MANAGEMENT SCIENCE
Vol. 32, No. 9, September 1986
Printed in U.S.A.

FORECASTING ERROR EVALUATION IN MATERIAL REQUIREMENTS PLANNING (MRP) PRODUCTION-INVENTORY SYSTEMS*

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The impact of forecasted demand and forecast error, introduced in the Master Production Schedule, upon Material Requirements Planning (MRP) Systems is investigated. A computerized simulation was built to examine several questions. Results indicate that forecasting error, especially the mean error, does impact MRP system inventory costs and shortages; the greater the forecast error the greater the shortages. An exception to this general relationship was that a slight forecast BIAS may improve MRP system performance, which was the case for systems studied herein. Lot-sizing rules and product structure (bill of material structure) were also found to impact total MRP system inventory costs and shortages. The more complicated the MRP structure, the greater the differentiation among lot-sizing rules and the greater the cost impact of forecast errors. A good lot-sizing rule appears to be the period order quantity rule. However, as the forecast error level gets higher, it becomes difficult to select the better lot-sizing rule. Based on this study, suggestions are presented for the production manager's consideration, especially the inventory-production control manager.
(MATERIAL REQUIREMENTS PLANNING; FORECASTING—APPLICATIONS; SIMULATION—APPLICATIONS)

Production and operations managers repeatedly express the view that forecasting is a critical activity since the accuracy of the forecast significantly impacts the quality of operation plans. Good (accurate) forecasts are an integral part of effective product, facility, process, and production planning. If these planning processes are well conceived and actual production effectively and efficiently carried out against the plan, there is likelihood of high productivity. However, if the forecast has considerable error, even well-conceived plans and excellent operating performance against the plan may result in very disappointing productivity.

A component of production planning is material requirements planning, an activity receiving increased attention by production managers the last several years due to high interest rates and the associated costs of carrying unnecessary inventory. Many of the material requirements systems, such as MRP, are management information systems which deterministically explode (or expand) end products into subcomponent and part requirements. The purpose of this research is to evaluate material requirements planning (MRP) systems when forecast error is introduced into the end product demand. Given variability in demand and subsequent forecasting errors, what will be the performance and cost consequences within MRP systems from introducing forecast error?

Previous Research

Forecasting and Planning

It is generally accepted that forecasting quality interacts with planning quality. General management literature typically views forecasting as an activity or subsystem

* Accepted by David G. Dannenbring; received August 9, 1983. This paper has been with the authors 5½ months for 2 revisions.

0025-1909/86/3209/1186$01.25

within planning, while production and operations management literature typically views forecasting as a distinct activity, separate from and a pre-requisite to many other operations activities such as production planning.

Hogarth and Makridakis (1981) examine forecasting and planning interactions, concluding that empirical evidence concerning forecasting accuracy has not been demonstrated for long- and medium-term planning, but it may be encouraging for short-term planning. They suggest that in short-term forecasting (three months or less), there is considerable inertia in most economic and natural phenomena. For this reason, simple mechanistic time series forecasting can be expected to perform well and improve planning efforts.

This latter forecasting time horizon is the environment in which most MRP systems tend to operate. Surveys of MRP users and case histories find the time horizon for MRP planning to utilize a master production schedule that varies considerably, with the immediate 2 to 12 weeks "firmed" in some manner (Anderson and Schroeder 1979; White, Anderson, Schroeder and Tupy 1982; and Vollman, Berry and Whybark 1984). In summary, we conclude: (1) short-term forecasting holds the most promise regarding improved planning (Hogarth and Makridakis); (2) forecast inaccuracy directly affects the master product schedule, the "front end" which feeds the MRP system "engine" in manufacturing planning systems (Vollman et al.); and (3) production planners using MRP are not getting the forecast accuracy desired (White et al.), which we interpret as errors passed through the master production scheduling system.

Forecasted Demand and Master Production Scheduling

The master production schedule (MPS) is a production plan that represents the first level for disaggregation of the overall aggregate plan into specific products. It is established by management and is based, in part, upon the aggregate plan, forecasts for individual parts, actual orders on hand, expectations for orders, and available capacity. It is a management set plan that will change from planning period to planning period as well as during the time period planned. The MPS changes because management is not capable of foreseeing the future exactly—*actual* will be different from *planned* both in the production process (on the shop floor) and from changing wants and needs of the customer (product demand).

The purpose of this paper is to investigate the errors introduced into the master production plan from inaccurate forecasts. More specifically, we desire to investigate how sensitive downstream material requirements planning (MRP) systems are to such errors.

In actual practice and in the production management literature the use of forecasting is generally an accepted input into master production scheduling (Biggs and Campion 1982, p. 574; Buffa 1983, p. 408; Buffa and Miller 1979, pp. 53 and 338; Collier 1980a, p. 12; Gaither 1981, p. 75; Schroeder 1981, p. 402; and Steinberg and Napier 1980, p. 1259). In summarizing principles necessary for MPS, Berry, Vollman and Whybark (1979, pp. 9–10) state "A single, consistent forecast of demand is necessary for master production scheduling." The eight firms they studied in depth employed some or all of these basic forecasting techniques to get the basic forecast: exponential smoothing and other mathematical approaches, executive opinion and field survey methods, and many market research-based techniques.

A key question is to what degree does the MPS depend upon and accept forecasting results? Consider two views on this question. Orlicky (1975, p. 232) in discussing master production scheduling concepts states

> A master *production* schedule should not be confused with a forecast. A forecast represents an estimate of *demand*, whereas a master production schedule constitutes a plan of *production*. These are not necessarily the same. A distinction should therefore be maintained between the

functions of developing a forecast and laying out a schedule of production, despite the fact that in some cases the two may be identical in content.

In a similar vein, Vollman, Berry, and Whybark (1984, p. 208) explain their views on MPS and forecasting interactions.

