company manufacturing solely for sales from finished stock might hold a fixed buffer at the highest level and a safety time for lower level items. Though this article does not offer any experimental results or any clear relationship between uncertainty types and levels, and different buffering factors, New does provide a theoretical basis for studying this problem.

Whybark and Williams (38) pioneered the experimental research on material planning under uncertainty. They disagree with the idea that safety stock should have a limited role in MRP systems. This position, as they said, assumed that sufficient production capacity and/or flexibility exists to absorb the results of changes that can occur when the MRP system is rerun each period. They argue that at some point this flexibility may not be sufficient.

In their study, uncertainty was categorized into four different categories: demand timing uncertainty, supply timing uncertainty, demand quantity uncertainty, and supply quantity uncertainty. The level of quantity uncertainty was measured by the standard deviation of the difference between projected inventory balance and actual inventory balance. Demand quantity uncertainty was measured in terms of the coefficient of variation of an items gross requirement. A uniform distribution, of the actual requirements around the projected gross requirement each period, was used to generate actual requirements. Similarly, the actual quantity received was assumed to be uniformly distributed around the quantity scheduled to be received for each order. On the other hand, demand timing uncertainty was introduced by interchanging gross requirements between periods while the exact timing of order arrival was generated by varying the scheduled arrival time by as much as ± 2 periods. Their simulation analysis focused on evaluating two inventory oriented buffering techniques, safety stock and safety lead time, for a single component item under each category of uncertainty. The relationship between the actual service level and average inventory was the criterion used to test the hypothesis that there would be a "preference" for either safety lead time or safety stock under each of the categories of uncertainty. In order to test the effect of demand variability of the gross requirements and the level of uncertainty on the preference between the buffering techniques, three levels of coefficient of variation and uncertainty were provided for each of the four uncertainty categories. They concluded that under conditions of uncertainty in timing, safety lead time is preferred, while safety stock is preferred under conditions of quantity uncertainty. After a number of validation runs, they concluded also that these effects did not change with the source of uncertainty (demand or supply), lot sizing technique, lead time, average demand level, uncertainty level, or coefficient of variation in their study. The study also indicated that as the coefficient of variation and uncertainty level increase, the importance of making the correct choice between safety stock and safety lead time increases.

This study represents a required step toward understanding the effect of uncertainty in MRP system. It provides a description of the behavior of a single part under different uncertainty conditions, which is a basis for understanding the whole system. It also provides a general guideline for choosing between the two buffering techniques: safety stock and safety lead time. However, it is difficult to generalize their results to any part when considering a multi-stage production-inventory system. Under such a system some additional factors must be considered. Some of these factors are the interaction of the buffering techniques, the different combinations of uncertainty environments, the different "joint" buffering techniques, and the performance of the whole system. This study also made no determination of how much safety stock or safety lead time should be used.

Banerjee (1) has studied the selection of different buffering techniques in an MRP system. He investigated several safety stock policies. The first policy has safety stocks provided for the finished products based on forecast error. The second policy has safety stocks provided for the finished products based on forecast error and for the raw materials based on supply uncertainty. The third policy has safety stocks provided at three levels with supply uncertainty buffered against at both intermediate and raw material levels. Although he claims that buffer inventories for the lower level items are automatically provided for during the process of product explosion and demand derivation at the lower levels, his first buffering technique turned out to be less efficient with a high stockout level according to his results. On the contrary, his results indicate that providing safety stocks for the finished products and raw materials turns out to be the best policy that considers all the uncertain input variables in the system. His conclusions, however, seem to support the conventional contention that safety must be provided only at the finished product and raw material levels if they should be allocated at different stages. Though his study is considered one of the few early empirical investigations of the problem of uncertainty in a multi-stage production environment, Banerjee used only demand uncertainty effect when calculating the required amounts of safety stock. This partially justifies not being able to generalize his results when supply uncertainty is considered. Moreover, the study was limited to only one buffering method, namely; providing safety stock, i.e. some other buffering methods, such as safety lead time, was not considered.

Callarman and Mabert (11) studied using material requirements planning systems with demand uncertainty. They provide a Service Level Decision Rule (SLDR) which might be used for estimating the amount of safety stock needed or the economic Time Between Orders (TBO) needed to gain a specified service level. This was done by mapping in a linear regression model service level performance against the independent variables of demand variation, forecast error, safety stock and TBO.

Then by solving this model once for safety stock or for TBO when safety stock equals zero, the two decision rules were developed. After testing the performance of the decision rules, they concluded that these decision rules do not give the exact amount of safety stock needed or the exact TBO needed to get the desired service levels. However, they give a good estimate of safety stock requirements to use as a starting point for further analysis.

Mehta (35) discussed how to handle safety stock in an MRP system. He explained some problems associated with deducting safety stock from on hand balance. He suggested another method in treating safety stock which may help to maintain valid priorities in the system. He recommended not to deduct safety stock from on hand balance, therefore making it available for use and to replenish safety stock in the very first period beyond aggregate lead time. In other words, companies must continuously use and plan safety stock.

Liaw (32) examined the effect of various safety stock policies in an MRP system that was subject to both demand and supply uncertainty. Nine different safety stock policies, derived from two heuristics, were studied. Heuristic A is based on the argument that total inventory risk can always be recognized by examining the difference between the actual requirement and the actual amount available for an end item. Therefore the required safety stock, for all items at any level, is a function of the average unforeseen inventory risk for the end items. This heuristic method resulted in three major safety stock policies. One is to install safety stock at the finished product level only. The second is to carry safety stock for work-in-process items only. The third is to carry it for raw materials only. Heuristic B on the other hand, suggested that various inventory risks at different inventory stages be treated separately which results in a policy that provides safety stocks for all items at all stages. Four more strategies were derived from heuristic B. One of them is to provide safety stock at all three levels but equal weights are assigned to the three levels, while the other strategies are using the safety stock of only two of the three levels with arbitrarily assigned equal weights at each level. Two other independent variables were used in this study to represent different operating conditions, namely inventory risk (degree of uncertainty) and cost structure.

The results of his study indicated that both of the structural variables (inventory stock and cost structure) may affect the performance of a safety stock policy on five selected criterion variables: number of stockouts, number of outages, inventory carrying cost, total cost and return on investment. Moreover, it was found that the interaction effect between inventory risk and cost structure was significant. This was interpreted to mean that these two factors should be considered together, rather than independently, to make the best use of safety stocks in a multi-stage or multi-product production-inventory system using MRP. In terms of any preference pattern that might exist among the buffering strategies, his results partially support the conventional contention that buffer stocks can be carried at finished product level only. This is only recommended where there is considerable inventory uncertainty involved at this level and the unit values of the items at other levels are sufficiently high. Otherwise, the strategy that provides buffers at all three levels become more desirable especially when there are high uncertainties involved at the lower levels.

In spite of the fact that this study is one of the few to consider using safety stock in MRP in a multi-stage and multi-product production-inventory system, some limiting aspects of this study are (1) only one type of supply uncertainty was studied, that is, quantity uncertainty, i.e., invariability of lead times was assumed, and (2) only various safety stock policies were considered without considering some other buffering techniques, like safety lead time.

Summary and Conclusions

A rather extensive review of the literature concerning the problem of protecting a multi-stage production system using MRP against demand and supply uncertainty has been presented. From this literature survey it is apparent that further systematic study needs to be accomplished incorporating more characteristics of multi-stage production systems. In the case of using MRP system, most of the buffering research to date has been limited to (1) the use of safety stock as the only buffering technique without considering some other inventory buffering techniques, like safety lead time (1, 7, 32), (2) the use of different buffering techniques for only a single "part" rather than studying a multi-stage production system (58), (3) buffering the system against different conditions of demand uncertainty only without considering supply uncertainty (11), and (4) considering quantity uncertainty as the only type of uncertainty in the system (32). Although these studies represent a required contribution toward the understanding of this problem, conclusions concerning the use of inventory buffering strategies under different types and levels of uncertainty in a multi-stage system have not been developed fully. This research hopefully adds to this body of knowledge.

A joint buffering strategy as used in this study is a combination of different buffering techniques (safety stock and safety lead time) applied to different levels of the product structure. Two different buffering techniques are used for purchased items level and in-process inventory level (this includes intermediate and end item levels) producing four buffering strategies. Two types of supply uncertainty, quantity and timing, are used at two levels, high and low, for each. Moreover, the idea of joint uncertainty is used in this study. It is a combination of different types and levels of supply uncertainty applied to different levels of the product structure. Therefore the performance of each buffering strategy is examined under different combinations of "joint" supply uncertainty. This point will be discussed in more depth in the next chapter dealing with experimental design.

CHAPTER III

RESEARCH METHODOLOGY

According to the research objectives described in Chapter I, and in light of the literature reviewed in Chapter II, additional aspects of the use of different buffering strategies in a multistage production system are explored in this research. In the case of multistage production system, multilevel conditions of supply uncertainty are relevant. Therefore the performance of the production system under different conditions of supply types and degrees of uncertainty is considered. Also, instead of applying a single buffering strategy at all levels of product structure, some proposed joint (multilevel) buffering strategies are evaluated.

Research Hypothesis

In order to investigate and study this problem a tentative set of null hypotheses of this research were developed:

Null Hypothesis No. 1 The buffering strategies (i.e., the joint buffering strategies defined earlier) have no effect on the system performance.

Null Hypothesis No. 2 Type of supply uncertainty has no effect on the system performance.

Null Hypothesis No. 3 Degree of supply uncertainty has no effect on the system performance.

Null Hypothesis No. 4 Type of supply uncertainty has no effect on the performance of the buffering strategies.

Null Hypothesis No. 5 Degree of supply uncertainty has no effect on the performance of the buffering strategies.

Null Hypothesis No. 6 No "preference" pattern exists for different buffering strategies.

System performance is measured using performance measures discussed in a later section of this chapter.

Experimental Design

In order to outline the experimental design to be adopted in this research, the various factors that are subject to experimental control and their levels are summarized in Table 3-1.

(1) Joint Buffering Strategies (B)

Two inventory oriented buffering techniques, safety stock (SS) and safety lead time (SLT), have been chosen to be examined in this study. The reason for selecting these techniques is two-fold. First, other techniques that rely on frequent MRP replanning and expediting assume that sufficient production capacity and/or flexibility exists. Sometimes this flexibility is not sufficient (58). There are some items where lead time actually is relatively fixed (42). Second, some of these selected techniques have been studied, to some extent, by previous researchers, therefore comparison of the results will be possible.

These selected buffering techniques are used, in conjunction with the product structure, to formulate the joint buffering strategies to be studied in this research. In order to reduce the potential number of combinations, the product structure levels were reduced to two. The "upper" level incorporates both end items and "intermediate" level items. The "lower" level includes raw materials and purchased items only. End items and intermediate components are made in-house, therefore they are similar from the view point of supply uncertainty. Because of the availability of information about production schedule and capacity

TABLE 3-1

SUMMARY OF EXPERIMENTAL FACTORS AND THEIR CLASSIFICATIONS*

Factor	Classification	Description
Buffering Strategy (B)	1	SS/SS
	2	SS/SLT
	3	SLT/SLT
	4	SLT/SS
	5	0/0
	6	SS/0
Type of Supply Uncertainty (T)	1	Timing uncertainty for both levels: T/T
	2	Quantity uncertainty for both levels: Q/Q
	3	Joint uncertainty 1: T/Q
	4	Joint uncertainty 2: Q/T
Degree of Supply Uncertainty (D)	1	High uncertainty for both levels: H/H
	2	Low uncertainty for both levels: L/L
	3	Mixed uncertainty 1: H/L
	4	Mixed uncertainty 2: L/H

*where:

0: no buffering, SS: safety stock strategy, SLT: safety lead time strategy, T: timing uncertainty, Q: quantity uncertainty, H: high uncertainty, and L: low uncertainty.

conditions for the internally produced items, it is assumed that management is able to control the situation, to some extent. This is not the case for raw materials and purchased items because most of the uncertainty factors are controlled by the outside vendors.

By applying safety stock (SS) and safety lead time (SLT) at both "upper" and "lower" levels, four joint buffering strategies are formulated, namely: safety stock at both levels (SS/SS), safety stock at the "upper" level and safety lead time at the "lower" level (SS/SLT), safety lead time at the "upper" level and safety stock at the "lower Level (SLT/SS), and safety lead time at both levels (SLT/SLT). Two more buffering strategies are used: no buffering at both levels (0/0), and safety stock at the "upper" level and no buffering at "lower" level (SS/0). The 0/0 strategy is used to represent a base point for analyzing the results concerning the relative performance of different buffering strategies. The SS/0 strategy is necessary because it is frequently mentioned in the literature (39, 53) as the appropriate way to protect a production system against uncertainty. Figure 3.1 is an example of a joint buffering strategy.

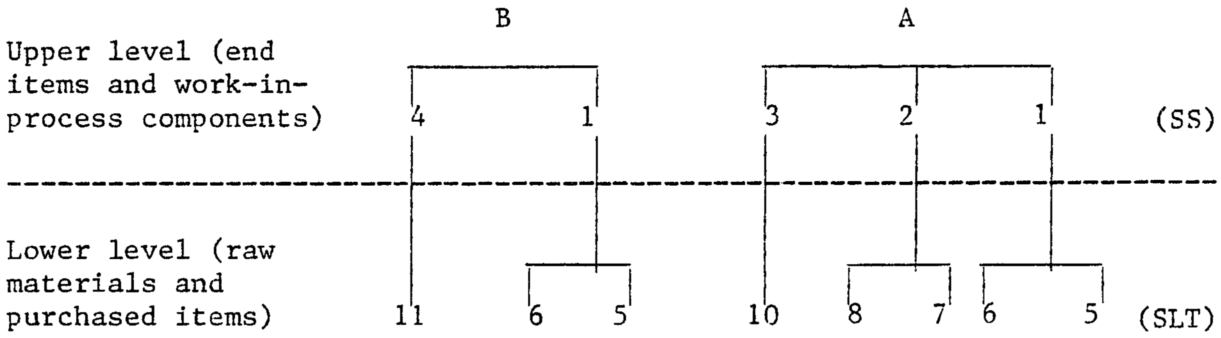

FIGURE 3.1

The procedure for determination of safety stock and safety lead times required for each level, is discussed in a later part of this chapter.

(2) Type of Supply Uncertainty (T)

Two different types of supply uncertainty are used in this study: Quantity uncertainty (Q), and Timing uncertainty (T). In conjunction with the "upper" and "lower" levels, four different combinations of supply uncertainty type are utilized. These include timing uncertainty at both levels (T/T), quantity uncertainty at both levels (Q/Q), timing uncertainty at the "upper" level and quantity uncertainty at the "lower" level (T/Q), and quantity uncertainty at the "upper" level and timing uncertainty at the "lower" level (Q/T). For "lower" level items, supply quantity uncertainty arises when suppliers deliver amounts other than that ordered; i.e., actual receipts are not equal to scheduled receipts because of excess supply or supply shortages. On the other hand, supply timing uncertainty for "lower" level items arises from variations in vendor lead times. Deliveries from suppliers are not always made according to that promised because vendor lead time is a function of many uncontrollable factors (50).

"Upper" level items are also subject to both quantity and timing uncertainty. When production lots incur scrap losses or when there are shortages of lower level materials, the actual receipts will vary from the amount scheduled. Delays, breakdowns, or a change in plan, on the other hand, may cause a variation in the manufacturing lead time for internally supplied items. Moghaddam and Bimmerle (38) reported nineteen factors influencing manufacturing lead time, most of them are of a probabilistic nature. Though his study was under independent demand environment, Vinson (55) indicated that lead time unreliability (variability of lead time from mean lead time) is of greater importance than either the mean lead time or the variability of demand in explaining inventory cost behavior.

In this study, quantity uncertainty is introduced through considering the scheduled receipt as the mean quantity to be received for each item, and the actual receipts is distributed about this mean according to exponential distribution and degree of uncertainty. Similarly, the actual lead time is distributed about the projected lead time according to the Poisson distribution.

(3) <u>Degree of Supply Uncertainty</u> (D)

Two levels of supply uncertainty are used in this study: low (L) and high (H) uncertainty. A large mean shortage (λ) is used in the exponential distribution to generate the high quantity uncertainty situation. Low quantity supply uncertainty is associated with a $\lambda_1 = .1$, and high quantity supply uncertainty is associated with a $\lambda_2 = .3$. On the other hand, low timing supply uncertainty is associated with a mean delay $\lambda'_1 = .1$ while high timing supply uncertainty is associated with a $\lambda'_2 = 1$.

These two selected levels of uncertainty, for both quantity and timing, are used for both low level and high level items. In conjunction with the product structure, they are used to formulate the four multilevel combinations of the uncertainty degree that are studied in this research. They are high uncertainty at both levels (H/H), low uncertainty at both levels (L/L), high uncertainty at the "upper" level and low uncertainty at the "lower" level (H/L), and low uncertainty at the "upper" level and high uncertainty at the "lower" level (L/H).

The process of introducing different uncertainty levels in the system will be explained in detail during the discussion about operation of the simulation model in the last section.

<u>Statistical Procedures</u>

To observe any possible main and interaction effects of all three factors, a full factorial experiment of dimension 4 x 4 x 6 = 96 will be adopted. Factorial experimentation is highly efficient because every observation supplies information about all the factors included in the experiment. Secondly, it is a method of investigating the relationship between the effects of different factors (35). The Three-Factor Classification model chosen to represent this experiment is (28):

$$Y_{ijk\ell} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + (\alpha\gamma)_{ik}$$

$$+ (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk\ell},$$

$$\varepsilon_{ijk\ell} \sim N\ (0, \sigma^2) \text{ indep.}$$

$$i = 1, \ldots, 6$$
$$j = k = 1, \ldots, 4$$
$$\ell = 1, \ldots, n$$

where

μ is the true mean effect,

α_i is the true effect of the ith level of factor (B),

β_j is the true effect of the jth level of factor (T),

γ_k is the true effect of the kth level of factor (D),

$(\alpha\beta)_{ij}$ is the true interaction of the ith level of factor (B) with the jth level of factor (T),

$(\alpha\gamma)_{ik}$ is the true interaction of the ith level of factor (B) with the kth level of factor (D),

$(\beta\gamma)_{jk}$ is the true interaction of the jth level of factor (T) with the kth level of factor (D),

$(\alpha\beta\gamma)_{ijk}$ is the true interaction of the ith level of factor (B) with the jth level of factor (T) and the kth level of factor (D), and

$(\varepsilon_{ijk\ell})$ is the error associated with the ℓth experimental unit subjected to the ijk^{th} treatment combination.

n = number of replications.

Though the three-way interaction $(\alpha\beta\gamma)_{ijk}$ is a part of this statistical model, it is not considered in this analysis. Most of the time it has very little meaning and is rarely tested (24). Figure 3.2 depicts the experimental design for this study.

Degree of Supply Uncertainty (D)			H/H				L/L				H/L				L/H			
Type of Supply Uncertainty (T)			T/T	Q/Q	T/Q	Q/T	T/T	Q/Q	T/Q	Q/T	T/T	Q/Q	T/Q	Q/T	T/T	Q/Q	T/Q	Q/T
Buffering Strategy (B)	1	SS/SS																
	2	SS/SLT																
	3	SLT/SLT																
	4	SLT/SS																
	5	0/0																
	6	SS/0																

FIGURE 3.2 THE EXPERIMENTAL DESIGN

In this study, all studied factors are considered fixed variables. Therefore the statistical model is treated as fixed effect model. This point will be clear in the statistical analysis section.

In this model, it is assumed that the same number of replications unit exists for all runs (treatments). The way this required number of replications was estimated is reported in the next section.

Number of Replications (Sample Size)

The number of replications (n) necessary to detect a difference (d) between means in the analysis of variance was estimated using the power approach. This approach permits controlling the risks of making both Type I and Type II errors. Feldt and Mohmoud charts (40, p. 493) are available to furnish the appropriate sample size directly. They are applicable only when all factors levels are to have equal sample sizes, which is the case in this study.

In order to be able to use these charts the following specifications were made:

1. A level of $\alpha = .05$, at which the risk of making a Type I error is to be set, is adapted for this study.
2. The value of a noncentrality parameter ϕ' at which the risk of making a Type II error is to be controlled is estimated as follows:

$$\phi' = \frac{d}{\sigma} \sqrt{\frac{1}{2r}} \text{ , where}$$

d the maximum difference between pairs of level means for which it is important to recognize differences in the population means,

σ the standard deviation of the considered performance measure, r number of levels of the considered factor. In this study r equals 5, 4 and 4 for factors B, D and T, respectively. A value of r = 5 is used as an average for the number of levels. This implies that Φ' will equal (.316)d/σ for all d/σ ratios. Table 3.2 is constructed to give the value of n required in terms of the ratio d/σ.

Six preliminary runs were conducted to estimate d and σ for selected performance measures. Table 3.3 presents the results of these primary runs. Table 3.3, in conjunction with Table 3.2, indicates that five replications are statistically sufficient. Therefore, five independent simulation runs were conducted for each cell. Throughout the study a reestimation of d and σ was done and the new values were used to recalculate the required number of replications. This precaution step was required to assure that the sample size used, five in this case, was always statistically adequate throughout the study. Table 3.3 includes also the overall estimates for d and σ for different performance measures. All new estimates support the initial conclusion that five replications are required. This implies that the power of the F-test is still above .90 whatever the performance measure being analyzed.

The Statistical Analysis

The final step in the procedure for conducting a simulation experiment involves the analysis of the data generated by the computer from the model of the simulated system. A number of alternative forms of analysis have been suggested (36). Among these, the analysis of variance and a multiple comparison procedure is utilized in this study.

Analysis of variance, in conjunction with an appropriate experimental design, has the capability of investigating the effects of several factors at once. It is frequently used in inventory simulation research (57),

TABLE 3.2

The Number of Replications Required in Terms of the Ratio d/σ

$\alpha = .05$, $\beta = .1$, $r = 5$

d/σ	ϕ'*	n
.25	.079	**
.50	.158	**
.75	.237	65
1.00	.316	35
1.25	.395	22
1.50	.474	18
1.75	.553	12
2.00	.632	10
2.25	.711	8
2.50	.790	7
2.75	.869	5

*$\phi' = (.316)(d/\sigma)$

**Values could not be found from Felt and Mahmoud's Charts

TABLE 3.3

Data Used to Calculate the Required Number of Replications

Performance Measure		Maximum Level Mean	Minimum Level Mean	d	σ	d/σ
HOLC	Prim.*	6879366.	25199798.	4359568.	926232.06	4.7067
	Study**	7949235.	2995972.	4953263.	1173551.26	4.2207
INVC	Prim.	7538398.	4003928.	3534470.	97599.54	3.6214
	Study	9218996.	5267181.	3951815.	1173511.51	3.3675
TOC	Prim.	7754654.	4173185.	3581469.	774405.16	4.6248
	Study	9262146.	4414284.	4847862.	12554744.44	3.8613
BO	Prim.	11817	1498	10319	1317.20	7.8340
	Study	9215	1819	7396	622.06	11.8902
STK	Prim.	107	14	93	15.39	6.0421
	Study	78	12	66	8.21	8.0036
SLVL	Prim.	.971192	.772750	.198442	.02382	8.3245
	Study	.965032	.821629	.143402	.012081	11.9323

* Prim.: data are taken from the six preliminary runs with 25 observations each.

** Study: data are taken from the overall simulation experiment (96 runs with five observations each).

and it has been reported that it is useful in all simulation studies where the analyst may wish to alter a variety of factors in the model to determine the ones which have a significant effect on performance of the model (36).

However, this procedure requires a number of assumptions, i.e., independent of observations, normality of populations and homogeneity of variance for each treatment and experimental unit (44). In this study, using the independent replications methods, as will be explained, assures the requirement of independence to be fulfilled. On the other hand, it has been reported that moderate departures from the assumptions of normality and homoscedasticity is not a critically important matter (14). Neter and Wasserman (40) state that the point estimators of factor level means and contrasts are unbiased whether or not the populations are normal. Moreover, the F-test for the equality of factor level means is little affected by lack of normality, either in terms of the level of significance or power of the test. They also indicate that the F-test is robust against unequal variances if the sample sizes are equal.

The F-tests, in the context of analysis of variance, will be used to indicate whether or not significant main and interaction effects of the studied factors exist. If the F-test leads to the conclusion that the factor level means are equal, the implication is that there is no relation between the factor and the performance measure. On the other hand, if the F-test leads to the conclusion that the factor level means differ, the implication is that there is a relation between the factor and the performance measure and a different procedure must be used to answer the question of how these factor level means differ.

Several procedures are available to examine how the different factor levels compare with one another in terms of the system performance measurement (14, 40, 52). The Tukey method of multiple comparisons is utilized in this research. This procedure is considered appropriate in this study because all factor level sample sizes are equal for most dependent variables (six out of seven), and only all pairwise comparisons of factor level means are of interest in this study. However, conditions of normality of populations and homogenity of variance must be fulfilled before using this method. Testing for these two conditions is reported in the next chapter.

