AN EXPERIMENTAL INVESTIGATION:
UNCERTAINTY IN MRP SYSTEMS

by

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Chapter 1

THE PROBLEM

Introduction

Manufacturing firms must order raw materials and component parts in advance of when they are needed in order to insure continuous operations. This involves a trade-off between holding raw materials and components inventory, versus risking the possibility of idle machine centers due to shortages of raw materials and components. Balancing the cost of carrying inventory against the cost of production halts due to shortages has been a persistent problem in many segments of the manufacturing industry. This problem is due, in part, to the complex nature of many manufactured products, where end items require several raw materials, components, and subassemblies for their production. In order to protect against the high cost of stockouts, manufacturing firms have often carried excessive amounts of inventory.

Material Requirements Planning

Material requirements planning (MRP) has evolved as a technique for the planning and controlling of inventories and production of complex manufactured products. Re-

quirements planning approaches have been known to practitioners for many years. The earliest published example of the use of MRP was in an illustrated advertisement for a Franklin stove in 1744 [35]. It was not, however, until mid-1960, when major advancements in computer technology occurred, that MRP became an effective technique for production planning and control.

Material requirements planning is a computer-based production planning and inventory control system. The major objectives of an MRP system are to simultaneously:

1. ensure the availability of materials, components, and products for planned production and customer delivery,

2. maintain the lowest possible level of inventory, and,

3. plan manufacturing activities, delivery schedules, and purchasing activities [38].

MRP keeps inventory levels at a minimum while assuring the timely availability of required materials, thus minimizing the cost of planning and controlling inventories.

Terminology in the field of production and inventory management is sometimes imprecise and confusing. The most serious terminology problem centers around the use of the term MRP. Originally, terms such as "time series planning" or "time-based requirements planning" were coined. In the 1970's the term material requirements planning came

into usage [35]. The field has now progressed to the point where different levels of MRP are specified as material requirements planning (MRP I) or manufacturing resources planning (MRP II).

The APICS dictionary [44] defines MRP I and MRP II as follows:

MRP I = Material Requirements Planning:

> A system which uses bills of material, inventory and open order data, and master production schedule information to calculate requirements for materials. It makes recommendations to release replenishment orders for material. Further, since it is time-phased, it makes recommendations to reschedule open orders when due dates and need dates are not in phase. Originally seen as merely a better way to order inventory, today it is thought of primarily as a scheduling technique, i.e., a method for establishing and maintaining valid due dates on orders.

MRP II = Manufacturing Resource Planning:

> A method for the effective planning of all resources of a manufacturing company. Ideally it addresses operational planning in units, financial planning in dollars, and has a simulation capability to answer "what if" questions. It is made up of a variety of functions, each linked together: Business Planning, Production Planning, Master Production Scheduling, Material Requirements Planning, Capacity Requirements Planning and the execution systems for capacity and priority. Outputs from these systems would be integrated with financial reports such as the business plan, purchase commitment report, shipping budget, inventory projections in dollars, etc. Manufacturing resource planning is a direct outgrowth and extension of MRP.

In this research, the first definition, MRP I, will be used exclusively.

A flow diagram of a typical MRP system is shown in Figure 1-1. The three major inputs to an MRP system are the master production schedule, the product structure records, and the inventory status records [38]. The master production schedule (MPS) outlines the production plan for all end items. The MRP system explodes the master schedule of end itmes into individual time-phased component requirements.

The product structure records (bill of materials) contain information on all raw materials, components, and subassemblies required for each end item. Each item's part number, description, quantity per assembly, next higher assembly, and quantity per end item, must be available to the MRP system.

The inventory status records contain the on-hand and on-order status for all items in inventory. The inventory status records must be kept accurate with respect to all receipts and withdrawals. The records also contain information on lead times and lot sizes.

The MRP system determines component gross requirements by exploding the bill of materials per the master production schedule as shown in Figure 1-2. The explod-

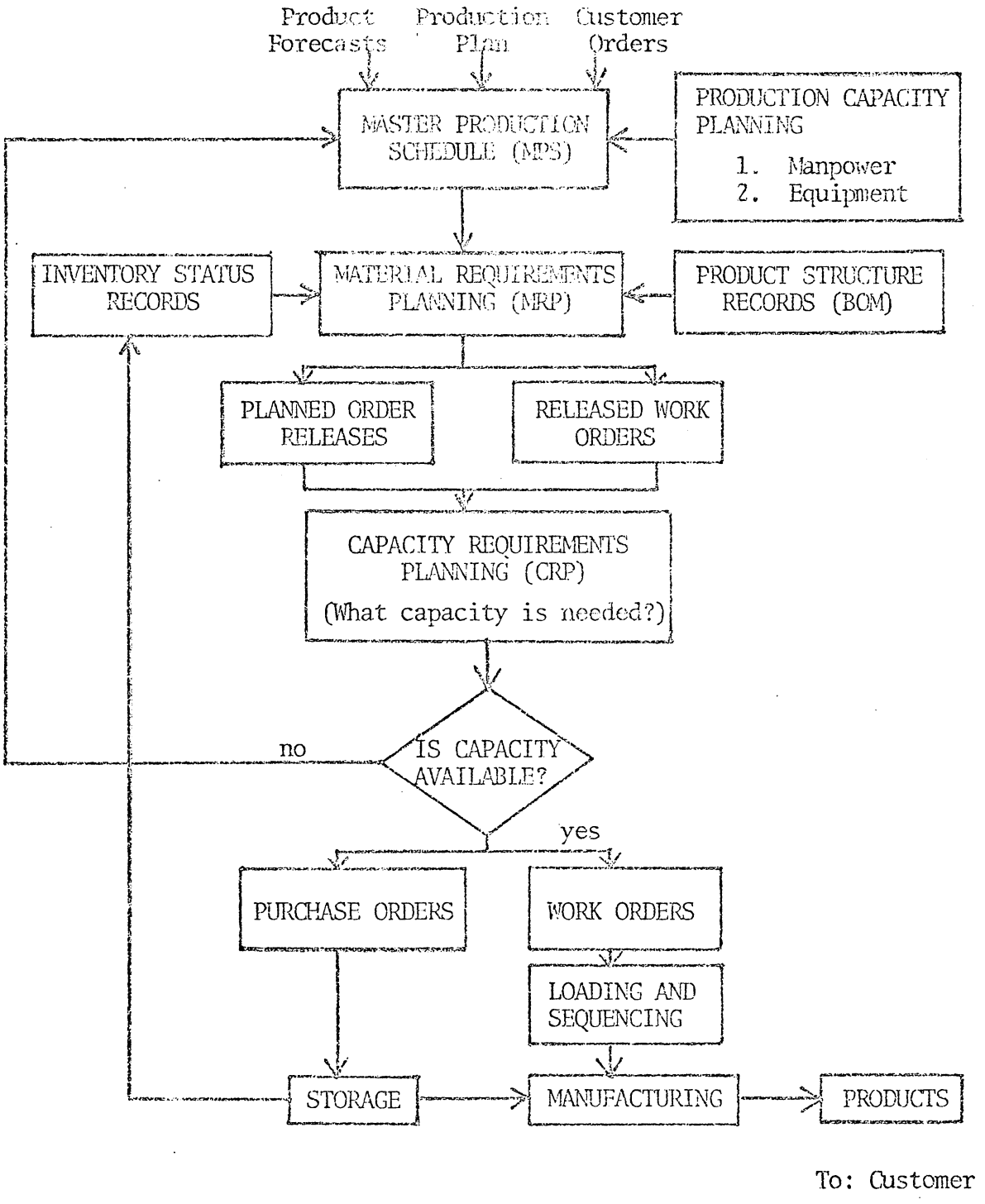


FIGURE 1-1

An MRP System

Source: R. J. Tersine [38]

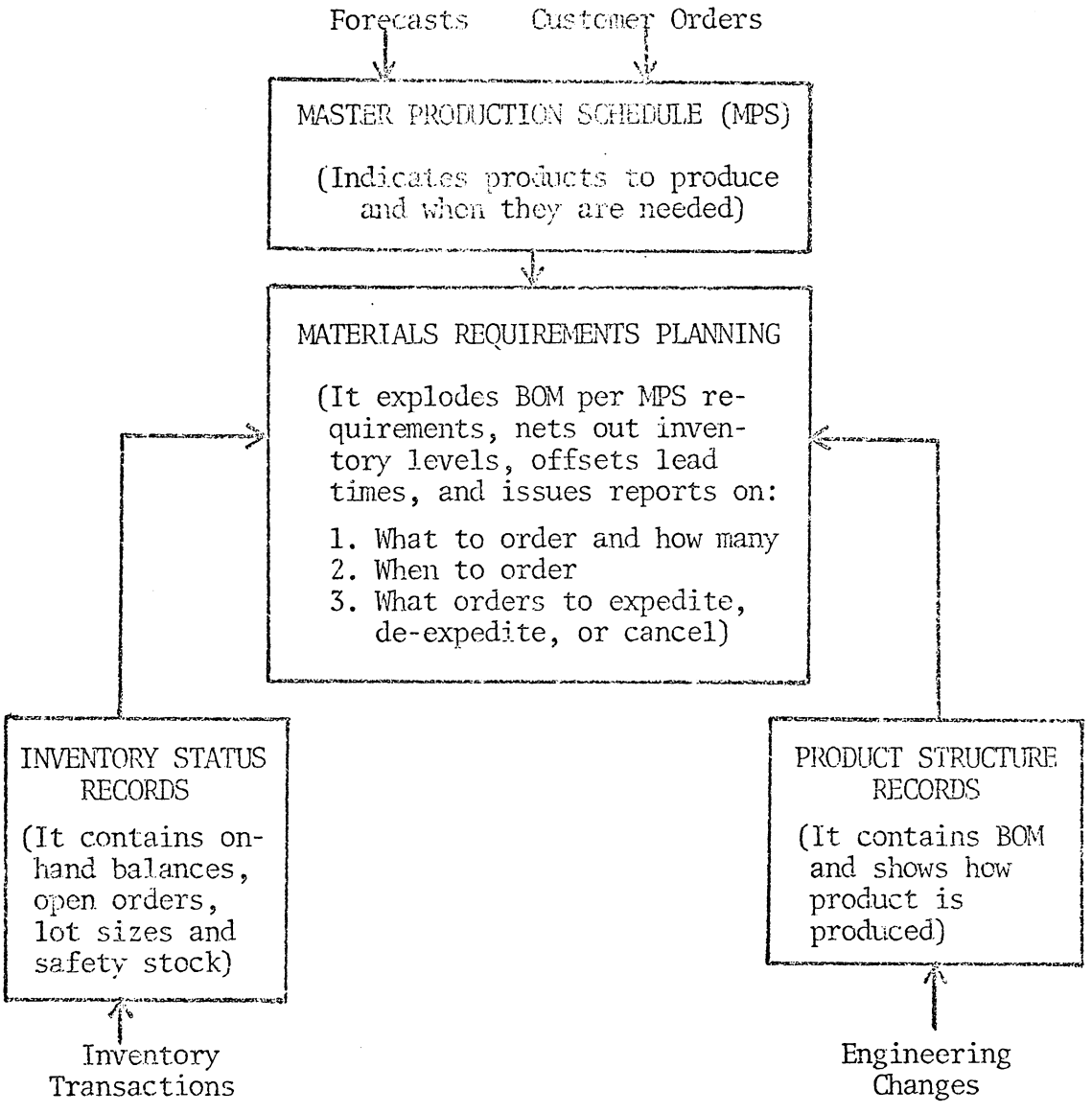


FIGURE 1-2

MRP Inputs

Source: R. J. Tersine [38]

ing process is simply a multiplication of the number of end items by the quantity of each input component required to produce a single end item. The gross requirements are netted by subtracting the available inventory indicated in the inventory status records to determine the net requirements. The timing of order releases is then determined by offsetting the receipt of requirements by their lead time. Thus, MRP specifies what, how much, and when to order.

The basic output of MRP logic is planned order releases as reflected in Figure 1-3. Planned order releases can take the form of purchase orders, work orders or reschedule notices. The planned order release provides the quantity and time period when work orders are to be released to the shop or purchase orders placed with vendors. At the time of release, the status of an order changes from planned to scheduled (also referred to as open or on order). Planned orders are used to generate material requirements at the next lower level and to project capacity requirements.

Reschedule notices usually take the form of delay, expedite or cancel. Reschedule notices are an attempt by the MRP system to make due dates and need dates coincide.

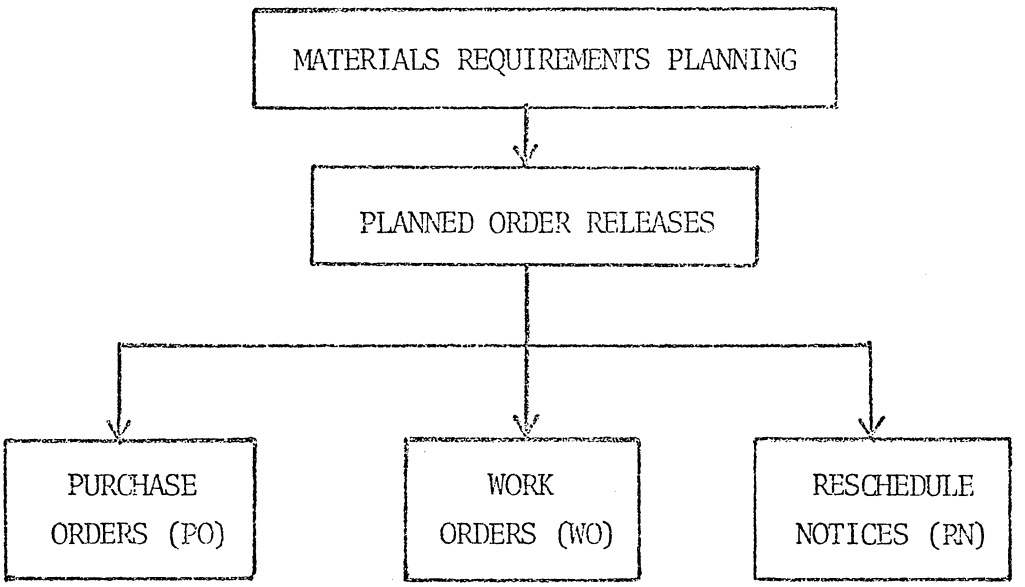


FIGURE 1-3

MRP Outputs

Source: R. J. Tersine [38]

Statement of the Problem

The problem addressed in this research is that of uncertainty in material requirements planning systems. The primary contributor of research in the area of uncertainty in MRP systems is Whybark [5,43].

Whybark and Williams [43] classify the sources of uncertainty in MRP into two categories: 1) demand uncertainties, and 2) supply uncertainties. Demand uncertainties are those which involve variations in the gross requirements of an end item, subassembly, or component part. Supply uncertainties deal with the variations in the scheduled receipts for a component.

Demand Uncertainties

Berry and Whybark [5] identify schedule revisions and engineering changes as two factors that may lead to changes in the gross requirements of a component.

Changes in the master production schedule (schedule revisions) can be of either the timing or quantity type. Timing changes involve the shifting of the gross requirements either ahead of schedule or into later time periods. Changes in the timing of the parent item's gross requirements will affect the dependent requirements of all component items.

Quantity changes to the master production schedule will also affect the requirements for component parts. Additions and subtractions to the master production schedule can be a result of increased demand, order cancellations, or assembly schedule modifications.

A change in a product's bill of materials (engineering changes) is the second factor leading to demand uncertainties identified by Berry and Whybark. Demand for a particular component can be substantially reduced or increased by engineering changes. For example, the requirements for a certain component can be completely eliminated if the item is no longer required in the production of its parent due to modifications in product design.

Supply Uncertainties

Late deliveries (timing) and order shrinkage (quantity) are the two factors identified in [5] that contribute to supply uncertainties. Variations in scheduled receipts can occur because of orders received late from within the system (shop orders) or orders received late from suppliers (purchase orders).

Supply uncertainty that results because of timing can involve the receipt of a shop order after its sched-

uled delivery date. This occurs when the MRP system's priority planning function (aligning need dates with due dates) is unable to adjust the progress of an order through the shop to match its completion with the final due date. For example, "if the machine processing time left to complete the order exceeds the time remaining until the scheduled delivery date, the priority planning function may not be able to complete the order in time" [5]. Orders received late from suppliers also contribute to the supply uncertainties that must be dealt with by the MRP system.

Quantity type supply uncertainty can also result in inventory shortages. Internally the shop may be unable to manufacture the original required quantity. A portion of the order quantity may be scrapped in the production process or defective items may be discovered upon receipt of the manufactured lot.