The master production schedule (MPS) is an anticipated build schedule for manufacturing end products (or product options). As such, it is a statement of production, not a statement of market demand. That is, the MPS is *not* a forecast. The forecast of sales is a critical input into the planning process that is used for the determination of the MPS, but the MPS is not identical to the forecast in most instances. The MPS takes into account capacity limitations as well as desires to utilize capacity fully. This means that some items may be built before they are needed for sale, and other items may not be built even though the market place could consume them.

We accept the relationships between forecasting, master production scheduling, and downstream planning such as material requirements planning systems. For the purposes of this research we are focusing on the cost impact of forecast errors as they pass through the master production planning system. We are *not* investigating forecasting procedures or master production scheduling procedures, both very important issues for effective planning.

One could argue that what we are calling "forecast errors" in this study are actually "MPS errors." A countervailing view is that MPS is so complex that it is meaningless to study one dimension, forecast error, as that is taken into account by managerial judgement in establishing the MPS. Similarly, one could accept the view that the MPS is accurate—without allowing for error after the MPS is "firmed." If either of the later views prevail, they do not accept our assumption (and belief) that forecast errors (or MPS errors) will impact downstream labor, equipment, and material planning. To those rejecting our assumptions, this study becomes trivial and is of little consequence.

Production and operations managers, we suggest, are primarily interested in cost consequences of forecast error. In this study, we utilize a few of the specific error measures as well as the cost consequences of forecast inaccuracy applied in specific MRP systems.[1]

MRP Production-Inventory Systems

Material Requirements Planning (MRP) is a contemporary production-inventory system, described elsewhere (Orlicky 1970; Plossl and Wright 1971; Berry 1972; Vollman et al. 1984). Features include (1) primary application in manufacturing where assembly of a final product is undertaken, (2) the use of a digital computer, and (3) computerized master production schedules, inventory status files, and bill of materials as system inputs. The use of MRP systems in the United States appears to be growing exponentially through the late 1970's (Anderson and Schroeder 1979).[2]

MRP Systems Performance Measures. Based on traditional inventory system analysis (Naddor 1966) and contemporary production and operations books and articles, this study will utilize traditional cost measures and timeliness to evaluate MRP system performance. Costs will include total inventory costs, total carrying costs,

[1] What is a "common" error measure is open to judgement. Depending upon who is making the judgement, common error measures are the average error (AE), mean absolute deviation (MAD), and mean squared error (MSE) (Buffa 1983); MAD and BIAS (Adam and Ebert 1986); or MSE and mean absolute percentages error (MAPE) (Makridakis and Wheelwright 1978). In this study we will use MAD and BIAS as representative error measures.

[2] MRP systems are "push" production and inventory systems popular in the United States. These contrast with "pull" systems typical of Japanese Just-in-Time and Kanban systems. See Vollman et al., Chapter 20; Hall (1983); and Schonberger, (1982, appendix on Kanban).

total setup costs, and total shortage costs. Timeliness measures will include both the number of shortage times and the number of shortage units.

MRP Systems Lot-Sizing Rules. A variable in MRP system design is the selection of method to determine *how much to order* (the lot-sizing rule), once the MRP system has determined it is now *time to order*. The determination of when to order involves the perpetual-inventory logic behind the MRP system, the result of which is time-phasing order requirements. How much to order, within the context of MRP systems, is a current topic of interest to both production/material planners and academics. Orlicky (1975), for example, listed nine distinct lot-sizing rules for discrete period-by-period inventory situations.

Several possible lot-sizing rules were discarded; one because of demonstrated inferiority (Gorham 1968), one because of the requirement to utilize dynamic programming (which was judged inappropriate because of the assumption of zero demand beyond the planning period and, therefore, frequent revision requirements), and others based on the results of a study by Biggs, Goodman, and Hardy (1977). In selecting the four lot-sizing rules for this study, a complete literature review was conducted, which included studies other than Biggs, et al. Studies evaluated alternative lot-sizing rules under conditions of perfect forecasts (see Berry 1972; Biggs 1979; Blackburn and Millen 1980, 1982; and Nappier and Steinberg 1981).

The study undertaken here extends the Biggs, Goodman, and Hardy evaluation of lot-sizing rules in MRP systems. Relying on their lot-sizing findings, we will explain how the current study (1) relaxes their assumption of demand certainty by introducing forecasting errors and (2) varies product structure.

Research Issues (Hypotheses) and the Experimental Procedure

Research Issues

The basic research issue involves the introduction of forecast error *into MRP systems and evaluating that impact upon system performance* (*cost, timeliness*). We suggested that increasing forecast error will result in increasingly poorer MRP system performance (higher costs, increased shortages). Rather than investigate alternative forecasting procedures, as we initially set out to do, the results of alternative forecasting procedures—varying forecast error (accuracy)—are treated as the primary variable of interest. *There is no forecasting system in this study;* forecast errors—the inaccuracy from exponential smoothing, Box Jenkins, or whatever forecasting systems—are entered directly into the master production scheduling system and passed into the MRP system. Similar to forecasting, there is no master production scheduling system in this study.

There are two characteristics of MRP systems, identified from the literature review and judgement, that appear critical as interacting variables between forecast error and MRP system performance: the *lot-sizing rule* used (previously discussed) and the *MRP system structure.*

The structure of the MRP system involves several dimensions:

(1) the number of levels in the product structure;
(2) the number of parent items for a component item;
(3) the number of component items for a parent item;
(4) the lead time in the parent-component relationship; and
(5) the cost structure associated with the production process of a parent or component item.

Collier identified that commonality (the average number of parent items for a component) has significant impact upon determining the aggregate safety stock levels (Collier 1982). Since the lot-for-lot rule was used in his research, he ignored the cost structure. However, in our research, there is no demand uncertainty for the component items, and cost structures are needed to apply the EOQ rule, the POQ rule and the PPB rule. In this exploratory study we are undertaking, we intend to catch the essence of MRP structures, the actual number of levels in the product structure (or bill of material) and the complexity of the interrelationships of the MRP component parts. There exists no typical MRP system structure in the literature which can be claimed as representative, therefore one or more MRP structures needed to be specified.[3]

Formal Hypotheses. Formal statements of hypotheses are provided as Figure 1. Briefly, the first four hypotheses look at the impact of introducing forecast error into MRP production-inventory systems as error effects performance and interacts with lot-sizing rule and MRP structure. The last four hypotheses examine the impact of lot-sizing rules on MRP production-inventory system performance as lot-sizing rules effects performance and interacts with forecast error and MRP structure.