Performance Measures

The criterion performance measures that will be used in this research are:

(1) Total inventory carrying cost for items at all three levels in the system (HOLC),

(2) Total setup and carrying costs (INVC),

(3) Total cost (TOC) (sum of the setup, carrying, overtime, and stockout costs),

(4) Total number of units short (BO),

(5) Total number of stockout occasions (STK),

(6) Service level (SLVL) for the finished products, which measures the percent of the amount of the scheduled requirements of the finished products that were met during the planning horizon,

(7) Buffering Cost Effectiveness Measure (BCEM), this criterion measures the proportionate increase in the service level resulting from each increment in inventory cost. This performance measure seems to give more insight into the overall economical effect of a particular buffering

strategy. BCEM was calculated in this study as follows:

$$\text{BCEM}_{\text{for strategy } i} = \frac{\Delta \text{ shortages}/(\text{shortages})0/0}{\Delta \text{ inventory cost}}$$

where:

Δ shortages:	the amount of decrease in the finished products shortages (performance measure 4) resulting from buffering strategy i, and calculated by subtracting number of shortages of each buffering strategy from number of shortages of buffering strategy 5 (No buffering at both levels).
$(\text{shortages})_{0/0}$:	number of shortages when "no-buffering" strategy is used. This value was the base for estimating (Δ shortages).
Δ inventory cost:	the extra inventory cost required to implement buffering strategy i, and measured by subtracting inventory cost of "no-buffering" strategy from inventory cost of each other buffering strategy.

Some of these measures are used directly for testing research hypothesis. Likewise several combinations of some of these measures help in explaining the results.

Simulation Model

A simulation model is considered a valid research vehicle for exploring MRP system performance (4). Therefore, this study was conducted using a simulation model to represent a multilevel production system. Some versions of this model have been used by previous researchers (5, 6, 31, 49). A version was modified incorporating the main features of this study.

The simulated factory consists of two departments: Final Assembly and Subassembly. There are three types of inventory: finished goods, subassemblies, and raw materials. Raw materials are ordered from suppliers, and sales of finished products are made to customers. There is no outside demand for subassemblies. A general schematic diagram of the system and the physical flows within it are presented in Figure 3.3.

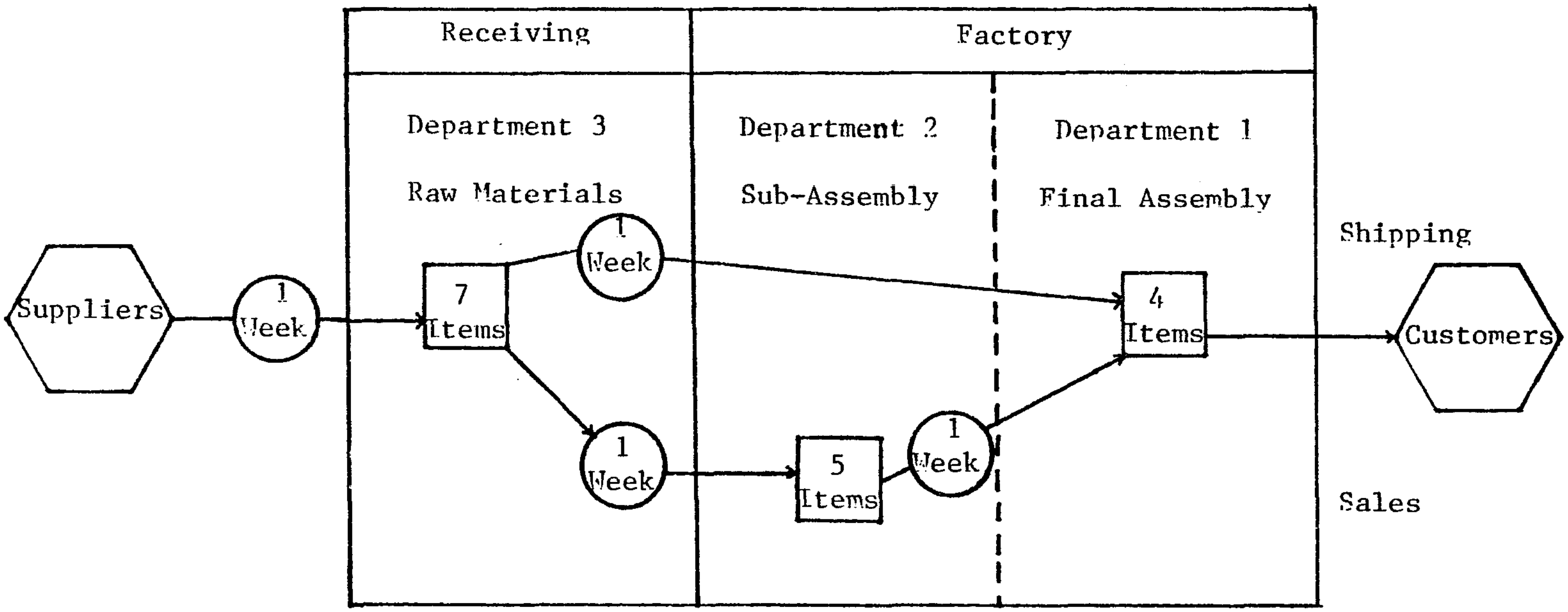

FIGURE 3.3, Schematic of Factory Organization and Work Flow

In each of the two departments, finished goods and subassemblies, there exists a machine group with adequate capacity to process the entire production plan in each period (unlimited capacity). Each department requires the same type of labor skills therefore, labor is perfectly transferable within each department. However, due to differences in skills required, workers cannot be transferred from one department to another. Limited overtime capacity, 30% of regular time capacity, is available in each department and desired production is automatically reduced if the limit is exceeded. Several more assumptions are made in this study. End-item demand is assumed to be deterministic (a perfect forecast), no production smoothing, and a lot for lot ordering strategy is used throughout the experiment.

The factory manufactures five end products, each calling for different assembly groups. Appendix (D) contains the product structure that shows the materials (raw materials, subassemblies) required to make subassemblies and finished products. This bill of materials includes 4 end items, 5 subassembly items, and 7 raw material items. Appendix (D) also includes the inventory file consisting of inventory on hand, setup time, run time per unit, lead time, setup cost per order, inventory value per unit, holding cost per unit, and any scheduled receipts for each item. A list of some other required initial conditions is also given in the appendix. One of these initial conditions is the gross requirements for each end item. It is assumed to be deterministic and available for the master production schedule at the initialization phase of this simulation.

The time unit used in this simulation is the week. Data about the performance of the system are collected for a planning horizon of fifty two weeks. Tocher (37) suggested a very practical way to approach the problem of the run length. He suggested that the longest cycle in the plant should have been executed at least three or four times. The longest cycle, which is called the frozen period by Liaw (32) and the longest assembly "path" by New (41), in this research according to the selected product structure and the expected lead time value does not exceed 12 weeks. Therefore a simulated horizon of fifty two weeks is long enough to execute the whole assembly process four times at least.

Operating the Simulation Model

A computer simulation model of the period-by-period transactions is used in this study. The operating logic of this model is as follows: at the beginning of each period, the projected gross requirements for each end item, and all the required initial conditions, including the updated inventory files, is available. According to the selected buffering strategy, this information is used with the MRP logic to complete the explosion and generate requirements and orders for each item. If an order is required, it is scheduled for receipt in the appropriate future period according to the projected lead time. Next, delivery shortages and expected delays during this period are generated in order to assess the supply uncertainty in the system. One of the different sixteen categories of supply uncertainty combinations studied in this research is used. Actual receipts and production lots are released for possible processing during the execution phase. If the requirements are available, a lot is completed and made available as input to the next higher stage as of the beginning of the next period. In the case of final products, the lot is made available to meet external demand in the next period. In the event of material shortage, the system is asked to use the available safety stock, if any. If the safety stock is not available, desired production is reduced proportionately in an attempt to just use up the available supply of the short material. Make-to-stock environments are assumed in the simulated model. This means that customers will not tolerate backorders, and failure to provide product on demand results in a lost sale and potential customer dissatisfaction. By the end of the period, records are updated according to the actual production and used as the basis for determining the requirement plan in the next period. This process is repeated for all periods during the simulated planning period. During the operation of the system, various statistics are collected to test the stated hypothesis. A diagram describing the simulation procedure is provided in Figure 3.4.

Initial Conditions and the Autocorrelation Problem

Before experimentation could begin, two issues had to be resolved: initial conditions and the autocorrelation problem. In this section, the criteria and data used to make decisions on both of these matters are presented.

Initial Conditions and Elimination of Transients.

The problem of determining how to start the model, and how to obtain measurements that are not biased by the initial conditions are among the most difficult procedural questions in simulation (16). In many simulations, as in this research, the measurements that are to be made must take place when the system has reached equilibrium or steady-state conditions, that is, when the state of the system does not depend on the time when it is viewed (time independent). Conway (16, p. 48) points out, however, that "equilibrium is a limiting condition which may be approached but actually never attained."

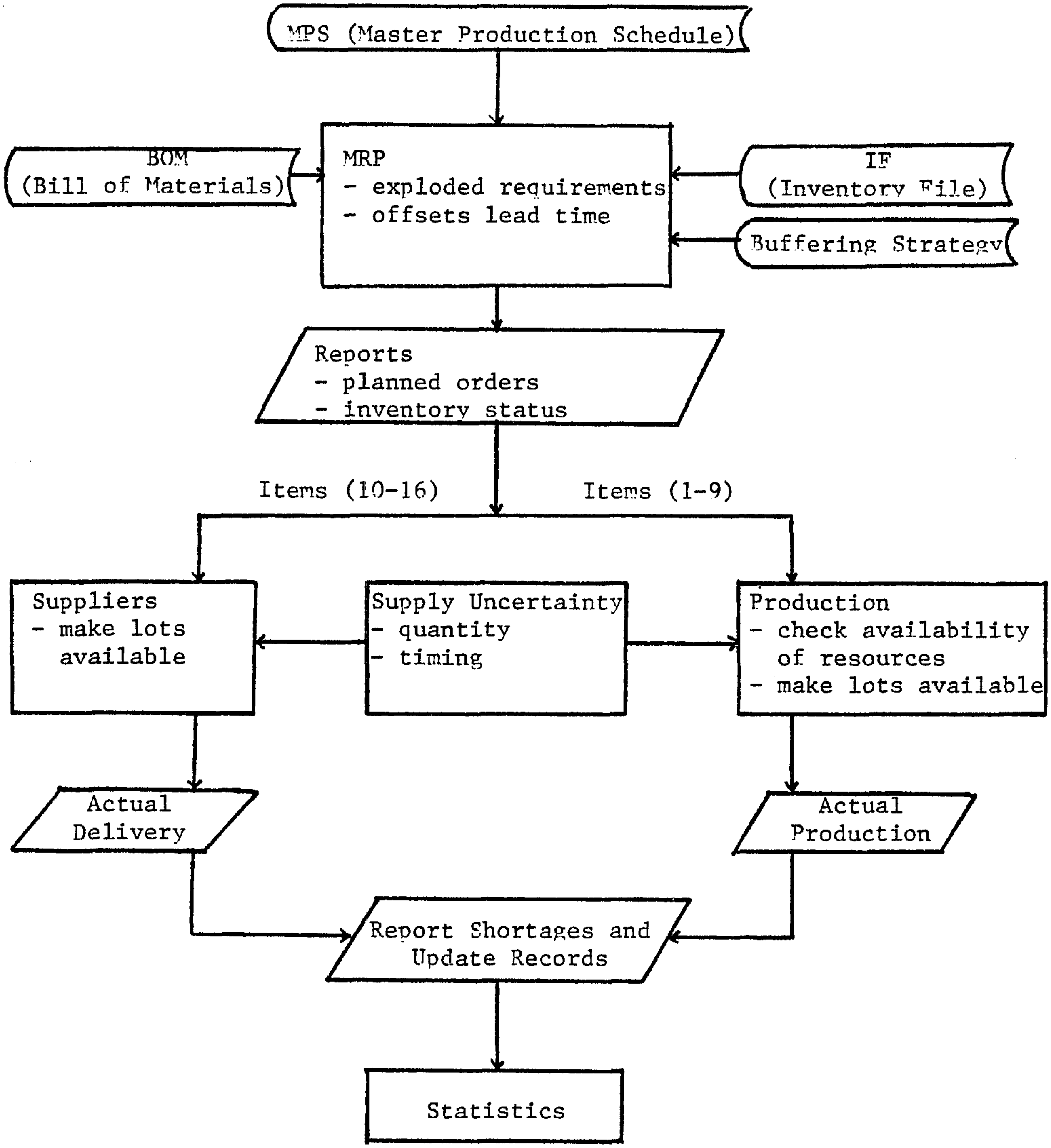

FIGURE 3.4 Elements of the Simulated System

Because of the selected initial conditions, a simulation run has a transient period when the state of the system is time dependent. During this period measurements of system behavior should not be taken since they could bias the results. To avoid this bias, this simulation had a "warm-up" or non-recording period prior to collecting measurements. At the end of this period the statistical accumulators were zeroed out, while the state of the system was left unchanged. From this point in the simulation, the system was considered to be in equilibrium.

The determination of the "warm-up" period length is subject to debate (30, 60), however, this length depends on the initial starting conditions of the model. Two basic strategies exist for setting starting conditions, one is to start with the system in the "empty and idle" state. Though it is easy to start the simulator under these conditions, the transient period is likely to be quite long (20). Under the second strategy, which was adopted in this research, the stabilization process can be accelerated by the choice of starting conditions that approximate the steady-state conditions of the system. Use of this alternative should reduce the transient period but in some cases, however, appropriate starting conditions may not be known in advance (56). In order to attack this problem in this research, three different sets of initial conditions were tried in twelve pilot runs to determine the effects each of it has on the behavior of the model. These pilot runs were selected to represent all combinations of supply uncertainty type (four cases) but under only the high degree of uncertainty condition. It was assumed that the variation of any of the performance measure throughout the study could not be greater than the variation detected under the high uncertainty case in these pilot runs. The three initial inventory values that were used are : (a) no initial inventory, (b) one-half period demand initial inventory, and (c) one-period demand initial inventory, for each item. By plotting key system performance measures against time, it was clear that (b) comprises a set that reduced the duration of the "warm-up" period. Appendix (D) includes the initial inventory values used in this study. This set was used for each replication under the same uncertainty condition and buffering strategy. Moreover, it was used for all simulation runs in order to be able to compare one version of the model with any other version. This eliminated any distortion effects caused by difference in starting conditions (36). A non-recording period was also used in some cases to avoid any wild variation of any of the performance measurement at the beginning of the simulation. Because of the careful selection of the initial inventory levels, a four-week period was enough as a non-recording period in most cases.

Data Collecting and the Autocorrelation Problem. Another source of difficulty in the analysis of simulated data is that the output from simulation models is often autocorrelated (27, 56). In order to be able to use the classical analysis of variance techniques some steps must be taken to ensure the independence of the observations. The independent replications and the batch method are among the common approaches that could be used in this situation (22).

The independent replications approach requires repeating the simulation a number of times with all conditions the same except for the random number stream used to generate random events. Hence, the performance measures from each replication are taken as independent observations. Each one can then be used in estimating a variance for that performance measure.

The batch method involves breaking a simulation run into a number of separate periods or batches. System performance measures are then recorded for each batch. The objective is to have each performance measure in each batch be an independent observation from every other batch. The interrupt block approach to data collection is often used to achieve this goal.

Replicating runs is inefficient in that the wasteful starting transients are repeated in each replication (20). However, if the transient period is short because of using the appropriate set of initial conditions, the independent replicating method has the advantage of simplicity and guarantees independency of observations.

In this research, the independent replications approach is adopted. A run of the model for fifty two weeks is treated as one observation with regard to the aggregate statistics of operation of the system, that is, a run would yield one observation for such quantities as total inventory cost and total number of stockouts for the finished products. Because of the stochastic elements, aggregate performance measures vary from run to run when different random number sequences are used. A sample of size n is obtained by making n runs of a model starting from the same initial conditions but using a different random number sequence in each.

As indicated above, introducing different uncertainty types and levels,and using different buffering strategies are key factors in this research. Therefore, this last section explains in detail the process of generating different uncertainty environments and how safety stock and safety lead time are estimated in this study.

Supply Quantity Uncertainty Levels

Two categories of distributions can be used for simulations: empirically-derived distributions and theoretical frequency distributions (13). Because of the lack of any empirical approximation for both the actual delivery of raw materials and purchased items, and the actual production rate for end items and intermediate components, a hypothetical probability distribution is used in this study.

Whybark and Williams (58) used a continuous uniform distribution of the actual requirements around the projected gross requirement to represent the delivery process. Accordingly, in their study, there was an equal likelihood of receiving more or less than the planned (or expected) order receipts. Receiving more than the ordered amount is probably not typically encountered in most materials management systems. This would simply cause higher inventory costs unless the extra amount is offered with a considerable discount price which justifies accepting it.

In his study, Liaw (32) used normal random numbers to approximate the "percentage receipt failure" for each assembly and the shortage data for each raw material item. Since very few actual receipts are greatly below their expected amounts, the exponential distribution seems appropriate to model the distribution of the deviation between planned orders receipts and the amount actually received for raw materials and assembly items.

As used in this research, the distribution depends on a single parameter (λ) which represents the average percentage shortage (APS). For each item, APS represents the expected percentage shortage for each order and desired as:

$$APS = \frac{\text{Planned Order Receipts - Actual Order Receipts}}{\text{Planned Order Receipts}}$$

A larger APS represents higher risk of the production process or raw material supply being short. Low quantity supply uncertainty is associated with a λ = APS = .10, while high quantity supply uncertainty is associated with a λ = APS = .30; i.e., the average shortage, as a percentage of the planned order receipts in the case of high uncertainty is expected to be three times as much as the shortage percentage in the low uncertainty case. Figure 3.5 represents the two cases of quantity uncertainty used in this study.

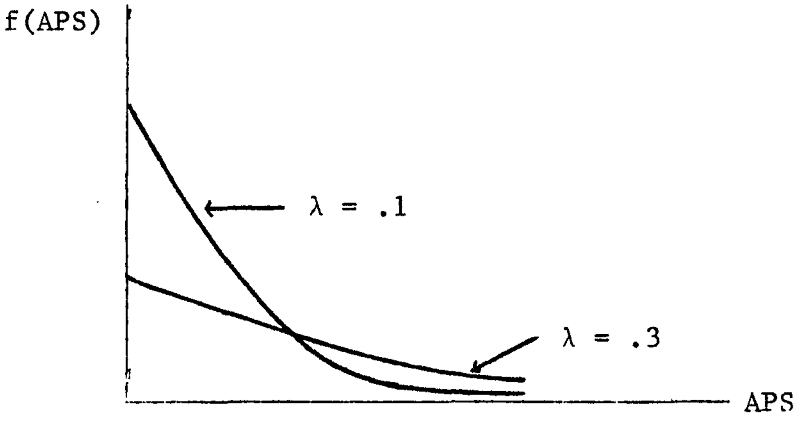

FIGURE 3.5 Quantity Uncertainty Levels

The procedure used for generating a random actual receipt for a particular order is as follows:

1. generate a standard uniform number, this will be a fraction, i.e., $0 \leq x > 1$,
2. transfer this number into an exponentially distributed number according to the specified level of λ. This value represents the APS for this order,
3. calculate the actual receipt for this order by using

Actual Order Receipt = (1 - APS)(Planned Order Receipts)

It is clear from the last formula, because APS is a positive fraction, that the actual receipts will always be less than or equal to the planned receipts, i.e., only the case of shortage in delivery is considered in this research.

These procedures were used to generate the percentage receipt shortage for each assembly and subassembly and also for each raw material item.

Supply Timing Uncertainty Levels

One of the reasons lead time variability is not adequately studied in inventory theory is the fact that variation in lead time may not fit familiar probability distribution and/or may shift around in a pattern (55). This explains, to some extent, why some researchers (34, 53) discussed how to deal with lead time variation without specifying any particular theoretical frequency distribution to represent actual lead time. Some others (29) created their own hypothetical distributions. Liaw (32) assumed in his study a deterministic zero lead time for all items. In practical situations this is simply not realistic. Whybark and Williams (58) used ± 1 and ± 2 delay periods to represent low and high timing uncertainty respectively. Therefore, an early arrival of the order was possible in their study.

A Poisson probability distribution is used in this study to approximate the amount of delay. Accordingly, this delay is always zero or a positive integer value. The reason for selecting this type of distribution is two-fold. First, receiving an order before its due date is not typical of most real situations. Secondly, it seems more logical to assume that the typical supplier is attempting to meet his due date, only for a few times will he fail to do so. If this assumption is reasonable, as length of delivery delay increases, the associate probability of delivery delay decreases.

The average delay (λ') is used to represent the degree of uncertainty. Low timing supply uncertainty is associated with an average delay of $\lambda' = .2$ period while high timing uncertainty is associated with an average delay of $\lambda' = 1$ period. These two levels of λ' implies a risk of having any delay equal to about .18 and .63 respectively.*

The procedure used for generating a simulated actual lead time for a particular order will be accomplished by generating a Poisson distributed random variable according the values of λ', then adding this value to the projected lead time to determine actual time of receiving an order:

Actual Lead Time(ALT) = Planned Lead Time(PLT) + Generated Delay(GD)

The Required Safety Stocks

Very little work has been done on any sort of "scientific" approach to the setting of the buffer stock levels (51). Banerjee and Saniga (3) introduced a procedure for determining appropriate safety stock levels for dependent demand inventory items. Starting with a particular end item demand distribution, normal or Poisson in their paper, they use the change of variable technique to obtain the probability distribution of the requirements for each dependent demand items. This estimated distribution is the basis for estimating safety stock for each item according to the desired service level. In addition to the complexity involved in the technique, a major drawback is that demand uncertainty is considered as the only reason for holding safety stock. While this

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* If $\lambda' = .2$ $p(\text{delay} \leq 0) = .819$, therefore $p(\text{delay} \geq 1) = .181$.

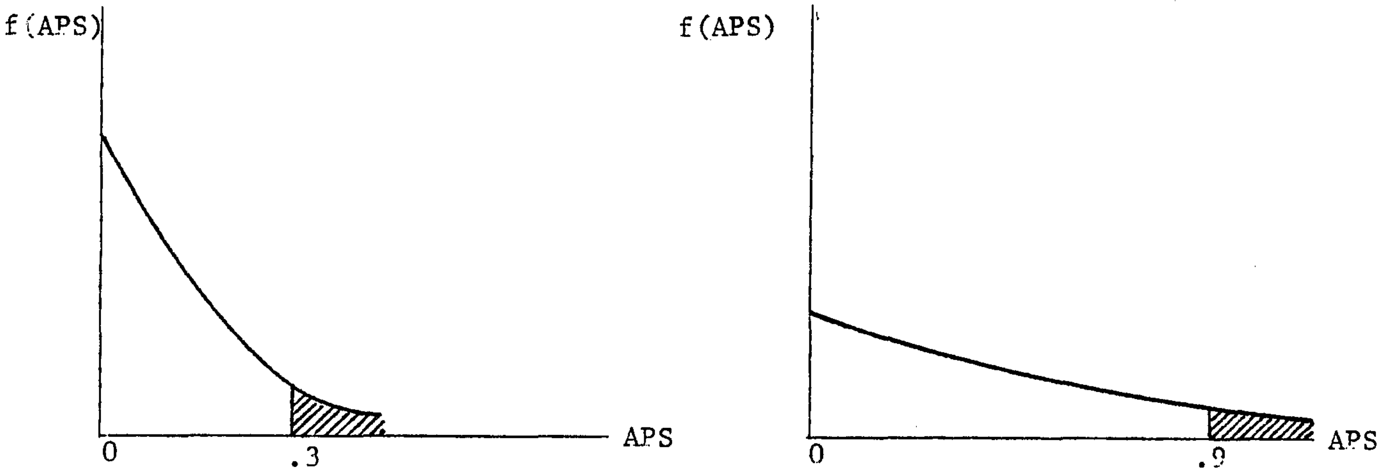
If $\lambda' = 1$ $p(\text{delay} \leq 0) = .368$, therefore $p(\text{delay} \geq 1) = .632$.

might be accepted in replenishment systems, it is hard to ignore the effect of supply uncertainty when estimating the amount of safety stock for dependent demand inventory items. Callarman and Mabert (11) also ignored supply uncertainty when they introduced their Service Level Decision Rule (SLDR) as a way for determining the buffer stock. They treated safety stock as a function of the forecast error, coefficient of variation, and time between orders (TBO). All of these factors are of demand type.

In this research, because demand is assumed to be deterministic, supply uncertainty must be the base for estimating the safety factor for each item. Therefore, classical statistical techniques, with some modification, is used. The parameters of the statistical distribution selected to represent the shortage percentage, in conjunction with a desired service level, are used to estimate the required safety stock for each item. Consequently different levels of safety stock

At this point, it seems necessary to indicate that various supply uncertainties which take place at different inventory stages are treated separately. This is equivalent to heuristic B used by Liaw (32). The implication of this approach is that safety stock for finished products is provided to protect against production loss at final assemblies. Safety stock for intermediate items are provided to protect against production loss at the subassemblies, and safety stocks for raw materials are provided to protect against supply uncertainty, i.e., safety stock decisions are made only for the next lowest level.