Externally, suppliers may ship quantities less than originally promised due to their own inventory shortages. Also, upon receipt of a purchased lot, certain items may be damaged and unusable, therefore causing component shortages.

Figure 1-4 summarizes the categorization of uncertainty in MRP systems by source and type.

SOURCE OF UNCERTAINTY	UNCERTAINTY	FACTORS CONTRIBUTING TO UNCERTAINTY TYPE
DEMAND	TIMING	Schedule revisions
	QUANTITY	Engineering changes or schedule revisions
SUPPLY	TIMING	Late orders (Shop or vendor)
	QUANTITY	Order shrinkages (Shop or vendor)

FIGURE 1-4

Uncertainty in an MRP System

Problems and Costs of Uncertainty

Questions that arise based on the preceeding discussion of the types of uncertainty in the MRP systems are:

1. What problems arise due to the presence of uncertainty in MRP systems?
2. What are the costs associated with each of these problems?

First, the problems caused by each type of uncertainty will be reviewed and then the costs associated with each problem will be described.

Problems Caused by Demand Uncertainties

Demand uncertainties are those uncertainties that enter the MRP system via changes in the master production schedule or bill of materials. Unplanned withdrawals from inventory due to MPS changes cause disruption of the normal assembly process because assemblies, components or raw material are not available when needed.

Figure 1-5 displays an example of an MRP logic [25]. This example consists of a product containing four levels; the finished product, a major assembly, a subassembly, and a purchased component. The master production schedule at the top of Figure 1-5 shows the quanti-

FINISHED PRODUCT

MASTER PRODUCTION SCHEDULE

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
AMOUNT			20		30		25		35	

ITEM MA LLC 1 ON HAND 10 ALLOC - SS - ROQ L4L LT 1

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS			20		30		25		35	
ON HAND		10	10							
SCHEDULED RECEIPTS			10							
NET REQUIREMENTS					30		25		35	
PLANNED ORDERS				30		25		35		

ITEM SA LLC 2 ON HAND - ALLOC - SS - ROQ L4L LT 2

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS				30		25		35		
ON HAND										
SCHEDULED RECEIPTS				30						
NET REQUIREMENTS						25		35		
PLANNED ORDERS				25		35				

ITEM PC LLC 3 ON HAND 40 ALLOC - SS - ROQ 100 LT 4

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS				25		35				
ON HAND		40	40	40	15	15				
SCHEDULED RECEIPTS										
NET REQUIREMENTS						20				
PLANNED ORDERS		100								

FIGURE 1-5

EXAMPLE MRP LOGIC

Source: H. Mather [25]

ties of the finished product to be manufactured in each time period (bucket in MRP terminology). Item specific data is provided across the top of each table. Each table represents a level in the product structure tree as identified by ITEM. The low level code (LLC) indicates the lowest level in which an item resides in all bills of material. ON HAND and ALLOC specify the amount of inventory on-hand and the amount of inventory, if any, previously committed to a particular time period. SS, ROQ, and LT specify the amount of safety stock, the reorder quantity, and the lead time of each item.

The number of major assemblies (item MA) required to produce one end item is assumed to be one, for simplicity. Using a bill of materials and MRP explosion logic results in the major assembly quantities required to be finished and ready to be used in manufacturing the finished product. These requirements for finished major assemblies are netted (subtracted) from on-hand inventory and any open replenishment orders by time period. Net requirements (shortages) are then indicated. Using a lead time of one week, the planned release is calculated.

A subassembly (item SA) that is needed to make the major assembly is the next item shown in Figure 1-5.

The gross requirements for finished subassemblies are calculated using the major assembly planned orders and the subassembly bill of materials. Again, assume one subassembly needed per major assembly for simplicity. The subassemblies are required at the same time that orders for the major assembly are scheduled to be started. The same netting and lead time offsetting logic is used to calculate the net requirement and the planned release date of the subassemblies.

Details for determining the requirements of the purchased component (item PC) are analogous to those described for the two assemblies. Note the reorder quantity (ROQ) is 100 for the purchased component, as indicated in the PC table shown in Figure 1-5.

Figure 1-6 shows the effects of a change in the MPS requirements of the end item. Increasing the finished product demand from 20 units to 40 units in period two, changes the demand for the major assembly, the subassembly and purchased component. The open order (scheduled receipt) of 30 in period 3 (subassembly) is now required in period 1. The purchase order for the component part must be released immediately. In addition, the lead time for the part will have to be substantially compressed.

FINISHED PRODUCT

MASTER PRODUCTION SCHEDULE

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
AMOUNT			40		30		25		35	

ITEM MA LLC 1 ON HAND 10 ALLOC - SS - ROQ L4L LT 1

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS			40		30		25		35	
ON HAND		10	10							
SCHEDULED RECEIPTS			10							
NET REQUIREMENTS			20		30		25		35	
PLANNED ORDERS		20		30		25				

ITEM SA LLC 2 ON HAND - ALLOC - SS - ROQ L4L LT 2

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS		20		30		25		35		
ON HAND										
SCHEDULED RECEIPTS				30						
NET REQUIREMENTS				20		25		35		
PLANNED ORDERS	20			25		35				

ITEM PC LLC 3 ON HAND 40 ALLOC - SS - ROQ 100 LT 4

PERIOD	PAST DUE	1	2	3	4	5	6	7	8	9
GROSS REQUIREMENTS	20			25		35				
ON HAND		40	20	20						
SCHEDULED RECEIPTS										
NET REQUIREMENTS				5		35				
PLANNED ORDERS	100				100					

FIGURE 1-6

EXAMPLE MRP LOGIC

Source: H. Mather [25]

Problems Caused by Supply Uncertainties

Orders that are received early and orders that are received late are potential problems. Orders received from suppliers ahead of required due dates result in excess inventory being held, and thus, unnecessary holding costs. Production orders filled ahead of schedule can be indicative of inflated lead times. Also, production orders completed early indicate that material was purchased earlier than necessary and production capacity was committed earlier than necessary.

Orders that arrive late, either purchased or manufactured, cause problems. For example, an order arriving one period late will cause all requirements for that item to remain unfilled for that particular time period. Subsequently, assembly procedures are disrupted and shipment plans delayed. Late orders also expand inventories on other components which cannot be used as a result of the shortage.

Referring to Figure 1-5, if the purchased component is unavailable in period 5, then the subassembly order cannot be released on schedule. If the subassembly is rescheduled into a later period, the need dates on all other components in the subassembly bill of materials

(BOM) will change. To minimize inventory investment and maximize capacity usage, the subassembly could be rescheduled. But, rescheduling will not achieve these goals if one component necessary to make the subassembly cannot be obtained when all other items (in the subassembly BOM) are received or manufactured on schedule. Furthermore, excessive rescheduling leads to "nervous" MRP systems. Nervousness in MRP systems can lead to a lack of confidence in the system priority planning function. In some situations, this nervousness and lack of confidence in the priority planning function has led to the lack of successful implementation and use of MRP systems. For a complete discussion of nervous MRP systems see [10, 37].

An open order that comes in too late results in a negative available balance or "below safety stock" condition. An order arriving too soon results in inventory in excess of the amount required to support a particular MPS.

Quantity variations, from suppliers or from in-house production, result in shortages and/or excess component inventories. An analysis of the effects of quantity variations on the overall MRP system would be similar to that discussed for timing variations.

The problems caused by uncertainty inherent in MRP systems have related costs. When excess inventories are held, regardless of the cause, unnecessary holding costs are incurred. When shortages occur, again regardless of the cause, serious disruptions of the assembly process and shipping plans can result. A lateness penalty charge is used to reflect the cost incurred as a result of shortages.

Limitations of Previous Approaches

The problem of determining operating policies in MRP systems involving uncertainty is very difficult. Previous work focuses primarily on the work of Whybark.

Berry and Whybark [5] have identified the sources of uncertainty in MRP systems as indicated in the previous section. The types of uncertainties are classified and perceived buffering alternatives are delineated. A strong case for research to investigate the effects of time buffering is presented. Reference is made to a simulation model [43] used to evaluate the effects of safety lead time and safety stock on average inventory levels. Their intentions were to begin to develop the

conditions under which one buffering technique is preferred over the other.

Whybark and Williams [43], report the results of simulation research into the effects of safety stock and safety lead time on the performance of an MRP system. The basic ideas of Whybark and Williams' paper form the motivational impetus for this research. The major limitation of their work is the analysis of a "single part." Because very little work has been done on the problem of uncertainty in MRP systems, the authors chose to start by studying a single part which could represent any manufactured or purchased part, fabricated component or assembled unit anywhere in an MRP system. Although this contention is somewhat unrealistic, their article is a valuable beginning. This research will differ substantially from theirs in that several end items, components (parts), and raw materials will be examined simultaneously. In other words, multilevel complex products will be researched. A more detailed discussion of Whybark and Williams' research is found in the Literature Review section.

Walker [40] has, to date, performed the most realistic research into the uncertainty problem. The primary outcome of Walker's research was the development of the

MRP/Production simulator. Walker's MRP/Production simulator is very sophisticated and versatile. It allows for the analysis of both the flat and multilevel product structure. It also enables the examination of safety stock and safety lead time policies within the MRP environment. A secondary objective of Walker's research was to conduct planned lead time experiments. Lead time strategies and product structure were the two factors analyzed by Walker. The Walker simulator will be utilized in this research.

This research will examine several additonal factors. The amount of lead time variability, lot-size rule, safety lead time, safety stock and the system's cost parameters will be studied. Also, a balanced factorial experiment will be performed, as opposed to the comparison of alternatives on an iterative basis.

Other articles dealing with uncertainty in MRP systems, as well as the ones mentioned above, are discussed in the Literature Review section. In general, these articles either: 1) focus exclusively on the problem of uncertainty, or 2) present research results on MRP systems less sophisticated than that proposed in this research. The simulators employed are simplistic and/or the statistical analysis is limited. This is not to say that the existing research has not significantly contri-

buted to the evolution of MRP systems. In fact, this present study is an extension of some of the significant prior research efforts.

Purpose and Objectives

Purpose

The purpose of this research is to examine the impact of specific operating policies on the performance of an MRP system under conditions of uncertainty. It was not deemed practical to study the effects of all the kinds and types of uncertainty mentioned in the previous discussion. Therefore, the supply/timing variety of uncertainty was selected for the efforts of this research. Supply uncertainties include either the timing or quantity type. Supply uncertainty that results because of timing involves the receipt of an order (shop or purchase) after or before its scheduled delivery date. The specific supply/timing uncertainty examined in this study will be that which is caused by variability in the lead time of purchased parts.

Experiments will be conducted in order to assess how the amount of lead time variability, the amount of safety stock, the amount of safety lead time, and the lot-size rule, effect the total cost of the MRP

system. In addition, the question of whether the results obtained are sensitive to changes in the system's cost parameters will be examined. The results will be classified as insensitive if they do not change when the system's cost parameters are varied. This will allow for the generalization of the results to other MRP systems.

Answers to the following questions will be addressed in this research.

1. Is the total cost of the MRP system affected by any of the factors tested?
2. Does the amount of safety stock or the length of safety lead time have any impact on system performance?
3. Does the amount of variability in lead time affect the choice of buffering alternatives?
4. Does the lot-size rule employed affect the choice of buffering alternatives?
5. Will changes in the holding cost fraction and lateness penalty charges affect the choice of buffering alternatives?

Objectives

There are two objectives of this research. The primary objective is to develop guidelines for practi-

tioners to use when making decisions involving uncertainty in MRP systems. The information obtained by examining the impact of several factors on an MRP system's performance will be utilized to establish these guidelines.

The second objective of this research is to expand on the work started by Walker [40]. Walker has developed a versatile and powerful MRP/Production simulator which can be used in this research. Walker's simulator will be employed to perform an experiment to analyze various treatments and treatment combinations. Multifactor analysis of variance (ANOVA) will be used to assess significant differences in the total cost of the MRP system under the various alternatives examined.

The simulator is a generalized version of the Carlson Simulator [9] developed at UCLA under a National Science Foundation Grant. The Carlson Simulator (written in BASIC) was modified and converted to the GASP IV simulation language [36]. A brief discussion of the Carlson Simulator and a detailed discussion of the Walker simulator (modified where necessary to perform this research) will be given in Chapter 2.

Scope

The statement of the purpose and objectives confines the scope of this research to a consideration of safety stocks and safety lead times used as buffering alternatives in MRP systems. An alternative to buffering against uncertainty in MRP systems is to increase the gross requirements in the master production schedule (MPS). However, increasing the MPS will not be considered because of its severe disadvantage. Overstating the gross requirements at the top of the product structure tree means that these inflated requirements will be exploded down through the rest of the system. This will result in overstating the requirements, by the same relative quantity, at each level throughout the system. This is not consistent with the objective of maintaining the lowest possible inventory at each level in the product structure [5].

An additional alternative to buffering against uncertainty is to reduce the amount of uncertainty that exists. Suggestions for reducing the amount of uncertainty that exists in MRP systems include:

1. Develop more accurate forecasts.
2. Freeze the MPS (i.e., do not allow changes for any reason).

3. Improve the priority planning function.

4. Insure more accurate inventory data.

5. Reduce rejects and scrap.

This research will assume that these suggestions have either (1) already been incorporated or (2) are not appropriate for the given situation. Therefore, uncertainty will exist in the MRP system analyzed in this research. The methods for protecting against uncertainty will be limited to safety stock and safety lead time (at varying amounts). A discussion and justification of the levels of these two factors, plus lead time variability, lot-size rule and cost value levels, will be given in Chapter 3.

The ordering disciplines employed by the MRP system analyzed in this research will be lot-for-lot (L4L), economic order quantity (EOQ), and periodic order quantity (POQ). Other lot-sizing techniques available but not included in this study are: least total cost (LTC), least unit cost (LUC), part-period balancing (PPB), and the Wagner-Whitin algorithm (WW).

Lot-sizing has received much attention in MRP literature. (See Krajewski [22] for an overview of the lot-sizing question as it pertains to MRP). To date, however, there is still ambiguity and inconsistency re-

garding the appropriate choice of a lot-sizing rule to use in an MRP system. Traditional lot-sizing techniques generally use information for a single level in the product hierarchy. Order quantities are calculated ignoring the dependent relationships obvious in an MRP system.

From a practitioner's viewpoint, L4L, EOQ, and POQ are the most commonly employed techniques. Also, by limiting the levels of the lot-sizing factor to three, the size of the experiment is kept reasonable.

Other factors which could be varied in this experiment are:

1. product structure,
2. commonality of components,
3. number of products,
4. number of time periods,
5. demand patterns,
6. priority scheduling, and
7. shop capacity.

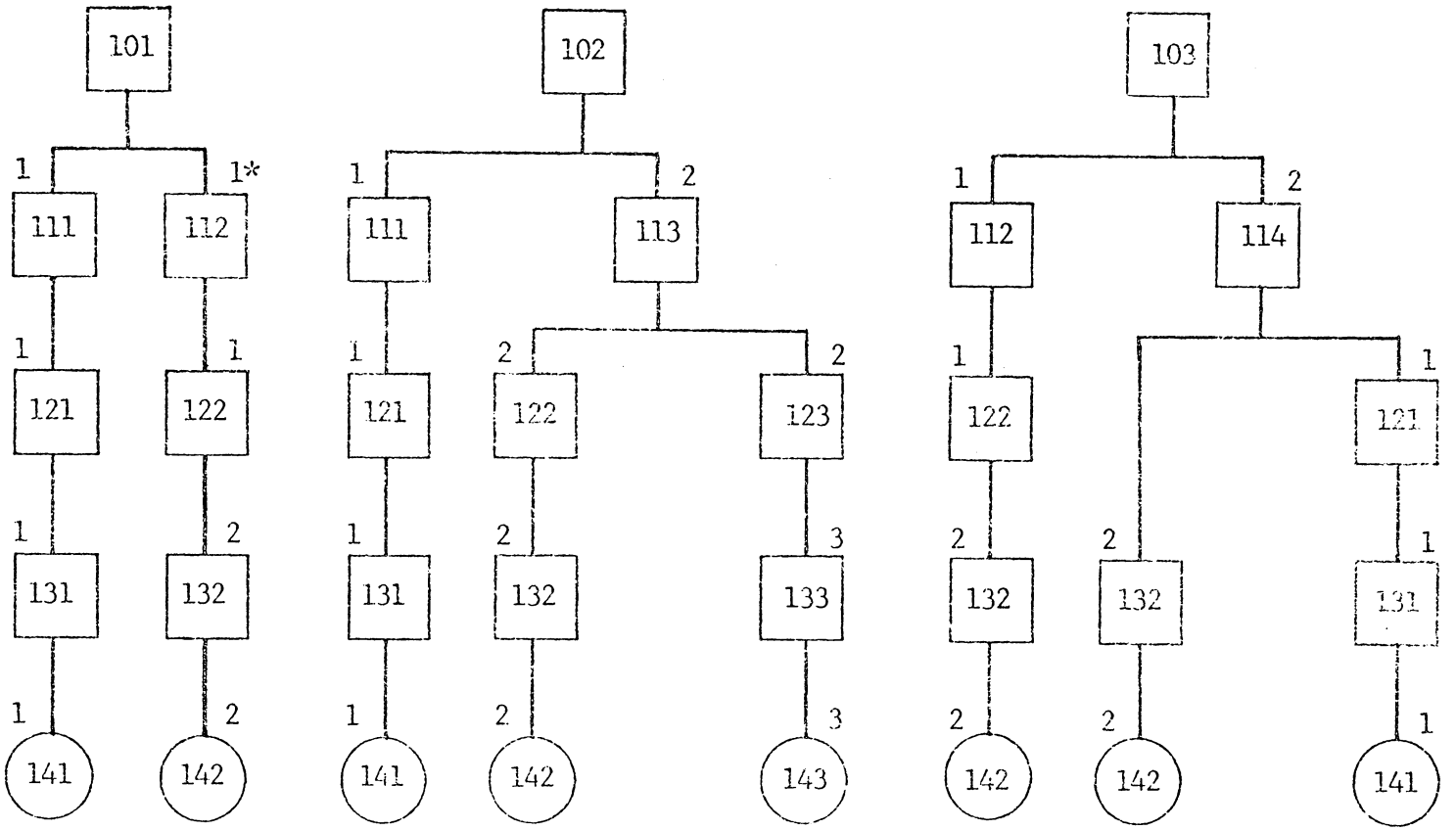
Time and the prohibitive size of the resulting experiment dictate holding these factors at constant levels.