Research Procedure

The following steps were employed to explore the research issues in this study:

1. Computer simulation models were constructed for MRP systems with four different product structures and components relationships, and with specific lot-sizing rules.
2. End-item demand forecasts and the associated errors (randomly generated from the error distributions) were introduced into the master production schedule for each MRP system.
3. Over the simulated planning horizon, the realized forecast errors were measured as were the costs of production operations.

Design of the Simulation Experiments

Three independent variables and one dependent variable are adopted in a series of simulation experiments. The independent variables—lot-sizing rules, MRP structure, and forecast error distribution—and the dependent variable—operations cost—are described below.

Lot-Sizing Rules (LSRs). Four lot-sizing rules are selected to test the difference of cost impact due to different LSRs upon system performance. The selected rules are: (1) the lot-for-lot (L4L) rule, (2) the economic order quantity (EOQ) rule, (3) the period order quantity (POQ) rule, and (4) the part period balancing (PPB) rule.

MRP Structures. Four different levels (or types) of MRP system structures are illustrated in Figure 2. These were selected to represent variations in the complexity of the bill of material and subcomponent relationships.

Forecast Error Distribution. The forecast error distribution for an end item is normally distributed with a specified mean (μ) and standard deviation (σ). The seven levels of the mean and four levels of the standard deviation are shown in Figure 3. Forecast error is measured by MAD and BIAS, positive BIAS implying over-forecast and negative BIAS an under-forecast.

[3] Kriebel's (1971) "Factory-2" is one complex structure that is often used in MRP simulations. The logic represents simply one structure, with rather randomly chosen relationships, that in total provide one complex structure. Collier (1980) in studying the relationship between lot sizing rules and capacity utilizes a structure with 5 levels and 18 total parts. In Collier's study structure was not a research variable, which is typical of MRP studies.

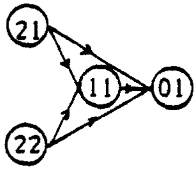
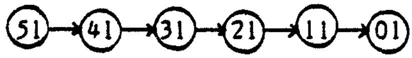
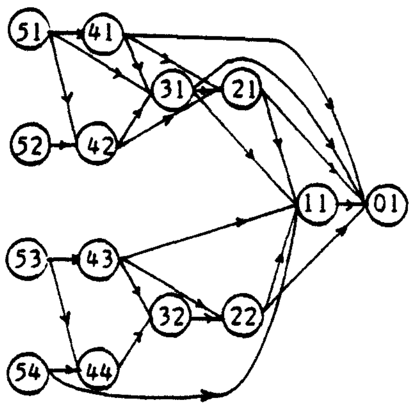
Hypothesis	Statement of Hypothesis
	IT IS HYPOTHESIZED THAT IN MRP PRODUCTION-INVENTORY SYSTEMS
1	using heuristic lot-sizing rules the impact of forecasting error upon system performance is significant and, furthermore, the greater the forecasting error the higher the total cost.
2	using heuristic lot-sizing rules the impact of forecasting error upon system performance is contingent upon which lot-sizing rule is used.
3	using heuristic lot-sizing rules the impact of forecasting error upon system performance is contingent upon the MRP system structures.
4	using heuristic lot-sizing rules the impact of forecasting error upon system performance is contingent upon both the lot-sizing rules and the MRP system structure.
5	the system's performance is significantly related to the selected lot-sizing rules.
6	the performance evaluation of lot-sizing rules is contingent upon the forecasting error levels.
7	the performance evaluation of lot-sizing rules is contingent upon MRP system structures.
8	the performance evaluation of lot-sizing rules is contingent upon forecasting error levels and MRP system structures.

FIGURE 1. Formal Statement of Research Hypotheses.

Operations Costs. Operating costs for each simulated time period include inventory carrying costs, setup costs, and end-item shortage costs (Figure 4). The total of these costs is used as the ultimate criterion for performance evaluation. To further clarify the costs being measured, the final products have both carrying and stockout costs while for components only carrying costs are considered. A discussion of the sensitivity analysis performed to set these cost values can be found in Lee (1982). Figure 5 is a summary of the study variables, the MRP system components (middle block) hypothesized to moderate the relationship between the forecasts and errors and the outcomes.

Simulation Logic. The computer simulation logic has the following key characteristics:

1. The operating system is an MRP system, including a master production schedule, inventory status files, and bill-of-material files.
2. The structure of the MRP system is a single-product, multiple-stage production-inventory system.
3. End-item forecasts and the associated errors are the inputs to the master production schedule.
4. The requirements of each dependent component are derived from the order releases of the parent items. There is no uncertainty (no forecast errors) involved in the requirements of all dependent components.

MRP System	System Structure*	BOM Level	Complexity
MRP11		3 Levels	Simple
MRP12		3 Levels	Complicated
MRP21		6 Levels	Simple
MRP22		6 Levels	Complicated

* Each circle represents one component. All components are coded by two digits. The first digit represents the level of bill-of-material (BOM) with the final product being coded at the highest level (level 0). The second digit represents the component identity in the BOM level.

FIGURE 2. MRP Systems Structure.

5. One lot-sizing rule is applied to the final product and its dependent components to determine production schedules for all items in an MRP system.

6. Nominal end-item demand is 1,000 units per period upon which is superimposed a forecast error that is randomly generated from the error distribution.

7. With the final product being coded at the highest level (level zero), the operations for ordering a lower level component or delivering to a higher level component occur at the beginning of each period.

