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The Development of an Inventory Control Procedure for Low Usage Maintenance Spare Parts

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To the Graduate Council:

I am submitting herewith a thesis written by Asa L. Whitaker Jr. entitled "The Development of an Inventory Control Procedure for Low Usage Maintenance Spare Parts." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

D.H. Hutchinson, Major Professor

We have read this thesis and recommend its acceptance:

Harold W. Henry, M. Goodman

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

176

July 17, 1972

To the Graduate Council:

I am submitting herewith a thesis by Asa L. Whitaker, Jr., entitled "The Development of an Inventory Control Procedure for Low Usage Maintenance Spare Parts." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

D H Hutchinson
Major Professor

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Harold W. Henry

M H Goodman

Accepted for the Council:

Hilton A. Smith
Vice Chancellor for
Graduate Studies and Research

THE DEVELOPMENT OF AN INVENTORY CONTROL PROCEDURE FOR LOW USAGE MAINTENANCE SPARE PARTS

A Thesis

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Asa L. Whitaker, Jr.

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ABSTRACT

This analysis was made in an attempt to establish an inventory control procedure which would be applicable for low wage maintenance spare parts. Spare parts inventories are unique in industry since they are maintained as insurance stock to provide protection against the inability to procure a part readily when it is needed for a repair. Due to this characteristic, the demand for these items is low and unpredictable; therefore, classical inventory models are not applicable. More sophisticated approaches have been developed to take these characteristics into account; however, these approaches require assumptions to be made which may not hold true when applying these concepts in everyday operations.

In an effort to gain understanding of the inventory process a simulation model was developed to parallel the inventory cycle as it is operated on a daily basis. In order to develop a realistic simulation model the physical attributes of the system and their interactions were established and provisions were made for evaluating the effect of various control parameters on these characteristics. By simulating the inventory cycle over an extended period of time the model provided an opportunity to introduce various inventory control points at predetermined usage rates. Consequently, the effect of these various control points on the inventory level, reorder cycle, and stockout frequency could be studied at each level of annual usage selected.

The classical total variable cost equation was used to convert the results of the simulation into information which takes into account the cost factors of the inventory cycle. Using the values obtained from the simulation an economic evaluation was made for each set of fixed attributes in order to determine the most economical control point for each level of annual usage and lead time range. As could be expected, many combinations of unit cost and stockout cost are possible for inclusion in the total variable cost equation; however, in keeping with the characteristics of the majority of items in these inventories, these costs were limited to five hundred dollars each.

The data from the economic evaluations was consolidated and arranged in graphical form in order to use the data as a tool for decision making. By determining the expected annual usage, lead time, unit cost, and probably stockout cost, the user can quickly determine the max-min control point which is the most economical for that set of variables. In addition to the graphical representation, the logic represented in the graphs was incorporated into a computerized inventory control system where it has been used successfully for several months.

Although this analysis does not represent an exacting scientific approach to this type of inventory problem, experience indicates that near optimization has been achieved through proper application of the procedure.

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CHAPTER I

INTRODUCTION

Maintenance personnel, whether or not directly involved with the operation of material control, are vitally interested in its effectiveness. If replacement parts are not readily available when required, scheduled manpower utilization and production can be affected seriously; however, maintaining large inventories in an attempt to have 100 percent availability is an expensive solution in terms of capital investment in inventories, warehouse facilities, material obsolescence, and operating labor costs. In the past few years industry has become more and more aware of the large amounts of money they have invested in maintenance spare parts. With today's ever increasing technology in machine design and modification this problem is becoming more and more acute.

Spare parts inventories are unique in industry in the sense that they provide primarily insurance for keeping production units on line to produce a product, consequently the philosophy of maintaining inventory levels is that of maintaining a significant level of insurance at a minimum cost. Needless to say, a very significant level of insurance can be attained through natural process of the inventory cycle; however, it is the balancing of this insurance cost with the cost of being without it that has become the acute problem.