A hypothetical MRP system, as opposed to a model of a particular firm's system, is studied in this research. A hypothetical model provided a means of controlling the

variables of interest while holding other factors constant. The results obtained by studying a hypothetical model provide more generality and comparability than those obtained by studying an individual firm.

Three end items (labeled 101, 102 and 103 in Figure 7), will be manufactured. Each end item has a five-level product structure tree and moderate component part commonality. For example, component number 112 is used in the manufacturing of end items 101 and 103 as shown in Figure 7. Similar commonalities can be identified by examining the multilevel product structure diagram. This combination of end items, product structure level, and component part commonality will allow for meaningful interpretation of the experimental results while still being representative of reality. The purchased parts are at the lowest level of the product structure tree. Introducing variability in lead time at the lowest level will influence the behavior of all higher level items in the product structure.

Each of the three levels, between the purchased part and end item levels, represents a separate machining operation. The end item demand pattern will be held constant throughout the experiment. The demand pattern used will be randomly generated to balance the shop at 80%



*Quantity required in assembly of next higher level item.

FIGURE 1-7

Multi-Level Product Structure

capacity. A constant shop capacity of 80% was selected as representative of an actual shop utilization rate.

All priority scheduling is done according to the MRP due date. The total number of time periods simulated is a function of when the model reaches steady state.

This research will be exploratory in nature. The results will not provide optimal answers to the problem of uncertainty in MRP systems. The results will reflect the response of the MRP system to the factor and factor levels examined. The output will be statistical data and any resulting inferences must be viewed accordingly.

Background and Significance

Background

The use of MRP systems to plan and control complex fabrication and assembly processes has resulted in a major shift in the design of manufacturing planning and control systems during the past decade. While substantial operating experience has been gained with MRP systems, very little systematic research has been directed toward understanding the impact on manufacturing performance caused by changes in the operating parameters of an MRP system [3].

In an MRP system, the production and inventory plans

for component parts are determined from an end item production schedule or master production schedule (MPS). Thus, the demand for component parts is directly related to or the result of the demand for a higher level item. Dependent demand is not necessarily random but, tends to occur in a lumpy (highly variable) manner at specific points in time. This lumpiness occurs because most manufacturing occurs in lots and all items needed to produce the lots are usually withdrawn from inventory simultaneously. End item demand may be independent and continuous, but lower-level demand tends to be discrete and derived from higher level items.

Because of dependent demand, decisions as to when and how much inventory to order are significantly different from those determined by statistical inventory management techniques (i.e., EOQ/ROP, etc.). The fact that many firms have recognized statistical inventory control as inappropriate in a manufacturing environment has provided the impetus for research on the design, implementation, and operation of MRP systems [43, 5, 22, 18].

To quote Wagner [39],

> The development impetus of MRP has come mostly from practitioners. Its conceptual underpinnings rest on a deterministic view of reality (bills of materials, shrinkage and yields, production times, capacity utilization, and forecast demand). Inso-

> far as actuality differs from the postulated deterministic world, experienced practitioners have formulated pragmatic remedies to handle the resultant problems. Only recently have operations researchers started to examine the elements of MRP scientifically.

The purpose of this research is to scientifically examine certain operational elements of an MRP system.

Significance

Given the extent to which MRP systems have already been implemented in real-world manufacturing systems and, the promise of MRP systems as a valuable management tool for improved planning and control of production operations, further research directed toward gaining additional knowledge and understanding of MRP systems and their operation, is extremely desirable [4]. Buffa, in the inaugural issue of the Journal of Operations Management, lends support to the overall significance of this research, in which he states, that "A whole generation of research needs to be repeated in the MRP arena. New simulators must be developed to replace the old obsolete job shop simulators of the 60's and 70's" [8]. Buffa also confirms the usefulness of computer simulation to test operating policies and the effect of parameter changes on the performance levels of MRP systems.

The use of either safety stock or safety lead time has generally not been recommended for use in MRP systems. The theoretical reasoning behind omitting safety stock or safety lead time is: (1) the demand for components can be calculated exactly from the master production schedule, and, (2) due date changes can be relayed to the shop (via the priority planning function of MRP), therefore, allowing production lead times to be shortened.

However, IBM's Communication Oriented Production Information and Control System (COPICS) states, "Yet, in practice, one can frequently find exceptions to the principle that safety stock is not required for dependent demand items" and, "safety stock could be carried for certain selected dependent demand items as an exception to the general rule"[5].

The delivery of orders consisting of component parts from suppliers are often made later than promised. A frequently suggested alternative form of buffering is safety lead time. Basically a safety lead time entails the placement of orders earlier than if planned lead times are used.

Thus far much ambiguity exists in guidelines (what few there are) regarding the uses of safety stock versus

safety lead time as buffering alternatives in an MRP system. This suggests that the proper use of either of these buffering choices is affected by the same demand and supply variations that affect items having independent demand.

"However, unlike the case of independent demand items, these demand and supply variations, and their impact on the production and inventory system, are not yet a well understood phenomena" [5]. Further, the interaction effects of these buffering techniques with a particular lot-sizing rule and/or the amount of lead time variability, along with the simultaneous sensitivity of these factors to a particular system's cost parameters, has not been investigated.

Peterson and Silver [34], state:

> Outright elimination of safety stocks or safety time (the latter meaning that orders are scheduled for completion slightly ahead of the requirements time) for the dependent demand items may not be the final answer in MRP; in particular, it would appear attractive in some cases to maintain safety stock in common semi-finished material rather than in a myriad of finished items. An exact analysis of how much safety stock to include in which items would be very complicated because of the erratic time-varying nature of the demand patterns at the dependent levels.

Review of Related Literature

An extensive literature search was undertaken to assure that this research will not duplicate prior work. A search was conducted of several journals including, Management Science, Operations Research, Production and Inventory Management, Decision Sciences, AIIE Transactions, Journal of Operations Management, Naval Research Logistics Quarterly plus other lesser known publications. In addition, the national and regional proceedings of several professional societies were searched. Copies of relevant papers discovered in these proceedings were requested from their respective authors. Dissertation abstracts and Operations Research/Management Science Services were also examined. Operation Research/Management Science Services contains abstracts of articles found in the journals mentioned above (plus others) from 1961 to date.

The efforts of the literature search indicate that this study is unique in the following aspects. First, this experiment will combine four factors and factor levels not previously studied together. Second, except for Walker, this study performs experiments using the GASP IV MRP/Production simulator developed by Walker. Third, this research undertakes scientific inquiry into

the relatively unstudied area of uncertainty in MRP systems.

Much of the material written concerning MRP can be found in Production and Inventory Management (PIM), the Journal of the American Production and Inventory Control Society (APICS). The majority of the articles, however, are either (1) tutorials on MRP concepts and ideas, or (2) descriptions of MRP implementations and uses within an individual organization. Articles reporting the results of experimentation into the effectiveness of various operating procedures are rarely published in PIM.

The literature review is separated in two sections. The first covers literature dealing with uncertainty in MRP systems. The second section discusses available simulators and previous simulations of actual MRP systems. How this study differs from previous research will be pointed out where it is not obvious.

Uncertainty in MRP Systems

Berry and Whybark [5] identify the sources of uncertainty that produce the need for buffering in MRP systems. The sources of uncertainty are classified by type and kind. Buffering alternatives available to pro-

tect against these uncertainties are described in detail. Much information contained in [5] has been discussed in the earlier sections of this proposal. Therefore, it will not be repeated again, except to emphasize that the working paper by Berry and Whybark provides the underlying foundation for this study.

After a brief discussion of uncertainties in MRP systems and the alternatives available for protecting against uncertainty, Whybark and Williams, [43], discuss their simulation study. The simulation experiments were conducted to determine if a preference existed for either safety stock or safety lead time under each category of uncertainty.

Statistical analysis, in the form of t-tests and ANOVA, were conducted to identify the preferred buffering alternative. Their results indicate that safety lead time was preferred under conditions of uncertainty in timing and safety stock preferred under conditions of quantity uncertainty.

Although the Whybark and Williams' article represents a first step in analyzing the effects of uncertainty in MRP systems, a major limitation is apparent. The simulation model in their study was designed to examine what they called "a representative part." In other words,

a single level within an MRP system was investigated. Whybark and Williams felt it was important to understand the behavior of a single part before examining a more complex MRP system.

Although they have made a significant contribution by initiating research in the area of MRP uncertainties, Whybark and Williams admit that much additional work remains. This research will differ substantially from that of Whybark and Williams in that a complex multilevel system is simulated as opposed to a single level system.

After developing the MRP/Production simulator, Walker [40] conducted planned lead time experiments. In these experiments Walker compared planned lead time strategies in conjunction with three different product structures. A flat, multilevel, and mixed product structure were studied. Planned lead time strategies were iteratively compared with each different product structure. Strategies ranging from the historical mean (μ), to the historical mean (μ) plus 1, 2, and 3 standard deviations (σ) above the mean, were compared.

Simple t-tests were conducted to assess significant difference in system performance for each planned lead time strategy based on a given product structure. Although Walker actually analyzed two distinct factors

(product structure and planned lead time strategy) an ANOVA model was not used to analyze his results.

Walker's simulator will be used as the vehicle to perform this research. However, the analysis performed will differ substantially from Walker's research. A four factor balanced factorial analysis will be performed and all hypotheses tested. The main and interaction effects will be analyzed and interpreted.

Berry [3] examined the impact of two factors on the performance of an MRP system. The length of the planned production lead times and the size of the production order quantity were examined in simulation experiments. Regression analysis was used to describe the performance effects of varying these two factors. The emphasis was on production lead times (versus supply lead times) and only two factors were studied.

Boe and Leaw [7] have performed research in the area of using heuristics to calculate safety stock in MRP systems. Experiments were conducted incorporating safety stock at various levels within an MRP system. Simulations were performed to evaluate the effectiveness of two different safety stock heuristics on several performance measures. Their work into heuristic safety stock procedures appears promising. This research

differs from Bow and Leaw's study in that safety stock is the only buffering alternative considered. Boe and Leaw do not consider safety lead time as a buffering technique.

Several authors have written about the use of safety stock and safety lead time in MRP systems. (See Buffa [8], New [32], Moore [28], Orlicky [33] and Wight [41].) These articles either discuss the possibility of incorporating safety stock or safety lead time in MRP systems or suggest alternative ways of calculating each. None perform experimentation on the effectiveness of using safety stock or safety lead time to protect against uncertainty.

Available Simulators and Simulations

In addition to the Carlson simulator and Walker's MRP/Production simulator, Kriebel's FACTORY simulator [23], in its many versions, has been suggested as a potential tool for examining MRP systems. In fact, Krajewski [22] suggests that everyone use the FACTORY simulator to perform experimentation on the effectiveness of various operating policies on the performance of MRP systems.

The primary reason for not using FACTORY is the

lack of documentation concerning the details of the simulator. Little was found in the literature describing the actual simulation model. Further, it is not practical, nor a wise use of time, to obtain and load (if possible) the FACTORY simulator on VPI's computer system.

Aggarwal and Dhavale (1) conducted simulation experiments to test the overall response to parameter changes in an actual MRP type system. Their study was based on empirical data from a multiproduct multiechelon inventory-distribution system. The system contained one central warehouse and five regional distribution centers. Analysis of variance was used with three factors and several different dependent variables. An important result of their study was that lead time variability was identified as an important factor in the performance of an MRP system.

Other simulation studies have been performed for manufacturing firms. These simulations are company specific, and thus, not appropriate for the type of analysis to be undertaken in this study.

Previous work in determining operating policies in MRP systems has sometimes fallen under the category of Multi-Echelon Inventory Theory. Clark [11] discus-

ses much of this material. This work relies heavily on dynamic programming and network techniques. Many of the multiechelon studies often fail to give managerial insights in terms of operating policy alternatives. Others, because of simplifying assumptions or restrictions, have taken the problem out of the context of reality. For example, assuming single level or at most two level systems, or allowing only one predecessor for each component is not representative of the manufacturing environment.

Plan of Presentation

Chapter 2, entitled The Simulation Model, includes a description of the GASP IV MRP/Production simulator and a discussion of the general considerations in simulation. The events, attributes, files, and non GASP IV variables are each defined. The inputs and outputs associated with using the simulator are described. A brief description of each subroutine employed in the simulator is given. The sections on validation, steady state and start-up conditions discuss the inherent difficulties associated with Monte Carlo simulations.

Chapter 3, entitled Experimental Design, defines the factors and factor levels and the factorial experi-

ment. The multifactor ANOVA model is constructed and each of its terms and assumptions are defined. The appropriate hypothesis and test statistics are constructed. Post ANOVA analysis and a summary of the experiment conclude this chapter.

Chapter 4, entitled Experimental Results, reports and interprets the results of the experimental investigation of uncertainty in MRP systems. Linear contrasts and confidence intervals are also developed in this chapter.

Chapter 5 presents the summary and conclusions of the dissertation, along with practical guidelines, limitations of the study, and recommendations for future research.

Chapter 2

THE SIMULATION MODEL

General Description

The simulation model used in this research is a versatile MRP/Production simulator, developed by Walker [40], and designed to provide a framework for the investigation of a wide variety of MRP related problems. Much of what is contained in this portion of the methodology section can be found in either Walker's thesis [40] or by examining and analyzing the GASP IV coding of the simulator.

In general the MRP/Production simulator has the following capabilities:

1. The capability to explode requirements for any type or combination of product structure over a variable length planning horizon.

2. The capability to load released orders onto various work centers and then simulate their production.

3. The capability to account for the dependent demand nature of component parts as they flow through simulated machinery and assembly operations. This is accomplished by blocking any operation for which all component parts are not available.

4. The unique capability to adjust machine utilization levels in relation to a particular

master schedule.

5. The capability to generate stochastic actual (as opposed to planned) lead time values for purchased parts according to a variety of distributions.

6. The capability to apply different lot-sizing methodologies and corresponding safety stock or safety lead time levels.

7. The capability to record simulated work-in-process inventory costs and end item lateness penalty costs.

8. The capability to re-explode requirements as the simulator proceeds through time [40].

Walker's simulator performs four basic functions.

1. It explodes the requirements of a user supplied master schedule.

2. It generates sufficient plant capacity to manufacture the products called for in the master production schedule.

3. It simulates the shop production of the MRP master schedule.

4. It records the resulting systems performance information (i.e., costs) [40].

A further explanation of these four basic functions performed by Walker's simulator follows.

Requirements Explosion

The explosion of the master production schedule is accomplished by the simulator using the conventional MRP logic described earlier. The net requirements resulting from the explosion process are time-phased (off-

set by lead time) into weekly time buckets.

Capacity Planning

To achieve the user specified utilization rate, the simulator calculates the required level of productive capacity at each work center. To accomplish this, all planned order releases for manufactured or assembled parts are loaded on their respective work centers to determine the total load on each work center during the entire planning horizon. Average weekly required output (parts/week) for each work center is then calculated by dividing total load by the number of time periods in the planning horizon.