8. The demand for the final product occurs at the beginning of each period.

9. The lead time between any dependent item and its parent(s) is equal to one period.

10. The lead time includes the time needed for ordering lower level components, setting up the production run, and delivering to meeting higher level components' operation.

11. The beginning inventory is used to compute the carrying cost for the dependent components, therefore carrying costs for the raw materials and for the work in process

	Independent Variables	Level	Description
1	Forecasting Error		
	(a) the mean	1	$\mu = 0$ for error generating function
		2	$\mu = 100$ for error generating function
		3	$\mu = 300$ for error generating function
		4	$\mu = 500$ for error generating function
		5	$\mu = -100$ for error generating function
		6	$\mu = -300$ for error generating function
		7	$\mu = -500$ for error generating function
	(b) the standard deviation	1	$\sigma = 100$ for error generating function
		2	$\sigma = 200$ for error generating function
		3	$\sigma = 300$ for error generating function
		4	$\sigma = 400$ for error generating function
2	Lot Sizing Rule	1	the Lot for Lot (L4L) rule
		2	the Economic Order Quantity (EOQ) rule
		3	the Period Order Quantity (POQ) rule
		4	the Part Period Balancing (PPB) rule
3	MRP System Structure	11	the MRP11 System
		12	the MRP12 System
		21	the MRP21 System
		22	the MRP22 System

FIGURE 3. Independent Variables of Experimental Design.

(WIP) inventory are accounted for. The ending inventory is used to compute the carrying cost for the final product.

The logic of the simulation model was verified, its operating characteristics were validated as similar to a "typical" MRP system (Anderson and Schroeder 1979), its starting and ending conditions were established, and the required sample size was calculated based on desired precision, all following accepted simulation design procedures. Figure 6 flow charts the computer program for the simulation.

Simulated Planning Horizon. In order for an MRP system using forecasting to be effective, the forecasting process for time t should be conducted at a time not later than t-TLP, where TLP represents the total lead time from ordering the raw material through the completion of a final product. Thus, the last point in time for ordering raw materials to meet the demand for the final product at time t, is t-TLP.

The simulated forecasting errors are associated with the forecasts imminent to the MRP production-inventory decisions. That is to say, if an order for processing a final product is released and this order is based upon forecasts for a certain time period into the future, these forecasts are the imminent forecasts. When the planned order is received the independently-generated forecasting error is then implemented and the actual demand is realized. The implication is that the designed forecasting errors are independent of the forecasting process and the revisions of forecasts. Only the forecasts that are imminent to MRP production-inventory decisions, and the forecast errors that have impact upon system performance, are of interest to this study.

Dependent Variables	Description
Total Cost	the sum of all component costs over the simulation period
Total Carrying Cost	the cost of holding inventory over the simulation period
Total Shortage Cost	the cost of incurring shortage over the simulation period
Total Setup Cost	the cost of setting up production or ordering materials over the simulation period
Number of Shortage Times	the number of times incurring shortage over the simulation period
Number of Shortage Units	the number of shortage units over the simulation period

FIGURE 4. Dependent Variables of Experimental Design.

Experimental Procedure

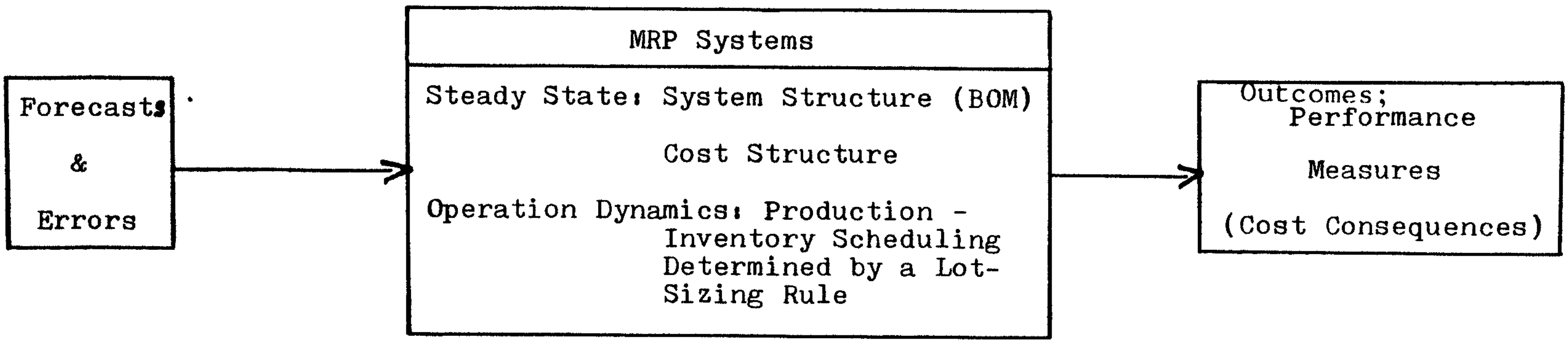
Each simulation run is 120 periods covering from 12 to 120 planning cycles (i.e., number of setup times for the final product) conditional upon the lot-sizing rule and the MRP system. The simulation run length combined with the number of replications minimizes the effects of start-up and termination conditions.

To explore the research issues, 896 simulation runs were conducted. The runs included two replications of all combinations of forecast error mean (7 levels), standard deviation of error (4 levels), lot-sizing rules (4 levels), and MRP system (4 levels). From the inputted error distribution for each simulation run, forecast error variates were randomly generated for each period in the planning horizon. This procedure yielded the "actual" forecast errors for end items which were used in the subsequent analyses.

Results

Twelve of the 896 individual simulation runs (observations) were selected and are presented in Figure 7. The experimental results are summarized in Figure 8. All the main effects are significant across each of the six dependent variables. Many two-way independent variable interactions and some three-way independent variable interactions are significant, contingent upon the dependent variable. Consider the first column of Figure 8. These total cost results are detailed in the analyses of variance (ANOVA) table summarized as Figure 9.