The amount of safety stock (SS) required for each raw material item is estimated according to the value of λ, which represents the uncertainty level, and the desired service level. The same service level must be used for all runs when estimating the safety stocks. A .95 service level is used in this study. Figure 3.6 represents the amount of safety stock required to satisfy this service level in the case of low and high uncertainty.



Low Risk
($\lambda = .1$)

High Risk
($\lambda = .3$)

Figure 3.6

The above estimated values of APS are used directly to estimate SS as follows:

$$SS = \begin{cases} (\text{planned receipts})\ (.3) & \text{if } \lambda = .1 \\ (\text{planned receipts})\ (.9) & \text{if } \lambda = .3 \end{cases}$$

The amount of safety stocks required for each other intermediate and end items are estimated in the same manner except that the values .1 and .3 represents a production loss percentage rather than supply shortage percentage in the raw material case.

To incorporate these safety stock values in the simulated model, first a separate pilot run, for the total planning horizon, was conducted to calculate the planned receipts of all items, therefore all safety stock values could be estimated according to the formula indicated above. In each regular simulation run, these values are added to the gross requirements to inflate the projected orders. As mentioned before, the system is asked to use these safety stocks when the need arises.

The Required Safety Lead Times

Safety lead time (SLT) implies a slight forward adjustment to the component order due date. The conventional statistical techniques are used in this study to estimate the required SLT for each item. A desired protection level against any change in the lead time of .98 is selected. This means a buffer lead time of one week must be used in the case of low timing uncertainty and three weeks must be used in the case of high timing uncertainty.*

Introducing safety lead time in the system is accomplished through moving the due date one or three weeks forward rather than increasing the lead time by the required amount of safety lead time.

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*According to the Poisson distribution tables and the selected two level of λ',

$p(x \leq SLT) = p(\text{delay} \leq SLT) = .982$ when $\lambda' = .2$, therefore SLT = 1

$p(x \leq SLT) = p(\text{delay} \leq SLT) = .981$ when $\lambda' = 1$, therefore SLT = 3

CHAPTER IV

ANALYSIS OF DISCUSSION OF THE EXPERIMENTAL RESULTS

The purpose of this chapter is to present and analyze the data generated from the simulation experiment that tested buffering strategy, type of supply uncertainty and degree of supply uncertainty hypotheses as outlined in the previous chapter. The results of these tests are presented and analyzed in the first section of this chapter. In a next section, comparisons of the performance of the different buffering strategies in each supply uncertainty category are presented and discussed. A general conclusion is then made in terms of the choice among various buffering strategies and some guidelines for selecting appropriate buffering strategies are provided in the last section.

Tests of Hypothesis

The analysis of variance (ANOVA) procedure was used to test the first five null hypotheses formulated in Chapter III concerning the main and interaction effects of the three factors on each of the response variables. Appendix A includes all analysis of variance (fixed effect model) results in Tables A.1 through A.7. These results are summarized in Table 4.1.

Although the F-test, used in ANOVA, is little affected by lack of normality and was reported to be robust against unequal variances, testing for normality of populations and homogenity of variance was required before using Tukey's multiple comparison test. Normality was examined by the Kolmgorov-Smirnov test for all dependent variables, while Hartly's test was used to check for equality of variances. Results of these two procedures, as reported in Appendix B, seems to support the

TABLE 4.1

SUMMARY OF ANALYSIS OF VARIANCE SIGNIFICANCE LEVELS OF FACTORS

Factors[a]		Performance Measures[b]						
		HOLC	INVC	TOC	BO	STK	SLVL	BCEM
Main Effects	B	.0001	.0001	.0001	.0001	.0001	.0001	.0001
	T	.0001	.0001	.0001	.0001	.0001	.0001	.0001
	D	.0001	.0001	.0001	.0001	.0001	.0001	.0261
Interaction Effects	BT	.0095	.0077	.0495	.0001	.0001	.0001	.0009
	BD	.0001	.0001	.0001	.0001	.0001	.0001	N.S.
	TD	.0001	.0001	.0001	.0001	.0003	.0001	.0007
	BTD	N.S.	N.S.	N.S.	.0003	.0001	.0001	N.S.

a. Factors

B = Buffering Strategy
T = Type of Supply Uncertainty
D = Degree of Supply Uncertainty
BT = Interaction Between B and T
BD = Interaction Between B and D
TD = Interaction Between T and D

b. Performance Measures

HOLC = Inventory Carrying Cost
INVC = Total Setup and Carrying Cost
TOC = Total Cost
BO = Total Number of Units Short
STK = Total Number of Stockouts
SLVL = Service Level
BCEM = Buffering Cost Effectiveness

Note:

1. The first six performance measures are in terms of the planning horizon (52 periods). BCEM is for each extra one hundred thousand dollars inventory invested.
2. This description of both the factors and the performance measures holds for all subsequent tables.

the assumption of normality and equality of variances in most cases. Therefore, using Tukey's test is justified.

Whenever the F-test lead to the conclusion that the factor level means differed significantly, Tukey's test was utilized to examine how the different factor levels compare with one another in terms of the system performance measurement. The results of this test are reported in Tables B.3 through B.5 in Appendix B. A summary is reported in Tables 4.2 through 4.4.

In general, Table 4.1 indicates that the main effects due to all factors are significant with respect to each of the seven performance measures. All the two-way interaction effects are also significant with respect to each of the seven performance measures with one exception. The interaction between factors "buffering strategy" and "degree of supply uncertainty" has no significant effect at .05 level on the "buffering cost effectiveness" criterion. For only three of the seven performance criteria was the three-way interaction found to be significant ($P \leq .001$)

The findings of ANOVA presented in Tables A.1 through A.7 and in Table 4.1 are used in the next part to test each of the null hypotheses presented in Chapter III. The results of the Tukey's test are utilized to support the analysis concerning the significance between different level means for each factor.

Null Hypothesis No. 1. It was hypothesized that different buffering strategies have no significant effect on the system performance.

The results of the ANOVA reported in Table 4.1 indicate that the main effect of the factor "buffering strategy" is significant at the .01 level for all performance criteria. Therefore this hypothesis is rejected. This implies that the system performance might be significantly different for any of the seven performance measures based on the particular buffering strategy(s) adopted. This conclusion is consistent with both the Whybark and Williams (58), and the Liaw (32) results. Although the first study was considering only a single item, it implies that significant differences exist in terms of service level when using safety stock rather than safety lead time or vice-versa. Liaw also reported that a significant main effect was found for "safety stock policy" factor in terms of the number of stockouts and number of outages. It should be noted that Liaw did not consider providing safety lead time as a way of buffering the system against uncertainty. Therefore his conclusions must be taken with caution when comparing results.

This finding that different buffering strategies have different impacts upon the performance of the system is not surprising. New (41), without any empirical evidence, indicated that each strategy is likely to have its own distinct operating characteristic. For instance, a safety time policy will cause the projected stock to vary widely from period to period while a fixed buffer policy requires the buffer quantity to be held all the time. Therefore they were expected to perform differently in terms of inventory cost and service level, under different production environments.

In order to explore how the multilevel buffering strategies differ in terms of the effects on system performance, Tukey's test results are used. Table 4.2 indicate that (a) all strategies performed significantly differently in terms of the first two response variables: holding cost and inventory cost, (b) both strategy 1 (SS/SS) and strategy 6 (SS/0) performed almost the same in terms of the total cost variable

TABLE 4.2

A SUMMARY OF TUKEY'S MULTIPLE COMPARISON TEST FOR BUFFERING STRATEGIES*

$\alpha = .05$

	Performance Measure						
SUBSET	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
A	3	3	3	5	5	3,4	6
B	4	4	4	6	6	2,1	1,2
C	2	2	2	1,2	1,2	6	2,4,3
D	1	1	1,6	4,3	3,4	5	
E	6	6	5				
F	5	5					

*1 = (SS/SS), 2 = (SS/SLT), 3 = (SLT/SLT), 4 = (SLT/SS), 5 = (0/0), 6 = (SS/0)

measure. When considering the number of shortages and service level, the table shows that (a) both strategies 5(0/0) and 6(SS/0) performed significantly different from any other strategy, (b) both strategies 1(SS/SS) and 6(SS/0) performed almost the same. The table shows also that the difference between the last three response variables generated from strategies 3(SLT/SLT) and 4(SLT/SS) is not significant. As for buffering cost effectiveness measure, strategy 6(SS/0) is performing significantly different from any other buffering strategy while no significant difference existed among strategies 4(SLT/SS), 3(SLT/SLT), and 2(SS/SLT) or among strategies 2(SS/SLT) and 1(SS/SS).

In summary, the most pronounced difference across all performance measures is between strategy 3(SLT/SLT) and strategy 5(0/0) with one exception. In terms of buffering cost effectiveness, the most significant difference is between strategy 6(SS/0) and strategy 3(SLT/SLT).

Null Hypothesis No. 2. It was hypothesized that different supply uncertainty types have no significant effect on the system performance.

The ANOVA data presented in Table 4.1 suggest that the main effect of the factor "type of supply uncertainty" is significant at the .01 level with respect to all performance criteria. Therefore this hypothesis is rejected.

Tukey's test was conducted to understand how the four types of supply uncertainty differed in terms of their effect on all performance measures. Table 4.3 summarizes the results.

Across all cost performance measures, Table 4.3 indicates that the difference between the effect of supply uncertainty type 4(Q/T) and any other supply uncertainty type is significant, while the difference is almost negligible between the effects of type 2(Q/Q) and type 3(T/Q) in terms of holding cost only. On the other hand, all differences are significant among all uncertainty types in terms of the number of shortages, number of stockouts and the service level. Type 3(T/Q) is the only type to differ significantly in terms of buffering cost effectiveness measure.

In summary, the most noticeable difference cost criteria exsits between types 4(Q/T) and 3(T/Q) while the next most is between 4(Q/T) and 2(Q/Q). Another interesting finding is that the difference

TABLE 4.3

A SUMMARY OF TUKEY'S MULTIPLE COMPARISON TEST FOR TYPE OF SUPPLY UNCERTAINTY*

$\alpha = .05$

	Performance Measure						
SUBSET	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
A	4	4	1	1	1	2	3
B	1	1,2	3	3	3	4	1,4,2
C	2,3	3	4	4	4	3	
D			2	2	2	1	

*1 = (T/T), 2 = (Q/Q), 3 = (T/Q), 4 = (Q/T)

between types 2(Q/Q) and 1(T/T) is insignificant in terms of inventory cost criterion while the difference between the same two uncertainty types, 2(Q/Q) and 1(T/T), is reported to be the most significant according to service level criterion. This leads to the conclusion that the effect of different uncertainty types on the performance of the system depends on the criteria used to judge the performance of the system.

Null Hypothesis No. 3. It was hypothesized that different supply uncertainty levels have no significant effect on the system performance.

Table 4.1 indicates that the main effect of the factor "degree of supply uncertainty" is significant at the .01 level with respect to performance measures one through six and significant at .05 level with respect to the last criterion "buffering cost effectiveness." Therefore, this hypothesis is rejected.

This conclusion is, to some extent, congruent with the results reported by most previous empirical buffering strategies studies including Whybark and Williams (58) and Liaw (32). Whybark and Williams concluded that both the coefficient of variation and the level of supply uncertainty have a significant effect on the service level at the .05 level for each uncertainty category. Liaw reported also a significant effect for the inventory risk on the number of stockouts and number of outages.

Tukey's test was conducted to explore how the four multilevel combinations of supply uncertainty degree differed in terms of the effect on all performance measures. Table 4.4 summarized these results.

The table reveals that the difference between degree 2(L/L) and degree 1(H/H) represents the largest difference across all performance measures. This result was expected because of the distinguished behavior of the number of shortages, service level, and shortage cost under each of these uncertainty conditions. A system operating under a high degree of uncertainty at all levels should incur a higher number of shortages, a lower service level and a higher shortage cost than a system operating under a low degree of uncertainty.

Null Hypothesis No. 4. It was hypothesized that different types of supply uncertainty have no effect on the performance of the buffering strategies.

Table 4.1 shows that the interaction effect of these two factors is significant at .05 level for all performance measures. Therefore, this hypothesis is rejected.

TABLE 4.4

A SUMMARY OF TUKEY'S MULTIPLE COMPARISON TEST FOR DEGREE OF SUPPLY UNCERTAINTY*

$\alpha = .05$

	Performance Measure						
SUBSET	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
A	1	1	1	1	1	2	2,4,3
B	4,3	4	4	3	3	4	4,3,1
C	2	3	3	4	4	3	
D		2	2	2	2	1	

*1 = (H/H), 2 = (L/L), 3 = (H/L), 4 = (L/H)

Null Hypothesis No. 5. It was hypothesized that different degree of supply uncertainty has no effect on the performance of different buffering strategies.

Table 4.1 indicates that the interaction effect of these two factors is significant at .01 level for all performance measures with only one exception. The interaction effect is negligible with respect to the buffering cost effectiveness measure. Therefore, this hypothesis is rejected.

This conclusion seems to reinforce Whybark and Williams' (58) results with respect to choosing between safety stock and safety lead time.

Null Hypothesis No. 6.

In this section, a comparison of the relative performance of all buffering strategies is presented and discussed. The results of this discussion are then used to test null hypothesis number six concerning the existence of any preference pattern among all buffering strategies. In order to test that, all buffering strategies were ranked in terms of the different performance criteria. These ranks were presented in Table 4.5. This table, in conjunction with Tukey's test results in Table 4.2, is used to explore any significant rank difference among all buffering strategies. It should be noted at this point that these comparisons are in terms of the overall performance of the buffering strategies without discussing any potential effects of both uncertainty types and level on the performance of a particular strategy. This analysis will be performed in a later section.

Examination of Tables 4.2 and 4.5 reveals the following points: (1) According to all cost criteria, buffering strategy 5(0/0) performed better than any other strategy. Apparently this is due to the minimal inventory cost incurred because no extra inventory is carried at any level according to this strategy. Because the total cost criterion includes the total shortage cost, which is expected to be relatively high in this case, this performance of strategy 5 seems to indicate that this high shortage cost is offset with a very low inventory investment. This might also indicate that the cost structure applied in this study involves a relatively low shortage cost compared to the carrying cost. Further investigation of the effect of different cost structures seems required.

TABLE 4.5

BUFFERING STRATEGIES RANKED IN TERMS OF DIFFERENT PERFORMANCE MEASURES

(Ranking is based on the overall mean values)

BUFFERING STRATEGY	Performance Measures						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 SS/SS	3	3	3	4	4	4	2
2 SS/SLT	4	4	4	3	3	3	3
3 SLT/SLT	6	6	6	1	2	1	5
4 SLT/SS	5	5	5	2	1	2	4
5 0/0	1	1	1	6	6	6	NA
6 SS/0	2	2	2	5	5	5	1

(2) A close examination of the meaning of all ranks reported in Table 4.5, in light of the results reported in Table 4.2, might reverse the previous conclusion. Table 4.2 shows that the differences between strategies 6(SS/0) and 1(SS/SS) is insignificant regarding total cost criterion. Therefore, if strategy 5 (no buffering) is not considered, both strategies 6(SS/0) and 1(SS/SS) would be ranked first for the total cost criterion, and with significant differences from strategies 2(SS/SLT), 3(SLT/SLT), and 4 (SLT/SS).

(3) The relative lower ranks for strategies 2(SS/SLT), 3(SLT/SLT) and 4(SLT/SS) seems to indicate that if safety lead time is used at either level (higher and/or lower), inventory cost tends to be relatively high.

(4) As expected, buffering strategy 5(0/0) showed the poorest performance results in terms of the number of shortages, number of stockouts and service level. Table 4.2 supports this by indicating that the difference between 5(0/0) and any other strategy is significant.

(5) Strategy 3(SLT/SLT) provides the best protection against supply uncertainty. This strategy was at the top of the list for both number of shortages and service level. However, the difference between this strategy and strategy 4(SLT/SS) is reported to be insignificant. This might imply that using safety lead time for upper level items (end and intermediate items) will yield a good service level regardless of the strategy at the lower level (raw materials) might be. Again, if strategy 5 (no buffering) is not considered, both strategies 6(SS/0) and 1(SS/SS) were the worst in terms of number of shortages and service level criteria. This indicates that the rank for both strategy 6(SS/0) and strategy 1(SS/SS) would be reversed if the performance criterion used is service level rather than inventory cost. At this point, it is also concluded that providing safety stock at all levels or for finished and intermediate items only is more likely to yield the lowest inventory cost but the poorest service level. This conclusion challenges, to some extent, depending on safety stock as the only buffering technique in the multilevel production environment without considering safety lead time as an alternative means to provide protection against supply uncertainty.

(6) From an economic point of view, it seems that strategy 6(SS/0) is the best. This policy out performed all other strategies when considering the buffering cost effectiveness measure. Moreover, strategy 1(SS/SS) ranked the second best with a significant difference from strategy 3(SLT/SLT). Strategy 3, which was the best in terms of the amount of protection provided, is among the worst performance based on the buffering cost effectiveness. In general, Table 4.2 reveals that providing safety lead time at any level (strategies 2, 3, 4) has no economic justification, i.e., the increase in the service level does not justify the extra inventory cost under any of these policies.

(7) Strategy 2(SS/SLT) which was recommended by New (41) never proved to be the best, or even the next best, for any of the response variables.

This analysis shows that some strategies are preferred in terms of all cost criteria while they are undesirable in terms of the number of shortages and service level response variables. Both strategies 6(SS/0) and 5(0/0) are examples of this case. Moreover, the same strategy 6(SS/0) is highly desirable with respect to the buffering cost effectiveness measures. These results seem to lead to rejection of hypothesis number six.

The Effect of Type and Degree of Uncertainty on Selecting a Buffering Strategy.

The analysis up to this point has demonstrated that a buffering strategy may result in different costs and service levels with different supply types and levels. Consequently, one strategy might be preferred under particular uncertainty conditions while the same strategy is undesirable under some other circumstances. This section investigates, in detail, how supply uncertainty types and levels might effect the performance of a given buffering strategy with respect to some key performance measures. These include inventory cost, service level and buffering cost effectiveness.

Although some conclusions in this part are not statistically significant, this investigation may indicate general behavior of particular strategy under specific uncertainty conditions. Through the plots of the means of these response variables generated for each strategy under all combinations of uncertainty types and levels, conclusions regarding the relationships between a buffering strategy and uncertainty conditions might be drawn. Figures C.1 through C.12 present the data reported in Tables C.1 through C.4 for the three performance measures.

Inventory Cost

With respect to inventory cost, Figures C.1 through C.4 show the following:

(1) Buffering strategies 5(0/0) and 6(SS/0) result in the lowest inventory cost. Since strategy 5(0/0) is a "no buffering" policy, strategy 6(SS/0) might be considered the best among all buffering strategies.

(2) If the uncertainty involved at each inventory level is sufficiently low (L/L), the range of the total inventory costs among all the buffering strategies is lower than with the other uncertainty situations.

(3) If the production-inventory system is facing timing uncertainty at both levels (T/T), the range of the total inventory costs between strategies 1(SS/SS) and 6(SS/0) tends to be lower than with the quantity uncertainty at both levels case (Q/Q). This is true in three of the four uncertainty level combinations.

(4) Apparently providing safety lead time at both levels (SLT/SLT) is the worst strategy under all uncertainty conditions. This imples that

it is performing poorly when the system is operating under timing uncertainty at both level (T/T) as well.

(5) Providing safety lead times for upper level items and safety stock for lower level items (SLT/SS) did not perform among the best under the mixed uncertainty case (T/Q). To the contrary, this strategy performs as poorly as the poorest strategy (strategy 3) when a high uncertainty level exists at both levels (H/H) or at the higher level only (H/L).

Service Level

In terms of the service level, Figures C.5 through C.8 show the following:

(1) Buffering strategies 3(SLT/SLT) and 4(SLT/SS) are always among the top performing strategies under all uncertainty types and levels. As expected, strategy 5 (no buffering) consistently showed the poorest performance results.

(2) No noticeable difference is demonstrated among all buffering strategies (except 5) if the system is operating under uncertainty levels 2(L/L) or 3(H/L).

(3) Providing safety stock for finished product and intermediate items only (SS/0) seems undesirable in general especially if the system is facing a high uncertainty at both levels (H/H) or at lower level only (L/H). Moreover, this strategy should be avoided completely if finished and intermediate items are encountering timing uncertainty and high quantity uncertainty exists at the raw material level items.

(4) The insignificant difference among strategies 1 through 4 in most cases seems to challenge Whybark and Williams' (58) logic, SLT for timing uncertainty and SS for quantity uncertainty, when considering buffering a multilevel inventory system if service level is the criterion.

Buffering Cost Effectiveness

With respect to buffering cost effectiveness measure, Figure C.9 through C.12 show the following:

(1) Providing safety stocks for finished and intermediate items only, strategy 6(SS/0), outperformed all other strategies under most uncertainty conditions.

(2) Strategy 6(SS/0) had outstanding performance in two cases as shown in Figures C.10 and C.12. The first case is when both finished and intermediate items encounter low timing uncertainty while raw material items are expecting low quantity uncertainty (LT/LQ). The second case is when upper level items, finished and intermediate, are expecting a low timing uncertainty but low level items, raw materials, are expecting a high quantity uncertainty (LT/HQ).

(3) Surprisingly, neither strategies 2(SS/SLT), 3(SLT/SLT) or 4(SLT/SS) performed well when the system is operating under timing uncertainty at both levels (T/T). They are almost the poorest strategies under this uncertainty condition. This result strongly suggests not to use safety lead time at any level as a part of the buffering strategy in the multi-level buffering case. Once more, this result seems not to confirm the Whybark and Williams' (58) conclusion that using safety lead time is preferred when buffering against timing uncertainty.

CHAPTER V

SUMMARY AND CONCLUSIONS

Objective of the Study

The main objective of this research was to provide some insights into the behavior of a hypothetical multistage multiproduct production-inventory system using different buffering strategies to face different supply uncertainty conditions. Therefore, investigation of the relative effect of different joint (multilevel) buffering strategies on the performance of the system was possible. Moreover, an attempt was made to establish some guidelines for choosing among different buffering strategies when buffering the system against different combinations of supply uncertainty types and levels. Several performance criteria, including inventory cost, service level and buffering cost effectiveness were used to evaluate system performance.

Tests of Hypotheses

Three null hypotheses concerning the main effects of buffering strategy, degree of supply uncertainty and type of supply uncertainty on system performance were presented. The effect of the latter two factors on buffering strategies was also hypothesized in null hypotheses 4 and 5. Finally, null hypothesis 6 was presented to test the existence of any "preference" pattern among different buffering strategies.

The analysis of variance (ANOVA) procedure was used to test the first five null hypotheses concerning the main and interaction effects of the three factors on each of the response variables. Whenever the F-test lead to the conclusion that the factor level means different significantly, Tukey's test was utilized to examine how the different factor levels compare with one another in terms of the system performance measurements. All buffering strategies were ranked according to the overall means of the different performance criteria. These ranks, in conjunction with Tukey's test results were used to test null hypothesis number six. The results of the statistical analysis testing these hypotheses are summarized below.

1. The system performance is affected by the choice of buffering strategy with respect to all seven performance measures employed in this research.
2. The system performance is affected by degree of supply uncertainty with respect to all seven performance measures employed in this research.
3. The system performance is affected by type of supply uncertainty with respect to all seven performance measures employed in this research.
4. Type of supply uncertainty is a significant decision variable regarding the selection of an appropriate buffering strategy according to all performance measures.
5. Degree of supply uncertainty is a significant decision variable regarding the selection of an appropriate buffering strategy according to six of the seven performance measures. The effect of supply uncertainty types on buffering strategy with respect to buffering cost effectiveness measure is not significant.
6. Some strategies are preferred in terms of all cost criteria while they are undesirable in terms of the number of shortages, service level, and buffering cost effectiveness. The opposite was also true for some other strategies, i.e., the "preference" depends on the criteria used to judge the performance of the system.

Summary and Conclusions

The results of the present study show that performance of the production system is significantly influenced by the "buffering strategy" factor. This implies that the system might perform significantly differently, in terms of any of the used seven perofrmance measures, when adapting a particular buffering strategy. Although the relative impact of the strategies is dependent on the performance measure considered, this conclusion seems to be consistent with both the Whybark and Williams (58), and the Liaw (32).

The effect of different uncertainty types on the performance of the system, for this study, is also noticeable for most performance measures. For instance, a system operating under quantity uncertainty at the upper level (finished and intermediate items) and timing uncertainty at the lower level (raw material items) incurs a relatively higher cost than a system operating under the reversed circumstances, i.e., quantity at the lower level and timing at the higher level (T/Q). Another interesting finding is that the difference beween conditions of quantity uncertainty at all levels (Q/Q) and timing uncertainty at all levels (T/T) is insignificant in terms of inventory cost, while the difference between the same two uncertainty types, 2(Q/Q) and 1(T/T), is reported to be the most significant according to service level criterion.

The study also shows that degree of supply uncertainty has a significant impact on system performance. A system operating under a high degree of uncertainty at all levels is likely to incur a higher number of shortages, a lower service level and a higher shortage cost than a system operating under a low degree of uncertainty. Moreover, it was reported that having a higher degree of uncertainty at the upper level (finished and intermediate items) will cause a poor system performance regardless of the degree of uncertainty at the lower level (raw material items) might be. This latter observation can be used to explain the relative importance of the finished and intermediate items.