Average weekly output=Total Load/Total # of Periods

The required production rate of each work center necessary to handle the demands of the particular master production schedule, at the user specified utilization rate, is then calculated by taking the reciprocal of average weekly output and multiplying by the percentage utilization:

Production rate=1.0/Average weekly output x Utilization Rate

The resulting output rates, expressed in weeks/part,

are used in the production segment of the simulator to determine service times for jobs at the various work centers. Service times are therefore a function of the production rate and the production lot size (planned order size).

Simulation of Production

To start the actual simulation of jobs, the simulator pulls all MRP planned orders scheduled for release during the first weekly time period. As each planned order is removed, the simulator makes a test to determine whether the order requires either a purchased or a manufactured part.

For all order releases associated with purchased parts, a parts arrival event will be scheduled. A stochastically generated actual lead time is produced, and an order arrival event for the item is placed in the GASP IV events list.

For all order releases associated with a manufactured part or assembly, it is first necessary to check the availability of all associated component parts before the job is allowed to move to its designated work center. This is accomplished by referencing the product structure file to identify all component parts which go

into the manufactured part specified in the order release. Once identified, the simulator checks the inventory records of each component to determine if the quantity on hand is sufficient to meet the requirements of the parent order release.

If all components are on hand in sufficient quantities, the requirements for each component are removed from their respective inventories. The job for the manufactured part or assembly is then placed in the queue of the designated work center.

Any manufactured job whose components are not on hand in sufficient quantity to meet the net requirements is placed in a blocked file. All jobs remain in the blocked file and will not be allowed to proceed to their designated work centers until the missing components arrive in inventory. Component inventory levels can be increased by either a purchase part arrival or a manufactured completion event.

When all planned orders scheduled for release in the first period have been pulled, plant operations will be simulated until the beginning of the second week. During the shop simulation that is performed from one order pulling operation to the next, any manufactured part completion and purchased part arrival event that

occur will be processed.

The simulation proceeds through time by repeating the above process for each successive time period until all weeks in the planning horizon have been exhausted.

Cost Calculation

During the simulation, all work-in-process inventory costs and end item lateness penalty costs are continuously updated. Each time an end item is completed, its tardiness is determined and a lateness penalty which reflects the degree of lateness and the value of the job is recorded if necessary.

Work-in-process inventory carrying costs are updated each time there is a change in the value of on-hand inventory or whenever there is a change in the value of a job which is moving through the system. Work-in-process cost, when updated, reflects any carrying cost incurred since the previous time of update. All new materials once received are included in the work-in-process cost calculations.

At the end of the simulation, average lateness penalty costs per week and average work-in-process inventory carrying costs are added to give average com-

bined cost. This combined cost is the performance measure for the simulator.

The following assumptions are made in the simulation model:

1. Priority by MRP due date.
2. Constant utilization rate.
3. No machine failures.
4. No premptive priorities.
5. No scrap or rework allowances.

The GASP IV MRP/Production Simulator

The first function of the MRP/Production simulator is to explode the master production schedule into net requirements. The logic required for this function was adapted from an interactive MRP simulator developed by Carlson [9]. The Carlson simulator, developed under a National Science Foundation Grant, is an educational tool developed to emulate the performance of a commercial MRP system.

The Carlson simulator was written in BASIC. The logic was converted to FORTRAN and serves as the basis of subroutines written to perform the MRP explosion segment of the MRP/Production simulator.

Events and Attributes

The MRP/Production simulator is written in the FORTRAN based GASP IV simulation language [36]. A total of 16 subroutines, 30 non-GASP variables, 6 attributes and 6 files are used in the simulator. A discussion of these subroutines, variables and attributes, as well as the necessary inputs and subsequent outputs follows.

A planned order (generated from the MRP segment of the program) is the entity modeled in the simulator.

The events used to model the production system are:

1. load planned orders
2. completion of manufactured parts
3. arrival of purchased parts
4. end of a period (or time bucket).

Six attributes are employed in the simulation as follows:

ATRIB(1) = time of event occurence

ATRIB(2) = code describing type of event

ATRIB(3) = item number (part number)

ATRIB(4) = cost of production batch at a particular point in time

ATRIB(5) = time lot begins manufacturing process

ATRIB(6) = number of items currently completed.

Non-GASP IV Variables

The definitions of the non-GASP variables used in the simulator are given below. The values of those non-GASP variables initialized at the beginning of the simulation experiment, are given in parenthesis.

Non-GASP Variable	Definition
INV	Number of inventory items (16)
NBOM	Number of bills of material (3)
ITP	Total number of weeks in planning horizon (375)
NMACH	Number of machines (4)
ITEMX	Item number
ISTAT	Inventory information array (STATIC INFORMATION)
IBOM	Bill of materials array
IREQ	Requirements array
P	Current period
ISRFLG	Schedule receipts flag used to indicate re-explosion option
LOTSZ	Lot size
ACTLT	Actual lead time distribution
MLOAD	Machine load
AVCAP	Average capacity
DDCAP	Production rate equation
ULEVEL	Utilization level (.80)

IBUF	The number of time periods before ITP that the simulation stops processing planned orders (6)
CC	Carrying cost
ITC	Total cost
VALUE	Value added for manufacturing
CCTIME	Length of time an item is held in inventory
IBUSY	Machine status indicator
CMACH	Machining cost
CCRATE	Carrying cost rate (.20 per year)
TLP	Total lateness penalty
IBKFLG	Blocked item flag
ITPMAX	Maximum number of weeks in planning horizon (380)
ISTREQ	First period in which master schedule requirements are generated (6)

Simulator Inputs

The following inputs must be provided to use the MRP/Production simulator. Again, the values of those non-GASP variables initialized at the beginning of the simulation experiment, are given in parenthesis.

A. INPUT TO SIMULATION CODE

Subroutine INTLC

ITPMAX	Maximum number of weeks in planning horizon (380)

ITP	Total number of weeks in planning horizon (375). (ITP<ITPMAX)
ISTREQ	First period in which master schedule requirements are generated (6)
IBUF	The number of time periods before ITP that the simulator will stop processing planned orders (6)
CLR	Time period at which the collection of statistics will start (1500)
ULEVEL	Utilization level for capacity planning (.80)
CCRATE	Carrying cost rate for work-in process inventory per dollar of inventory carried per 1/100 week (.20 per year)

Subroutine CMPLT

TLP	The penalty rate as a percent of job value per week late (.03 per week)

B. NON-GASP INPUT DATA CARDS

Card

1. Specifies the number of work centers in the simulation (4)

2. Specifies the number of items in the inventory master file (19)

Inventory Master File Data Cards

Card

1. 8 digit alphanumeric product name

2. 9 fields of information as follows:

1- Product number

2- Bill of material address of first lateral component

3- Bill of material address of first lateral parent

4- Lowest level code

5- Planned lead time

6- Current on-hand

7- Lot-size amount

8- Safety stock amount

9- Amount allocated

3. 2 fields of information as follows:

FIELD

1- Purchase price (10)

2- Work center produced on

Product Structure File Data Cards

Card

1. Specifies the number of unique assemblies in product structure file

2. 5 fields of information (one card for each unique assembly)

FIELD

1- Inventory address of parent item

2- Inventory address of component item

3- Bill of material address of next lateral component

4- Bill of material address on next parent

5- Quantity of component required to produce parent

C. GASP IV INPUT CARDS

(The GEN card through FIN card) needed to run simulation

Simulator Output

The output generated by the MRP/Production simulator is:

1. Capacity Report

   Total load on each machine

   Average load on each machine

   Time (weeks/part) part spends on each machine

2. Intermediate Results

   Total lateness for each end item.

   Total lateness for all end items.

   Average lateness for all end items.

   Total lateness penalty cost for all items.

   Total carrying cost for each product.

   Total carrying cost for all products.

   Combined carrying cost and lateness cost.

   Average lateness penalty per week.

   Average carrying cost per week.

   Average combined cost per week.

3. GASP Summary Reports

Description of Subroutines

A brief description of the subroutines employed in the simulator is appropriate at this point.

SUBROUTINE MAIN

Subroutine MAIN is used in all GASP IV programs to dimension NSET, equivalence NSET and QSET and specify values for NCRDR, NPRNT and NTAPE. GASP IV is called from subroutine MAIN.

SUBROUTINE INTLC

Subroutine INTLC is called before each simulation run to set initial conditions and schedule initial events.

SUBROUTINE PRELD

Subroutine PRELD reads data from the inventory master file required in the MRP explosion process. The gross requirements for all end items (or master production schedule requirements) are generated in subroutine PRELD.

SUBROUTINE EXPLD

Subroutine EXPLD performs the conventional MRP explosion procedures and generates the planned orders necessary to support the master production schedule.

SUBROUTINE TABLES

Subroutine TABLES constructs, for each period, the required MRP information. Tables are printed which indicate the following:

1. The part name and number
2. The purchase cost
3. The machine produced on
4. The on-hand inventory balance
5. The amount allocated
6. The amount of safety stock
7. The reorder quantity
8. The lead times
9. The simulated future period

Each table also contains, for each period, a line corresponding to the:

1. GROSS REQUIREMENTS
2. SCHEDULED RECEIPTS
3. PROJECTED AVAILABLE
4. NET REQUIREMENTS
5. PLANNED ORDERS

SUBROUTINE CAPCTY

Subroutine CAPCTY calculates average weekly output and the necessary production rates required to support the master production schedule given the user specified

utilization rate.

SUBROUTINE EVNTS (IX)

Subroutine EVNTS (IX) calls the appropriate event subroutines.

SUBROUTINE LOADPO

Subroutine LOADPO loads shop with all planned orders due in current week. Processing of manufactured and purchased parts is scheduled. Scheduled receipts, amounts allocated and blocked parts are recorded.

SUBROUTINE CMPLT

Subroutine CMPLT schedules the completion of manufactured parts, assemblies, and end items as well as actual arrival of purchased parts. Lateness penalty costs and work-in-process carrying costs are calculated.

SUBROUTINE CKBLK

Subroutine CKBLK determines if those items blocked because of missing material can now be unlocked.

SUBROUTINE CKINV

Subroutine CKINV determines if all required components are available in inventory. A test is made to determine if on-hand inventory is sufficient to cover requirements. Inventory balances are updated and all pertinent inventory costs calculated. Also, CKINV determines the status of each work center. If a work center is busy,

jobs are placed in queue. If work centers are idle, jobs are placed in service and a completion event is generated. Actual lead times for manufactured items are calculated and recorded.

SUBROUTINE SREC

Subroutine SREC converts planned orders to scheduled receipts and subsequently reduces scheduled receipts after material arrives.

SUBROUTINE OTPUT

Subroutine OTPUT prints user desired output information.

SUBROUTINE GRAPH

Subroutine GRAPH plots total carrying cost, total lateness penalty cost and total combined costs.

General Considerations in Simulation

Validation

Modeling a hypothetical system does not allow for the empirical validation of the model. That is, data produced by the simulation cannot be compared with real system data. This is not to say, however, that the model cannot be validated.

To validate the accuracy of the MRP/Production simulator, a number of diagnostic tests were conducted [40].

The GASP IV trace command was used to trace all events through the system to insure they were processed correctly by the various work centers.

Hand calculations were made to insure the accuracy of the lateness penalty and work-in-process cost figures. The GASP IV COLCT subroutine was used to monitor actual lead time for purchased parts to insure they fit the specified distribution. The COLCT subroutine was also used to insure that manufactured part lead times were consistent with the specified utilization rate of 80%. Examination of the output of simulations performed in this experiment provided a means of checking face validity.

Based on the above comments and an examination of the GASP IV coding, the simulator appears to be performing properly and is considered an accurate representation of an MRP/Production system.

Steady Start and Start-Up Conditions

Steady state conditions can be obtained in two basic ways. First, the simulator can be run long enough so that error resulting from including the transient period data is small. Second, when equilibrium conditions are obtained the data from the transient period can be elimin-

ated. The first method may require very long and costly simulation runs. The second method requires the exact determination of the length of the transient state.

Since exact determination of the transient period length can be difficult, a compromise procedure is used. Each simulation is run for a 375 week planning horizon. Also, the initial 15 week time period is discarded. All initial orders were processed through the MRP system by week ten. Therefore, 15 weeks was used as a conservative estimate of the warm-up period. Statistics are collected only after the warm-up period to minimize the impact of start-up conditions.

Summary

The GASP IV MRP/Production simulator and a discussion of the general considerations in simulation were presented in this chapter. A general description of the simulator's capabilities and basic functions was provided. The events, attributes, files and non-GASP IV variables used in the MRP/Production simulator were defined. The inputs and outputs associated with using the simulator were described in detail. A brief description was given for each of the subroutines employed in the simulator. The chapter was terminated by a discussion of the inherent difficulties asso-

ciated with Monte Carlo simulations: validation, steady state and start-up conditions. The next chapter presents a detailed discussion of the experiment designed to conduct a scientific investigation into the affects of uncertainty on the total cost of an MRP system.

Chapter 3

EXPERIMENTAL DESIGN

The primary objective of this study is to examine the impact of four factors on the performance of the previously described MRP/Production system. The hypothetical manufacturing system is simulated and its total cost (performance criterion) is recorded for varying levels of lead time variability (i.e., the probability distribution), buffering alternative (i.e., safety stock, safety lead time), lot-size rule, and the holding cost and lateness penalty values.

Analysis of variance (ANOVA) is used to assess significant differences in the system's total cost. Post ANOVA analysis is conducted in the form of general linear contrasts and rankings of those means judged significantly different.

The experiment is a 3x5x3x3 balanced factorial experiment. There are four factors, three at three levels each and one at five levels. The experiment is balanced because the number of observations on each combination is equal. The experiment tests 135 possible treatment combinations.

Factors and Factor Levels

The factors and factor levels analyzed are defined below:

FACTOR A =	lead time distribution	(LTD)
a_1=	uniform discrete	(UD)
a_2=	symmetrical discrete	(SD)
a_3=	asymmetrical discrete	(AD)
FACTOR B =	buffering alternative	(BA)
b_1=	no buffering	(0)
b_2=	200 units of safety stock	(200)
b_3=	300 units of safety stock	(300)
b_4=	1 week safety lead time	(1)
b_5=	2 weeks safety lead time	(2)
FACTOR C =	lot size rule	(LSR)
c_1=	lot-for-lot	(L4L)
c_2=	economic order quantity	(EOQ)
c_3=	periodic order quantity	(POQ)
FACTOR D =	cost values	(CV)
d_1=	high values	(HV)
d_2=	medium values	(MV)
d_3=	low values	(LV)

Lead Time Distribution

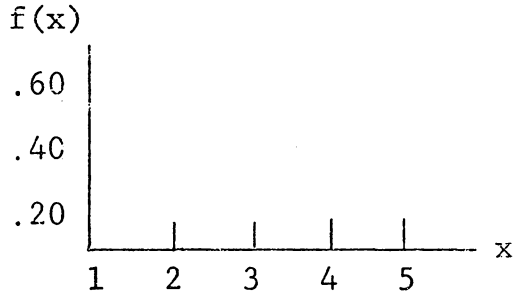
Lead time is modeled by three different discrete probability distributions. Each distribution takes on values from one to five allowing for a one month lead time window. The three distributions differ by the amount of variability in each.

The first distribution, a discrete uniform, allows for the maximum variability. The second distribution, a discrete symmetrical, allows for a lead time of three weeks (a representative industry average) to occur 60% of the time. Lead times of 1, 2, 4, or 5 weeks are equally likely to occur with probability of 10%. The third distribution, a nonsymmetrical discrete, also allows for a lead time of three weeks to occur 60% of the time. But, unlike the second distribution, the third distribution allows a lead time of four weeks to occur 25% of the time while allowing the lead times of 1, 2, and 5 weeks each to occur only 5% of the time. This seems consistent with the industry phenomena of parts arriving late more often than arriving early. The three distributions are portrayed in Figure 3-1.