In Figure 9 it can be observed that MRP structure (shown as the "MRP" main effect) is a dominant factor in influencing the total cost. This is because of the significant different cost structure associated with each selected MRP structure. The implication is that the cost impact of forecast errors and the performance of lot sizing rules should be analyzed across different structures and within each MRP structure to further understand the results.



Independent Variables

(1) Forecasting Error - mean
- standard deviation

(2) MRP System Structure

(3) Lot-Sizing Rule

Dependent Variables

Total Cost
Total Carrying Cost
Total Shortage Cost
Total Setup Cost
No. of Stockouts
No. of Shortage Units

FIGURE 5. Summary of Study Components.

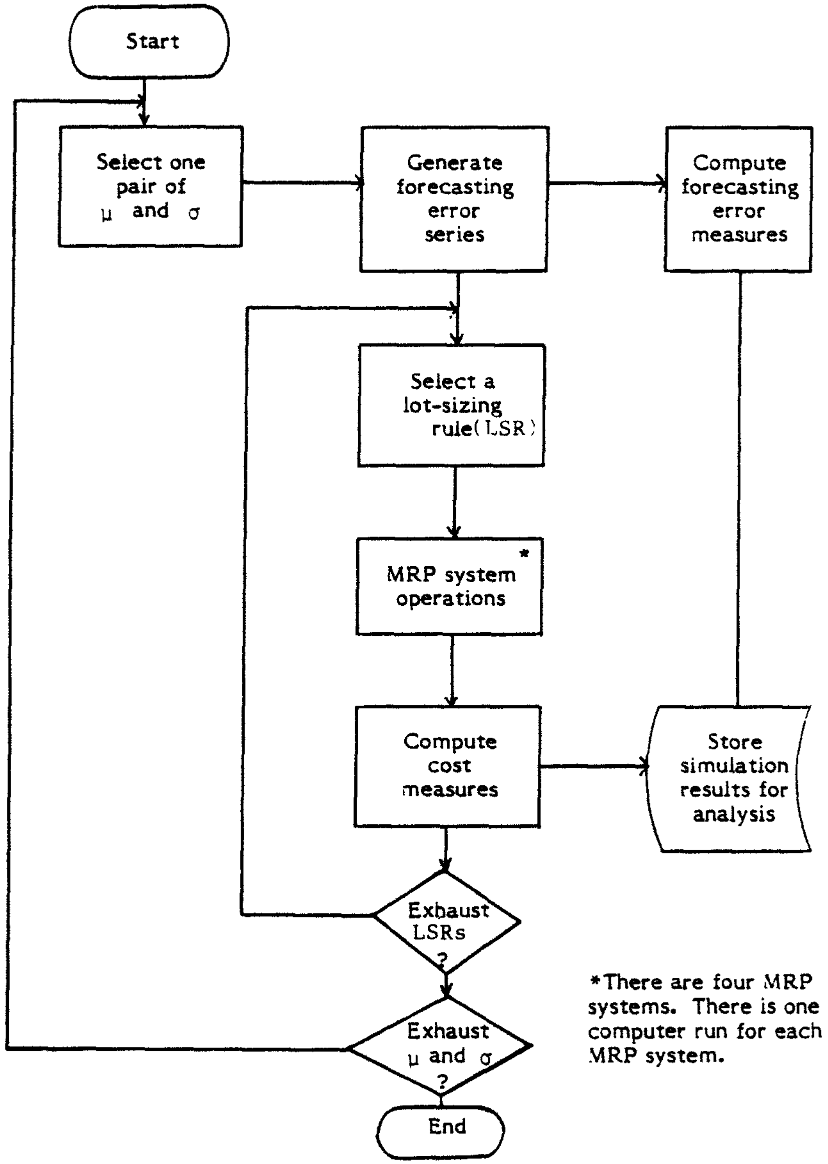


FIGURE 6. The Flowchart of Computer Program for MRP Systems Simulation.

Results Across MRP Structures

Hypothesis 1 addressed the macro view for evaluating the impact of forecasting errors upon MRP systems, results shown in Figure 10. The impact of BIAS upon carrying cost and shortage cost generally conforms to the belief that a positive BIAS (over forecast) would result in higher inventory level, and a negative BIAS (under forecast) would incur frequent shortage times and higher number of shortage units. The impact of BIAS upon setup cost is mixed: higher positive BIAS would result in higher inventory level, therefore reducing the number of setups; and higher negative BIAS would underestimate the need for setups. The total cost is the net result of the

Observation	MRP Structure	Mean Forecast Error	Expected Standard Deviation	BIAS	Standard Deviation	MAD	Mean Square Error	Total Cost	Total Carrying Cost	Total Shortage Cost	Total Setup Costs	Number of Shortage Times	Number of Units Short	Lot Sizing Rule
1	11	0	100	2.436	89.333	72.908	7920	1111931	61931	0.0	1050000	0	0.0	1
2	11	0	100	2.436	89.333	72.908	7920	308990	141610	1130.2	166250	1	239.4	2
3	11	0	100	2.436	89.333	72.908	7920	310811	153311	0.0	157500	0	0.0	3
4	11	0	100	2.436	89.333	72.908	7920	311049	144799	0.0	166250	0	0.0	4
81	11	−300	100	−295.26	106.119	295.259	98345	1252077	34842	167235	1050000	120	35431.1	1
82	11	−300	100	−295.26	106.119	295.259	98345	330927	103193	52734	175000	20	11172.5	2
83	11	−300	100	−295.26	106.119	295.259	98345	327428	105332	55847	166250	21	11832.0	3
84	11	−300	100	−295.26	106.119	295.259	98345	341560	105681	60879	175000	23	12898.2	4
225	12	0	100	1.53	93.400	74.108	8653	1412848	204000	8848	1200000	7	601.1	1
226	12	0	100	1.53	93.400	74.108	8653	866538	481204	334	385000	1	22.7	2
227	12	0	100	1.53	93.400	74.108	8653	693806	386909	6897	300000	3	468.5	3
228	12	0	100	1.53	93.400	74.108	8653	740756	348859	6897	385000	3	468.5	4

FIGURE 7. MRP Systems Simulation Results: Selected Simulation Runs.