This research provides empirical evidence that both supply uncertainty type and level are significant decision variables regarding the selection of an appropriate buffering strategy. Interactions between buffering strategy and either type of supply uncertainty or degree of supply uncertainty were found to be significant in most cases. This result indicates that an identification of the uncertainty conditions encountered by the system at each level is a recommended step to make the best of buffering strategies in a multistage, multiproduct production-inventory environment.

With respect to the relative impact of different buffering strategies, the study indicates that it depends on the criteria used to judge the performance of the system. Some strategies were found to be preferred in terms of the cost criteria while they are undesirable in terms of the number of shortages and service level. For instance, providing safety stock at all inventory levels (strategy 1) or for finished and intermediate items only (strategy 6) are more likely to yield the lowest inventory cost but the poorest service level. Another example is strategy 3(SLT/SLT). Providing safety lead time at both levels (strategy 3) yields the best service level but the lowest buffering cost effectiveness in all cases. Thus, the benefits of this strategy are questionable due to its relatively high cost. This result seems to suggest not to use safety lead time at all levels as a buffering strategy. However, a relatively high unit shortage cost to holding cost may alter this conclusion. More research is warranted in this area.

The investigation of the effect of different uncertainty conditions on the performance of different buffering strategies was also conducted in this research to conclude some guidelines which might help the practitioner in selecting the appropriate buffering strategy. These guidelines are summarized in this section according to three selected performance measures. These are inventory cost, service level and buffering cost effectiveness.

According to inventory cost, the investigation indicates that if the uncertainty involved at each inventory level is sufficiently low (L/L), the range of the total inventory cost among all the buffering strategies is lower than with the other uncertainty situations. In light of this observation, it is recommended to MRP users to assess the degree of uncertainty existed at all stages in the system before searching for the "most appropriate" buffering strategy. Under low uncertainty, there always exists a set of "accepted" buffering strategies, among which one can be selected. On the other hand, when the degree of uncertainty at both levels increases, the importance of making the right choice among buffering strategies increases. It is observed also that providing safety lead time at both levels (SLT/SLT) represents the poorest strategy under all uncertainty conditions in terms of inventory cost. Overall, providing safety lead time does not prove to be the best method to protect the system against timing uncertainty. Consistently, strategy 6(SS/0) out performs all other strategies for all cost criteria.

When unit shortage cost is relatively high, MRP users might be interested in using service level as the performance measure. Under such circumstances, using safety lead time at both levels (SLT/SLT) or at upper level only (SLT/SS) are the most recommended strategies. They are always among the top performing strategies under all uncertainty types and levels. Under this case, users must also avoid using strategy 6(SS/0), especially if the system is facing a high uncertainty at both levels (H/H). Using this policy under this circumstance will cause a higher number of shortages and a lower service level. According to the overall performance measure (buffering cost effectiveness) strategy 6(SS/0) seems appropriate. This strategy out performs all other strategies in most cases.

In conclusion, the use of strategy 6(SS/0) is recommended for a lower inventory cost and better buffering cost effectiveness while providing lead times at all levels (SLT/SLT) is recommended for lower shortages and a higher service level.

Toward the end of this research, it is important to mention that all concluded findings during the course of this research should be viewed with a certain amount of caution. These findings are based on the characteristics of the specific simulated system, including the product and cost structures, demand patterns, production system structure, and other specifications resulting from the stated assumptions. To generalize these results, to any extent, requires further investigation along these lines.

Directions for Future Research

Several assumptions have been made to keep the size of this study reasonable. Simply by relaxing any of these assumptions, new avenues of research will be available.

Additional research is warranted to determine why some buffering strategies are superior under a particular uncertainty environment. A close examination of the data, on a case-by-case basis, may be helpful in understanding why a particular strategy affects the system in a specific way under each uncertainty conditions. Many other areas for additional research remain. An obvious extension of this research would be to examine the impact of altering both system structure (more than three stages) and product structure (degree of commonality) on the reported results. The problem will be more complicated if the lead times are different among levels, especially when a parent item requires some component items with considerably different lead time lengths. The effect of different cost structures (unit shortage cost to unit holding cost) on the relative performance of each buffering strategy is another area open to further investigation. Examining the interaction between buffering decisions and various lot-sizing techniques and the effect of demand uncertainty, in addition to supply uncertainty, would be most interesting and would provide a valuable contribution to the body of research in this area.

APPENDIX A

THE RESULTS OF ANALYSIS OF VARIANCE

TABLE A.1

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Buffering Strategy (B)

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	195.38**	.0001
2	Total Setup and Carrying Costs	195.02**	.0001
3	Total Cost	167.04**	.0001
4	Total Number of Units Short	1656.33**	.0001
5	Total Number of Stockouts	748.24**	.0001
6	Service Level	1672.27**	.0001
7	Buffering Cost Effectiveness	19.34**	.0001

$F_{.95\ (5,\ 384)} = 2.21$, $F_{.99\ (5,\ 384)} = 3.02$

TABLE A.2

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Type of Supply Uncertainty (T)

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	60.58**	.0001
2	Total Setup and Carrying Costs	76.50**	.0001
3	Total Cost	61.22**	.0001
4	Total Number of Units Short	495.53**	.0001
5	Total Number of Stockouts	78.27**	.0001
6	Service Level	509.42**	.0001
7	Buffering Cost Effectiveness	9.39**	.0001

$F_{.95\ (3,\ 384)} = 2.60$, $F_{.99\ (3,\ 384)} = 3.78$

TABLE A.3

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Degree of Supply Uncertainty (D)

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	99.00**	.0001
2	Total Setup and Carrying Costs	85.53**	.0001
3	Total Cost	81.83**	.0001
4	Total Number of Units Short	440.44**	.0001
5	Total Number of Stockouts	83.96**	.0001
6	Service Level	439.10**	.0001
7	Buffering Cost Effectiveness	3.12*	.0261

$F_{.95\ (3,\ 384)} = 2.60$, $F_{.99\ (3,\ 384)} = 3.78$

TABLE A.4

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Interaction Between B and T

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	2.10**	.0095
2	Total Setup and Carrying Costs	2.15**	.0077
3	Total Cost	1.70*	.0485
4	Total Number of Units Short	43.19**	.0001
5	Total Number of Stockouts	9.75**	.0001
6	Service Level	45.36**	.0001
7	Buffering Cost Effectiveness	2.87**	.0009

$F_{.95\ (15,\ 384)} = 1.67$, $F_{.99\ (15,\ 384)} = 2.04$

TABLE A.5

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Interaction Between B and D

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	11.44**	.0001
2	Total Setup and Carrying Costs	11.30**	.0001
3	Total Cost	11.04**	.0001
4	Total Number of Units Short	125.93**	.0001
5	Total Number of Stockouts	29.39**	.0001
6	Service Level	125.64**	.0001
7	Buffering Cost Effectiveness	1.34	.1952

$F_{.95}$ (15, 384) = 1.67, $F_{.99}$ (15, 384) = 2.04

TABLE A.6

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Interaction Between T and D

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	11.08**	.0001
2	Total Setup and Carrying Costs	11.97**	.0001
3	Total Cost	10.85**	.0001
4	Total Number of Units Short	12.74**	.0001
5	Total Number of Stockouts	3.64**	.0003
6	Service Level	12.81**	.0001
7	Buffering Cost Effectiveness	3.36**	.0007

$F_{.95\,(9,\ 384)} = 1.88$, $F_{.99\,(9,\ 384)} = 2.41$

TABLE A.7

ANALYSIS OF VARIANCE-FIXED EFFECT MODEL

Source of Variation: Interaction Between B, T and D

No.	Performance Measure	Observed F Statistic	PR > F
1	Inventory Carrying Cost	.87	.7165
2	Total Setup and Carrying Costs	.86	.7256
3	Total Cost	.85	.7473
4	Total Number of Units Short	2.00	.0003
5	Total Number of Stockouts	3.25	.0001
6	Service Level	2.23	.0001
7	Buffering Cost Effectiveness	1.05	.3990

$F_{.95\ (45,\ 384)} = 1.35$, $F_{.99\ (45,\ 384)} = 1.59$

APPENDIX B

THE RESULTS OF TUKEY'S MULTIPLE COMPARISON TEST

TABLE B.1

D STATISTIC FOR THE MODIFIED VERSION OF KOLMOGOROV-SMIRNOV TEST OF NORMALITY, FOR ALL PERFORMANCE MEASURES

PERFORMANCE	D-STATISTIC	PROB>D
HOLC	0.17037	<0.01
INVC	0.151875	<0.01
TOC	0.156375	<0.01
BO	.216795	<0.01
STK	0.22551	<0.01
SLVL	0.218704	<0.01
RRHTH	0.264667	<0.01

Conclusion: Normality assumption is satisfied for all performance measures.

TABLE B.2

THE HARTLEY'S TEST STATISTIC H FOR ALL PERFORMANCE MEASURES AND FACTOR LEVELS

$\alpha = .01$

Performance Measure	Among B Levels(1)	Among T Levels(2)	Among D Levels(2)
HOLC	17.380	3.397	9.808
INVC	14.157	3.679	9.078
TOC	15.428	3.956	8.225
BO	37.937	2.532	8.146
STK	43.784	1.370	3.703
SLVL	38.412	2.565	7.810
BCEM	134.623(3)	29.592	23.500

(1) $H_{(.99,\ r\ =\ 6,\ n\ =\ 5} = 69$

(2) $H_{(.99,\ r\ =\ 4,\ n\ =\ 5)} = 49$

(3) $H_{(.99,\ r\ =\ 5,\ n\ =\ 5)} = 59$

Decision Rule:

If $H \leq H_{(1-\alpha;\ r,\ n)}$, Conclude $C_1 : \sigma_1^2 = \sigma_1^2 = \sigma_2^2 = \ . \ . \ . \ \sigma_r^2$

If $H > H_{(1-\alpha;\ r,\ n)}$, Conclude C_2 : not all σ_i^2 are equal.

Conclusion:

The equality of variances assumption is fulfilled for all measures among each factor levels with one exception. The assumption is not fulfilled for BCEM among factor B levels.

TABLE B.3

TUKEY'S MULTIPLE COMPARISON TEST FOR BUFFERING STRATEGY

$\alpha = .05$

SUBSET	GROUPS
	<u>Performance Measure: HOLC</u>
A	3(SLT/SLT)
B	4(SLT/SS)
C	2(SS/SLT)
D	1(SS/SS)
E	6(SS/0)
F	5(0/0)
	<u>Performance Measure: INVC</u>
A	3(SLT/SLT)
B	4(SLT/SS)
C	2(SS/SLT)
D	1(SS/SS)
E	6(SS/0)
F	5(0/0)
	<u>Performance Measure: TOC</u>
A	3(SLT/SLT)
B	4(SLT/SS)
C	2(SS/SLT)
D	1(SS/SS), 6(SS/0)
E	5(0/0)

TABLE B.3 (Continued)

	Performance Measure: BO
A	5(0/0)
B	6(SS/0)
C	1(SS/SS), 2(SS/SLT)
D	4(SLT/SS), 3(SLT/SLT)
	Performance Measure: STK
A	S(0/0
B	6(SS/0)
C	1(SS/SS), 2(SS/SLT)
D	3(SLT/SLT), 4(SLT/SS)
	Performance Measure: SLVL
A	3(SLT/SLT), 4(SLT/SS)
B	2(SS/SLT), 1(SS/SS)
C	6(SS/0)
D	5(0/0)
	Performance Measure: BCEM
A	6(SS/0)
B	1(SS/SS), 2(SS/SLT)
C	2(SS/SLT), 4(SLT/SLT), 3(SLT/SLT)

TABLE B.4

TUKEY'S MULTIPLE COMPARISON TEST FOR TYPE OF SUPPLY UNCERTAINTY

$\alpha = .05$

SUBSET	GROUPS
	Performance Measure: HOLC
A	4(Q/T)
B	1(T/T)
C	2(Q/Q), 3(T/Q)
	Performance Measure: INVC
A	4(Q/T)
B	1(T/T), 2(Q/Q)
C	3(T/Q)
	Performance Measure: TOC
A	1(T/T)
B	3(T/Q)
C	4(Q/T)
D	2(Q/Q)
	Performance Measure: BO
A	1(T/T)
B	3(T/Q)
C	4(Q/T)
D	2(Q/Q)

Table B.4 (Continued)

	Performance Measure: STK
A	1(T/T)
B	3(T/Q)
C	4(Q/T)
D	5(Q/Q)
	Performance Measure: SLVL
A	2(Q/Q)
B	4(Q/T)
C	3(T/Q)
D	1(T/T)
	Performance Measure: BCEM
A	3(T/Q)
B	1(T/T), 4(Q/T), 2(Q/Q)

TABLE B.5

TUKEY'S MULTIPLE COMPARISON TEST

FOR DEGREE OF SUPPLY UNCERTAINTY

$\alpha = .05$

SUBSET	GROUPS
	Performance Measure: HOLC
A	1(H/H)
B	4(L/H), 3(H/L)
C	2(L/L)
	Performance Measure: INVC
A	1(H/H)
B	4(L/H)
C	3(H/L)
D	2(L/L)
	Performance Measure: TOC
A	1(H/H)
B	4(L/H)
C	3(H/L)
D	2(L/L)
	Performance Measure: BO
A	1(H/H)
B	3(H/L)
C	4(L/H)
D	2(L/L)

TABLE B.5 (Continued)

	Performance Measure: STK
A	1(H/H)
B	3(H/L)
C	4(L/H)
D	2(L/L)
	Performance Measure: SLVL
A	2(L/L)
B	4(L/H)
C	3(H/L)
D	1(H/H)
	Performance Measure: BCEM
A	2(L/L), 4(L/H), 3(H/L)
B	4(L/H), 3(H/L), 1(H/H)

TABLE B.4

MEAN VALUES OF ALL PERFORMANCE MEASURES FOR DIFFERENT BUFFERING STRATEGY LEVELS

BUFFERING STRATEGY	Performance Measure						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 (SS/SS)	4399011.	5696064.	5716908.	2651	21	.9492	5.0030
2 (SS/SLT)	5774867.	7058400.	7118643.	2384	18	.9542	2.8997
3 (SLT/SLT)	7949158.	9218915.	9262057.	1819	12	.9650	1.7641
4 (SLT/SS)	6441580.	7728412.	7833235.	1876	12	.9639	2.5527
5 (0/0)	2992965.	4267145.	4414256.	9215	78	.8216	NA
6 (SS/0)	3823996.	5106880.	5177692.	3641	32	.9296	8.5542

TABLE B.5

MEAN VALUES OF ALL PERFORMANCE MEASURES FOR DIFFERENT TYPES OF SUPPLY UNCERTAINTY

TYPE OF SUPPLY UNCERTAINTY	Performance Measure						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 (T/T)	5502899.	653391.	6661081.	5075	36	.9014	3.8278
2 (Q/Q)	4645480.	6152078.	6229350.	2125	20	.9593	2.6560
3 (T/Q)	4487193.	5576480.	5671005.	4066	31	.9218	6.6013
4 (Q/T)	6287336.	7778196.	7786982.	3126	27	.9399	3.5341

TABLE B.6

MEAN VALUES OF ALL PERFORMANCE MEASURES FOR DIFFERENT DEGREES OF SUPPLY UNCERTAINTY LEVELS

DEGREE OF SUPPLY UNCERTAINTY	Performance Measure						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 (H/H)	6474212.	7651837.	7760093.	4958	36	.9045	2.9745
2 (L/L)	3886796.	5253766.	5267746.	2078	20	.9601	5.1956
3 (H/L)	5120979.	6330905.	6440000.	3888	32	.9250	3.7739
4 (L/H)	5230729.	6793945.	6880584.	3467	29	.9328	4.6751

TABLE B.7

TYPE OF SUPPLY UNCERTAINTY LEVELS RANKED IN TERMS OF DIFFERENT PERFORMANCE MEASURES

TYPE OF SUPPLY UNCERTAINTY	Performance Measures						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 T/T	3	3	3	4	4	4	2
2 Q/Q	2	2	2	1	1	1	4
3 T/Q	1	1	1	3	3	3	1
4 Q/T	4	4	4	2	2	2	3

TABLE B.8

DEGREE OF SUPPLY UNCERTAINTY LEVELS RANKED IN TERMS OF DIFFERENT PERFORMANCE MEASURES

DEGREE OF SUPPLY UNCERTAINTY	Performance Measures						
	HOLC	INVC	TOC	BO	STK	SLVL	BCEM
1 H/H	4	4	4	4	4	4	4
2 L/L	1	1	1	1	1	1	1
3 H/L	2	2	2	3	3	3	3
4 L/H	3	3	3	2	2	2	2

APPENDIX C

SOME TABLES AND GRAPHS FOR RELATIVE PREFERENCE ANALYSIS

TABLE C.1

TOTAL SETUP AND CARRYING COST, SERVICE LEVEL AND BUFFERING COST EFFECTIVENESS WITH DEGREE OF SUPPLY UNCERTAINTY = 1(H/H)

(Average of Five Runs)

TYPE OF SUPPLY UNCERTAINTY	Buffering Strategy					
	1(SS/SS)	2(SS/SLT)	3(SLT/SLT)	4(SLT/SS)	5(0/0)	6(SS/0)
1(T/T)	5716617. .9015 4.70	8433757. .9014 1.86	11684632. .9412 1.12	10136111. .9411 1.41	4140845. .5850 -	5506390. .8579 4.28
2(Q/Q)	6022291. .9662 4.27	7547021. .9679 2.43	10788702. .9722 1.29	9357132. .9722 1.64	4052835. .7861 -	5215265. .9572 6.89
3(T/Q)	5307630. .9237 4.24	6774632. .9278 2.37	9449184. .9533 1.45	8122208. .9532 1.86	3518008. .7014 -	4537552. .8935 6.58
4(Q/T)	7978082. .9489 3.36	10510178. .9495 1.77	1459282. .9532 .99	12212308. .9532 1.29	5254234. .7536 -	6787520. .9375 5.64

TABLE C.2

TOTAL SETUP AND CARRYING COST, SERVICE LEVEL AND BUFFERING COST EFFECTIVENESS WITH DEGREE OF SUPPLY UNCERTAINTY = 2(L/L)

(Average of Five Runs)

TYPE OF SUPPLY UNCERTAINTY	Buffering Strategy					
	1(SS/SS)	2(SS/SLT)	3(SLT/SLT)	4(SLT/SS)	5(0/0)	6(SS/0)
1(T/T)	4491037. .9402 8.03	5089676. .9463 4.76	5817591. .9633 4.10	5580978. .9644 4.18	3798475. .8556 -	4275338. .9208 8.94
2(Q/Q)	4909840. .9810 1.25	5422126. .9825 .74	6573204. .9810 .39	6060766. .9810 .49	4156522. .9787 -	4631670. .9809 2.00
3(T/Q)	4529998. .9647 10.64	5052058. .9667 5.79	6004788. .9772 3.82	5480592. .9772 5.22	3880533. .9047 -	4247177. .9586 20.64
4(Q/T)	5625173. .9749 6.11	6384629. .9756 3.48	7690174. .9756 1.95	6919010. .9756 2.61	4687813. .9436 -	5263081. .9718 8.97

TABLE C.3

TOTAL SETUP AND CARRYING COST, SERVICE LEVEL AND BUFFERING COST EFFECTIVENESS WITH DEGREE OF SUPPLY UNCERTAINTY = 3(H/L)

(Average of Five Runs)

TYPE OF SUPPLY UNCERTAINTY	Buffering Strategy					
	1(SS/SS)	2(SS/SLT)	3(SLT/SLT)	4(SLT/SS)	5(0/0)	6(SS/0)
1(T/T)	5031107. .9254 4.90	5595356. .9335 3.68	8329023. .9541 1.76	5680978. .9404 3.66	3580978. .7389 -	4781046. .9172 5.53
2(Q/Q)	5695553. .9696 5.09	6207214. .9698 3.84	9572210. .9739 1.51	6295208. .9706 3.70	4127314. .8492 -	5421675. .9687 6.12
3(T/Q)	4922469. .9286 5.71	5455774. .9328 4.10	8322444. .9600 1.84	7776051. .9600 2.10	3591623. .7352 -	4675796. .9219 6.89
4(Q/T)	6652067. .9641 4.21	7415191. .9658 3.07	11299634. .9689 1.29	10531587. .9689 1.45	4675067. .8204 -	6296836. .9623 5.04

TABLE C.4

TOTAL SETUP AND CARRYING COST, SERVICE LEVEL AND BUFFERING COST EFFECTIVENESS WITH DEGREE OF SUPPLY UNCERTAINTY = 4(L/H)

(Average of Five Runs)

TYPE OF SUPPLY UNCERTAINTY	Buffering Strategy					
	1(SS/SS)	2(SS/SLT)	3(SLT/SLT)	4(SLT/SS)	5(0/0)	6(SS/0)
1(T/T)	7235842.	10558841.	11432057.	9021264.	5023460.	5858185.
	.9178	.9365	.9531	.9519	.7867	.8511
	3.21	1.47	1.30	2.20	-	5.45
2(Q/Q)	5256403.	6760785.	7900914.	6370693.	4469439.	4836967.
	.9747	.9781	.9783	.9779	.9485	.9614
	3.07	1.78	1.34	2.01	-	3.23
3(T/Q)	4879885.	6355802.	7270832.	5831007.	3774232.	4077050.
	.9536	.9669	.9771	.9769	.8149	.8936
	7.01	3.23	2.58	4.46	-	31.71
4(Q/T)	6884038.	9372527.	10775550.	8280555.	5131293.	5699245.
	.9522	.9583	.9583	.9583	.8486	.9186
	4.39	2.01	1.50	2.56	-	8.99

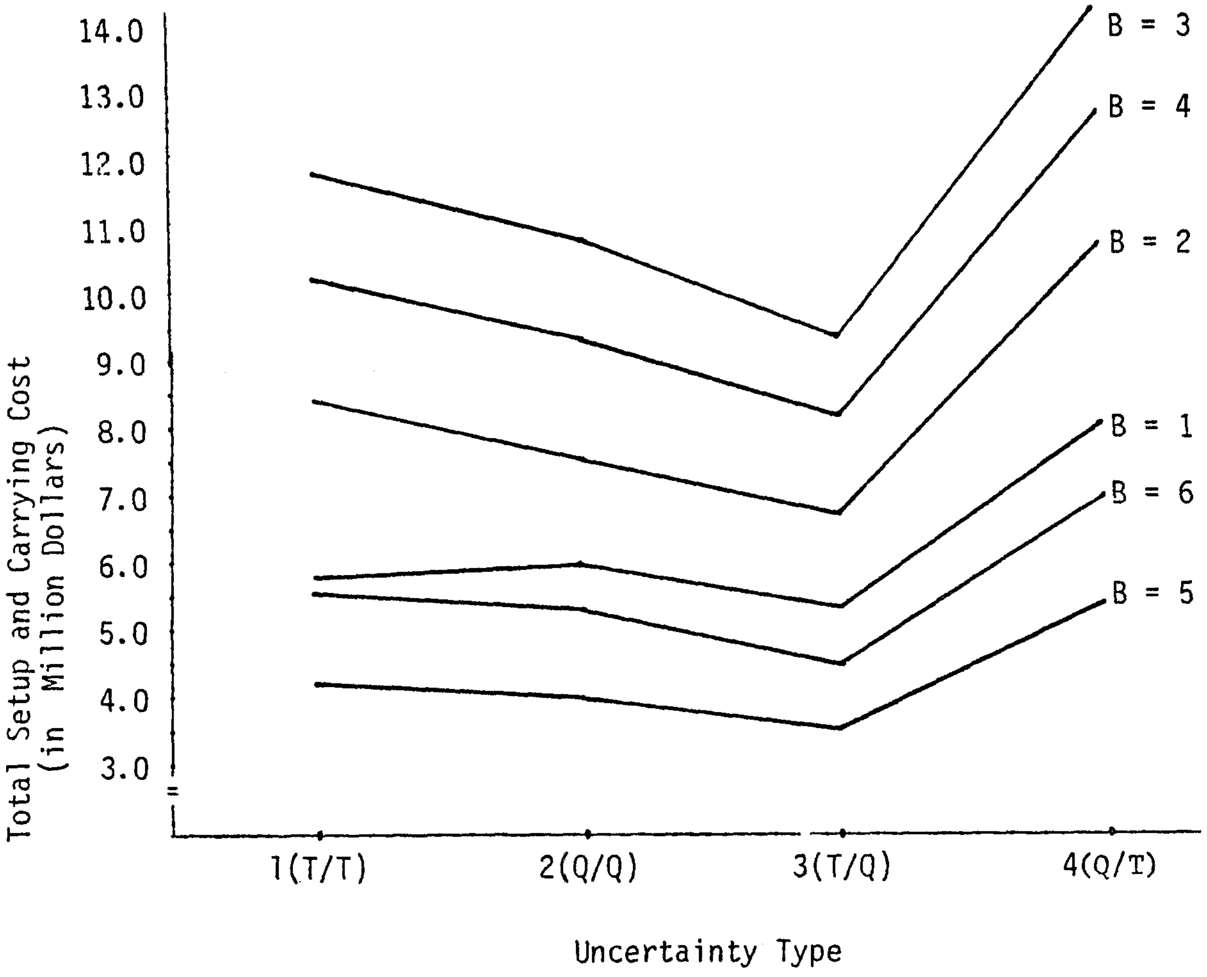

FIGURE C.1 Total Setup and Carrying Cost
Degree of Uncertainty (D)= 1(H/H)