Buffering Alternative

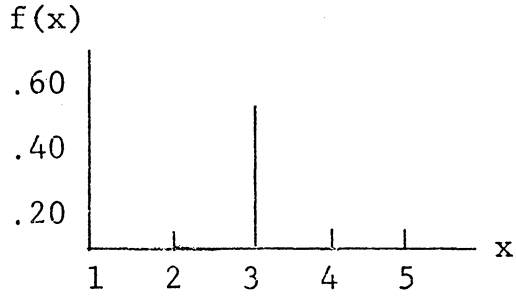
The amount of safety stock or the amount of safety lead time incorporated into the simulator are the levels

UNIFORM



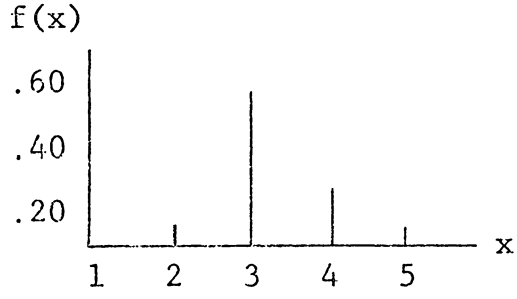
x	f(x)
1	.20
2	.20
3	.20
4	.20
5	.20

SYMMETRICAL



x	f(x)
1	.10
2	.10
3	.60
4	.10
5	.10

ASYMMETRICAL



x	f(x)
1	.05
2	.05
3	.60
4	.25
5	.05

FIGURE 3-1

Discrete Lead Time Distributions

of the buffering alternative factor. A different amount of safety stock or safety lead time is used depending on the desired service level. For the purposes of this research, service level (as it relates to purchased parts) is defined as the ratio of purchased parts available to purchase parts needed.

The first level of the buffering alternative factor provides for no buffering (i.e., zero safety stock and zero safety lead time). Pilot simulation runs at the no-buffering level yielded a service level of between 60% to 70% depending on the levels of the other factors. To determine the amounts of safety stock or safety lead time necessary to provide service levels of at least 85% and 95% an iterative approach was employed. Many pilot simulations were required to determine the amounts of each buffering alternative. As a result of these pilot simulations, a safety stock of 200 units or a safety lead time of 1 week is required to insure a service level of at least 85%. To insure a service level of at least 95% a safety stock of 300 units or a safety lead time of 2 weeks is necessary.

At this point, it is appropriate to define safety lead time and distinguish safety lead time from inflated lead time. Safety lead time is not simply an inflated

lead time. With safety lead time, the arrival date (or completion date) is always earlier than the need date, the difference being the safety lead time. Inflated lead time increases the time between placing and receiving an order, however, safety lead time implies releasing the order early. Ordering early, while not changing the actual lead time, results in parts arriving (or being completed) before they are needed, thus creating safety lead time.

Lot-Size Rule

Three lot-size rules are included in the experiment because of the anticipated interaction effects of lot-size and the effectiveness of using safety stock or safety lead time. Lot-size rules, which result in more inventory, indirectly provide buffering by reducing the number of exposures to a stockout. Therefore, these possibilities are examined in this study. The three lot-size rules chosen lot-for-lot (L4L), economic order quantity (EOQ), and periodic order quantity (POQ) correspond to those most commonly found in industry.

Cost Values

In order to facilitate the inclusion of cost parameter changes into the model a factor which combines holding cost and lateness cost is used. The cost values

are varied over a high, medium and low range. Combining holding cost and lateness cost effectively eliminates one factor. This substantially reduced the size of the experiment. For example, including both holding costs and lateness costs, separately at three levels, would yield 405 treatment combinations versus the 135 possible combinations currently available.

Varying the cost values over the high, medium and low levels will allow for the determination of the sensitivity of the model to changes in these cost parameters. The medium level will correspond to the initial values of holding cost and lateness penalty charges. Carrying cost is initially set at a rate of 20% of dollar value carried per year and will be varied between 25% and 15% to correspond to reasonable holding cost values used in industry. The lateness penalty is initially set at 3% of the dollar value of the jobs per week late, and, will be varied between 5% and 1%. Holding costs will be converted to a weekly basis to allow for correct units of measure when forming the cost ratio.

The Factorial Experiment

Assignment of Treatment Combinations

Since the experimental unit in this study is the simulation model, the treatment combinations can be

applied in any order. The simulation model does not respond differently because of the order used in assigning the treatment combinations. Therefore, there is no experimental design source of variation to contend with, only variations attributed to the treatment combinations and residual variation. Estimates of the treatment combination means represent measures of the impact of the various factors on system performance. These mean estimates are subjected to ANOVA-F tests to assess significant differences among the treatment combinations.

Each treatment combination is initially replicated five times. A discussion of the number of replications is forthcoming. The random number seed is changed between each replication to guarantee independence of the generated observations. Independence in simulation can be realized by generating each run with a new sequence of random numbers, the response of one run being an observation [20]. Treating each period of simulated time as one observation and replicating this period with a new sequence of pseudorandom numbers yields independent observations [21]. Thus, the assumption of statistically independent error terms is satisfied.

The same set of five random number seeds is used to replicate (five times) each treatment combination. Syn-

chronization of the random numbers allows for the best comparison of the alternative system configurations (i.e., applying the different treatment combinations to the simulation model). Any variance between systems should then be attributable to the treatment combinations applied to the system.

Sample Size Determination

A major element in this experimental design is the number of simulation replications (sample size). The problem of determining the appropriate sample size for computer simulation experiments is complex and has been treated by a number of researchers. (See for example Naylor et al. [29].) Neter and Wasserman [30] suggest three approaches for the determination of sample size: the power approach, the "finding the best treatment approach," and the estimation approach.

The power approach requires the specification of the magnitude of the difference between a particular population mean and the grand mean we wish to detect for each treatment combination. At this point, estimates cannot be specified due to the lack of familiarity with the system to be simulated.

The "finding the best treatment approach" is applicable to experiments in which multiple ranking procedures

are employed. The use of multiple ranking procedures is not consistent with the stated objectives of this research. Therefore, this approach to planning the sample size is inappropriate.

The estimation approach is utilized, in this study, to determine the number of required replications. The estimation approach is an iterative procedure. Starting with an initial judgment of the needed sample size, confidence intervals are constructed. If the anticipated widths of the confidence intervals are satisfactory, the iterative procedure terminates. If the confidence interval widths are too wide or unnecessarily tight, larger or smaller sample sizes are tried. The procedure is continued until the sample size is found which yields satisfactory confidence intervals.

Rather than attempt to specify what is meant by a satisfactory width, in absolute terms, an approach suggested by Law [24] can be employed. Law's method requires the specification of an appropriate confidence interval width (or half length) in relative terms. For example, the width of the confidence interval can be stated as one having a half length of five percent. Precision is then obtained when the constructed confidence

intervals are no wider than ± 5% of the difference between the two means of interest.

A sample size of five is used as the initial starting point. Five was chosen arbitrarily, based somewhat on the size of the experiment to be performed and the subsequent amount of computer time and funds required. Running all 135 treatment combinations, each replicated 5 times, totals 675 runs. Estimating the cost of each run to be approximately $2.00, yields an approximate cost of $1400.00 in computer funds required to generate the data; not an unreasonable computer expenditure for an experiment of this size and complexity.

A sample size of five is used in the actual experiment because of time and resource limitations. Law [24] recommends always making at least three replications of a simulation to assess the variability of interest, regardless of the cost per replication. A large sample size is desirable. However, a small sample size is appropriate when performing an exploratory study or when computer time is limited.

The Multifactor ANOVA Model

The following fixed-effects multifactor ANOVA model is constructed to test the main effects and all interaction effects of the lead-time distributions, buffering alternatives, lot-sizes and cost values on the

MRP/Production system. The model components are consistent with that in Neter and Wasserman [30].

Model:

$$Y_{ijk\ell m} = \mu\ldots + A_i + B_j + C_k + D_\ell + (AB)_{ij} + (AC)_{ik} + (AD)_{i\ell} + (BC)_{jk} + (BD)_{j\ell} + (CD)_{k\ell} + (ABC)_{ijk} + (ABD)_{ij\ell} + (ACD)_{ik\ell} + (BCD)_{jk\ell} + (ABCD)_{ijk\ell} + \varepsilon_{ijk\ell m}$$

where:

i = indicator of lead time distribution, $i = 1,2,3$

j = indicator of buffering alternative, $j = 1,2,3,4,5$

k = indicator of lot-size rule, $k = 1,2,3$

ℓ = indicator of cost value level, $\ell = 1,2,3$

m = indicator of the number of simulation replications, $m = 1,2,\ldots,n$

$Y_{ijk\ell m}$ = response (total cost) to the ith lead time distribution, j^{th} buffering alternative, k^{th} lot-size rule, ℓ^{th} cost value, for m^{th} replication

$\mu\ldots$ = reference point

A_i = main effect of the ith lead time distribution

B_j = main effect of the jth buffering alternative

C_k = main effect of the kth lot-size rule

D_ℓ = main effect of the ℓth cost values

$(AB)_{ij}$ = interaction effect of ith lead time distribution and j^{th} buffering alternative

$(AC)_{ik}$ = interaction effect of ith lead time distribution and k^{th} lot-size rule

$(AD)_{i\ell}$ = interaction effect of ith lead time distribution and ℓ^{th} cost values

$(BC)_{jk}$ = interaction effect of jth buffering alternative and k^{th} lot-size rule

$(BD)_{j\ell}$ = interaction effect of jth buffering alternative and ℓ^{th} cost values

$(CD)_{k\ell}$ = interaction effect of kth lot-size rule and ℓ^{th} cost values

$(ABC)_{ijk}$ = interaction effect of ith lead time distribution, j^{th} buffering alternative and k^{th} lot-size rule

$(ABD)_{ij\ell}$ = interaction effect of ith lead time distribution, j^{th} buffering alternative and ℓ^{th} cost values

$(ACD)_{ik\ell}$ = interaction effect of ith lead time distribution, k^{th} lot-size rule and ℓ^{th} cost values

$(BCD)_{jk\ell}$ = interaction effect of jth buffering alternative, k^{th} lot-size rule and ℓ^{th} cost values

$(ABCD)_{ijk\ell}$ = interaction effect of ith lead time distribution, j^{th} buffering alternative, k^{th} lot-size rule and ℓ^{th} cost values

$\epsilon_{ijk\ell m}$ = residual term = variation not accounted for by model components defined above

Assumptions

The following ANOVA assumptions and restrictions are made:

1. $\epsilon_{ijk\ell m}$ are independent $N(0,\sigma^2)$
2. A_i, B_j, C_k, D_ℓ, $(AB)_{ij}$, $(AC)_{ik}$, $(AD)_{i\ell}$, $(BC)_{jk}$, $(BD)_{j\ell}$, $(CD)_{k\ell}$, $(ABC)_{ijk}$, $(ABD)_{ij\ell}$, $(ACD)_{ik\ell}$, $(BCD)_{jk\ell}$, $(ABCD)_{ijk\ell}$ are constants with the following restrictions:

$$\sum_i A_i = \sum_j B_j = \sum_k C_k = \sum_\ell D_\ell = 0$$

$$\sum_i (AB)_{ij} = \sum_j (AB)_{ij} = 0$$

$$\sum_i (AC)_{ik} = \sum_k (AC)_{ik} = 0$$

$$\sum_i (AD)_{i\ell} = \sum_\ell (AD)_{i\ell} = 0$$

$$\sum_j (BC)_{jk} = \sum_k (BC)_{jk} = 0$$

$$\sum_j (BD)_{j\ell} = \sum_\ell (BD)_{j\ell} = 0$$

$$\sum_k (CD)_{k\ell} = \sum_\ell (CD)_{k\ell} = 0$$

$$\sum_i (ABC)_{ijk} = \sum_j (ABC)_{ijk} = \sum_k (ABC)_{ijk} = 0$$

$$\sum_i (ABD)_{ij\ell} = \sum_j (ABD)_{ij\ell} = \sum_\ell (ABD)_{ij\ell} = 0$$

$$\sum_i (ACD)_{ik\ell} = \sum_k (ACD)_{ik\ell} = \sum_\ell (ACD)_{ik\ell} = 0$$

$$\sum_j (BCD)_{jk\ell} = \sum_k (BCD)_{jk\ell} = \sum_\ell (BCD)_{jk\ell} = 0$$

$$\sum_i (ABCD)_{ijk\ell} = \sum_j (ABCD)_{ijk\ell} = \sum_k (ABCD)_{ijk\ell}$$

$$= \sum_\ell (ABCD)_{ijk\ell} = 0$$

<u>Hypothesis</u>

The following hypothesis are tested for the multi-factor ANOVA model described above.

ALTERNATIVES	TEST STATISTIC	PERCENTILE
H_0: all $A_i = 0$ H_1: not all $A_i = 0$	$F^* = \frac{MSA}{MSE}$	$F(1-\alpha; a-1, (n-1)abcd)$
H_0: all $B_j = 0$ H_1: not all $B_j = 0$	$F^* = \frac{MSB}{MSE}$	$F(1-\alpha; b-1, (n-1)abcd)$
H_0: all $C_k = 0$ H_1: not all $C_k = 0$	$F^* = \frac{MSC}{MSE}$	$F(1-\alpha; c-1, (n-1)abcd)$
H_0: all $D_\ell = 0$ H_1: not all $D_\ell = 0$	$F^* = \frac{MSD}{MSE}$	$F(1-\alpha; d-1, (n-1)abcd)$
H_0: all $(AB)_{ij} = 0$ H_1: not all $(AB)_{ij} = 0$	$F^* = \frac{MSAB}{MSE}$	$F(1-\alpha; (a-1)(b-1), (n-1)abcd)$
H_0: all $(AC)_{ik} = 0$ H_1: not all $(AC)_{ik} = 0$	$F^* = \frac{MSAC}{MSE}$	$F(1-\alpha; (a-1)(c-1), (n-1)abcd)$

ALTERNATIVES	TEST STATISTIC	PERCENTILE
H_0: all $(AD)_{i\ell} = 0$ H_1: not all $(AD)_{i\ell} = 0$	$F^* = \frac{MSAD}{MSE}$	$F(1-\alpha;(a-1)(d-1),(n-1)abcd)$
H_0: all $(BC)_{jk} = 0$ H_1: not all $(BC)_{jk} = 0$	$F^* = \frac{MSBC}{MSE}$	$F(1-\alpha;(b-1)(c-1),(n-1)abcd)$
H_0: all $(BD)_{j\ell} = 0$ H_1: not all $(BD)_{j\ell} = 0$	$F^* = \frac{MSBD}{MSE}$	$F(1-\alpha;(b-1)(d-1),(n-1)abcd)$
H_0: all $(CD)_{k\ell} = 0$ H_1: not all $(CD)_{k\ell} = 0$	$F^* = \frac{MSCD}{MSE}$	$F(1-\alpha;(c-1)(d-1),(n-1)abcd)$
H_0: all $(ABC)_{ijk} = 0$ H_1: not all $(ABC)_{ijk} = 0$	$F^* = \frac{MSABC}{MSE}$	$F(1-\alpha;(a-1)(b-1)(c-1),$ $(n-1)abcd)$
H_0: all $(ABD)_{ij\ell} = 0$ H_1: not all $(ABD)_{ij\ell} = 0$	$F^* = \frac{MSABD}{MSE}$	$F(1-\alpha;(a-1)(b-1)(d-1),$ $(n-1)abcd)$

ALTERNATIVES	TEST STATISTIC	PERCENTILE
H_0: all $(ACD)_{ik\ell} = 0$ H_1: not all $(ACD)_{ik\ell} = 0$	$F^* = \frac{MSACD}{MSE}$	$F(1-\alpha;(a-1)(c-1)(d-1),$ $(n-1)abcd)$
H_0: all $(BCD)_{jk\ell} = 0$ H_1: not all $(BCD)_{jk\ell} = 0$	$F^* = \frac{MSBCD}{MSE}$	$F(1-\alpha;(b-1)(c-1)(d-1),$ $(n-1)abcd)$
H_0: all $(ABCD)_{ijk\ell} = 0$ H_1: not all $(ABCD)_{ijk\ell} = 0$	$F^* = \frac{MSABCD}{MSE}$	$F(1-\alpha;(a-1)(b-1)(c-1)(d-1),$ $(n-1)abcd)$

Aptness of the Model

It is not necessary nor is it usually possible, that an ANOVA model fit perfectly (i.e., satisfies all assumptions). The ANOVA model is reasonably robust or insensitive to certain types of departures from the assumed model. The purpose, therefore, of examining the aptness of the model is to detect serious departures from those conditions assumed in the model.

The assumptions of statistically independent error terms is guaranteed by generating each run with a new sequence of random numbers. Serious violations of the assumptions of normality and equality of variances are not likely in this experiment because of equal cell replications. The impact of nonnormality and heterogeneity of variance in ANOVA is minimal in the case of an equal number of replications per cell [20]. By a minimal impact it is meant that departure from the ANOVA assumptions has little effect on the specified alpha level or the power of the F-test.

Nevertheless, the residuals were obtained and appear to be normally distributed around their mean of zero. The model is highly significant and has an R^2 = .987 which indicates the 98.7% of the variability in average total cost is accounted for by the four factors

used in this model.