Hypotheses	Independent Factors \ Performance Measures (Dependent Variables)	Total Cost	Total Carrying Cost	Total Setup Cost	Total Shortage Cost	Total Number of Shortage Times	Total Number of Shortage Units
H1	Forecasting Error Mean (μ)						
H1	Forecasting Error Standard Deviation (σ)						
H5	Lot-Sizing Rule (LSR)						
	MRP System Structure (MRP)						
H1	$\mu*\sigma$		X				
H2 H6	$\mu*$LSR						
H3	$\mu*$MRP						
H2 H6	$\sigma*$LSR				X		X
H3	$\sigma*$MRP				X	X	X
H7	LSR*MRP						
H2 H6	$\mu*\sigma*$LSR	X			X		X
H3	$\mu*\sigma*$MRP		X	X			
H4 H8	$\mu*$LSR*MRP						
H4 H8	$\sigma*$LSR*MRP			X	X	X	X
H4 H8	$\mu*\sigma*$LSR*MRP	X	X	X	X	X	X

** An X indicates an *insignificant* difference at the 0.05 level of significance.

FIGURE 8. Summary Results of Hypotheses Testing.**

sum of the carrying, shortage, and setup costs. *It is interesting to notice that a significant BIAS, 10% to 30% over-forecast, would result in lower total cost.* This result further reinforces the findings by Biggs and Campion, i.e., to BIAS the forecast may improve the system performance.

The impact of standard deviation of forecast errors upon system performance is not so significant as BIAS (Figure 9). It is logical to suspect that higher standard deviation would result in higher carrying cost and higher shortage cost. On the contrary, results from Figure 10 indicate higher standard deviation results in lower setup cost. Why is this so? One consistent explanation about the cost impact is that higher standard deviation would result in (1) over-forecast, therefore higher inventory level, hence to reduce the need for future setups and (2) under-forecast, therefore ignorance of the need for setups.

Addressing Hypotheses 5, results for evaluating the performance of lot-sizing rules are given in Figure 11. The relative performance of the lot-sizing rules are across MRP

)EPENDENT VARIABLE: TOTCOST

'OURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
1ODEL	447	1669055128069537	3733904089641	966.04	0.0001
:RROR	448	1731592423353	3865161659		
'ORRECTED TOTAL	895	1670786720492891			

ł-SQUARE	C.V.	STD DEV	TOTCOST MEAN
.998964	4.2080	62170	1477436.56304373

SOURCE	DF	ANOVA SS	F VALUE	PR > F
:XBIAS	6	106522496430698	4593.27	0.0001
'XSTD	3	41238556605	3.56	0.0144
:XBIAS*EXSTD	18	737824589258	10.61	0.0001
.SR	3	149734776105271	12913.20	0.0001
.SR*EXBIAS	18	14566473401619	209.37	0.0001
.SR*EXSTD	9	308165632897	8.86	0.0001
.SR*EXBIAS*EXSTD	54	195549527370	0.94	0.6040
1RP	3	1257588308581431	99999.99	0.0000
XBIAS*MRP	18	93783769152506	1347.99	0.0001
XSTD*MRP	9	178537710359	5.13	0.0001
XBIAS*EXSTD*MRP	54	907494794155	4.35	0.0001
SR*MRP	9	37708677430963	1084.00	0.0001
SR*EXBIAS*MRP	54	6143520564580	29.43	0.0001
SR*EXSTD*MRP	27	276975825448	2.65	0.0001
SR*EXBIAS*EXSTD*MRP	162	361319766378	0.58	1.0000

FIGURE 9. ANOVA Results for MRP Systems Simulation: Total Cost as the Dependent Variable.

Evaluation Criteria (Dependent Variables) / Subjects for Evaluation	Total Cost	Total Carrying Cost	Total Shortage Cost	Total Setup Cost	Total Number of Shortage Times	Total Number of Shortage Units
Impact of Expected Bias of Forecasting Errors	100	−500	500	500	500	500
	300	−300	300	300	300	300
	0	−100	100	−500	100	100
	500	0	0	100	0	0
	−100	100	−100	0	−100	−100
	−300	300	−300	−300	−300	−300
	−500	500	−500	−100	−500	−500
Impact of Expected Standard Deviation of Forecasting Errors	100	100	100	400	300	100
	200	200	200	300	400	200
	300	300	300	200	200	300
	400	400	400	100	100	400

* Factor levels are ranked in descending order of performance by average value of the dependent variable (the factor level with the least average value is ranked at the top). They are differentiated by Duncan's method at the 0.05 level of significance. Indifference between factor levels is marked by a sidebar.

FIGURE 10. Evaluation of the Impact of Forecasting Error Main Effects upon MRP Systems by Different Dependent Variables* (Across MRP Systems).

structures as well as across forecast error (both BIAS and standard deviation) levels. Based on total cost, the POQ rule is best followed by the EOQ rule. The lot-for-lot rule results in the least total carrying cost and highest setup cost. This conforms to common belief. The result of highest shortage cost may be due to its lack of cushion. The PPB rule, the POQ rule, and the EOQ rule intend to balance the carrying and setup cost. Results indicate mixed ranks of performance under each component cost for these three rules. Overall, the POQ rule turned out to be the best decision rule in this study.

Results Within MRP Structures

The ANOVA analyses were conducted for each MRP structure, as summarized in Figure 12. Based on total cost, the main effects of lot-sizing rule and bias of forecast errors are significant in every structure. The standard deviation is insignificant in MRP12 and MRP21 structures.

With any one MRP structure, what are the interactions between forecast error and lot-sizing rule? Figures 13 and 14 illustrate the analysis performed for the MRP11 structure. Measuring total cost as the dependent variable, results from the figures included (Figures 13 and 14) and those not included lead us to summarize findings relating to Hypotheses 4 and 8 as follows.