I. STATEMENT OF THE PROBLEM

Due to the nature of spare parts usage classical inventory models either deterministic or stochastic have not provided a meaningful means of determining the optimum inventory levels for the majority of these parts. Experience indicates that over 80 percent of the items are used less than six times per year. Application of the classical EOQ model below this usage level gives results which seem to be inconsistent. More complex models have been developed to attack this particular problem; however, their complexity and/or their misuse has left industry with a lack of confident control for this segment of inventory. Due to these complexities and the need for some measure of control, it was felt that some measure should be developed to simplify and quantify the solution of this problem in terms of dollar value to the enterprise.

II. METHODOLOGY AND SCOPE OF THE STUDY

As with other inventory systems, there are seemingly an infinite number of problems associated with operating a maintenance storeroom. One of the major problems is the establishment of inventory control policies for the items maintained as shelf items. For years, inventory analysts have applied inventory policies, both basic and sophisticated, to maintenance inventories but the area most seemingly neglected is that of low-usage items. This study will be conducted in a large continuous process industrial plant and will include the development, testing, and implementation of an inventory control procedure for optimizing the inventory level of low-usage maintenance spare parts. No provisions will be made or considerations given to the stores items which will fall

easily into the normal inventory patterns for which several models and variations have been developed. The approach taken will be that of developing a simulation model which will depict the inventory cycle as it is conducted on a daily basis with provisions for evaluating various sets of control parameters to establish their effect on the attributes of the system. The first step of the study will be to establish the physical attributes and interactions of the inventory cycle as it is now conducted. Having determined the physical interactions of the inventory cycle, a simulation model will be developed which parallels the physical system. This model will be designed to provide an opportunity to introduce various inventory control points at predetermined usage rates to measure the effects of these various points on the inventory level, reorder cycle, and stockout frequency. Using the values obtained from the simulation, an economic evaluation will be made for each set of fixed attributes in order to determine the most economical control point at each level of usage and/or lead time. This data will then be consolidated and arranged in such a manner that the results, once established, will be easy to use in the everyday operation of a maintenance storeroom while maintaining validity for use as management decision rules.

III. IMPORTANCE OF THE STUDY

As previously mentioned, the outlook for curbing investments in maintenance spare parts inventories is not promising. The maintenance operation in many large companies is a multimillion dollar business with

40 percent of this cost being realized as maintenance material. As recently reported in Factory, maintenance costs have increased 23.8 percent since 1968 (5, page 66). In the ever-expanding manufacturing facility, new technology and design are constantly introduced and improved upon; consequently, the maintenance materials manager is continually confronted with new and different parts being added to existing inventories. As can be seen in Figure 1, the inventory level of one segment of the inventory under investigation has steadily increased over the past ten years with recent years indicating an even sharper increase. As can be expected, part of this increase in inventory is due to expansion of the manufacturing facility. The true effect of expansion can be evaluated however by calculating an annual value for the ratio of spare parts inventory to the actual value of machinery and equipment for which the parts were purchased. Comparison of the results, shown by the dotted lines, indicates that the ratio has more than doubled. If the ratio as experienced in 1962 was still valid, the value of inventory would be approximately one-half of what it is today.

Often the keynote of manufacturing managements' thinking is that of always making sure that parts are on hand to fix production equipment if and when it fails. In the past maintenance management has responded to this concept by establishing inventory levels to insure this criterion is met. Maintenance inventories are no longer a "nuts and bolts" operation, and all levels of management have come to realize that these inventories must be managed rather than simply maintained.