Post ANOVA Analysis

Duncan's Multiple Range Test and Linear Contrasts

If the F tests indicate that factor level means differ, one may proceed directly to estimate the factor effects of interest [30]. Duncan's multiple range test and linear contrasts are employed to examine the effects of those factor level means showing statistical significance. Many useful conclusions can be made from Duncan's test and linear contrasts. A linear contrast indicating the difference in the effectiveness of safety stock versus safety lead time when L4L ordering is used in conjunction with the uniform lead time distribution is one of several such contrasts that can be developed.

If, for example, a contrast involving the factor level means $\mu_{i\cdots}$ is to be estimated:

$$L = \Sigma c_i \mu_{i\cdots} \qquad \text{where: } \Sigma c_i = 0$$

The unbiased estimator of L is:

$$\hat{L} = \Sigma c_i \bar{y}_{i\cdots}$$

The variance of L is:

$$\sigma^2(\hat{L}) = \left(\frac{\sigma^2}{nbcd}\right) \Sigma c_i^2$$

Replacing σ^2, the unknown population variance with MSE the sample variance of $\hat{L}$ is:

$$S^2(\hat{L}) = \left(\frac{MSE}{nbcd}\right)\Sigma c_i^2$$

Bonferroni Confidence Intervals

When a small number of contrasts among the factor level means $\mu_{i\ldots}$ are to be estimated and assurance is to be provided by a family confidence coefficient, the Bonferroni confidence interval is appropriate [30]. The Bonferroni confidence interval for L is:

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$$

where:

$$B = t(1-\alpha/2s;(n-1)abcd)$$

Contrasts based on factor level means $\mu_{.j..}$, $\mu_{..k.}$, and $\mu_{...\ell}$, are estimated in similar fashion.

If interaction effects prove to be significant, contrasts among treatment means may be desired. For example, contrasts among the treatment means $\mu_{ijk.}$ could be constructed as follows:

$$L = \Sigma\Sigma\Sigma c_{ijk}\mu_{ijk.} \quad \text{where:} \quad \Sigma\Sigma\Sigma c_{ijk} = 0$$

An unbiased estimate of L is:

$$L = \Sigma\Sigma\Sigma c_{ijk}\bar{y}_{ijk..}$$

and the variance of $\hat{L}$ is:

$$S^2(\hat{L}) = \frac{MSE}{n}\ \Sigma\Sigma\Sigma c_{ijk}^2$$

Again, the $1 - \alpha$ Bonferroni confidence interval for L is:

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$$

where:

$B = t(1-\alpha/2s;(n-1)abc)$

The procedures described above allow for indepth analysis of the results generated from the simulation experiments. The behavior of the MRP/Production system in response to changes in the different factors and factor levels is explored.

Summary of Experiment

The steps involved in performing the experiment are as follows:

1. Randomly select and record five random number seed values.
2. Perform pilot runs with the simulator to approximate:
   - length of start-up period
   - steady state
   - variance estimate
3. Apply the first treatment combination to simulator. For example, treatment combination a_1 b_1 c_1 d_1 specifies a simulation with the discrete uniform distribution, no safety stock or safety lead time, lot-for-lot ordering, and a high cost values. Thus, setting the factor levels is

analogous to setting the parameters within the simulator.

4. Run (replicate) the simulator five times with first treatment combination, changing the random number seed between each run.
5. Record total inventory cost for each replication. This provided five observations for the first cell in the experiment.
6. Repeat steps 3, 4, and 5 for the remaining 134 treatment combinations using the same sequence of the five random number seeds.
7. Analyze the data generated from the simulation runs using ANOVA and post ANOVA analysis.
8. Interpret the results.

Summary

A simulation experiment was designed to examine the impact of specific operating policies on the performance of an MRP system under conditions of uncertainty. The experiment considered four factors: 1) the lead time distribution of purchased parts, 2) the buffering alternative, 3) the lot-sizing rule, and 4) the holding cost and lateness penalty values. The experiment constructed was a 3x5x3x3 balanced factorial

design. Multifactor ANOVA was used to detect statistical differences in the system's total cost as a result of the four factors investigated in this study. A discussion of post ANOVA analysis and a summary of the experiment concluded this chapter. The next chapter reports and interprets the results of the experimental investigation of uncertainty in a hypothetical MRP system.

Chapter 4

RESULTS AND INTERPRETATIONS

The MRP/Production simulator was run 675 times, with 5 replications, for each of the 135 factor combinations. Each of the 135 cells represents a unique combination of a lead time distribution, a buffering alternative, a lot-size rule, and a set of cost values. The data generated by the simulation experiment is then entered into SAS (PROC ANOVA) to assess the significance of the impact of lead time variability, buffering strategy, lot-size rule, and cost values on the average total cost of the hypothetical manufacturing system.

The Multifactor Analysis of Variance

The multifactor analysis of variance is conducted to test the statistical significance of the factors specified in the ANOVA model constructed in Chapter 3. The results are given in Table 4-1. The ANOVA model specified is highly significant at the .0001 level. Almost 99% of the variation among the 135 treatment combinations is explained by this model. Therefore, the specified ANOVA model is appropriate.

TABLE 4-1 ANOVA Test Results

Source	D.F.	F Value	Significance level
A	2	26.98	.0001
B	4	1577.48	.0001
C	2	370.40	.0001
D	2	16893.81	.0001
A*B	8	.33	.9538
A*C	4	3.09	.0156
A*D	4	1.41	.2301
B*C	8	.71	.6846
B*D	8	29.75	.0001
C*D	4	2.33	.0546
A*B*C	16	.58	.9030
A*B*D	16	.53	.9320
A*C*D	8	1.17	.3134
B*C*D	16	.74	.7512
A*B*C*D	32	.60	.9630

A = Lead Time Distribution
B = Buffering Alternative
C = Lot-Size Rule
D = Cost Values
D.F. = Degrees of Freedom

All of the hypothesis constructed to test the significance of the main effects of lead time variability, buffering alternative, lot-size rule, and cost values are highly statistically significant at the .0001 level. The first-order interaction effects between lead time variability and lot-size rule (AC) and the first-order interaction effects between buffering alternative and cost values (BD) are highly statistically significant. None of the remaining first-order, second-order, or third-order interaction effects are statistically significant.

In summary, the analysis of variance indicates that lead time distribution, buffering alternative, lot-size rule, and cost values not only are significant factors, but also that interaction between certain factors is significant. Therefore, further analysis of the differences in average total cost in the hypothetical manufacturing system was conducted.

Duncan's Multiple Range Test

The ANOVA F-test indicated that each of the four factors are highly statistically significant. Therefore, Duncan's multiple range test is used to assess significant differences among the factor level means.

Factor A Means

Duncan's multiple range test indicated that there is no significant difference between the means of the first two levels of the lead time distribution factor (factor A). The average total cost of the hypothetical manufacturing system is not significantly different when purchased parts lead times follow the uniform discrete distribution or the symmetrical discrete distribution. However, these two distributions each yield a mean average total cost significantly higher than the mean average total cost yielded by using the asymmetrical discrete lead time distribution. The factor A means are ranked in Table 4-2.

The mean average total cost is highest when the distribution of purchased parts lead time is uniformally distributed. The uniform discrete distribution exhibits the largest variability of the distributions tested. Therefore, a greater number of purchased parts are received early, as well as, late. The holding cost per week and the lateness penalty charges both increase to reflect this extreme variability in the lead time of purchased parts.

The mean average total cost is lower (but not significantly lower) when purchased parts lead times follow the symmetrical distribution. The symmetrical

Table 4-2 Ranking of Factor A Means

MEAN ATC	GROUPING	LEVEL
4196.96	A	1
4176.37	A	2
4111.42	B	3

Factor A = Lead Time Distribution

Level 1 = Uniform Discrete Distribution
2 = Symmetrical Discrete Distribution
3 = Asymmetrical Discrete Distribution

Grouping = means with same letter are not significantly different.

ATC = Average Total Cost

distribution exhibits less variability in the lead times of purchased parts, but still results in parts arriving earlier and later than needed. Therefore, the holding cost and lateness penalty charges are high.

The mean average total cost is lowest when lead times for purchased parts is asymmetrically distributed. The asymmetrical distribution allows purchased parts to arrive late more often than it allows parts to arrive early. It was expected that more parts arriving after their due date would cause a higher average total cost. This because of the disruption to the system resulting from higher level components blocked because of unavailable purchased parts. But, the combination of the system's ability to absorb purchased part tardiness and the decrease in holding costs because of fewer parts arriving early resulted in a reduction in lateness penalty charges and a reduction in inventory holding costs.

Thus, based on the distribution employed in this study, it would seem advantageous from a practical point-of-view to be more concerned with purchased parts that arrive earlier than with those purchased parts that arrive late. Once a part arrives early, nothing can be done about the subsequent carrying cost charges. But,

when a part is late, the tardiness can be partially offset by subsequent operations, and therefore reduce potential lateness penalty charges.

This observation is consistent with Walker's observations in [40],

> In the multilevel product structure, a purchased part after it arrives in inventory, must go through a number of subsequent machining or assembly operations before it reaches the end item level. Thus, in the multilevel product structure, purchase part tardiness is often made up in subsequent operations which reduce its impact on end item lateness.

Factor B Means

Duncan's multiple range test indicated that the means of the first three levels of the buffering alternative factor (factor B) are not statistically different from each other. The mean average total costs are not significantly different from each other when using either zero buffering or the two safety stock amounts to buffer against supply/timing uncertainty. However, when buffering against supply/timing uncertainty takes the form of safety lead time, either 1 week or 2 weeks, the mean average total cost of the system is significantly higher than the mean average total cost of the system using no buffering or safety stock buffering. Further, the difference in the mean average total cost using 1 week versus 2 weeks safety lead time is signi-

ficant. The 2 weeks safety lead time strategy yielded the highest mean average total cost of the factor B means. The factor B means are ranked in Table 4-3. Since a major objective of this research is to investigate the effectiveness of buffering alternatives, further discussion is warranted concerning the difference in the mean average total cost for each level of factor B.

Under both safety lead time strategies, the scheduling of purchased parts to arrive earlier than actually needed resulted in inventory holding costs higher than justified. Even by providing a higher purchase parts availability, and therefore a subsequent reduction in purchased part tardiness, the decreased lateness penalty charges are not large enough to offset the safety lead time inventory. Average lateness costs can only be reduced, never completely eliminated in the multilevel product structure. Thus, some "noise" inherent in multilevel MRP systems will remain. In some cases, orders for common parts released in advance of their actual need dates are possibly being used by higher level components produced ahead of time. The assembly that actually required the parts is forced to wait.

Table 4-3 Ranking of Factor B Means

MEAN ATC	GROUPING	LEVEL
4853.37	A	5
4354.55	B	4
3874.07	C	3
3865.39	C	2
3860.53	C	1

Factor B = Buffering Alternative

Level 1 = Zero Buffering
2 = 200 Units Safety Stock
3 = 300 Units Safety Stock
4 = 1 Week Safety Lead Time
5 = 2 Weeks Safety Lead Time

Grouping = means with same letter are not significantly different.

ATC = Average Total Cost

Using a safety stock of 200 units or 300 units to buffer against supply/timing uncertainty resulted in mean average total costs that are not significantly higher than the mean average total cost with no buffering. Carrying safety stock increases holding costs but, the decrease in lateness penalty charges somewhat offset the safety stock related holding costs. The mean average total cost employing safety stock buffers is lower than the mean average total cost when employing safety lead time buffers. Even though some holding cost is always incurred by carrying safety stock, fewer orders are released early thus avoiding the additional carrying costs of the early arriving parts.

Under the safety lead time strategy all orders for purchased parts are scheduled to arrive sooner than their actual need date. The only time an order is scheduled to arrive earlier under the safety stock strategy, than it would have been scheduled under the no buffering strategy, is when on-hand inventory falls below the safety stock amount. Therefore, no buffering and safety stock buffering yield lower mean average total costs than safety lead time buffering.

The lowest mean average total cost, under factor B, occurs with no buffering of either kind. The purchased part tardiness that occurs without buffering against

supply/timing uncertainty is absorbed by subsequent operations in the multilevel system, thus reducing the potential lateness penalty. Therefore, increasing the holding cost by using either safety stock or safety lead time is not justified strictly on a cost basis. Further, if buffering is used to maintain smoothness of operations, then safety stock is the strategy suggested by this research. This contradicts the results reported by Whybark and Williams [43]. The multilevel product structure and the commonality of parts, not present in their single-part simulation experiments, may be the reason for this apparent contradiction. In summary, zero buffering and safety stock buffering (at either level) resulted in mean average total costs significantly lower than safety lead time buffering (at either level).

Factor C Means

All three factor C level means are judged significantly different by Duncan's multiple range test. Each of the three lot-size rules, applied at the purchased parts level, resulted in significantly different mean average total costs. The EOQ rule resulted in the highest mean average total cost, while the L4L yielded the lowest mean average total cost. The factor C means are

ranked in Table 4-4.

The L4L performed better than either the POQ or EOQ rules in the hypothetical manufacturing system. Using either the EOQ or POQ lot-sizing rules result in more inventory being carried and therefore an increased holding cost. Again, lateness penalty charges did not decrease enough to justify the increased carrying charges.

Factor D Means

The three levels of factor D were all judged significantly different by Duncan's multiple range test. The mean average total cost under each set of cost values is significantly different. The high, medium, and low cost values produced high, medium, and low mean average total costs, respectively. The factor D means are ranked in Table 4-5.

Under the high holding cost and lateness cost values (25% and 5% respectively) the mean average total cost of the MRP system is $5280.54. But, when the holding cost and lateness cost values are lowered to the medium level (20% and 3% respectively) the mean average total cost decreases to $4157.86. A further significant decrease in the systems average total cost occurs when the cost values are decreased to its lowest level (15% and 1% respectively). The mean average total cost is $3046.35

Table 4-4 Ranking of Factor C Means

MEAN ATC	GROUPING	LEVEL
4350.17	A	2
4093.46	B	3
4041.11	C	1

Factor C = Lot-Size Rule

Level 1 = Lot-for-Lot
2 = Economic Order Quantity
3 = Periodic Order Quantity

Grouping = means with same letter are not significantly different.

ATC = Average Total Cost

Table 4-5 Ranking of Factor D Means

MEAN ATC	GROUPING	LEVEL
5280.54	A	1
4157.86	B	2
3046.35	C	3

Factor D = Cost Values

Level 1 = High Cost Values
2 = Medium Cost Values
3 = Low Cost Values

Grouping = means with same letter are not significantly different.

ATC = Average Total Cost

using the low holding cost and lateness cost values.

Because of the significant differences in mean average total cost under each set of cost values, the simulation model is sensitive to changes in its cost parameters. The results generated by running the MRP/Production simulator will therefore change if the cost parameters are varied. Thus it is important for users to input cost values representative of their own particular firm or system under investigation.

Interaction Analysis

The results of the multifactor analysis of variances indicated significant first-order interaction effects between the lead time distributions and the lot-size rules (AC), as well as, significant first-order interaction effects between the buffering alternatives and the cost values (BD). The presence of these significant first-order interaction effects indicates that analysis of factor effects depends somewhat on the level of the other factor.