Hypothesis 4. (1) The least cost condition for the lot-for-lot rule tends to include a significant positive BIAS. For the other three rules, the least cost tends to center around zero BIAS.

(2) The relative impact of BIAS and standard deviation is contingent upon the lot-sizing rules and MRP structures.

(3) The relative impact of a high BIAS level (resulting in higher total cost) increases in magnitude when moving from a low BOM level and simple structures (MRP11 & MRP12) to a high BOM level and complicated structures (MRP21 & MRP22).

Hypothesis 8. (1) The performance of the lot-for-lot rule is the poorest of the lot-sizing rules studies.

(2) The relative performance of the PPB rule, the EOQ rule, and the POQ rules is contingent upon MRP structures and forecast error levels.

Evaluation Criteria (Dependent Variables) / Subjects for Evaluation	Total Cost	Total Carrying Cost	Total Shortage Cost	Total Setup Cost	Total Number of Shortage Times	Total Number of Shortage Units
Lot-Sizing Rules Performance[a]	POQ	L4L	EOQ	POQ	EOQ	EOQ
	EOQ	POQ	PPB	PPB	POQ	POQ
	PPB	EOQ	POQ	EOQ	PPB	PPB
	L4L	PPB	L4L	L4L	L4L	L4L

* Lot-sizing rules are ranked in descending order of performance (the lot-sizing rule with the least average value of the dependent variable is ranked at the top). They are differentiated by Duncan's method at the 0.05 level of significance. Indifference between factor levels is marked by a sidebar.

[a] Lot-sizing rules: L4L is the lot-for-lot rule; EOQ is the economic order quantity rule; POQ is the period order quantity rule; PPB is the part period balancing rule.

FIGURE 11. Evaluation of the Performance of Lot-Sizing Rules in MRP Systems by Different Dependent Variables* (Across MRP Systems).

Factor \ MRP Structure	MRP11	MRP12	MRP21	MRP22
LSR	52750.61	6637.00	6009.48	2961.73
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
EXBIAS	660.82	1052.52	1500.68	2369.49
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
LSR*EXBIAS	427.55	105.71	55.06	71.78
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
EXSTD	18.28	1.66	1.70	5.34
	(0.0001)	(0.1783)	(0.1703)	(0.0019)
LSR*EXSTD	26.28	8.44	1.18	4.21
	(0.0001)	(0.0001)	(0.3155)	(0.0001)
EXBIAS*EXSTD	1.53	7.04	2.79	6.45
	(0.0926)	(0.0001)	(0.0005)	(0.0001)
	1.09	0.94	0.32	0.71
LSR*EXBIAS*EXSTD	(0.3455)	(0.5955)	(1.0000)	(0.9217)

* F values are the listed figures and a corresponding significance level is indicated in the parentheses for each F value.

FIGURE 12. Summary of F-Value and Significance Level of ANOVA for Each MRP System* (Dependent Variable: Total Cost).

(3) In simple MRP structures (MRP11 & MRP21), lot-sizing rules exhibit little performance differentiation. However, in complicated structures (MRP12 & MRP22), there exists significant performance differentiation among lot-sizing rules.

Lot-Sizing Rules / Subjects for Evaluation	Lot-for-Lot Rule (L4L)		Economic Order Quantity Rule (EOQ)		Period Order Quantity Rule (POQ)		Part Period Balancing Rule (PPB)	
	Rank[a]	Relative Impact[b]	Rank	Relative Impact	Rank	Relative Impact	Rank	Relative Impact
Impact of Expected Bias Under Each Lot-Sizing Rule	500	100	−100	100	−100	100	−100	100
	300	109	0	100	0	100	0	100
	100	122	100	102	100	103	100	101
	0	130	−300	108	300	107	300	105
	−100	138	300	108	−300	108	−300	108
	−300	149	500	114	500	116	500	114
	−500	161	−500	123	−500	124	−500	124
Impact of Expected Standard Deviation Levels Under Each Lot-Sizing Rule	400	100	100	100	100	100	100	100
	300	102	200	101	300	101	300	100
	200	106	400	101	200	101	200	101
	100	106	300	102	400	101	400	102

[a] Factor levels are ranked in descending order of performance by average total cost (the factor level with the least average total cost is ranked at the top). They are differentiated by Duncan's method at the 0.05 level of significance. Indifference between factor levels is marked by a sidebar.

[b] Relative impact of a forecasting error level is the percentage of its average total cost relative to the average total cost of the top ranked forecasting error level.

FIGURE 13. Evaluation of the Impact of Forecasting Error Main Effects upon System Total Cost under Each Lot-Sizing Rule (MRP 11 System).

Expected Bias	−500		−300		−100		0		100		300		500	
	Rank[b]	Rel.[c] Perf.	Rank	Rel. Perf.	Rank	Rel. Perf.	Rank	Rel. Perf.	Rank	Rel. Perf.	Rank	Rel. Perf.	Rank	Rel. Perf.
Performance	EOQ	100	EOQ	100	POQ	100	POQ	100	PPB	100	PPB	100	EOQ	100
of Lot-	POQ	101	POQ	100	EOQ	101	EOQ	100	EOQ	101	POQ	101	PPB	100
Sizing	PPB	101	PPB	100	PPB	101	PPB	101	POQ	102	EOQ	102	POQ	101
Rules[a]	L4L	340	L4L	359	L4L	359	L4L	338	L4L	313	L4L	267	L4L	227

Expected Std.	100		200		300		400	
Performance	EOQ	100	EOQ	100	PPB	100	EOQ	100
of Lot-	PPB	100	PPB	101	POQ	101	PPB	101
Sizing	POQ	101	POQ	101	EOQ	101	POQ	101
Rules	L4L	324	L4L	319	L4L	310	L4L	301

[a] Lot-sizing rules: L4L is the lot-for-lot rule; EOQ is the economic order quantity rule; POQ is the period order quantity rule; PBB is the part period balancing rule.