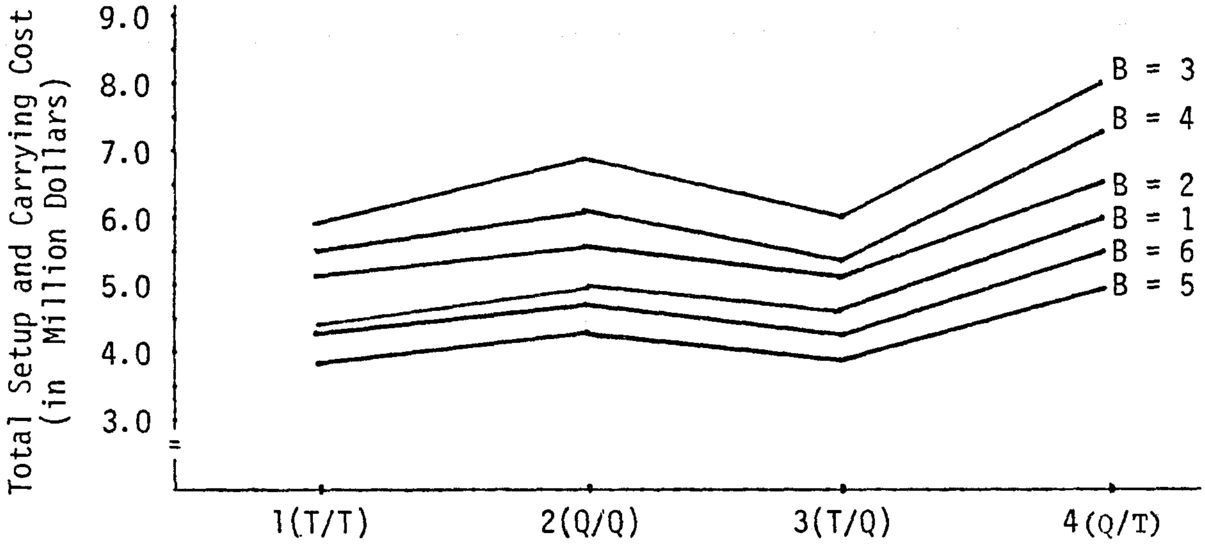

FIGURE C.2 Total Setup and Carrying Cost
Degree of Uncertainty (D)= 2(L/L)

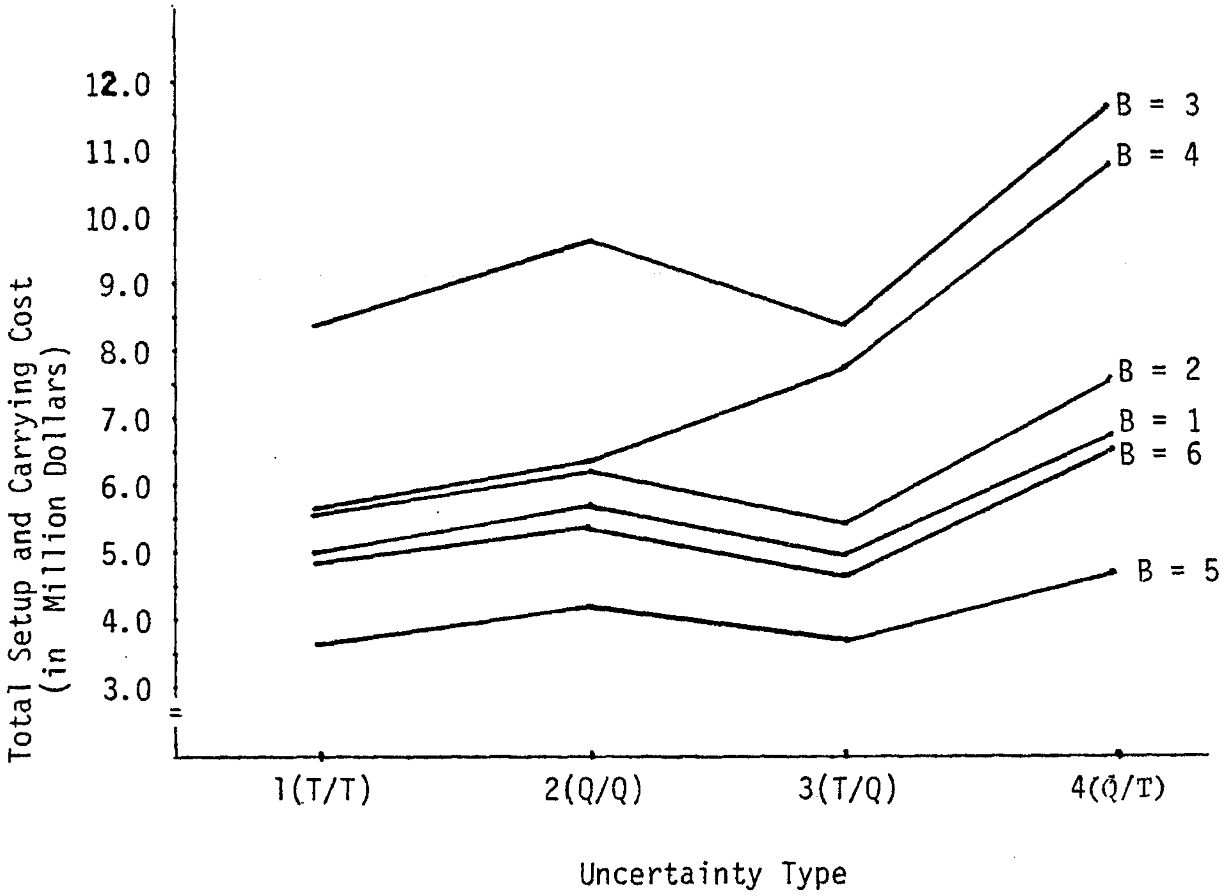

FIGURE C.3 Total Setup and Carrying Cost
Degree of Uncertainty (D)= 3(H/L)

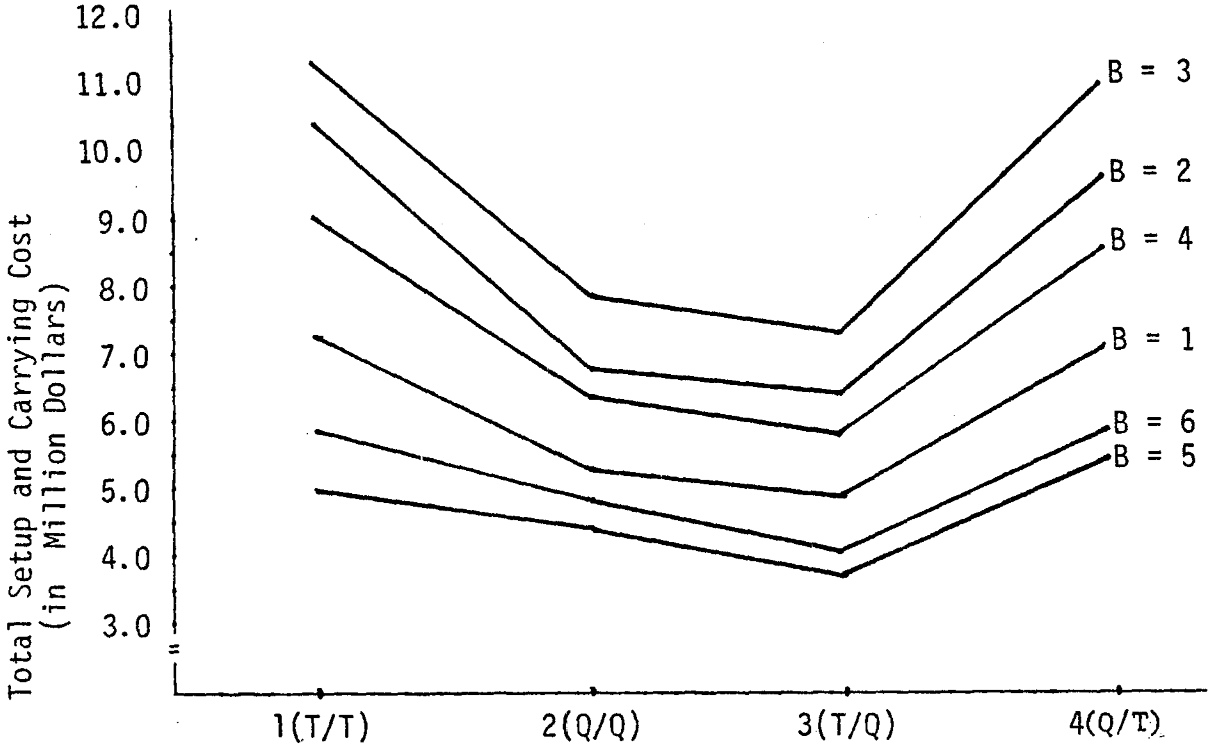

FIGURE C.4 Total Setup and Carrying Cost
Degree of Uncertainty (D)= 4(L/H)

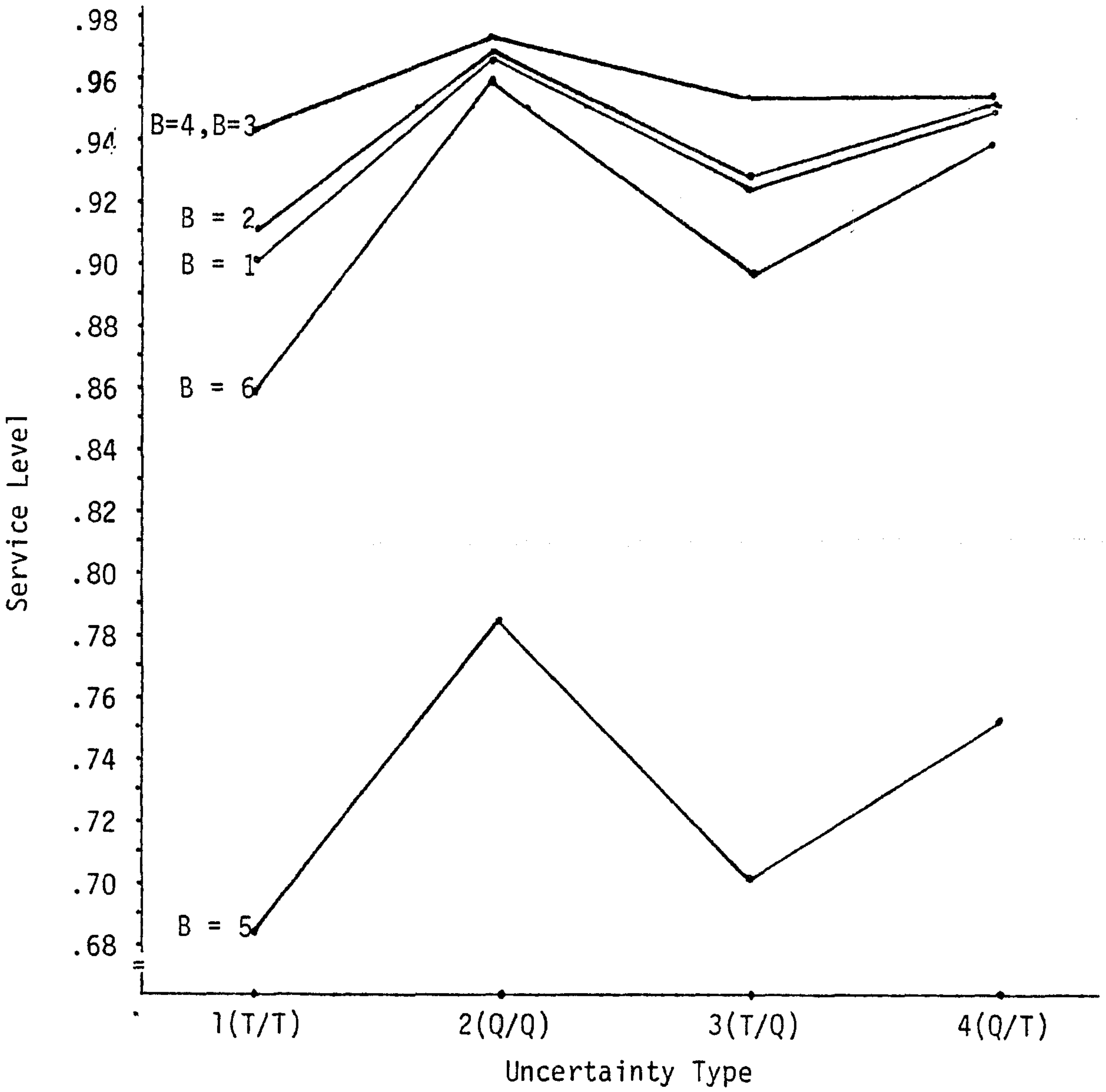

FIGURE C.5 Service Level Values
Degree of Uncertainty (D)= 1(H/H)

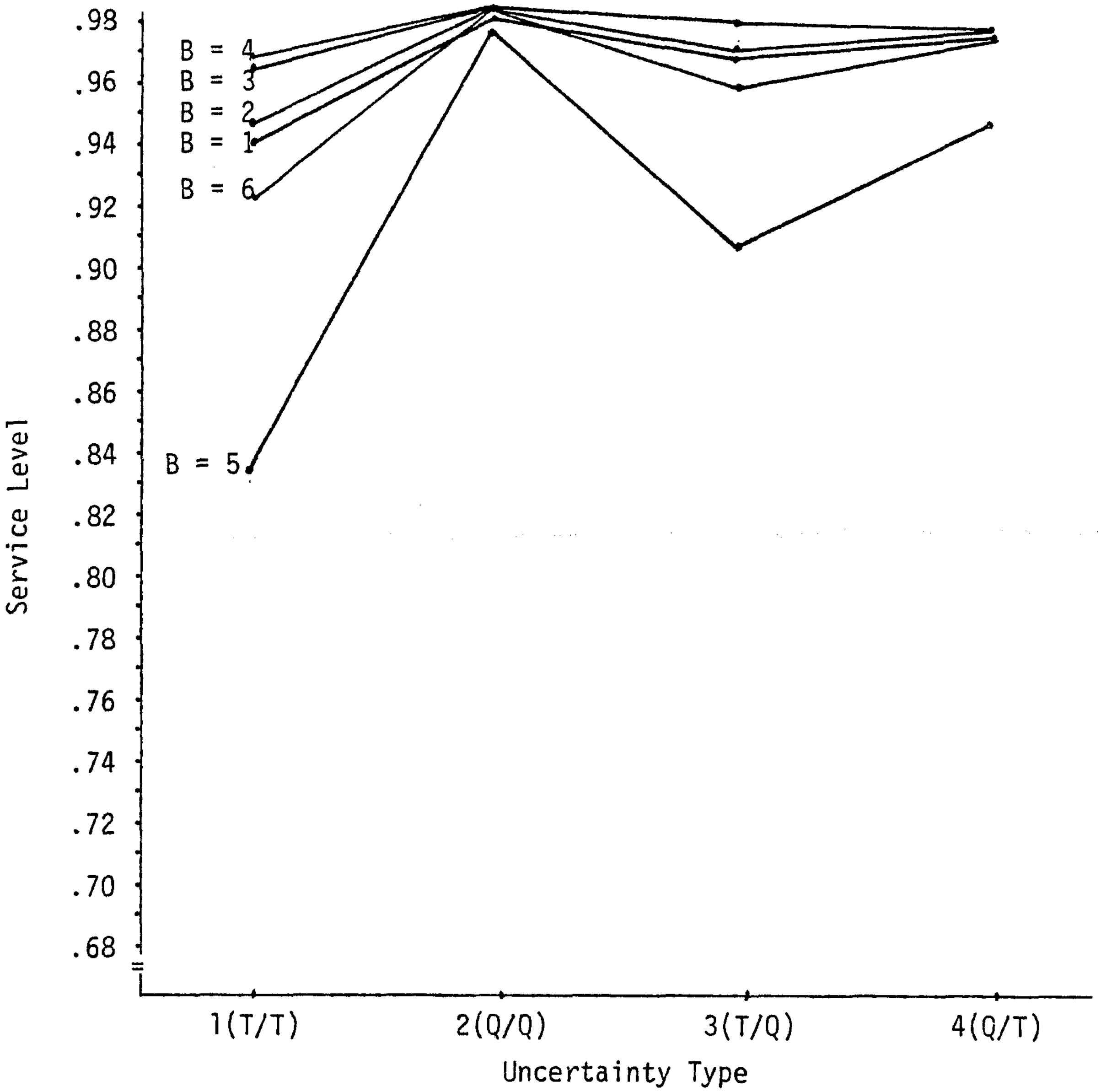

FIGURE C.6 Service Level Values
Degree of Uncertainty (D)= 2(L/L)

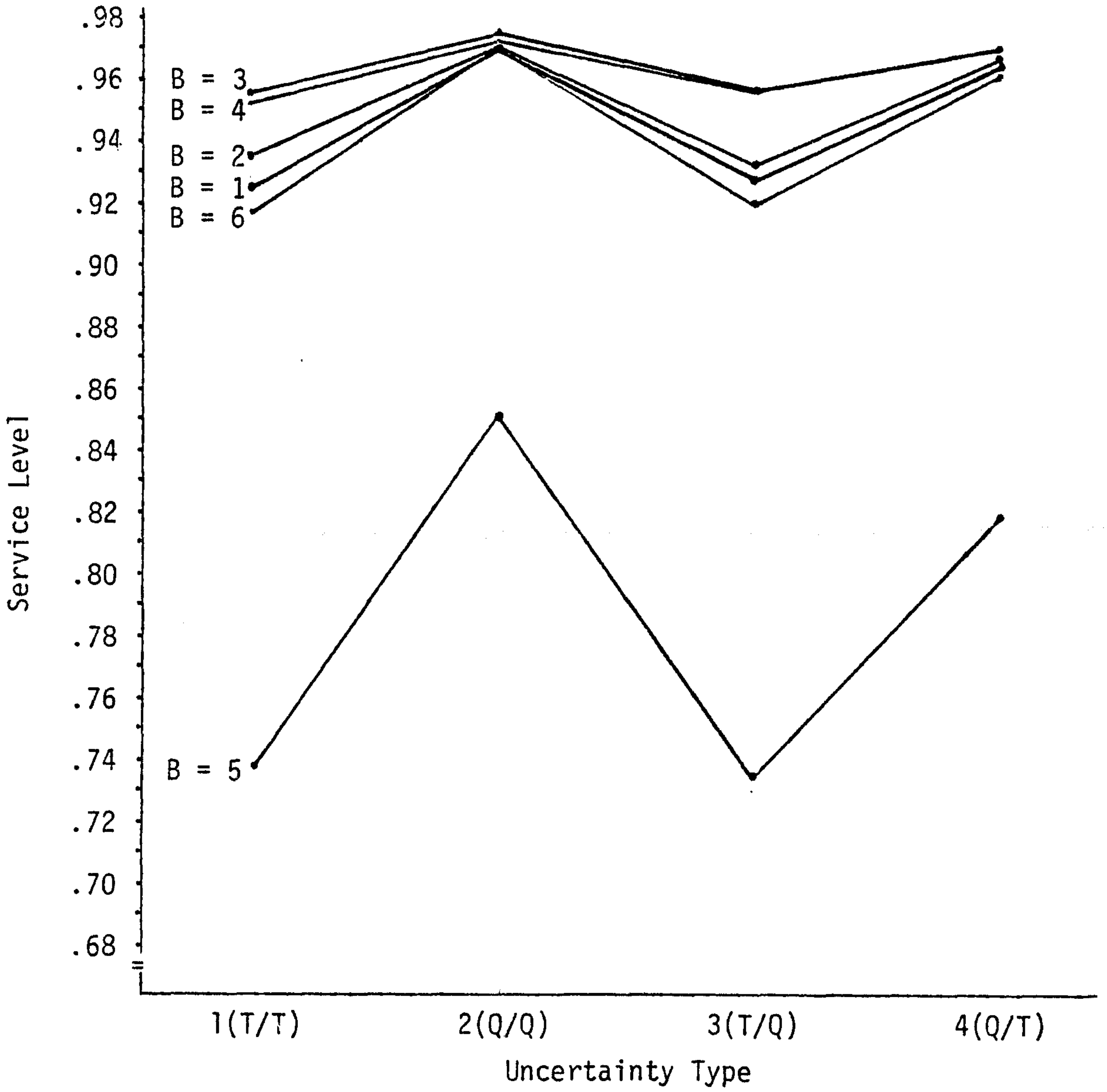

FIGURE C.7 Service Level Values
Degree of Uncertainty (D)= 3(H/L)

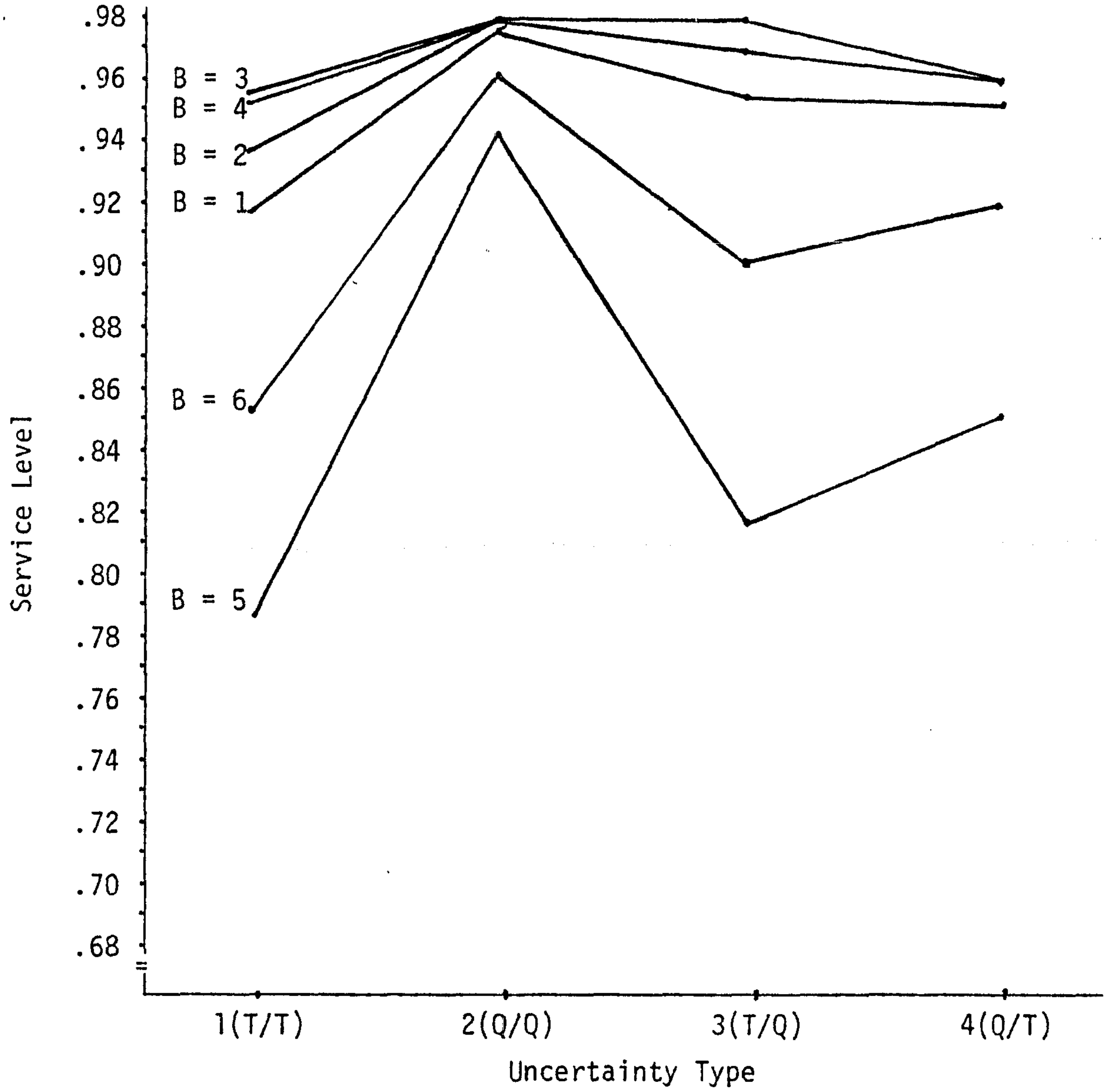

FIGURE C.8 Service Level Values
Degree of Uncertainty (D)= 4(L/H)