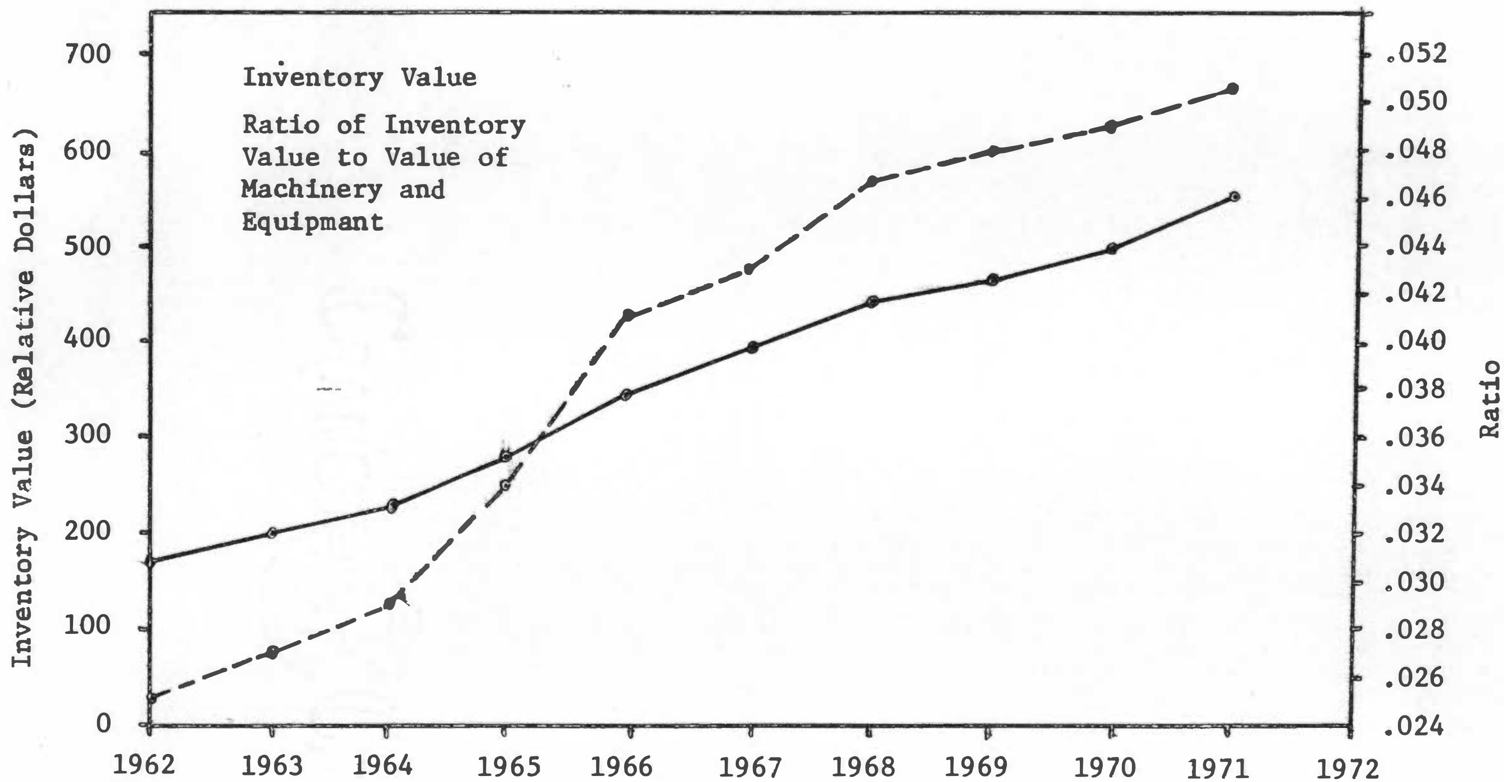

FIGURE 1

LEVEL OF INVENTORY EXPERIENCED IN PAST TEN YEARS

CHAPTER II

LITERATURE SEARCH

Over the past several years, countless articles, books, and miscellaneous literature have been written and published on the theory and application of inventory control. This is immediately recognizable on the outset of a literature search. During the past twenty years the trend has been toward more sophisticated models and many inventory management decisions have been reduced to formulas, some of which are very simple (26). On the other hand, some authors contend that some of the works published under the title of inventory control belong in the realm of pure mathematics (14). Starr and Miller (31), Welsh (36), and Naddor (23) have made explicit contributions to tie the inventory theory presented by Whitin (27) and earlier writers with practical techniques of application. Throughout this vast array of scientific knowledge there is a heavy concentration of operations research applied to inventory systems which can be found in most all sectors of manufacturing with the exception of inventories of maintenance spare parts. There is some indication that the problem of spare parts control is coming more to the forefront, but it is the opinion of the author that this is brought about by an increased interest in the control of maintenance cost in aggregate moreso than a subject of intellectual pursuit. Due to the nature of spare parts inventories, a large number of slow moving items, a great deal of the published material approaches this area of inventory

control from the concept of managerial decisions moreso than analytical analysis (17, 29).

Several recent articles were discovered, however, which directed their attention to the problem of developing an analytical approach for controlling slow-moving items.