AC Interaction Effects

A plot of the first-order interaction between the lead time distributions and the lot-size rules is shown in Figure 4-1. The three separately located line seg-

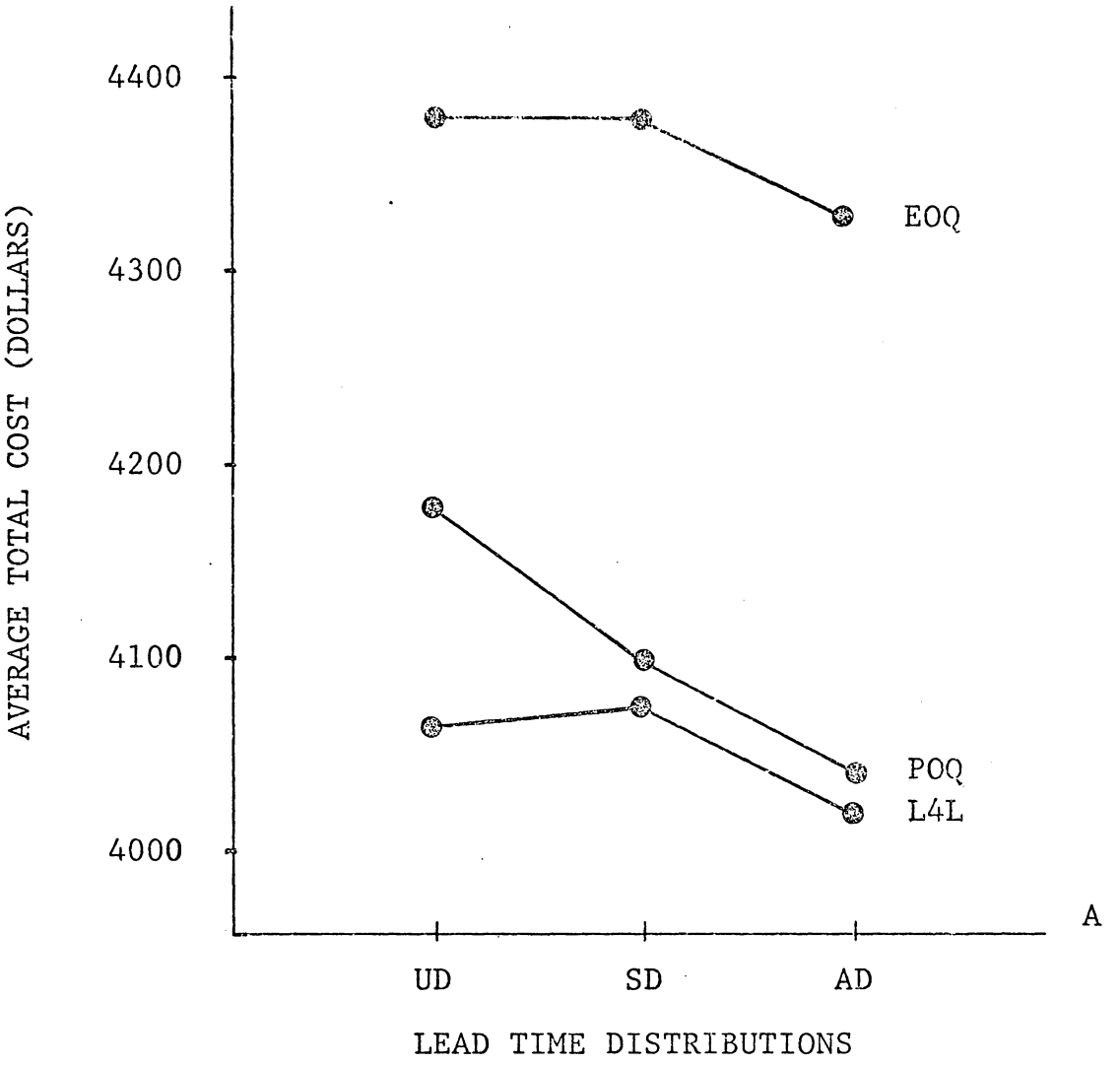


FIGURE 4-1

Lead Time Distribution Effect,
Lot-Size Rule Effect, and
Interaction Effect (AC)

ments indicate significant differences in average total cost per week when different lot-size rules are used to order purchased parts. This is consistent with the previous discussion of the factor C main effects. When L4L ordering is used the average total cost per week is about $4050. POQ ordering results in an average total cost per week slightly higher at about $4100. The EOQ rule yields the highest average total cost of about $4350 per week.

Observing figure 4-1, the L4L rule performs better than the other two rules under each of the three lead time distributions. The EOQ rule yielded the worst average total cost regardless of the lead time distribution. The EOQ rule resulted in more inventory being carried and thus a significant increase in average carrying cost per week without a significant decrease in average lateness penalty.

The three lot-size rules perform differently depending on the amount of variability in the lead time of purchased parts. The L4L rule yielded the lowest average total cost when the asymmetrical discrete distribution is employed. The asymmetrical distribution allows for purchased parts to arrive after they are needed. Under the asymmetrical distribution, the L4L

rule produced an average carrying cost lower than the average carrying cost under either the POQ or EOQ rules. Under the asymmetrical distribution and L4L rule combination, fewer parts are being held in inventory ahead of their actual need date. Although a few parts do arrive late, and therefore create some tardiness, this tardiness is absorbed by the system and results in a small average lateness penalty increase.

The POQ rule resulted in average total cost slightly higher than the L4L rule under both the asymmetrical discrete and symmetrical discrete distributions. This occurs because the POQ rule defaults to L4L ordering whenever the order period is one. This actually occurred several times within the experiment. Under the uniform discrete distribution the POQ rule yielded an average total cost significantly higher than the L4L rule. Under this particular case, the average lateness penalty increased dramatically, along with an increase in the average carrying cost. The average carrying cost increase is due to the extremely early arrival of purchased parts when purchased parts lead time is uniformally distributed, as well as, parts for future periods being lumped together with POQ ordering. Also, just as frequently, parts arrive extremely late under the uniform discrete distribution causing the average lateness pen-

alty to increase. Also, the POQ lumping of requirements tends to make parts for more than one period late.

Although the EOQ rule performed poorly, it did result in lower average total cost when used under the asymmetrical discrete distribution as opposed to the other two lead time distributions. The average lateness penalty was about the same, whereas the average carrying costs decreased when purchased parts are not allowed to arrive early as frequently as they are allowed to arrive late.

Many practical guidelines can be set from these observations. The purchased parts lead time distribution makes a difference in average total cost. It is better to have purchase parts arrive on time, obviously. But in terms of variability, it's better to have purchase parts arrive late more often than early. Tardiness can be absorbed by the system, and therefore potentially reduce possible lateness charges, whereas carrying cost once incurred cannot be eliminated. Therefore, with respect to controlling lead times, it would be advantageous not to allow suppliers to ship purchased parts early. The customer should let the supplier hold the parts (and incur holding cost).

Given that a certain purchased parts lead distribution exists the decision concerning lot-size rule can

be significant. Under a uniform discrete distribution the L4L rule is superior to either the POQ or EOQ rule. Under the symmetrical discrete or asymmetrical discrete distribution the L4L rule performs best, but not significantly better than the POQ rule. Observe the POQ and L4L parallel line segments under the symmetrical and asymmetrical distribution on Figure 4-1.

Under no circumstances should the EOQ rule be used. It performs poorly under any of the three distributions. Thus, depending on lead time variability of purchased parts, lot-size rule decisions have an impact on system performance.

BD Interaction Effects

A plot of the first-order interaction between the buffering alternatives and the cost values is shown in Figure 4-2. The three separately located line segments indicate significant differences in average total cost per week when the cost values are varied. When the cost values are low, the average total cost per week is about $3050. The average total cost per week increases to approximately $4150, and then to about $5300, as the cost values increase from low to medium, to high.

Observing Figure 4-2, under both the low and medium cost value levels the zero buffering alternative provides

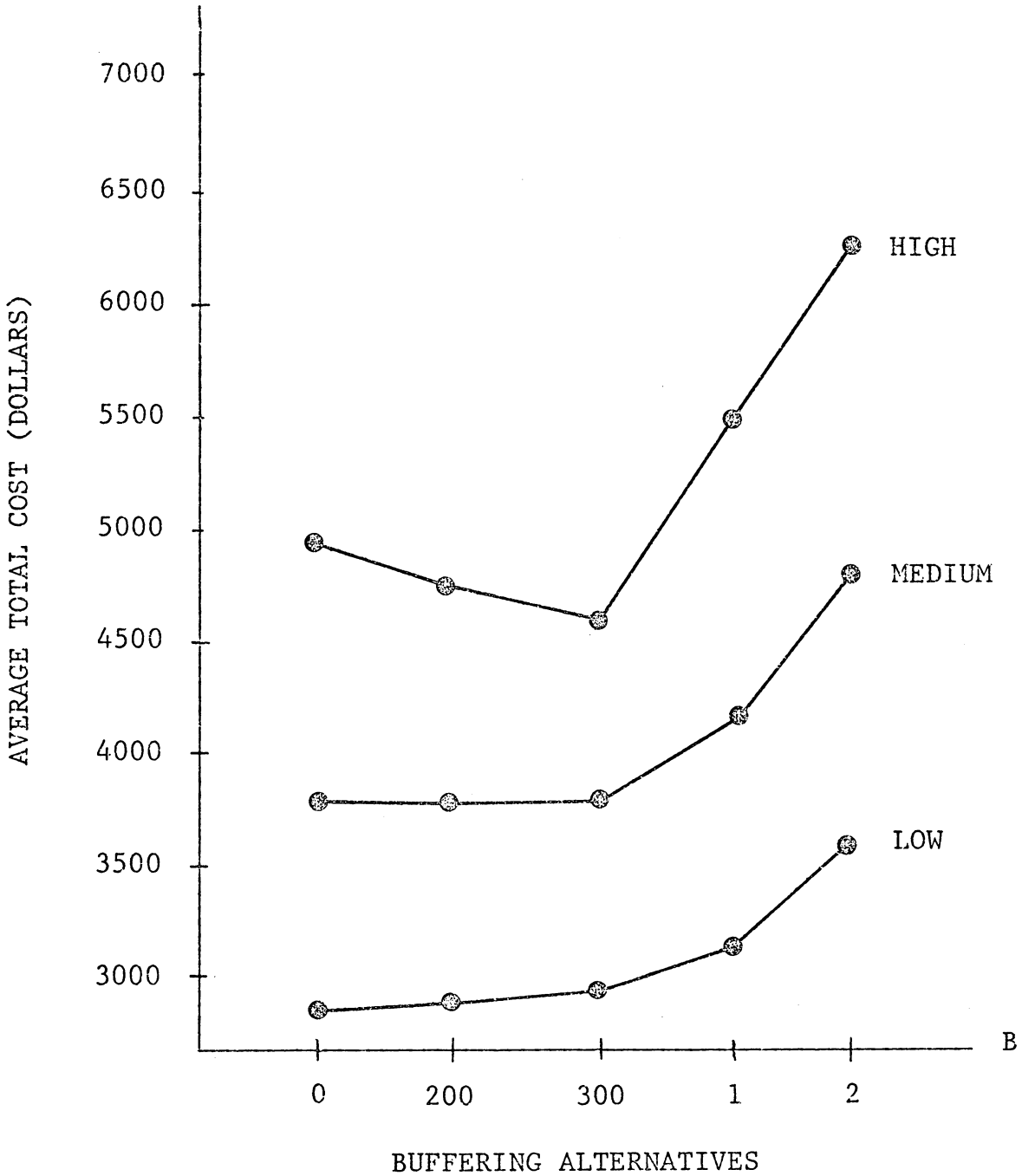


FIGURE 4-2

Buffering Alternative Effect, Cost Values Effect, and Interaction Effect (BD)

the lowest average total cost. The two safety stock alternatives result in average total cost slightly higher than the zero buffering alternatives under both the low and medium cost value levels. The two safety lead time alternatives yield average total costs significantly higher than either zero buffering or the two safety stock alternatives when the cost values are low or medium.

At the high cost values the second safety stock alternative (300 units) results in the lowest average total cost. Buffering against uncertainty with 200 units of safety stock yields the second lowest average total cost, while zero buffering results in the third best average total cost. As with the low and medium cost value levels, both safety lead time buffering alternatives yield significantly higher average total costs at the high cost ratio.

In the case of the safety lead time strategies not only was there an increase in average carrying costs but in some cases an increase in average lateness penalty. "Due to variation in the actual lead times of manufactured parts resulting from the stochastic nature of work center queues, a certain level of average lateness penalty is always incurred in multilevel product structures. This inherent noise cannot be reduced regardless of the level of safety lead time employ" [40].

Likewise, with safety stocks, increased inventory levels tend to absorb the impact of purchased part tardiness.

Under the high cost values, the safety stock alternatives provide average total costs less than the zero buffering alternative. What happened in this case is that average lateness penalty was high to begin with, because of the higher cost values, and therefore was able to be reduced somewhat when buffering with safety stock.

Again, the two safety lead time strategies yielded significantly higher average total costs under the high cost values, as with the low and medium cost values.

From a practical viewpoint, safety lead time buffering is not warranted at the purchased parts level in the multilevel product structure. When the holding cost and lateness penalty charges are low or medium, safety stock buffering may be warranted. Under high carrying cost and high lateness penalty charges buffering using safety stock at the purchased parts level of the multilevel product structure is warranted.

Linear Contrasts

This research performs an experiment on a hypothetical manufacturing system to assess the significance

of four factors on the average total cost of an MRP system. It is not intended to provide specific information about the magnitude of the difference between factor or treatment means. However, practitioners using the MRP/Production simulator may be interested in the magnitude of the differences under various factor level combinations. Therefore, an example of the type of information which general linear contrasts may provide is given.

Linear contrasts are constructed which provide the answers to the following questions:

1. What is the magnitude of the difference in average total cost when purchased parts lead time follows the uniform discrete distribution as opposed to the asymmetrical discrete distribution?
2. What is the overall difference in mean average total cost of using L4L, POQ, or EOQ lot-sizing?
3. How much greater is the mean average total cost when 200 units of safety stock buffering is employed instead of 1 week safety lead time under the medium cost values, the asymmetrical discrete distribution, and L4L ordering?
4. How much greater is the mean average total cost using 2 weeks safety lead time versus 300 units

of safety stock under the medium cost values, the asymmetrical distribution, and L4L ordering?

5. How much greater is the mean average total cost when 300 units of safety stock is used versus no buffering under the medium cost values, the asymmetrical distribution, and L4L ordering?

Bonferroni CI on Factor A Means

Duncan's multiple range test indicated that the mean average total cost differed significantly when lead time variability followed the uniform discrete distribution versus the asymmetrical discrete distribution. To answer question 1, a 95% confidence interval indicating the magnitude of this difference is given below.

The comparison of interest is

$L = C_1\mu_{1\cdots} + C_3\mu_{3\cdots}$

where:

$\mu_{1\cdots}$ = mean average total cost when lead time distribution is uniform discrete

$\mu_{3\cdots}$ = mean average total cost when lead time distribution is asymmetrical discrete.

The Bonferroni confidence interval, as defined in Chapter 3, is $\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$.

$$\hat{L} = C_1\bar{Y}_{1\cdots\cdot} + C_3\bar{Y}_{3\cdots\cdot}$$

where:

$$C_1 = +1 \quad \bar{Y}_{1\cdots\cdot} = 4196.96$$

$$C_3 = -1 \quad \bar{Y}_{3\cdots\cdot} = 4111.42$$

$$\hat{L} = (+1)(4196.96) + (-1)(4111.42) = 85.54$$

$$B = t(1-\alpha/2s;(n-1)abcd)$$

$$= t(1-.05/2(5);(5-1)(3)(5)(3)(3))$$

$$= t(.995;540) = 2.576$$

$$S^2(\hat{L}) = \left(\frac{MSE}{nbcd}\right)C_1^2 + C_3^2$$

where:

$$MSE = 16620.19$$

$$S^2(\hat{L}) = \left(\frac{16620.19}{(5)(5)(3)(3)}\right)1^2 + (-1)^2 = 147.74$$

$$S(\hat{L}) = \sqrt{147.74} = 12.15$$

The 95% confidence interval is:

$$85.54 - (2.576)(12.15) \leq L \leq 85.54 + (2.576)(12.15)$$

$$85.54 - 31.30 \leq L \leq 85.54 + 31.30$$

$$54.24 \leq L \leq 116.84$$

Interpreting the interval, we are 95% sure that the average total cost is between \$54.24 and \$116.84 greater when uncertainty of purchased parts is unifor-

mally distributed as opposed to asymmetrically distributed.

Bonferroni CI on Factor C Means

As indicated by Duncan's multiple range test, the mean average total cost is significantly different for each of the three lot-sizing rules employed in the experiment. To answer question 2, a contrast involving these three means is given below. The contrast of interest is

$$L = C_1\mu..1. + C_2\mu..2. + C_3\mu..3.$$

where:

$\mu..1.$ = mean average total cost using L4L ordering

$\mu..2.$ = mean average total cost using EOQ ordering

$\mu..3.$ = mean average total cost using POQ ordering

The Bonferroni confidence interval is

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L}).$$

$$\hat{L} = C_1\overline{Y}..1.. + C_2\overline{Y}..2.. + C_3\overline{Y}..3..$$

where:

$C_1 = +1 \quad \overline{Y}..1.. = 4041.11$

$C_2 = +1 \quad \overline{Y}..2.. = 4350.17$

$C_3 = -2 \quad \overline{Y}..3.. = 4093.45$

$$\hat{L} = (+1)(4041.11) + (+1)(4350.17) + (-2)(4093.45) = 204.38$$

$$B = t(1-\alpha/2s;(n-1)abcd)$$
$$= t(1-.05/2(5);(5-1)(3)(5)(3)(3))$$
$$= t(.995;540) = 2.576$$

$$S^2(\hat{L}) = \left(\frac{MSE}{nabd}\right)C_1^2 + C_2^2 + C_3^2$$
$$= \left(\frac{16620.19}{(5)(3)(5)(3)}\right)1^2 + 1^2 + (-2)^2 = 443.28$$
$$S(\hat{L}) = \sqrt{443.28} = 21.05$$

The 95% confidence interval is:

$$204.38 - (2.576)(21.05) \leq L \leq 204.38 + (2.576)(21.05)$$
$$204.38 - 54.22 \leq L \leq 204.38 + 54.22$$
$$150.16 \leq L \leq 258.60$$

Interpreting the interval, with 95% confidence, the difference in mean average total cost depending upon the lot-size rule used is between \$150.16 and \$258.60.