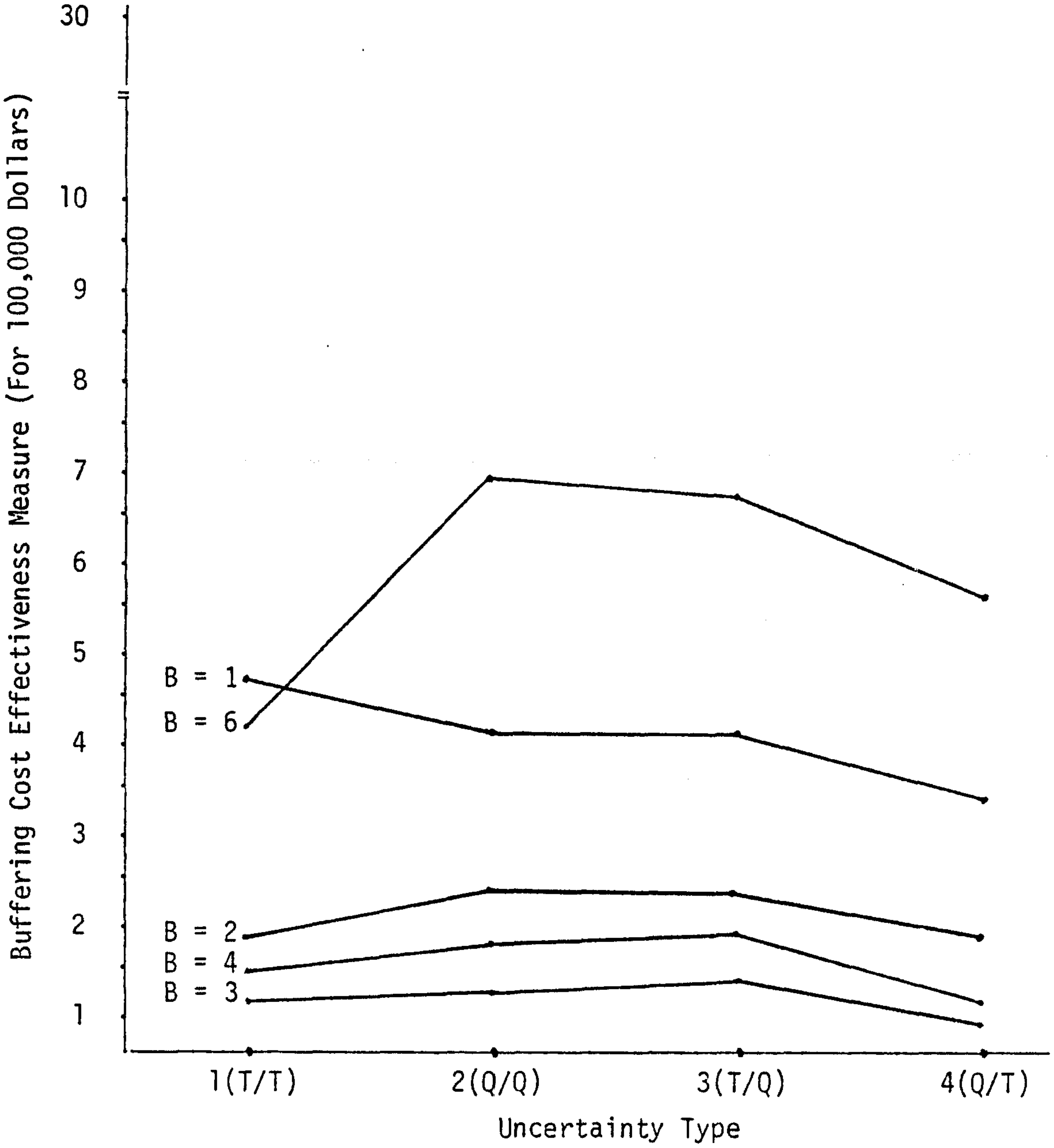

FIGURE C.9 Inventory Rate of Return
Degree of Uncertainty (D)= 1(H/H)

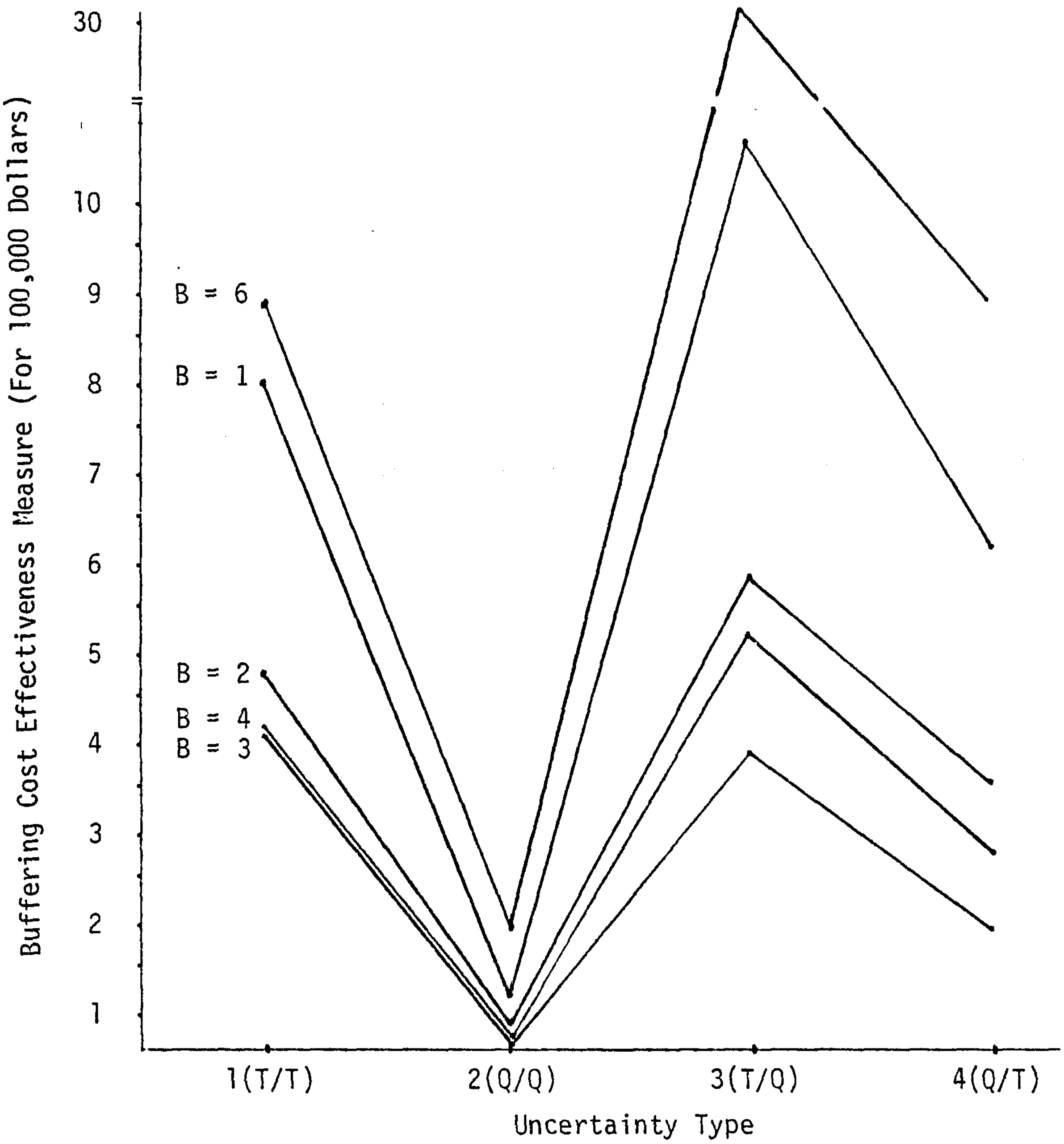

FIGURE C.10 Inventory Rate of Return
Degree of Uncertainty (D)= 2(L/L)

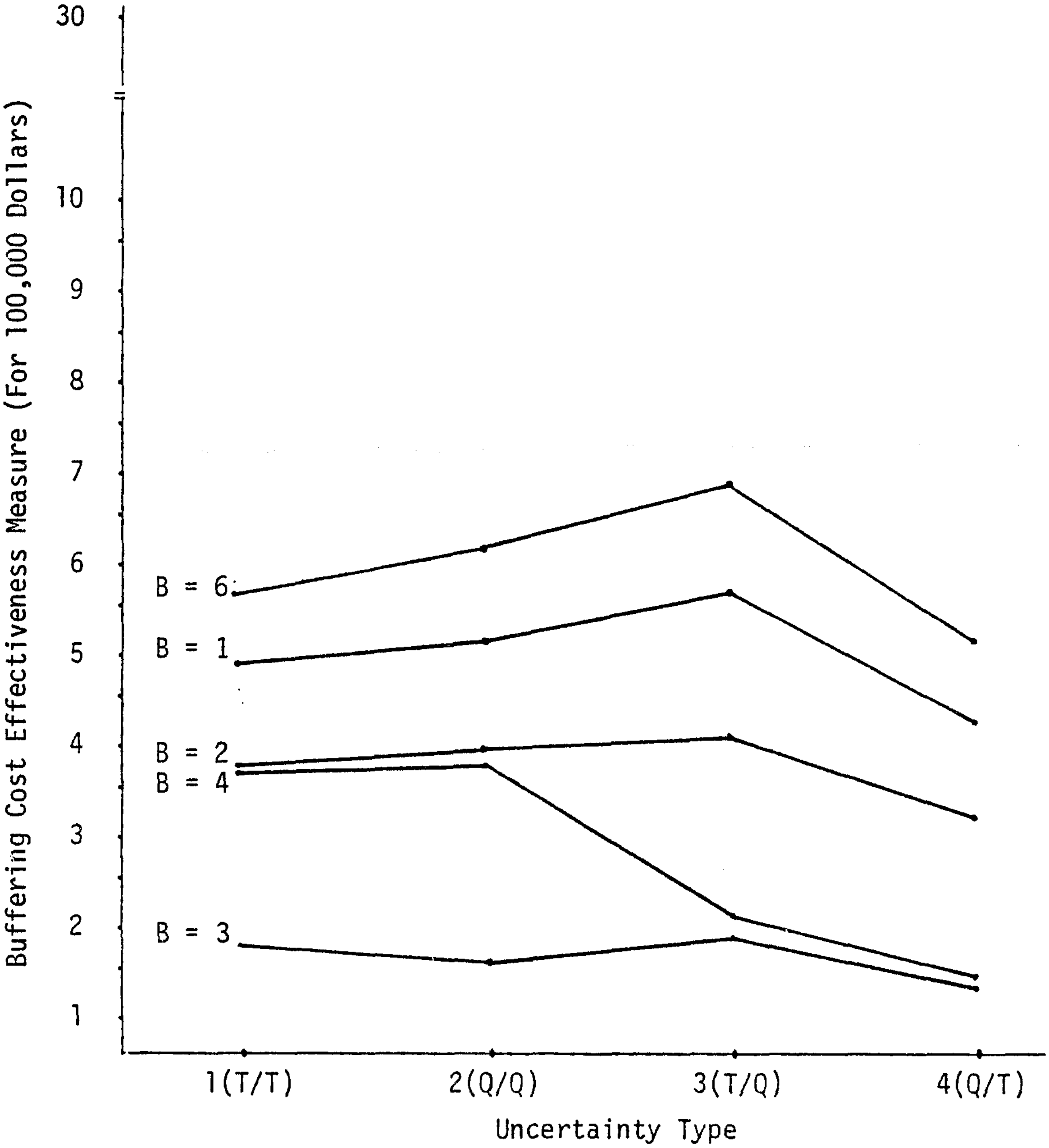

FIGURE C.11 Inventory Rate of Return
Degree of Uncertainty (D)= 3(H/L)

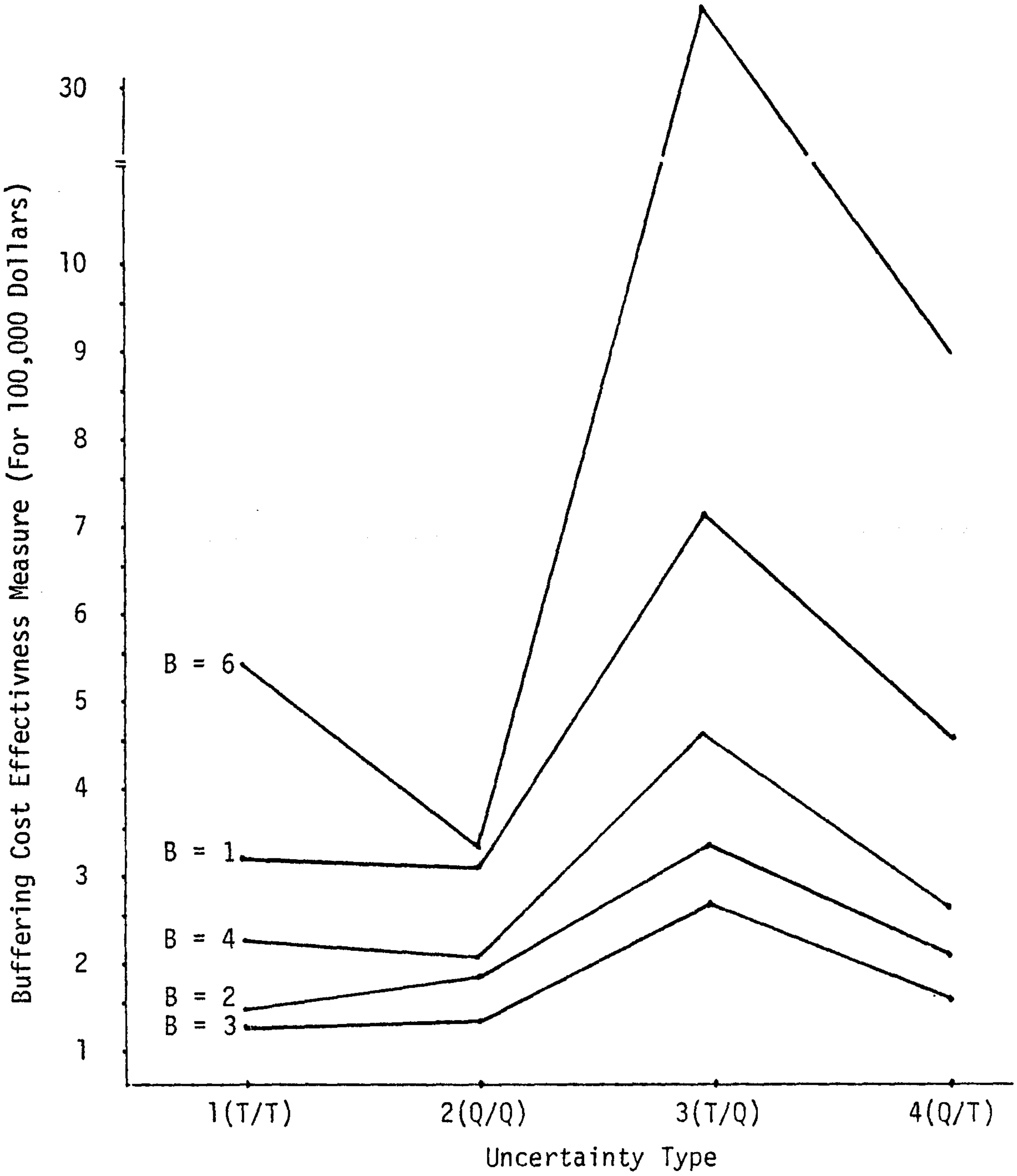

FIGURE C.12 Inventory Rate of Return
Degree of Uncertainty (D)= 4(L/H)

APPENDIX D

SIMULATION PARAMETERS

Three different types of data were required to conduct this study. Some of them are required as an input to the MRP system. The second type is related to the production and replenishment process of all orders released by the MRP stage. The last category is some cost data required to evaluate the performance of the production system as a whole. This appendix presents these three categories of data.

MRP INPUT

The three major inputs of an MRP system are the master production schedule, the product structure records, and the inventory status files. Some details about the information provided in each are reported in this section.

Master Schedule

A deterministic and constant demand by planning period and quantity for end items are stated in the Master Schedule File. Because uncertainty of supply is the only source of risk considered in this study, a deterministic end-item demand was assumed; i.e., a perfect forecast. Also, in order to eliminate the effect of demand variability on the need for safety stocks a constant end-item demand was used. Callarman and Mabert (11) have shown that for very small demand variability, as measured by the coefficient of variation, no safety stock was needed to attain high service levels.

A constant weekly demand of one hundred units, two hundred units, three hundred units and four hundred units, for end items one through four respectively, was provided.

Bill of Materials File

This file includes product structure and the number of units required in each assembly.

There are four end products in the product structure file, each calling for two assembly groups and one raw material. Seven categories of raw materials are used in the assembly process and are assumed to be purchased from outside suppliers. Figure D.1 shows the bill of material with a hierarchy of components in each assembly and subassembly. Parent-component relationship and the number of units of the components required in an assembly or subassembly are also specified in Table D.1. In spite of the fact that degree of commonality is not of major concern in this study, the selected product structure implies the high commonality level case according to Collier's measure for the degree of commonality (15). Commonality degree (C) is equal to 2.33 in this research.

TABLE D.1

Parent-Component Relationship in the Product Structure File

Parent Item	Component Item	Units Required in Assembly
1	5, 6, 16	One
2	5, 7, 16	One
3	5, 8, 16	One
4	5, 9, 16	One
5	10, 11	One
6	10, 12	One
7	10, 13	One
8	10, 14	One
9	10, 15	One

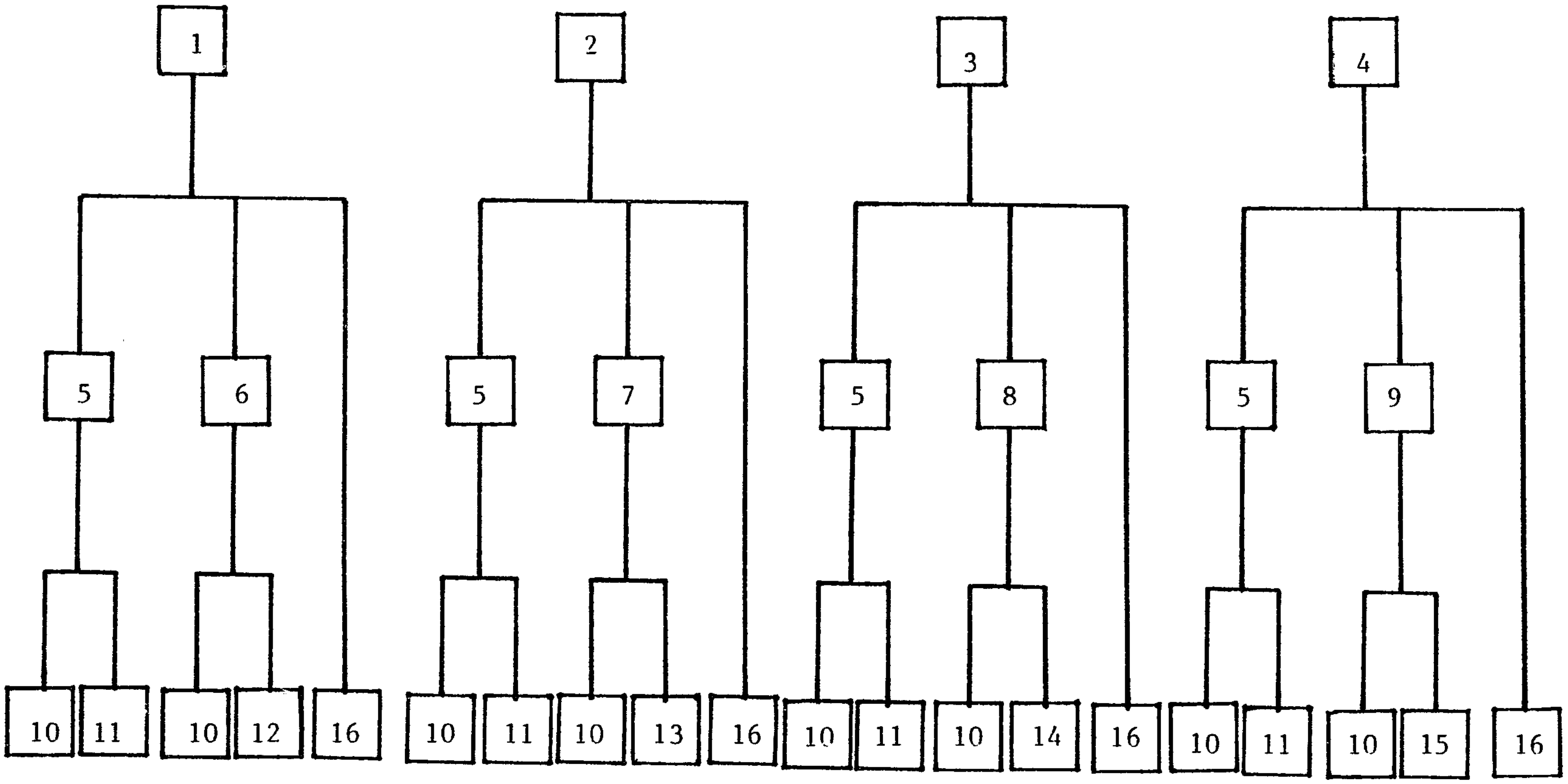

FIGURE D.1 Hierarchy of Bill of Materials

Inventory Files

These files include information about initial inventory, lead time, lot sizing rule, the amount of safety stock and any scheduled receipts for each item in the product structure. The initial inventory for each item was selected at a level that minimizes the warm-up period as indicated in Chapter III. This level is equivalent to one-half period demand for each item. The demand for all intermediate items was derived from the requirements of its parent item(s).

The lead times for all inventory items are assumed to be one period, a week, in the simulation model. For items processed in the factory, this one week includes both setup and processing times.

As for lot sizing rule, a lot-for-lot rule was selected for all items all over the hierarchy. This eliminated the variation in the projected stock due to batching.

The amount of safety stock required for each item was estimated as a function of the degree of supply uncertainty and the desired service level as explained in Chapter III. These values are as follows:

a. D = High (HQ = .3 or HT = 1)

Items	1-8	90	180	270	360	900	90	180	270
Items	9-16	360	1800	900	90	180	270	360	900

b. D = Low (LQ = .1 or LT = .2)

Items	1-8	30	60	90	120	300	30	60	90
Items	9-16	120	600	300	30	60	90	120	300

All scheduled receipts were set to equal zero for all items in this study.

PRODUCTION AND REPLENISHMENT DATA

This set of data includes setup and run times for each item and the amount of capacity available at each department in terms of the size of the work force. Following is a list of both setup and run times in terms of the amount of manhours required.

Item No.	Setup Time							
1 - 8	1000.0	900.0	800.0	700.0	600.0	550.0	500.0	450.0
9 - 16	400.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Item No.	Run Time							
1 - 8	5.0	3.0	4.0	4.5	3.0	3.0	4.0	2.5
9 - 16	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The regular capacity available was specified in terms of number of people available in each department as 300, 500 and 5 in departments one, two and three respectively. This is equivalent to 120,000, 20,000 and 200 weekly man-hours (assuming 40 working hours a week). An overtime capacity is also available in each department for situations when the labor requirements exceed the available labor force. It is limited to only 30% of regular time capacity.

COST DATA

The labor cost was set at five dollars per hour in all three departments, while raw material unit costs for items 10 - 16 were as follows:

$ 20.00 5.00 2.00 10.00 50.00 5.00 10.00

The unit cost of each item throughout the simulation was calculated based on the cost of its components and the labor cost involved in producing one unit of that item. Carrying cost was set at 24% of the calculated unit cost for each item. A shortage cost per unit of 40% of the unit cost of the item short and an overtime cost set at one and one-half times the regular time cost were used to calculate the "total cost" performance measure.