Heyvaret and Hurt (16), and Hadley and Whitin (12) approached the problem from the standpoint of establishing base assumptions to consider a Poisson demand distribution with relatively long lead times, with allowable variations in lead time of plus or minus 10 percent. Somewhat later Smith and Vemugantic (30) attacked the problem from the standpoint that the assumption of a stable demand distribution was unnecessarily arbitrary. Consequently their study resulted in a model which takes into account the uncertainty of the unknown parameters and arrives at an optimum policy. The development of this approach was based on the use of an undefined gamma function to describe the distribution of time between two successive demands. In the final analysis this approach, although seemingly the most conclusive and exacting formulation, required assumptions to be made beyond those desired in the conceptual approach of this undertaking.

In addition to mathematical approaches, work has been done to establish a methodology of control through simulation. Several authors, including Reed (27), Gavett (10), Flagle (8), and Naddor (22) strongly support the use of simulation to study the interactions of the inventory system for the purpose of establishing control policies and procedures. Gavett approached the specific problem of the slow-moving item from the standpoint of simulation. Although he specifically considered the

problem in relation to setup costs for production runs, the concept is easily translatable to the maintenance storeroom situation. Graphical representation of his solution was the end result of his analysis. Buckland (4) arrived at a similar end result; however, he chose to establish a nomograph based on a mathematical approach rather than through simulation.

Although the writings found in a literature search of this type are most impressive, it is troublesome to note th lack of actual application of even the simplest of inventory control models to spare parts inventories. Truly, no simple models exist and it is questionable as to the existence of a model that will apply to the low-usage items; however, the problem of practical application of inventory control theory is the subject to which this study must address itself.

CHAPTER III

DEVELOPMENT OF THE SIMULATION MODEL

At the onset of this analysis, it was felt that simulation would give more thorough understanding of the system and how it might react with alterations in basic parameters. As pointed out by Brown (1), the interactions between the many rules that go to make up an inventory control system are so complex that without a simulation of the system it is almost impossible to determine what the over-all effect will be. Mathematical analysis may give some very good ideas of what might happen, but the assumption going into the mathematics may not represent a true representation. While the application of mathematical formulation to the real system may not be too disastrous, it may not be as effective as anticipated.

I. ESTABLISHMENT OF SYSTEM CHARACTERISTICS

The primary objective was to develop new inventory policies to resolve specific inventory situations. However, before the simulation model could be constructed, basic study of the existing system was conducted to establish its flow and operating characteristics. As suggested by Reed (27), systematic steps in the development of the model were followed as indicated in the schematic shown in Figure 2. Being able to alter the parameters of the simulator provides a means whereby results can be compared with previous simulations and changes