[b] Lot-sizing rules are ranked in descending order of performance. They are differentiated by Duncan's method at the 0.05 level of significance. Indifference between performance of lot-sizing rules is marked by a sidebar.

[c] Relative performance of a lot-sizing rule is the percentage of its average total cost relative to the average total cost of the top ranked lot-sizing rule.

FIGURE 14. Evaluation of the Performance of Lot-Sizing Rules in Total Cost under Different Levels of Forecasting Error Main Effects (MRP 11 System).

(4) Generally, when moving toward a high forecast error level (lower negative BIAS, higher positive BIAS, higher standard deviation), lot-sizing rule performance differentiation becomes less and less.

Conclusions and Discussions

Conclusions from the Proposed Hypotheses

Examining the structure of the hypotheses proposed in this study (summarized in Figure 1), the first four hypotheses address the cost impact of forecast errors. Note that these four hypotheses have cumulative characteristics, moving from a general belief (Hypothesis 1) toward a contingency view (Hypothesis 4). When the results are exposed for Hypothesis 4, the implications for the first three hypotheses become self-explanatory. These were summarized previously. Similarly, the implications for Hypotheses 5, 6, and 7 are clear when the results for Hypothesis 8 are summarized, as was done in the previous section.

Actually, Hypotheses 4 and 8 are dual hypotheses. Both focus on the same interaction terms (MRP structures, lot-sizing rules, forecast errors). Hypothesis 4 observes the interaction with an eye toward the cost impact of forecast errors while Hypothesis 8 emphasizes the performance evaluation of lot-sizing rules.

Interpretation of Results

Focusing on Figure 8, which provides the overall results of testing the hypotheses, we first want to examine the impact forecast error has in MRP system performance. Rows 1, 2, and 5 of Figure 8 indicate that forecasting error mean, standard deviation, and their interaction significantly impact all six performance measures. The only exception is in row 5 where the mean-standard deviation interaction does not significantly affect total carrying cost. As hypothesized, forecast error (as a variation in the Master Production Schedule demand) can be said to significantly impact MRP system performance.

From the ANOVA results, in Figure 8 most hypotheses hold. However, there is one significantly unexpected finding. *Although BIAS and standard deviation of forecast errors are significant factors found in this study, greater error level may not result in greater total cost.* For the lot-for-lot rule used in each of the four MRP structures, a significant positive BIAS would result in the least total cost. For the other rules, the least cost exist around zero BIAS; in most cases, a slight positive BIAS (over-forecast) or negative BIAS (under-forecast) resulted in acceptable or even better results than exactly zero BIAS. The standard deviation of forecast errors implied the same tendency for the lot-for-lot rule, i.e., higher standard deviation would result in lower total cost. Generally, for the other rules, standard deviation revealed insignificant cost impact.

Implications and Discussion

Exploring the cost impact of forecast errors upon simulated MRP systems, this study suggests several points. First, higher forecast error level may not result in higher total cost. Although this seems to contradict what we intuitively believe, in this study, the lot-for-lot rule resulted in the least total cost at a significant positive BIAS. Even for other rules in this study, a slight BIAS (positive or negative, contingent upon the use of lot-sizing rule and the MRP structure) may result in better performance. The rationality of higher total cost resulted from higher forecast error was not preserved in this study. Perhaps this can be attributed to the design of this study, yet Biggs & Campion achieved similar results. But the implication is clear. For a complicated production-inventory system (such as an MRP system) that utilizes forecasts, the rationality of higher forecast error resulting in higher total cost may not be guaranteed.

Another issue involves forecast error. Two dimensions of forecast errors were studied in this research: BIAS and standard deviation. In terms of the magnitude of the cost impact, standard deviation is of secondary importance. Intuitively this is reasonable. Usually multiple period forecasts are involved in the decision of releasing an order. The random fluctuations of forecast errors are cancelled out lowering the standard deviation, while the net error remains in the form of BIAS.

A third point relates to MRP product structure. Although only four MRP structures are included in this study, there exists a tendency for the cost impact of forecast errors to become more severe in complicated structures. Also, in the complicated structures the lot-sizing rule's performance differentiation becomes more significant. The implication is that for a more costly, complicated MRP system there exists a greater potential to improve forecasting performance as well as system efficiency in using decision rules.

A final point involves lot-sizing rules. Figure 11 gives us some additional insight into lot-sizing rule selection, a key managerial decision variable in MRP systems. Which rule should one choose? Based on this study, we know the choice of rule will provide a significant difference in MRP system performance and we can recommend the period order quantity (POQ) rule as the apparent best overall. This is a different finding than previous studies, which tend to recommend the EOQ rule (see, for example, Biggs, et al. 1977). The EOQ rule and part period balancing (PPB) rule are similar in performance, with perhaps a slight edge to EOQ (based on total cost).

Implications for the Production/Operations Manager. If you accept the assumption of this paper that forecasting error can pass through the master production schedule into downstream detail planning, then what are the major findings of this study that are valuable to the manager in production/operations, especially the production/inventory control manager? This study suggests that *a combination of high forecasting error (mean and standard deviation), a poor choice of lot-sizing rule, and an MRP structure (or environment) unique to any one technology (that magnifies the forecast* *error and lot-sizing rule), could easily provide devastating cost consequences to an organization.*

What, then, can a manager do? First, one might verify that a good lot-sizing rule exists. This study suggests POQ; other studies suggest EOQ, which was found second best here. Second, a manager might take action to reduce the forecast error within the Master Production Schedule. Just *recognizing* that the error an organization has been accepting is costly might be a first step toward improving the forecasts that are behind the Master Production Scheduling effort. Finally, this study suggests that MRP structure—that is the unique number of levels and interrelationships in any one manufacturing structure—*is important* to total MRP costs. In conclusion, although we have summarized what the manager might find from this study, we caution the manager to be aware of the limitations of this or any simulation study.

We remain enthused about the general findings that forecast error (or master production scheduling error) is important to MRP system performance. Further, we hope this study encourages others—managers and academics—to pursue forecast error as it impacts MRP systems and costs.

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