APPENDIX E

THE PROGRAM DOCUMENTATION

LIST OF SYMBOLS

AP(I) = Actual Production of Item I

BMR(D) = Beginning Item Number for Department D

BN(D) = Number of Items Made in Department D

BO(I) = Lost Sales Units for Product I

C(I) = Per Unit Cost of Item I

CLOSTS = Lost Sales Cost Per Unit of Stockout

CM(IP) = Per Unit Cost of Material for Item IP

COMP(I,L) = The Immediate Lower Level Components for Item I

COST(1) = Inventory Carrying Cost for the Period

COST(2) = Setup Cost for the Period

COST(3) = Total Setup and Carrying Cost for the Period

COST(4) = Over Time Cost

COST(5) = Lost Sales Cost

COST(6) = Idle Time Cost

COSTPA = Payroll Cost

COSTY(I) = Year to Date Cost for Cost (I)

DFG(I,M) = Actual demand for Product I in Period M

DL = The Amount of Delay (Timing Uncertainty)

DORDER = Order Processed Or Delivered After the Scheduled Date

FGP(I) = Productivity Factor for Item I

IINV(I) = Initial Inventory of Product I

FORCST(I,M) = Forecasted Demand for Product I in Period M

GROSS(I,M) = Gross Requirements for Item I in Period M

HSLT = High Safety Lead Time

IBO = Total Number of Units Short to Date

INV(I,M) = Inventory On Hand Used in the MRP Procedure

JMS(NMS) = Item Number which its Production

KMS(NMS) = Item Which Its Shortage Caused a Reduction in Production of Item IP

LSLT - Low Safety Lead Time

NMS = A Counter of Number of Material Shortage Occasions for this Period

LDTIME(I) = Lead Time for Product I

LEVEL(I) = The Lowest Level on the Bill of Material on which Item I resides

MM = Number of Periods (weeks) being Simulated

NET(I,M) = Net Requirements for Item I in Period M

NFGS = Number of Finished Goods

OB Performance Measure = The Value of this Performance Measure for One Observation

ORDER(I,M) = Lot Size for Item I in Period M

OTH(D) = Over Time Hours Used in Department D

P = Planning Horizon (12 weeks)

PART = Item Number

PAYCST = Payroll Cost for this Period

PP(N) = A Temporary Storage Variable Used During MRP Product Explosion

POTH = Over Time Man Hours Used in all Departments in this Period

PSUH = Setup Man Hours Used in all Departments in this Period

PXIP = Idle Time Man Hours Incurred in All Departments in this Period

Q(I) = Number of Immediate Lower Level Components for Item I

RECPT(I,M) = Schedule Receipt for Item I in Period M

RELSD(I,M) = Schedule Released for Item I in Period M

RH(D) = Run Man Hours Used in Department D

RUNTIM = Run Time Used to Produce this Item in this Department

S(I) = Setup Man Hours Incurred if Item I is Produced

SCHED(I,M) = Schedule Receipt for Item I in Period M

SETUP(ID) = Number of Setups in Department ID for this Period

SETUPS = Total Number of Setups in All Departments To Date

SFG(I) = Sales of Finished Good I

SSH = High Safety Stock

SSHF = High Safety Stock Factor Used in MRP Calculations

SSL = Low Safety Stock

SSLF = Low Safety Stock Factor Used in MRP Calculations

STH(D) = Straight Time Man Hours Available in Department D

STKOUT = Total Number of Stockouts to Date

SUH(D) = Setup Man Hours Used in Department D

T = The Present Period

TB(I) = Total Number of Units Short of Product I (Lost Sales)

TBO = Total Units of Lost Sales

TCOST = Period Total Cost

TCOSTY = Year to Date Total Cost

TI = Total Inventory Value this Period

TINVV = Total Inventory Value to Date

TOTLVL = Total Number of Levels in the Bill of Materials

TRH(D) = Total Run Man Hours Used in Department D

TV = Total Inventory Value for this Item in This Period

TXIH = Total Idle Man Hours in this Period

TYOTH = Total Year to Date Overtime Hours Used in All Departments

TYSUH = Total Year to Date Setup Hours Used in All Departments

TYXIH = Total Year to Date Idle Time Hours Used in All Departments

U(I) = Run Time Per Unit for Item I (MAN HOURS)

US(I) = Units Supplied of Product I Toward its Sale

USAGE(I,J) = Number of Units of the Jth Immediate Lower Level Component Used to Produce One Unit of Item I

V(I) = Inventory Total $ Value for Item I

WR = Wage Rate ($/Man Hours)

X = A Temporary Variable Used to Indicate the Item Number Being Netted

XI(I) = One Hand Inventory of Item I (Units)

XIC = Inventory Cost ($/$ Per Month)

XIH(D) = Idle Man Hours Used in Department D

XLW(D) = Work Force in Department D

XM(J) = Present Period Requirements of Item J

XM1(L,J) = Product Structure Array

XMOT = Maximum Overtime Fraction

XU = Shortage Percentage (Quantity Uncertainty)

Y(PREFIX) = A Variable with a Prefix Y is the Year to Date Value of the variable that follows Y