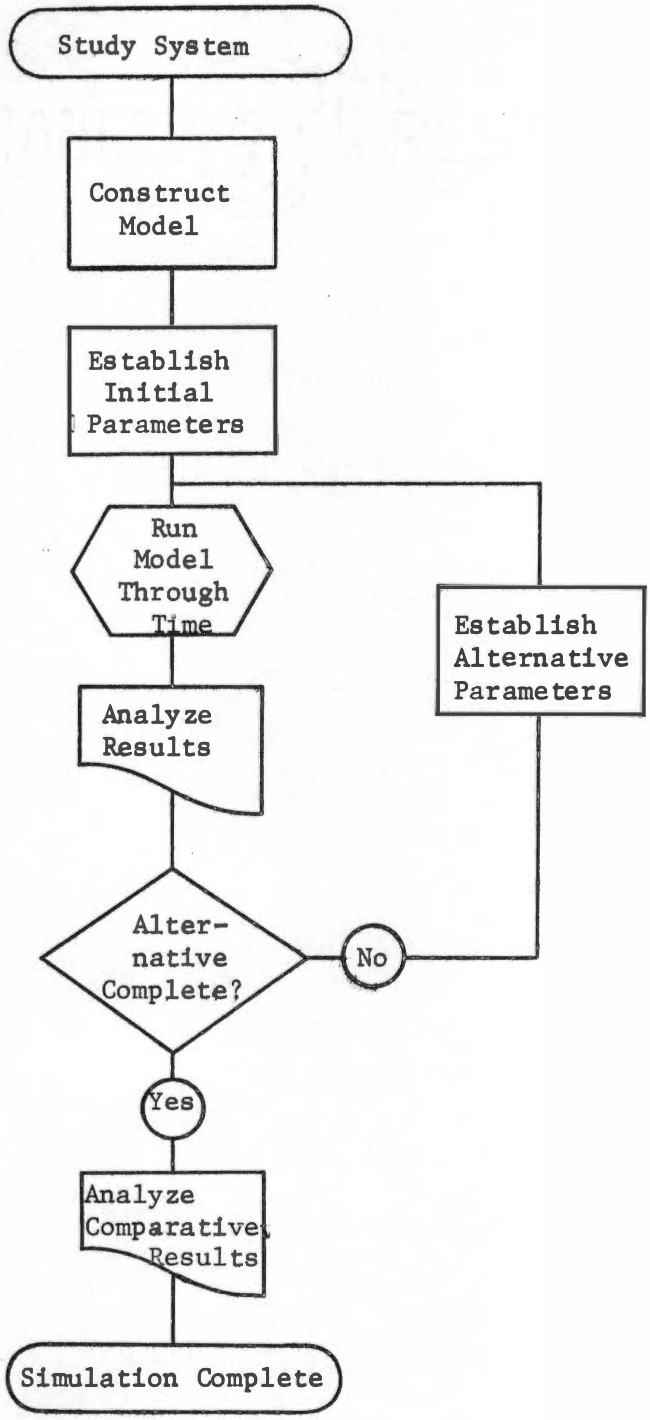

FIGURE 2

SCHEMATIC OF SIMULATION MODEL DEVELOPMENT

made to obtain maximum results. As with most spare parts inventories, the inventories under investigation were controlled by the max-min concept of control parameters. Existent policy dictated that all parts would have assigned to them an individual maximum and minimum inventory level at which they should be maintained. The system operated on a variation of the "two-bin" system of inventory control. The maximum inventory level is defined as that level of inventory which you do not want to exceed with the minimum inventory level being the point at which an order is placed for replenishment. The combination of the two levels then defined the order quantity to be used at the time of purchase. That quantity is defined as the difference between the maximum and minimum inventory levels. The inventory system opeates on the premise of daily review of inventory levels following an issue of a part from stores. When an issue is made, the quantity issued is subtracted from the quantity on hand and the resulting quantity compared with the predetermined minimum level. If the minimum has been reached an order is placed that day to bring the inventory level back up to the maximum level.

Following a procedure often advocated by material managers, the establishment of the max-min points was the responsibility of maintenance supervision. Using practical experience and expert knowledge of equipment, the maintenance foremen and supervisors would endeavor to establish a criterion which would provide them with the part when it was needed without grossly inflating the total inventory value. Although the study indicated later that these estimations usually provided excessive

protection against stockouts, experienced maintenance supervision provides an excellent source for estimates of expected parts usage.

As can be seen in Table I, approximately 55 percent of the inventory with which this study is dealing has not been used within the past two years. Of that 55 percent, approximately 65 percent or 36 percent of the total inventory has no activity recorded at all. Although these figures are startling, these phenomena are not limited to industrial plants.

A similar analysis was made of spare parts for submarines which indicated that 75 percent of the items in inventory had not moved in four years with 70 percent of the remainder moving once in four years (6). This type of analysis brings to mind serious questions as to the need of stocking these.

It is possible, especially with very expensive items, that the cost of maintaining an item in inventory will always exceed the cost of being without it when the item is needed. This area of analysis has been explored by some (18, 6) with some success in quantifying the results of such practices. Because of the type of inventories under consideration, it was assumed that an item being stocked in inventory was required since this action provided a means for satisfying the need for some level of protection desired by management.