Bonferroni CI on Treatment Means

When interaction effects prove to be significant, contrasts among treatment means may be constructed. To answer questions 3, 4 and 5 three such contrasts are provided below.

How much greater is the difference in average total cost between 200 units of safety stock and 1 week safety

lead time under the medium cost values, the asymmetrical distribution, and the L4L ordering rule? The comparison of interest is

$$L = C_{3412}\mu_{3412} + C_{3212}\mu_{3212}$$

where:

μ_{3412} = mean average total cost using 1 week safety lead time at the medium cost values, the asymmetrical distribution, and the L4L lot-size rule.

μ_{3212} = mean average rotal cost using 200 units safety stock at the medium cost values, the asymmetrical distribution, and the L4L lot-size rule.

The Bonferroni confidence interval is

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$$

$$\hat{L} = C_{3412}\overline{Y}_{3412.} + C_{3212}\overline{Y}_{3212.}$$

where:

$C_{3412} = +1 \quad \overline{Y}_{3412.} = 4210.73$

$C_{3212} = -1 \quad \overline{Y}_{3212.} = 3700.84$

$$\hat{L} = (+1)(4210.73) + (-1)(3700.84) = 509.89$$

$$B = t(1-\alpha/2s;(n-1)abcd)$$
$$= t(1-.05/2(5);(5-1)(3)(5)(3)(3))$$
$$= t(.995;540) = 2.576$$

$$S^2(\hat{L}) = \left(\frac{MSE}{n}\right)C^2_{3412} + C^2_{3212}$$
$$= \left(\frac{16620.19}{5}\right)^2 = 6648.08$$

$$S(\hat{L}) = \sqrt{6648.08} = 81.54$$

The 95% confidence interval is:

$$509.89 - (2.576)(81.54) \leq L \leq 509.89 + (2.576)(81.54)$$
$$509.89 - 210.05 \leq L \leq 509.89 + 210.05$$
$$299.84 \leq L \leq 719.94$$

Interpreting the interval, we are 95% sure that average total cost is between \$299.84 and \$719.94 greater when buffering via 1 week safety lead time versus 200 units safety stock, while holding the other factor levels constant at medium, asymmetrical, and L4L, respectively.

How much greater is the average total cost between 2 weeks safety lead time and 300 units of safety stock at the medium cost values, the asymmetrical distribution, and the L4L ordering? The comparison of interest is

$$L = C_{3512}\mu_{3512} + C_{3312}\mu_{3312}$$

where:

μ_{3512} = mean average total cost using 2 weeks safety lead time at the medium cost values, the asymmetrical distribution and, the L4L lot-sizing rule

μ_{3312} = mean average total cost using 300 units of safety stock at the medium cost values, the asymmetrical distribution and, the L4L lot-sizing rule

The Bonferroni confidence interval is

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$$

$$\hat{L} = C_{3512}\overline{Y}_{3512.} + C_{3312}\overline{Y}_{3312.}$$

where:

$$C_{3512} = +1 \quad \overline{Y}_{3512.} = 4692.73$$

$$C_{3312} = -1 \quad \overline{Y}_{3312.} = 3712.40$$

$$\hat{L} = (+1)(4692.73) + (-1)(3712.40) = 980.33$$

$$B = t(1-\alpha/2s;(n-1)abcd)$$

$$= t(1-.05/2(5);(5-1)(3)(5)(3)(3))$$

$$= t(.995;540) = 2.576$$

$$S^2(\hat{L}) = \left(\frac{MSE}{n}\right)C^2_{3512} + C^2_{3312}$$

$$= \left(\frac{16620.19}{5}\right)^2 = 6648.08$$

$$S(\hat{L}) = \sqrt{6648.08} = 81.54$$

The 95% confidence interval is:

$$980.33 - (2.576)(81.54) \leq L \leq 980.33 + (2.576)(81.54)$$

$$980.33 - 210.05 \leq L \leq 980.33 + 210.05$$

$$770.28 \leq L \leq 1190.38$$

Interpreting the interval, we are 95% sure that average total cost is between \$770.28 and \$1190.38 greater when buffering via 2 weeks safety lead time versus 300 units safety stock while holding the other factor levels at medium, asymmetrical, and L4L, respectively.

How much greater is the average total cost between no buffering and buffering using 300 units of safety stock at the medium cost values, the asymmetrical distribution, and the L4L lot-sizing rule? The comparison of interest is

$$L = C_{3312}\mu_{3312} + C_{3112}\mu_{3112}$$

where:

μ_{3312} = mean average total cost using 300 units of safety stock at the medium cost values, the asymmetrical distribution, and the L4L lot-sizing rule

μ_{3112} = mean average total cost with no buffering at the medium cost values, the asymmetrical distribution, and the L4L lot-sizing rule

The Bonferroni confidence interval is

$$\hat{L} - BS(\hat{L}) \leq L \leq \hat{L} + BS(\hat{L})$$

$$\hat{L} = C_{3312}\overline{Y}_{3312.} - C_{3112}\overline{Y}_{3112.}$$

where:

$$C_{3312} = +1 \quad Y_{3312.} = 3712.40$$

$$C_{3112} = -1 \quad \overline{Y}_{3112.} = 3677.73$$

$$\hat{L} = (+1)(3712.40) + (-1)(3677.73) = 34.67$$

$$B = t(1-\alpha/2s;(n-1)abcd)$$

$$= t(1-.05/2(5);(5-1)(3)(5)(3)(3))$$

$$= t(.995;540) = 2.576$$

$$S^2(\hat{L}) = \left(\frac{MSE}{n}\right)C^2_{3312} + C^2_{3112}$$

$$= \left(\frac{16620.19}{5}\right)^2 = 6648.08$$

$$S(\hat{L}) = \sqrt{6648.08} = 81.54$$

The 95% confidence interval is:

$$34.67 - (2.576)(81.54) \leq L \leq 34.67 + (2.576)(81.54)$$

$$34.67 - 210.05 \leq L \leq 34.67 + 210.05$$

$$-175.38 \leq L \leq 244.72$$

Interpreting the interval, we are 95% sure the difference in average total cost is between -175.38 and 244.72 when no buffering versus 300 units of safety stock buffering is used at the medium cost values, the asymmetrical distribution, and L4L ordering.

The above 3 confidence intervals are examples of the type of specific information available using linear contrasts. The levels at which certain factors are held constant were selected arbitrarily.

Major Findings

The major findings of this experiment can be summarized as follows:

1. When the purchased parts lead time distribution, buffering alternative, lot-size rule, or cost values are varied over the levels specified in this study, there is a significant difference in the mean average total cost of the hypothetical manufacturing system.
2. There is a significant difference in the mean average total cost of the system as a result of the first-order interaction effect of the purchased parts lead time distribution and the lot-size rule.
3. There is a significant difference in the mean average total cost of the system as a result of the first-order interaction effect of the buffering alternative and cost values.
4. None of the remaining first-order interaction effects or any of the higher-order interaction effects resulted in significant differences in average total cost.

Summary

The objective of this chapter was to provide information regarding the effects of varying the lead time distribution, the buffering alternative, the lot-size rule, and the cost values on the total cost of an MRP sys-

tem experiencing supply/timing uncertainty. Consequently, the results of the simulation experiment were presented and discussed. It was found that the main effects of the lead time distribution, buffering alternative, lot-size rule, and the cost values were highly statistically significant. Also, the first-order interaction effect of the lead time distribution and the lot-size rule, and the first-order interaction effect of the buffering alternative and the cost values were highly statistically significant. Several linear contrasts were developed as examples of the specific information available to practitioners. For those contrasts selected, confidence intervals were constructed to estimate the magnitude of the difference in the MRP system's average total cost. The next chapter provides the summary, conclusions and recommendations for future research. Also, the limitations of this research and the practical guidelines suggested by this study are presented in the next chapter.

Chapter 5

SUMMARY AND CONCLUSIONS

This research was an experimental investigation into uncertainty in MRP systems. The purpose of this study has been to examine the impact of specific policies on the performance of a hypothetical manufacturing system. In particular, supply/timing uncertainty at the purchased parts level of a multilevel product structure was investigated.

A GASP-IV MRP/Production simulator was used to generate the data. The data was analyzed using a multifactor analysis of variance model to assess the impact of four factors on the average total cost of the MRP system. The four factors analyzed were the lead time distribution of purchased parts, the buffering alternative, the lot-size rule, and the holding cost and lateness penalty values. The significance of each of these factors is summarized as follows:

1. Each of the four main effects has a significant effect on the average total cost of the hypothetical manufacturing system.

2. The first-order interaction effects of lead time distribution and lot-size rule and first-order interaction effects of buffering alternative and cost values have a significant effect on the average total cost of the hypothetical manufacturing system.
3. The remaining first-order interaction effects, second-order interaction effects, and third-order interaction effects do not have a significant impact on the average total cost of the hypothetical manufacturing system.

This experiment has provided the following answers to the questions stated in the purpose section of this study.

1. The total cost of the MRP system is affected by each of the four factors tested.
2. The amount of safety lead time, but not the amount of safety stock, has an impact on system performance.
3. The amount of variability in lead time does not affect the choice of buffering alternative but, does affect the choice of the lot-size rule.
4. The lot-size rule chosen does not affect the buffering alternative decision.

5. A change in the holding cost fraction and lateness penalty charges does affect the choice of the buffering alternative.

Practical Guidelines

A summary of the practical guidelines suggested by this research are:

1. Manage the lead time of purchased parts to reduce variability. Allow purchased parts to arrive late more frequently than allowing them to arrive early. The mean average total cost of the hypothetical MRP system was highest when the distribution of purchased parts lead time was uniformally distributed. The uniform distribution exhibited the largest amount of variability of the distributions tested and allowed purchased parts to arrive both extremely early and extremely late. The symmetrical distribution exhibited less variability in the lead time of purchased parts, but still resulted in parts arriving earlier and later than needed. Thus, the mean average total cost decreased by an amount that was not statistically significant. However, the mean average total cost of the system was lowest when the lead times for purchased parts was asymmetrically distributed. The

asymmetrical distribution allowed purchased parts to arrive late more often than it allowed purchased parts to arrive early. Thus, it would be advantageous from a practical point-of-view to be more concerned with purchased parts that arrive early than with purchased parts that arrive late.

2. When buffering against uncertainty of the supply/timing variety it is more prudent to use safety stock instead of safety lead time. Under both the low and medium cost value levels the zero buffering alternative provided the lowest average total cost. The two safety stock alternatives yielded average total costs slightly higher than the zero buffering alternative under both the low and medium cost value value levels. The two safety lead time alternatives yielded average total costs significantly higher than either zero buffering or the two safety stock alternatives when the cost values are low or medium. At the high cost values, the second safety stock alternative (300 units) resulted in the lowest average total cost. Buffering against uncertainty with 200 units of safety stock yielded the second lowest average total cost, while zero buffering resulted in the third best average total cost. As with the

low and medium cost values, both safety lead time buffering alternatives yielded significantly higher average total cost at the high cost values.

3. The lot-for-lot rule should be used when the lead time distribution of purchased parts follows the uniform discrete distribution (i.e., exhibits the most variability). Under the uniform discrete distribution, the lot-for-lot ordering rule resulted in average total costs significantly less than those obtained using either the economic order quantity or periodic order quantity lot-size rules.
4. The lot-for-lot rule or the periodic order quantity rule may be used if the lead time distribution of purchased parts follows either the symmetrical or asymmetrical discrete distribution. The periodic order quantity rule resulted in average total cost slightly higher than the lot-for-lot rule under both the symmetrical and asymmetrical discrete distributions. This occurred because the periodic order quanity rule defaults to lot-for-lot ordering whenever the order period is one.
5. The economic order quantity rule should not be used in MRP systems based on the results of this study.

The economic order quantity rule yielded the worst average total cost regardless of the lead time distribution. The economic order quantity rule resulted in more inventory being carried and thus a significant increase in average carrying cost per week without a significant decrease in average lateness penalty.

6. Assign correct values to the holding cost and lateness penalty charges because the average total cost of the MRP system is sensitive to changes in the values of these cost parameters. The mean average total cost was significantly different under each set of cost values. The high, medium, and low cost values produced high, medium, and low mean average total costs, respectively. Using the high holding cost and lateness cost values (25% and 5% respectively) the mean average total cost of MRP system was $5280. When the holding cost and lateness cost values were decreased to the medium level (20% of 3% respectively) the mean average total cost decreased to $4158. A further significant decrease in the systems average total cost occurred when the cost values were decreased to the lowest level (15% and 1% respectively). The mean average total cost was $3046 using the low holding cost and lateness cost values.

Limitations and Suggestions for Future Research

To confine this research to a manageable size several assumptions were made. Therefore, there are limitations to this study that should be emphasized.

First, only one product structure was analyzed in this experiment. The multilevel product structure studied was chosen as representative of reality. Product structures which are flatter or multilevel product structures having a different number of levels would change the results of the simulation.

Second, the cost of purchased parts and the value added in manufacturing were held at specific values. Changing either of these two parameters may effect the choice of the buffering alternative or the lot-size decision.

Third, the four factors examined in this experiment were varied over certain levels only. Changing the levels, over which these four factors are varied, will change the experimental results.

Fourth, the MRP/Production simulator does not consider inflation. The inventory carrying cost was not adjusted over the simulated planning horizon to allow for increases in prices. A factor accounting for the

effects of inflation will most likely change the simulation results.

Fifth, the MRP/Production system was able to absorb significant levels of purchased-part tardiness. This occurred for two reasons: 1) the capacity utilization level of 80% resulted in processing time being available at the higher-level manufacturing operations, and 2) the queue discipline (MRP due-date). These two items tended to limit the impact of purchased-part tardiness on end item lateness. Thus, the value of additional amounts of safety stock or safety lead time was reduced. Buffering against uncertainty, using either safety stock or safety lead time, may have a greater impact on MRP system performance at higher capacity utilization levels.

Suggestions for future research can involve any of the above limitations. Also, multivariate analysis of variance (MANOVA) could be used with more than one dependent variable (or performance measure). Average total cost, average lateness penalty, and average carrying cost could all be analyzed as dependent variables allowing for further analysis of the trade off that exists.

The MRP/Production simulator can be used to investigate a wide variety of MRP related problems. One that has

not been subjected to rigorous experimental investigation is the impact of inventory record accuracy on MRP system performance. This may be a challenging area for future research.

In the MRP/Production system simulated in this research the actual end item completion times did not necessarily coincide with the scheduled completion times. No provisions were made to force end-item completions to occur only at the MRP generated time periods. This may not be consistent with actual operating systems that use expediting and various priority due-date rules to restrict actual end item completions to occur as scheduled by the MRP system. Examining systems of this type may be an area fertile for future research.

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UNCERTAINTY IN MRP SYSTEMS:
AN EXPERIMENTAL INVESTIGATION

by

Edward Thomas Grasso

(ABSTRACT)

Material Requirements Planning (MRP) has evolved as a technique for the planning and controlling of inventories and production of complex manufactured products. The problem addressed in this research is that of uncertainty in MRP systems. Demand uncertainties are those which involve variations in the gross requirements for a component. Supply uncertainties deal with variations in the scheduled receipts for a component.

The purpose of this research is to examine the impact of specific operating policies on the performance of an MRP system under conditions of supply/timing uncertainty. Supply uncertainties include either the timing or quantity type. Supply uncertainty that results because of timing involves the receipt of an order after its scheduled delivery date. The specific supply/timing uncertainty examined in this study is that which is caused by variability in the lead time of purchased parts. Experiments are conducted in order to assess

the impact of lead time variability, the amount of safety stock buffering, the amount of safety lead time buffering, and the lot-size rule on the average total cost of an MRP system. In addition, the question of whether the results obtained are sensitive to changes in the system's cost parameters is examined. Based on the results, guidelines are developed for practitioners to use when making decisions involving uncertainty in MRP systems.

The simulation model used in this research is a versatile MRP/Production simulator designed to provide a framework for the investigation of a wide variety of MRP related problems. The hypothetical manufacturing system is simulated and its average total cost is recorded for varying levels of lead time varability, safety stock, safety lead time, lot-size rule and the holding cost and lateness penalty values. A 3x5x3x3 balanced factorial experiment is performed and multifactor analysis of variance is used to assess significant differences in the average total cost of the MRP system. On those means judged significantly different by Duncan's multiple range test, further analysis is provided in the form of general linear contrasts and confidence intervals.