Z = A Temporary Variable used to Indicate Per Unit Value of an Item

The Program Code

Enclosed is one version of the program that has been used in this study. This is the case of HT/HQ uncertainty category with SLT/SS buffering strategy. Number of replications is five in this case.

```
C$JOB           TIME=60,PAGES=55
C                                                                       C0CC0CC1
C                                                                       CCCC0C02
       DIMENSION AP(16),BMR(3),BN(3),BO(4),COST(7),COSTY(7),DFG(4,64),      10C10
      1FORCST(4,64),JMS(16),JOL(3),KMS(16),SETUP(3),OTH(3),RH(3),           2001
      2S(16),SFG(4),STH(3),SUH(3),TB(4),TRH(3),U(16),US(4),BOC(4),
      3V(16),XIH(3),XLW(3),XM(16),XMI(16,16),YCTH(3),YSETUP(3),NSETUP(3),00040C10
      4CM(16),TOTH(3),TSTH(3),TSUH(3),TTRH(3),COSTAL(7),COSTAV(7),       C0050C10
      5TXIH(3),YRH(3),YSTH(3),YSUH(3),YXIH(3),RATIO(16),XU(16),IRN(5),
      6OTHAL(3),OTHAV(3),XIHAL(3),XIHAV(3),R(6),NSETAL(3),NSETAV(3),     00070C10
      7DORDER(16,64),OBCO1(5),OBCO3(5),OBCO7(5),OBBO(5),OBSTK(5),
      8OBSLVL(5)
C                                                                       C0080010
       INTEGER AP,BMR,BN,BO,COMP,DFG,FORCST,GROSS,IINV,INV,JMS,JOL,KMS,KTC0090C10
      1,LDTIME,LEVEL,MAX,ORDER,P,PP,PART,Q,RECPT,RELSD,SCHED,SETUPS,SFG, 001C0C10
      2T,TB,TPO,TOTLVL,US,USAGE,X,XI,XLW,XM,XMI,COLECT,STKOUT,C,DD,SETUP,00110C10
      3YSETUP,STKAL,STKAV,VAR1,VAR2,VAR3,VAR4,DORDER,DL,SSL,SSH,SSLF,    00120C10
      4LSLT,HSLT
C                                                                       00130C10
       COMMON/AA/ COMP(9,3),GROSS(16,64),IINV(16),INV(16,64),YFL,DL(16), 00140C10
      1LEVEL(16),NET(16,64),ORDER(16,64),PART(16),Q(9),RECPT(16,64),IX,     150C10
      2RELSD(16,64),SCHED(16,64),USAGE(9,3),PP(65),P,MAX,T,X,XI(16),IY,     160C10
      3TOTLVL,LDTIME(16),IPP(16),IO(16),KT,LENT(16),MIN(12),D(16),          170C10
      4SSL(16),SSH(16),SSLF(16,64),SSHF(16,64),HSLT(16),
      5LSLT(16)
       COMMON/BB/C(16),CARY(16),SETUPC(16)                                  180C10
       DOUBLE PRECISION IIX                                               00200C10
       IIX=8931                                                           00210C10
C                                                                       00190C10
       IRN(1)=325647745
       IRN(2)=547746523
       IRN(3)=455623378
       IRN(4)=647745523
       IRN(5)=455247763
       DO 172 ID=1,3
       OTHAL(ID)=0.                                                       00890C10
       OTHAV(ID)=0.                                                       009C0C10
       XIHAL(ID)=0.                                                       C0910C10
       XIHAV(ID)=0.                                                       00920C10
   172 CONTINUE
       DO 173 K=1,7
        COSTAL(K)=0.                                                      00980C10
        COSTAV(K)=0.                                                      00990C10
   173 CONTINUE
       SLAL=0.
       ASL=0.
       STKAL=0                                                            01010C10
       STKAV=0                                                            01C20C10
       DO 191 IO=1,5
       IX=IRN(IO)
       WRITE(6,799)
       WRITE(6,801)IO
   801 FORMAT(40X,'**********   REPORTS  FOR OBSERVATION  ',I2,'   *******
      C**')
       WRITE(6,799)
       WRITE(6,799)
C                                                                       00220C10
C      INITIALIZATION                                                   00230C10
C                                                                       C0240C10
C      SET CONSTANTS AND CLEAR ARRAYS                                   00250C10
```

```
C                                                                       00260010
      VAR1=4
      VAR2=3
      VAR3=1
      P=12                                                              00340010
      MM=64
C                                                                       00370010
      DO 1 I=1,16                                                       00380010
      IF(I.GT.4) GO TO 2                                                00390010
      BO(I)=0                                                           00400010
      SFG(I)=0                                                          00410010
      TB(I)=0                                                           00420010
      US(I)=0                                                           00430010
      DO 18 M=1,MM                                                      00440010
      FORCST(I,M)=0                                                     00450010
   18 CONTINUE                                                          00460010
C                                                                       00470010
    2 AP(I)=0                                                           00480010
      DL(I)=0
      XU(I)=0.
      JMS(I)=0                                                          00490010
      KMS(I)=0                                                          00500010
      V(I)=0.                                                           00510010
      XI(I)=0                                                           00520010
      XM(I)=0                                                           00530010
      DO 19 M=1,MM                                                      00540010
      GROSS(I,M)=0                                                      00550010
      INV(I,M)=0                                                        00560010
      SSHF(I,M)=0
      SSLF(I,M)=0
      NET(I,M)=0                                                        00570010
      DORDER(I,M)=0
      ORDER(I,M)=0                                                      00560010
      RECPT(I,M)=0                                                      00590010
      RELSD(I,M)=0                                                      00600010
      SCHED(I,M)=0                                                      00610010
   19 CONTINUE                                                          00620010
    1 CONTINUE                                                          00630010
C                                                                       00640010
      DO 3 ID=1,3                                                       00650010
      JOL(ID)=0                                                         00660010
      NSETUP(ID)=0                                                      00670010
      NSETUP(ID)=0                                                      00680010
      OTH(ID)=0.                                                        00690010
      RH(ID)=0.                                                         00700010
      SETUP(ID)=0                                                       00710010
      STH(ID)=0.                                                        00720010
      SUH(ID)=0.                                                        00730010
      TBO=0                                                             00740010
      TRH(ID)=0.                                                        00750010
      TOTH(ID)=0.                                                       00760010
      TRH(ID)=0.                                                        00770010
      TSTH(ID)=0.                                                       00780010
      TSUH(ID)=0.                                                       00790010
      TTRH(ID)=0.                                                       00800010
      TXIH(ID)=0.                                                       00810010
      YOTH(ID)=0.                                                       00820010
      YSETUP(ID)=0                                                      00830010
      YRH(ID)=0.                                                        00840010
      YSTH(ID)=0.                                                       00850010
```

```
          YSUH(ID)=0.                                                   00860010
          YXIH(ID)=0.                                                   00870010
          XIH(ID)=0.                                                    00880010
    3     CONTINUE                                                      00930010
C                                                                       00940010
          DO 5 K=1,7                                                    00950010
          COST(K)=0.                                                    00960010
          COSTY(K)=0.                                                   00970010
    5     CONTINUE                                                      01000010
C                                                                       01030010
          COSTPA=0.                                                     01040010
          NMS=00                                                        01050010
          SETUPS=0                                                      01060010
          STKOUT=0                                                      01070010
          TCOST=0.                                                      01080010
          TCOSTY=0.                                                     01090010
C         READ IN THE PARAMETER VALUES                                  01100010
          READ(5,301)BMR,BN,XLW                                         01110010
  301     FORMAT(9I5)                                                   01120010
          READ(5,302)Q                                                  01130010
  302     FORMAT(16I2)                                                  01140010
          MAX=BN(1)+BN(2)+BN(3)                                         01150010
          MAT=BN(1)+BN(2)                                               01160010
          NFGS=BN(1)                                                    01170010
          MASY=BMR(2)+1                                                 01180010
          MATY=BMR(3)+1                                                 01190010
C                                                                       01200010
          DO 101 I=1,MAT                                                01210010
          READ(5,203)(COMP(I,J),J=1,3)                                  01220010
  203     FORMAT(3I5)                                                   01230010
  101     CONTINUE                                                      01240010
C                                                                       01250010
          DO 102 I=1,MAT                                                01260010
          READ(5,203)(USAGE(I,J),J=1,3)                                 01270010
  102     CONTINUE                                                      01280010
C                                                                       01290010
          DO 103 I=1,MAX                                                01300010
          READ(5,304)(XMI(I,J),J=1,MAX)                                 01310010
  103     CONTINUE                                                      01320010
C                                                                       01330010
          DO 104 I=1,NFGS                                               01340010
          READ(5,303)(DFG(I,M),M=1,MM)                                  01350010
  303     FORMAT(24I3)                                                  01360010
  104     CONTINUE                                                      01370010
          READ(5,310)CM                                                 01380010
  310     FORMAT(10X,11F5.0)                                            01390010
          READ(5,373)IINV
  373     FORMAT(12I5)
          WRITE(6,695)(I,IINV(I),I=1,MAX)                               01410010
  695     FORMAT(1X,8(2X,('IINV(',I2,')='),I4))
          READ(5,304)LDTIME                                             01430010
          READ(5,304)LEVEL                                              01440010
  304     FORMAT(16I1)                                                  01450010
          READ(5,302)PART                                               01460010
          READ(5,305)S                                                  01470010
  305     FORMAT(5X,6F10.0)                                             014800 1
          READ(5,309)U                                                  01490010
  309     FORMAT(5X,6F10.1)                                             015000 1
          READ(5,306)V                                                  01510010
  306     FORMAT(5X,6F10.0)                                             01520010
```

```
      READ(5,307)P,TOTLVL                                               01530C10
  307 FORMAT(5X,2I5)                                                    01540C10
      READ(5,308)CLOSTS,WR,XIC,XMOT                                     01550C10
  308 FORMAT(10X,4F10.2)                                                015600 0
      READ(5,719)SSL
      READ(5,719)SSH
  719 FORMAT(16I4)
      PRINT,SSL
      PRINT,SSH
      READ(5,719)LSLT
      READ(5,719)HSLT
      PRINT,LSLT
      PRINT,HSLT
      WRITE(6,799)                                                      01570010
      WRITE(6,799)                                                      01600C10
      WRITE(6,799)
      WRITE(6,818)
  818 FORMAT(2X,'T         COST(1)       COST(3)       TCOST       NMS
     C   BO(1)     BO(2)     BO(3)      BO(4)   STKOUT      IBO       PER
     CBO')
      WRITE(6,799)
C                                                                       01610010
C     START OPERATING THE FACTORY                                       01620C10
C     OPERATE DEPARTMENTS                                               01630C10
C                                                                       01640C10
C                                                                       01650010
      T=0                                                               01660C10
C                                                                       01670C10
 1000 T=T+1                                                             01680010
      IPBO=0
      NMS=0                                                             01690C10
  799 FORMAT('      ')                                                  01700C10
C                                                                       01730C10
      IF(T.EQ.1)GO TO 11                                                01740C10
      IF(T.GT.1)GO TO 21
C                                                                       01760C10
C                                                                       01810C10
C     START A NEW RUN OF P PERIOD                                       01820C10
C                                                                       01830C10
C     CLEAR THE PERFORMANCE MEASURE COLLECTORS                          01840C10
C                                                                       01850C10
   11 DO 12 I=1,7                                                       01860C10
      COST(I)=0.                                                        01870C10
      COSTY(I)=0.                                                       01880C10
   12 CONTINUE                                                          01890C10
      IBO=0                                                             019C0C10
      DO 13 ID=1,3                                                      01920C10
      NSETAL(ID)=0                                                      01930C10
      TOTH(ID)=0.                                                       01940C10
      YSETUP(ID)=0                                                      01950C10
      YOTH(ID)=0.                                                       01960010
      YSTH(ID)=0.                                                       01970010
      YSUH(ID)=0.                                                       01980010
      YXIH(ID)=0.                                                       01990C10
      YRH(ID)=0.                                                        02000C10
   13 CONTINUE                                                          02010C10
C                                                                       02020C10
      DO 14 I=1,NFGS                                                    02030C10
      BO(I)=0                                                           02040C10
   14 CONTINUE                                                          02050C10
```

```
      COSTPA=0.                                                         02060C10
      NMS=0                                                             02070C10
      SETUPS=0                                                          02080010
      STKOUT=0                                                          02090C10
      TCOSTY=0.                                                         02100C10
      TITH=0.                                                           02110C10
C                                                                       02120C10
      TYSUH=0.                                                          02130C10
      TYOTH=0.                                                          02140C10
      TYXIH=0.                                                          02150C10
      TINVV=0.                                                          02160C10
      IF(T.EQ.1)GO TO 33                                                02170C10
      GO TO 21                                                          02180C10
C                                                                       02190C10
   33 DO 34 I=1,MAX                                                     02200C10
      JMS(I)=0                                                          02210C10
      KMS(I)=0                                                          02220C10
      XI(I) = IINV(I)                                                   02230010
   34 CONTINUE                                                          02240C10
   21 KT=T+P-1
C                                                                       02250C10
C                                                                       02270010
      DO 1029 I=1,MAX                                                   02280C10
      DO 1028 M=T,KT                                                    02290C10
      GROSS(I,M)=0                                                      02300C10
 1028 CONTINUE                                                          02310C10
 1029 CONTINUE                                                          02320C10
C                                                                       02330C10
C     READ DEMAND
C                                                                       02350010
C                                                                       02360C10
      DO 1039 I=1,NFGS                                                  02370010
      DO 1038 M=T,KT                                                    0238001
      GROSS(I,M)=DFG(I,M)
 1038 CONTINUE                                                          02440C10
 1039 CONTINUE                                                          02450010
C                                                                       02460010
C                                                                       02470C10
C     A- CALCULATION OF YEARLY DEMAND                                   02490010
C                                                                       02500C10
      DO 151 I=1,MAX                                                    02510C10
      D(I)=0                                                            02520C10
  151 CONTINUE                                                          02530010
C                                                                       02540C10
      DO 159 I=1,NFGS                                                   02550010
      DO 153 M=1,P                                                      02560C10
      D(I)=D(I)+GROSS(I,M)                                              02570010
  153 CONTINUE                                                          02580010
C                                                                       02590C10
      DO 157 J=MASY,MAX                                                 02600C10
      IF(XMI(I,J))157,157,155                                           02610010
  155 D(J)=D(J)+D(I)*XMI(I,J)                                           02620C10
  157 CONTINUE                                                          02630C10
  159 CONTINUE                                                          02640C10
C                                                                       02650C10
      DO 165 I=MASY,MAT                                                 02660C10
      DO 163 J=MATY,MAX                                                 02670010
      IF(XMI(I,J))163,163,161                                           02680C10
  161 D(J)=D(J)+D(I)*XMI(I,J)                                           02690C10
  163 CONTINUE                                                          02700C10
```

```
  165 CONTINUE                                                          02710010
C                                                                       02720010
C     B- CALCULATION OF UNIT COSTS                                      02730010
C                                                                       02740010
      DO 467 I=1,MAX                                                    02750010
      IF(T.EQ.1)XI(I)=IINV(I)                                           02760010
      IF(XI(I).EQ.0)GO TO 467                                           02770010
      C(I)=V(I)/XI(I)                                                   02780010
  467 CONTINUE                                                          02790010
C                                                                       02800010
C                                                                       02910010
C     CALCULATION OF SETUP AND CARRYING COSTS FOR END ITEMS             02920010
C                                                                       02930010
      DO 171 I=1,MAX                                                    02940010
      SETUPC(I)=S(I)*WR                                                 02950010
      CARY(I)=C(I)*XIC*12                                               02960010
  171 CONTINUE                                                          02970010
C                                                                       02980010
C     CALCULATE SETUP TO INVENTORY CARYING COST RATIO                   02990010
C                                                                       03000010
      DO 7 I=1,MAX                                                      03010010
      RATIO(I)=SETUPC(I)/CARY(I)                                        03020010
    7 CONTINUE                                                          03030010
C                                                                       
C     CALCULATE LOST SALES COST PER UNIT OF END ITEM SHORT              03040010
C                                                                       
      DO 8 I=1,NFGS                                                     03050010
    8 BOC(I)=CLOSTS*C(I)                                                03060010
C                                                                       03070010
C                                                                       03250010
C                                                                       03260010
C                                                                       03280010
C                                                                       03290010
      CALL MRP                                                          03300010
C                                                                       03310010
C                                                                       03320010
C     PRINT ORDERS                                                      03330010
C     START DEPARTMENT LOOP                                             03340010
C                                                                       03350010
   35 DO 70 ID=1,3                                                      03360010
C                                                                       03370010
C     ZERO MATERIAL USAGE                                               03380010
C                                                                       03390010
      DO 36 J=1,MAX                                                     03400010
   36 XM(J)=0                                                           03410010
C     GET MATERIAL LOWER AND UPPER LIMITS FOR THIS DEPARTMENT           03420010
      IL=BMR(ID)+1                                                      03430010
      IU=BMR(ID)+BN(ID)                                                 03440010
C     COMPUTE MATERIAL REQUIREMENTS                                     03450010
C                                                                       03460010
      DO 38 IP=IL,IU                                                    03470010
      IF(IP.GT.MAT)GO TO 854
      DL(IP)=0
      KLF=0
      TOTAL=0
  920 CALL RANDU(IX,IY,YFL)
      G=1.-YFL
      WX=-1.*ALOG(G)
      TOTAL=TOTAL+WX
      IF(TOTAL.GE.1)GO TO 975
```

```
      KLF=KLF+1
      GO TO 920
  975 DL(IP)=KLF
      IF(DL(IP).LT.1)GO TO 853
      K=T+DL(IP)
      DORDER(IP,K)=ORDER(IP,T)+DORDER(IP,K)
      ORDER(IP,T)=DORDER(IP,T)
      GO TO 854
  853 ORDER(IP,T)=ORDER(IP,T)+DORDER(IP,T)
  854 DO 37 IZ=1,MAX
      XM(IZ)=XM(IZ)+XMI(IP,IZ)*ORDER(IP,T)
   37 CONTINUE
   38 CONTINUE                                                          03500010
C                                                                       03510010
      DO 49 J=1,MAX                                                     03520010
C     CHECK MATERIAL AVAILABILITY                                       03530010
C                                                                       
      IF(XI(J))39,40,40                                                 03540010
   39 XI(J)=0                                                           03550010
      V(J)=0                                                            03560010
   40 CONTINUE                                                          03570010
      IF(XM(J)-XI(J))49,49,41                                           03580010
C     THERE IS A SHORTAGE OF ITEM J                                     03590010
   41 AB=XI(J)                                                          03600010
      AC=XM(J)                                                          03610010
      F=AB/AC                                                           03620010
C     REDUCE DESIRED PRODUCTION                                         03630010
C                                                                       03640010
      DO 48 IP=IL,IU                                                    03650010
      IF (XMI(IP,J)-1)48,42,42                                          03660010
   42 CONTINUE                                                          03670010
   43 IF(ORDER(IP,T))46,46,44                                           03680010
   44 CONTINUE                                                          03690010
C     ADD = OF MATERIAL SHORTAGE OCCASIONS FOR THIS PERIOD              03700010
      NMS=NMS+1                                                         03710010
C     ITEM WHICH ITS PRODUCTION WAS CUT BECAUSE OF SHORTAGE OF ITEM J   03720010
C     JMS(NMS)=IP                                                       03730010
C     ITEM WHICH ITS SHORTAGE CAUSED A REDUCTION IN PRODUCTION OFITEM IF03740010
C     KMS(NMS)=J                                                        03750010
   46 ITEMP=ORDER(IP,T)                                                 03760010
C     ADJUSTED PRODUCTION PLANS 0                                       03770010
      ORDER(IP,T)=F*ORDER(IP,T)                                         03780010
      IR=ORDER(IP,T)-ITEMP                                              03790010
C                                                                       03800010
      DO 47 IZ=MASY,MAX                                                 03810010
   47 XM(IZ)=XM(IZ)+XMI(IP,IZ)*IR                                       03820010
   48 CONTINUE                                                          03830010
   49 CONTINUE                                                          03840010
C     END AVAILABILITY CHECK                                            03850010
C                                                                       03860010
C     ZERO MAN HOUR REQS                                                03870010
C     TR=TOTAL RUN TIME REQUIRED IN THE DEPT FOR THE PERIOD             03880010
C     TS=TOTAL SETUP TIME REQUIRED IN THE DEPT FOR THE PERIOD           03890010
C     TT=TOTAL SETUP AND RUN TIME REQUIRED IN THE DEPT FOR THE PERIOD   03900010
      TT=0.                                                             03910010
      TS=0                                                              03920010
      TR=0.                                                             03930010
C     GET MAN HOUR REQS                                                 03940010
C                                                                       03950010
      DO 51 IP=IL,IU                                                    03960010
```

```
      IF(ORDER(IP,T))51,51,50                                           03970010
   50 TS=TS+S(IP)                                                       03980010
      TR=TR+ORDER(IP,T)*U(IP)                                           03990010
      NSETUP(ID)=NSETUP(ID)+1                                           04000010
   51 CONTINUE                                                          04010010
      TT=TR+TS                                                          04020010
C
C     NOW WE HAVE MAN HOUR REQS IN DEPT(ID)                             04030010
C     STRAIGHT TIME MAN HOURS IN DEPT(ID)                               04040010
      ST=40.*XLW(ID)
C
C     CHECK OVERTIME AND CALC OVER AND IDLE TIME                        04060010
      IF(TT-ST) 52,52,53                                                04070010
C
C     AMPLE STRAIGHT MAN-HOURS AVAILABLE IN DEPT(ID)                    04080010
   52 OTH(ID)=0.                                                        04090010
      XIH(ID)=ST-TT                                                     04100010
      F=1                                                               04110010
      GO TO 64                                                          04120010
C     AVAILABLE STRAIGHT MAN-HOURS IN DEPT(ID) IS NOT SUFFICIENT       04130010
   53 F=TT/ST                                                           04140010
      WRITE(6,26)ID,T,F                                                 04150010
   26 FORMAT(10X,'F (OTH FACTOR) FOR DEPT',I2,'FOR PERIOD',I3,' IS ',   04160010
     *F10.2)                                                            04170010
   54 CONTINUE                                                          04180010
      IF(F-XMOT) 56,56,57                                               04190010
   56 F=1.                                                              04200010
      GO TO 63                                                          04210010
C
C     GET FACTOR TO REDUCE PRODUCTION
   57 F=XMOT/F                                                          04230010
      WRITE(6,27)ID,T,F                                                 04240010
   27 FORMAT(10X,'FF(OTH FACTOR) FOR DEPT',I2,' FOR PERIOD',I3,' IS',   04250010
     *F10.2)                                                            04260010
C     NOL=NOL+1                                                         04270010
C     JOL(NOL)=ID                                                       04280010
      TT=XMOT*ST                                                        04290010
      IF(TT-TS)61,61,62                                                 04300010
   61 F=0                                                               04310010
      TT=ST                                                             04320010
      GO TO 63                                                          04330010
   62 F=(TT-TS)/TR                                                      04340010
      WRITE(6,28)ID,T,F                                                 04350010
   28 FORMAT(10X,'FFF(OTH FACTOR)FOR DEPT',I2,' FOR PERIOD',I3,' IS',   04360010
     *F10.2)                                                            04370010
   63 OTH(ID)=TT-ST                                                     04380010
      XIH(ID)=0.                                                        04390010
   64 TR=0.                                                             04400010
      TS=0.                                                             04410010
C
C     OVERTIME COST FUDGE FACTOR                                        04420010
      G=((ST+1.5*OTH(ID))/(ST+OTH(ID)))*WR                              04430010
C
C     REDUCE PRODUCTION IF NECESSARY AND ADD SETUP AND RUN TIME         04440010
      SETUP(ID)=0                                                       04450010
  164 DO 69 IP=IL,IU                                                    04460010
      ORDER(IP,T)=F*ORDER(IP,T)                                         04470010
C
      IF(IP.LE.MAT)GO TO 947
      CALL RANDU(IX,IY,YFL)
```

```
      W=1-YFL
      XU(IP)=-.3*ALOG(W)
      SP=XU(IP)
      ORDER(IP,T)=(1-SP)*ORDER(IP,T)
C
C
C
C     ACTUAL = OF UNITS PRODUCED 0                                      04480010
  947 AP(IP)=ORDER(IP,T)
      IF(ORDER(IP,T)) 69,69,65                                          04500010
   65 TS=TS+S(IP)                                                       04510010
      SETUP(ID)=SETUP(ID)+1                                             04520010
      RUNTIM=ORDER(IP,T)*U(IP)                                          04530010
      TR=TR+RUNTIM                                                      04540010
C
C     ADD IN LABOR COST FOR THIS ITEM (IN THIS DEPT)                    04550010
      TL=(S(IP)+RUNTIM)*G                                               04560010
      TV=TL                                                             04570010
      IF(IP.LE.MAT)GO TO 265                                            04580010
      TV=TL+ORDER(IP,T)*CM(IP)                                          04590010
      GO TO 68                                                          04600010
C                                                                       04610010
  265 DO 67 IZ=MASY,MAX                                                 04620010
      IF (XMI(IP,IZ)-1)67,66,66                                         04630010
   66 IF (XI(IZ)) 465,465,166                                           04640010
  465 Z=0.                                                              04650010
      V(IZ)=0.                                                          04660010
      GO TO 167                                                         04670010
  166 Z=V(IZ)/XI(IZ)                                                    04680010
C     VALUE ADDED FROM INVENTORY                                        04690010
  167 TV=TV+ORDER(IP,T)*XMI(IP,IZ)                                      04700010
      XI(IZ)=XI(IZ)-ORDER(IP,T)*XMI(IP,IZ)
      V(IZ)=XI(IZ)*Z                                                    04710010
   67 CONTINUE                                                          04720010
C
C     ADD OUTPUT INVENTORY UNITS AND VALUE                              04730010
C     UPDATE THE END OF THE PERIOD INVENTORY VALUE FOR ITEM IP          04740010
   68 XI(IP)=XI(IP)+ORDER(IP,T)                                         04750010
      V(IP)=V(IP)+TV                                                    04770010
   69 CONTINUE                                                          04780010
C
C     END OF PRODUCTION                                                 04790010
C
C     RECORD STRAIGHT TIME HOURS                                        04800010
C     STRAIGHT TIME MAN-HOURS AVAILABLE IN DEPT(ID)                     04810010
      STH(ID)=ST                                                        04820010
C
C     SETUP MAN-HOURS USED IN DEPT(ID)                                  04830010
      SUH(ID)=TS                                                        04840010
C
C     RUN MAN-HOURS USED IN DEPT(ID)                                    04850010
      RH(ID)=TR                                                         04860010
C                                                                       04870010
C     PAYROLL COST FOR THIS PERIOD 0                                    04880010
      PAYCST=(ST +1.5*OTH(ID))*WR                                       04890010
C     TOTAL COST OF PAYROLL IN ALL DEPTS TO DATE                        04900010
      COSTPA= COSTPA + PAYCST                                           04910010
C                                                                       04920010
C     COLLECT DATA FOR TOTAL PERIODS                                    04930010
      YOTH(ID)=YOTH(ID)+OTH(ID)                                         04940010
```

```
      YRH(ID)=YRH(ID)+TR
      YSTH(ID)=YSTH(ID)+ST
      YSUH(ID)=YSUH(ID)+TS
      YXIH(ID)=YXIH(ID)+XIH(ID)
   70 CONTINUE
C
C
C     END OF DEPARTMENT LOOP
C
      POTH=0.
      PSUH=0.
      PXIH=0.
C
C
      DO 71 ID=1,3
      POTH=POTH+OTH(ID)
      PSUH=PSUH+SUH(ID)
      PXIH=PXIH+XIH(ID)
      YSETUP(ID)=YSETUP(ID)+SETUP(ID)
      SETUPS =SETUPS+YSETUP(ID)
      TYSUH=TYSUH+YSUH(ID)
      TYOTH=TYOTH+YOTH(ID)
      TYXIH=TYXIH+YXIH(ID)
   71 CONTINUE
C
C     START DEMAND AND SALES CALCULATION
C     FINISHED GOODS PRODUCT ITERATION
C
C
      COST(5)=0.
      DO 75 I=1,NFGS
C     CHECK IF ENOUGH INVENTORY
      IF(XI(I)-DFG(I,T)) 72,73,73
C     SHORTAGE OF FINISHED GOOD I
   72 US(I)=XI(I)
C     COUNT NUMBER OF UNITS SHORT
      BO(I)=DFG(I,T)-XI(I)
      IPBO=IPBO+BO(I)
      IBO=IBO+BO(I)
C     ADD NUMBER OF STOCKOUTS T
      STKOUT=STKOUT+1
      XI(I)=0
      V(I)=0.
      GO TO 74
C     THERE IS SUFFICIENT AMOUNT OF INVENTORY OF FINISHED GOOD I
   73 US(I)=DFG(I,T)
      BO(I)=0
  174 Z=V(I)/XI(I)
C     REDUCE UNITS AND VALUE FOR AMOUNT SUPPLIED
  175 V(I)=V(I)-US(I)*Z
      XI(I)=XI(I)-US(I)
C     LOST SALES COST (SHORTAGE COST)
   74 COST(5)=COST(5)+BOC(I)*BO(I)
   75 CONTINUE
C
C     END OF FINISHED GOODS LOOP
C
C     INVENTORY TOTALS FOR YEAR AND INV HOLDING COST
      TI=0.
      DO 80 IP=1,MAX
```

```
      IF (XI(IP)) 281,281,80                                            05540C10
  281 V(IP)=0.                                                          05550C10
   80 TI=TI+V(IP)                                                       05560010
      TINVV=TINVV+TI                                                    05570010
C     HOLDING COST FOR THE PERIOD IS                                    05580010
      COST(1)=TI*XIC                                                    05590C10
C     SETUP COST FOR THE PERIOD IS                                      05600010
      COST(2)=PSUH*WR                                                   05610C10
      COST(3)=COST(1)+COST(2)                                           05620C10
C     OVER TIME COST FOR PERIOD T IS                                    05630C10
      COST(4)=POTH*1.5*WR                                               05640C10
C     IDLE TIME COST FOR PERIOD T IS                                    05650C10
      COST(6)=PXIH*WR                                                   05660C10
      COST(7)=COST(3)+COST(4)+COST(5)                                   05670010
C     ADD COSTS FOR YEAR                                                05680010
      TC=0.                                                             05690C10
      DO 81 I=1,7                                                       05700C10
      COSTY(I)=COSTY(I)+COST(I)                                         05710010
   81 TC=TC+COST(I)                                                     05720C10
      TCOST=COST(3)+COST(4)+COST(5)                                     05730C10
      TCOSTY=TCOSTY+TCOST                                               05740C10
C                                                                       05750C10
C                                                                       05770010
C     PRINT RUN REPORTS                                                 05780C10
C                                                                       05790C10
      WRITE(6,717)T,COST(1),COST(3),COST(7),NMS,BO(1),BO(2),BO(3),BO(4),
     CSTKOUT,IBO,IPBO
  717 FORMAT(1X,I2,5X,F9.0,5X,F9.0,5X,F9.0,5X,I3,5X,I5,5X,I5,5X,I5,5X,I5
     C,5X,I4,5X,I8,5X,I5)
C                                                                       06580C10
C                                                                       06630010
C     CHECK FOR NUMBER OF RUNS                                          06850C10
      IF (T.LT.52)GO TO 1000
      DO 94 I=1,7                                                       06640C10
      COSTAL(I)=COSTAL(I)+COSTY(I)                                      06650C10
   94 CONTINUE                                                          06660C10
C                                                                       06670C10
      DO 95 ID=1,3                                                      06680010
      NSETAL(ID) =NSETAL(ID)+NSETUP(ID)                                  0669C0
      OTHAL(ID)=OTHAL(ID)+YOTH(ID)                                      06700C10
      XIHAL(ID)=XIHAL(ID)+YXIH(ID)                                      06710C10
   95 CONTINUE                                                          06720C10
      STKAL=STKAL+STKOUT                                                06730C10
C                                                                       06740C10
      XIBO=FLOAT(IBO)
      SRLVL=1-(XIBO/52000.)
C                                                                       06860C10
      SLAL=SLAL+SRLVL
      WRITE(6,799)
      WRITE(6,501)
  501 FORMAT(35X,'***** ONE YEAR REPORT *****')
      WRITE(6,502)
  502 FORMAT(6X,'HOLD.COST     TINV.COST      TOT.COST     TOT.BAKOR     S
     CTKOUT     SERV.LEVEL')
      WRITE(6,503)COSTY(1),COSTY(3),TCOSTY,IBO,STKOUT,SRLVL
  503 FORMAT(5X,F9.0,5X,F9.0,5X,F9.0,5X,I8,5X,I4,5X,F9.6)
      OBC01(IO)=COSTY(1)
      OBC03(IO)=COSTY(3)
      OBC07(IO)=COSTY(7)
      OBBO(IO)=IBO
```

```
      OBSTK(IO)=STKOUT
      OBSLVL(IO)=SRLVL
  191 CONTINUE
      DO 187 I=1,7                                                      06750C10
      COSTAV(I)=COSTAL(I)/5.
  187 CONTINUE                                                          06770010
C                                                                       06780C10
      DO 188 ID=1,3                                                     06790C10
      NSETAV(ID)=NSETAL(ID)/5
      OTHAV(ID)=OTHAL(ID)/5.
      XIHAV(ID)=XIHAL(ID)/5.
  188 CONTINUE                                                          06830C10
      STKAV=STKAL/5.
      ASL=SLAL/5.
      WRITE(6,799)                                                      06880C10
      WRITE(6,200)                                                      069C0C10
  200 FORMAT(35X,'*****   END OF THE SIMULATION REPORTS OF THE AVERAGES 06910C10
     (    ****')                                                        06920C10
      WRITE(6,799)
      WRITE(6,506)
  506 FORMAT(3X,'OBS     B  T  D     HOLD.COST       TINV.COST      TOT.
     ,COST     TOT.BAKOR     STKOUT      SERV.LEVEL')
      DO 505 IO=1,5
      WRITE(6,507)IO,VAR1,VAR2,VAR3,CBCO1(IC),CBCO3(IO),OCCO7(IO),OBBO(I
     ,O),OBSTK(IO),OBSLVL(IO)
      WRITE(7,508)IO,VAR1,VAR2,VAR3,OUCO1(IO),OBCO3(IO),OCCO7(IC),OBBC(I
     ,O),OBSTK(IO),OBSLVL(IO)
  507 FORMAT(4X,I2,5X,I1,2X,I1,2X,I1,5X,F9.0,5X,F9.0,5X,F9.0,5X,F8.0,
     C5X,F4.0,5X,F9.6)
  508 FORMAT(1X,I2,2X,I1,2X,I1,2X,I1,2X,F9.0,2X,F9.0,2X,F9.0,2X,F8.0,2X,
     CF4.0,2X,F9.6)
  505 CONTINUE
      WRITE(6,799)                                                      06930C10
      WRITE(6,96)(I,COSTAV(I),I=1,7)                                    06940C10
   96 FORMAT(7(' CAV(',I1,')=',F9.0))                                   06950C10
      WRITE(6,799)                                                      06960C10
      WRITE(6,97)(ID,OTHAV(ID),ID=1,3)                                  06970010
   97 FORMAT(3('    OTHAV(',I1,')= ',F8.0))                             06980C10
      WRITE(6,799)                                                      06990C10
      WRITE(6,98)(ID,XIHAV(ID),ID=1,3)                                  07CCCC10
   98 FORMAT(3('    XIHAV(',I1,')= ',F8.0))                             07010C10
      WRITE(6,799)                                                      07020C10
      WRITE(6,99)STKAV                                                  07C30C10
   99 FORMAT(1X,'STKAV= ',I6)                                           C7040010
      WRITE(6,799)                                                      07050C10
      WRITE(6,504)ASL
  504 FORMAT(1X,'AV.SERVICE LEVEL =  ',F8.6)
      WRITE(6,100)(ID,NSETAV(ID),ID=1,3)                                 0706C01
  100 FORMAT(3('    NSETAV(',I1,')=',I6))                               07070010
      WRITE(6,799)                                                      0708CC10
  190 STOP                                                              071C0010
      END                                                               07110C10
C                                                                       07120C10
C                                                                       07130C10
C
C

      SUBROUTINE MRP                                                    07670C10
C                                                                       07680C10
C     MRP PROGRAM                                                       07690C10
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      C                                                                 07700C10
             INTEGER AP.BMR.BN.BO.COMP,DFG.FORCST.GROSS.IINV.INV.JMS.JCL.KMS.KT07710C10
           1.LOTIME,LEVEL.MAX.ORDER,P,PP,PART.Q,RECPT,RELSD.SCHEC.SETUPS.SFG. 07720C10
           2T.IB.TBO.TOTVL.US.LSAGE.X.XI.XLW.XM.XMI.COLECT.STKOUT.C.CC.SETUP. 07730C10
           3YSETUP,STKAL.STKAV.VAR1.VAR2.VAR3.VAR4.DORDER.DL.SSL.SSH.SSLF.    00120C10
           4LSLT.HSLT
      C                                                                 07740C10
            COMMON/AA/ COMP(9,3).GROSS(16.64),IINV(16).INV(16.64).YFL.DL(16). 00140C10
           1LEVEL(16).NET(16.64).ORDER(16.64),PART(16),Q(9).RECPT(16.64).IX.    150010
           2RELSD(16.64).SCHED(16.64).USAGE(9.3).PP(65).P.MAX,T.X.XI(16).IY.    160C10
           3TOTLVL.LDTIME(16).IPP(16).IQ(16).KT.LENT(16).MIN(12).D(16).         170C10
           4SSL(16).SSH(16).SSLF(16.64).SSHF(16.64).HSLT(16).
           5LSLT(16)
            COMMON/BB/C(16).CARY(16).SETUPC(16)                                 180C10
      C                                                                 078C0C10
      C                                                                 07810C10
      C     MAIN ROUTINE                                                07820C10
      C                                                                 07830C10
      C           1.    FIND ALL COMPONETS ON THIS CURRENT LEVEL        07840C10
      C                                                                 07850C10
            KT=T+P-1                                                    07860C10
            DO 30 I=1.MAX                                               07870C10
            DO 29 M=T,KT                                                07880C10
            RELSD(I,M)=0                                                07890C10
         29 CONTINUE                                                    07900C10
         30 CONTINUE                                                    07910C10
      C                                                                 07920C10
         40 DO 50 I= 1.3                                                07930010
            K = I - 1                                                   07940C10
            IM = 0                                                      07950C10
            DO 43 J = 1.MAX                                             07960C10
            IF (LEVEL (J) .NE. K) GO TO 43                              07970010
            IM=IM+1                                                     07980010
            PP(IM) = PART (J)                                           07990C10
         43 CONTINUE                                                    08C00C10
            N = 1                                                       08010010
         45 X = PP(N)                                                   08020010
      C                                                                 08030C10
      C             2.    CALL NETTING  PROCESS                         08040C10
      C                                                                 08050C10
            INV (X,1) = IINV (X)                                        08060C10
            CALL NETOUT                                                 08070C10
      C                                                                 08080C10
      C      3.    DETERMINE IF ALL COMPONENTS ON THIS LEVEL HAVE BEEN  08090C10
      C              NETTED OF THEIR IMMEDIATE COMPONENTS UPCATED IN THEIR 08100C10
      C              GROSS REQUIREMENTS  WRITE OUT NETTING-HORIZON      08110C10
            N=N+1                                                       08120C10
            IF (N.LE.IM) GO TO 45                                       08130C10
         50 CONTINUE                                                    08140C10
        190 RETURN                                                      08150C10
            END                                                         08160C10

            SUBROUTINE NETOUT                                           07140C10
      C                                                                 07150C10
      C                                                                 07160C10
             INTEGER AP.BMR.BN.BO,COMP,DFG.FORCST.GROSS.IINV.INV,JMS.JOL.KMS.KT07170010
           1,LOTIME,LEVEL,MAX,ORDER,P,PP,PART,G,RECPT,RELSD,SCHEC,SERUPS,SFG. 07180C10
           2T,TB,TBO,TOTVL,US,USAGE.X,XI.XLW,XM,XMI.COLECT.STKOUT,C,DD,SETUP. 07730C10
           3YSETUP,STKAL.STKAV,VAR1,VAR2,VAR3.VAR4,DORDER.DL.SSL.SSH.SSLF.    00120C10
           4LSLT.HSLT
```

```
C                                                                       07200C10
      COMMON/AA/ COMP(9,3),GROSS(16,64),IINV(16),INV(16,64),YFL,DL(16), 00140C10
     1LEVEL(16),NET(16,64),ORDER(16,64),PART(16),Q(9),RECPT(16,64),IX,    150C10
     2RELSD(16,64),SCHED(16,64),USAGE(9,3),FP(65),P,MAX,T,X,XI(16),IY,    160C10
     3TOTLVL,LDTIME(16),IPP(16),IQ(16),KT,LENT(16),MIN(12),D(16),         170010
     4SSL(16),SSH(16),SSLF(16,64),SSHF(16,64),HSLT(16),
     5LSLT(16)
      COMMON/BB/C(16),CARY(16),SETUPC(16)                                 180010
C                                                                       07260C10
      MAT=9
      SSLF(X,T)=SSL(X)
      SSHF(X,T)=SSH(X)
      INV(X,T)=XI(X)                                                    07270C10
      JT=T+P-1                                                          07280C10
      DO 40 M=T,JT                                                      07290C10
      IF(X.LE.9)GO TO 777
      NET(X,M)=GROSS(X,M)+SSHF(X,M)-SCHED(X,M)-INV(X,M)
      GO TO 888
  777 NET(X,M)=GROSS(X,M)-SCHED(X,M)-INV(X,M)
  888 M1=M+1
      IF(NET(X,M).GE.0)GO TO 5                                          07320C10
      IF(NET(X,M).LT.0)GO TO 10                                         07330C10
    5 INV(X,M1)=0                                                       07340010
      GO TO 15                                                          07350010
   10 INV(X,M1)=IABS(NET(X,M))                                          07360C10
      NET(X,M)=0                                                        07370C10
   15 RECPT(X,M)=NET(X,M)
      IF(X.GT.MAT)GO TO 999
      DD=M-LDTIME(X)-HSLT(X)
      GO TO 666
  999 DD=M-LDTIME(X)
  666 IF(DD.LE.T)GO TO 20
      RELSD(X,DD)=RECPT(X,M)                                            07410C10
      GO TO 40                                                          07420C10
   20 RELSD(X,T)=RELSD(X,T)+RECPT(X,M)                                  07430C10
   40 CONTINUE                                                          07440010
C                                                                       07450C10
C                                                                       07460010
C     CALL LOT SIZE SUBROUTINE                                          07470010
      IF (LEVEL(X).EQ.0)CALL LFL                                        07480010
      IF (LEVEL(X).NE.0)CALL LFL                                        07490C10
C                                                                       07500C10
C     ENTER GROSS REQUIREMENTS INTO APPROPRIATE MONTHS OF IMMEDIATE     07510010
C     LOWER LEVEL COMPONENTS                                            07520C10
      MAT=9                                                             07530C10
      IF(X.GT.MAT)GO TO 55                                              07540C10
      IH=1                                                              07550C10
   48 Z = COMP (X,IH)                                                   07560C10
      IF (Z.EQ.0)GO TO 55                                               07570C10
      DO 52 M=T,JT
      GROSS(Z,M)=GROSS(Z,M)+ORDER(X,M)*USAGE(X,IH)                      07610C10
   52 CONTINUE                                                          07620C10
      IF(IH.EQ.3)GO TO 55
      IH = IH+1                                                         07630010
      GO TO 48                                                          07640C10
   55 RETURN                                                            07650C10
      END                                                               07660C10

      SUBROUTINE LFL                                                    09890C10
C                                                                       09900C10
```

```
C                                                                       09910C10
       INTEGER AP.BMR.BN.UO.COMP.DFG.FORCST.GROSS.IINV.INV.JMS.JCL.KMS.KT09920C10
     1.LDTIME.LEVEL.MAX.ORDER.P.PP.PART.Q.RECPT.RELSD.SCHED.SETUPS.SFG. 09930C10
     2T.TB.TBO.TOTVL.US.USAGE.X.XI.XLW.XM.XMI.COLECT.STKOUT.D.DD.SETUP. 07730010
     3YSETUP.STKAL.STKAV.VAR1.VAR2.VAR3.VAR4.DORDER.DL.SSL.SSH.SSLF.     00120C10
     4LSLT.HSLT
C                                                                       09950010
      COMMON/AA/ COMP(9,3).GROSS(16,64).IINV(16).INV(16,64).YFL.DL(16), 00140C10
     1LEVEL(16),NET(16,64),ORDER(16,64),PART(16),Q(9),RECPT(16,64),IX,      150C10
     2RELSD(16,64),SCHED(16,64),USAGE(9,3),PP(65),P,MAX,T,X,XI(16),IY,      160C10
     3TOTLVL,LDTIME(16),IPP(16),IQ(16),KT,LENT(16),MIN(12),D(16),          170010
     4SSL(16),SSH(16),SSLF(16,64),SSHF(16,64),HSLT(16),
     5LSLT(16)
      COMMON/BB/C(16),CARY(16),SETUPC(16)                                  180C10
C                                                                       10010C10
      DO 10 M=T,KT                                                      10020C10
      ORDER(X,M)=RELSD(X,M)                                             10030C10
   10 CONTINUE                                                          10040C10
C                                                                       10050C10
      RETURN                                                            10060C10
      END                                                               10070C10

      SUBROUTINE RANDU(IX,IY,YFL)
      IY=IX*65339
      IF(IY) 5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      YFL=YFL*.4656613E-9
      IX=IY
      RETURN
      END

C$ENTRY
```

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VITA

M. Tawfik Mady was born on April 10, 1947 in Berket El-Saba, Egypt. His elementary and high school education was completed in the Berket El-Saba, Egypt public schools in 1963. He majored in Business Administration at Cairo University, receiving his B.S. with the Second Honors degree in 1967 and an M.B.A. degree in 1974. During his graduate studies at Cairo University, he taught courses in the Department of Business Administration. After receiving his M.B.A., he went to the Sudan for two years on a special teaching assignment at Cairo University in Khartoum. His academic life in the U.S.A. started in Raleigh, North Carolina in the fall of 1976. In June 1978, he received his M.S. in Management with a GPA of 3.67. In August of 1978 he entered the Graduate School of Louisiana State University to work toward the degree of Doctor of Philosophy in the school of Business Administration. During the course of his studies, he majored in production/operations management and minored in quantitative methods. From September of 1980 to December of 1982, he served as a teaching assistant, teaching production/operations management in the Department of Management and the Department of Quantitative Business Analysis. He is a member of The Academy of Management, APICS, AIDS, and TIMS/ORSA.

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EXAMINATION AND THESIS REPORT

Candidate: Mohamed T. Aly Mady

Major Field: Business Administration (Management)

Title of Thesis: The Effect of Alternative Buffering Techniques to Protect a Multi-Product, Multi-Stage Production Inventory System Against Supply Uncertainty

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

William W. Willis

O. Jeff Harris

Date of Examination:

July 15, 1983