II. ESTABLISHMENT OF INPUT VARIABLES

Past experience with spare parts usage had indicated the seemingly unpredictable nature of this type of inventory system. Although estimates

TABLE I

SPARE PARTS ACTIVITY RATE

	Number	Percent of Total	Percent of Inventory Value
Items with Recorded Activity in 1970 or 1971	16,000	34.0	45.2
Items with Last Recorded Activity in 1968 or 1969	3,200	6.8	10.0
Items with Last Recorded Activity in 1967 or 1968	2,400	5.1	4.0
Items with Last Recorded Activity in 1960 Through 1966	3,000	6.6	5.0
Items with No Recorded Activity	22,400	47.5	35.8
Total Number of Items Surveyed	47,000	100.0	100.0

of annual consumption could often be established realistically, of utmost importance was the need to describe the order of demands during the year on the inventory system. As in most cases, the distribution of demand was not known and for the most part, a review of usage data revealed nothing concrete on which density function could be derived. It was generally felt that a Poisson distribution would describe the demand pattern as it existed, but this required that an assumption of distribution form be made which may or may not describe the actual situation. Because of the varied age of equipment, continuous operations, and noncyclical production runs, parts usage from year to year did not indicate that special treatment would be required to consider such attributes as seasonal demand and cyclical production runs. Due to the findings of this analysis, it was concluded that random demand occurrence with no preconceived demand distribution form would best describe the demands of the system during a given time period.

In addition to the treatment of demand pattern was the need to describe the nature of lead time and its relationship to the system. Although common practice in ordering indicates delivery dates and specified lead time durations, the experienced material manager learns to expect the variability in lead time duration which inevitably occurs. A study of historical records indicated that lead time for spare parts ranged from a minimum of one hour to 18 months with an extreme amount of variability. Continued analysis revealed that items could be categorized by describing lead time as a variable length of time within a specified range. As can be seen in Figure 3, approximately 83 percent of all

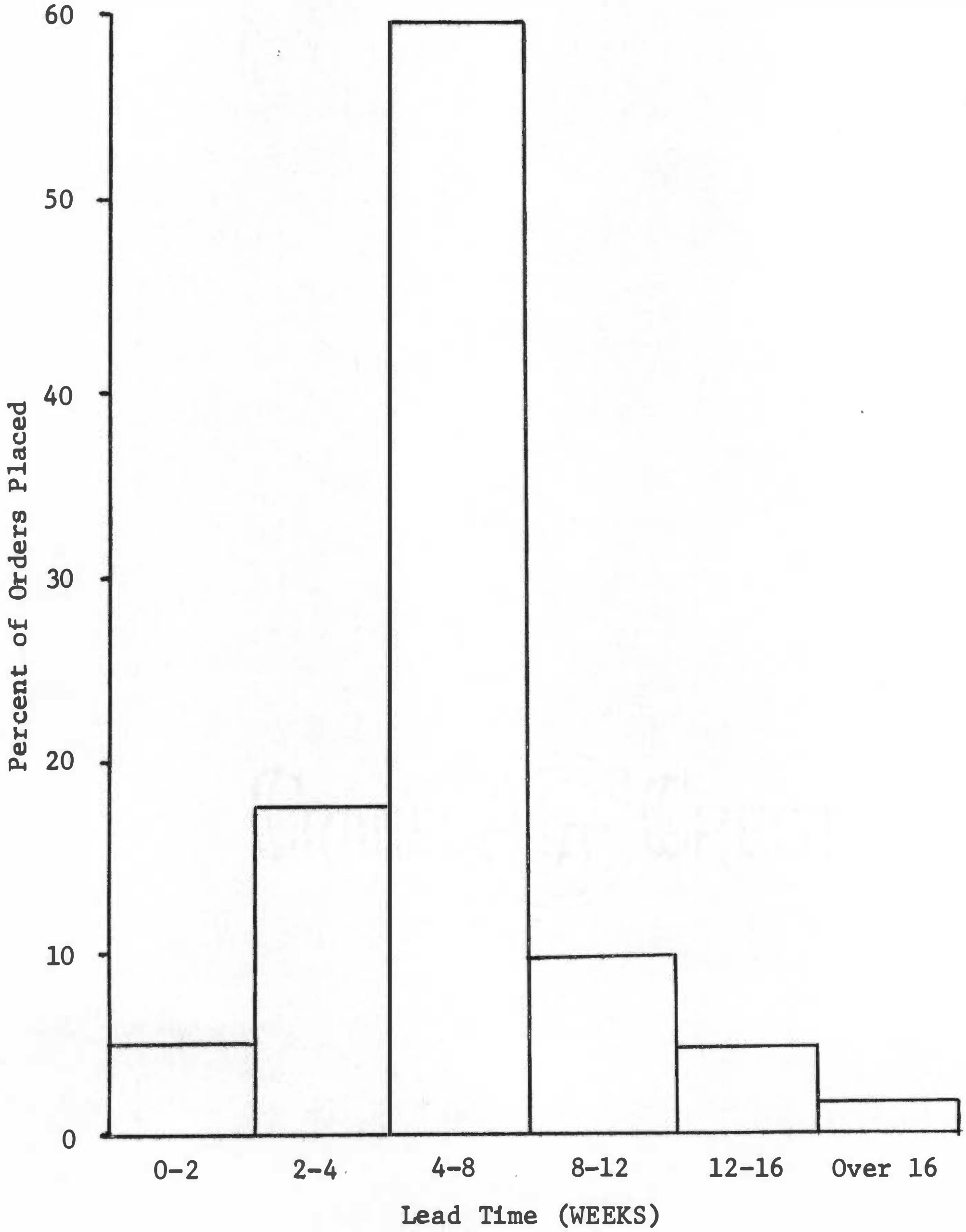

FIGURE 3

DISTRIBUTION OF LEAD TIME

parts ordered are received within eight weeks from the time the order was placed. As could be expected, few items are received quickly; however, the converse of that is also true since only 2 percent of the items required in excess of 16 weeks.

Once again, the problem of descriptive variability was evidenced with lead time. Given that a part would be received in 4-8 weeks, the question arose as to which day in this time range. Once again, the approach was taken that random occurrence with equal probability for a given day was most descriptive of the experience of the inventory system.

As in most inventory analyses, the lead time under consideration encompasses the total elapsed time from the time the order is written until the time the material is received in the storeroom. This cycle can often be long and complex simply from internal policies regarding approvals required and internal handling before the order actually leaves the plant. In addition, policies governing the receipt of materials at the plant site and interplant handling must also be considered. Wherever possible, most manufacturing concerns tend to circumvent this problem by establishing streamlined procedures and special arrangements with vendors to purchase frequently used items and one-of-a-kind items available at only one source.

III. CONSTRUCTION OF BASIC MODEL

The primary objective of the simulation model was to determine the effects of changes in lead time and annual usage under various max-min control points in an effort to establish optimality.

By definition, optimality can be determined for different criteria which may be preferred by various sectors of the manufacturing organization. While production management is insisting on a high service level, the comptroller is injecting demands to minimize investments in inventory and the purchasing department complains about too many purchase orders being written. Truly each segment of inventory cost is vitally important and under various circumstances optimality in service level, minimum inventory, or number of orders placed per unit time can be pertinent; however, based on the overview of all segments, it was concluded that an economical balance of these three factors would be the ideal situation. Using the total annual variable cost equation shown in Table II, it can be seen that the attributes of average inventory, number of stockouts per year, and the number of orders placed per year are necessary to calculate the optimum economic policy. Based on this required information the initial simulation model was constructed and followed the general logic described by the flow diagram in Figure 4 to satisfy these needs. As can be seen the logic of the simulation model is somewhat classical in form; however, some unusual practices have been introduced.

In order to maintain an ordered process, the simulation program maintains a built-in clock which operates on a time interval of one day. During each time interval stock issues are recorded, the inventory level noted, and counters for accumulating the number of orders placed and the stockouts which occur are incremented. In addition, the clock controls the frequency of demands on the system and the duration of the lead time. Demands on the system are introduced randomly over time according to a

TABLE II

THE TOTAL VARIABLE COST EQUATION

Total Variable Cost = Carrying Cost + Ordering Cost + Stockout Cost

$$TVC = C_c + C_o + C_s$$

Where:

C_c = (Carrying Cost Factor)(Unit Cost of Item)(Average Stock Levels)

$$C_c = K\ CI$$

C_o = (Number of Orders per Year)(Cost per Order)

$$C_o = (ORD_n)(C_{ord})$$

C_s = (Number of Stodkouts per Year)(Cost per Stockout)

$$C_s = (SKO)(C_{stk})$$

$$TVC = KCI + (ORD_n)(C_{ord}) + (SKO)(C_{stk})$$

Source: Eliezer Naddor, Inventory Systems. New York: John Wiley and Sons, Inc., 1967, p. 35.

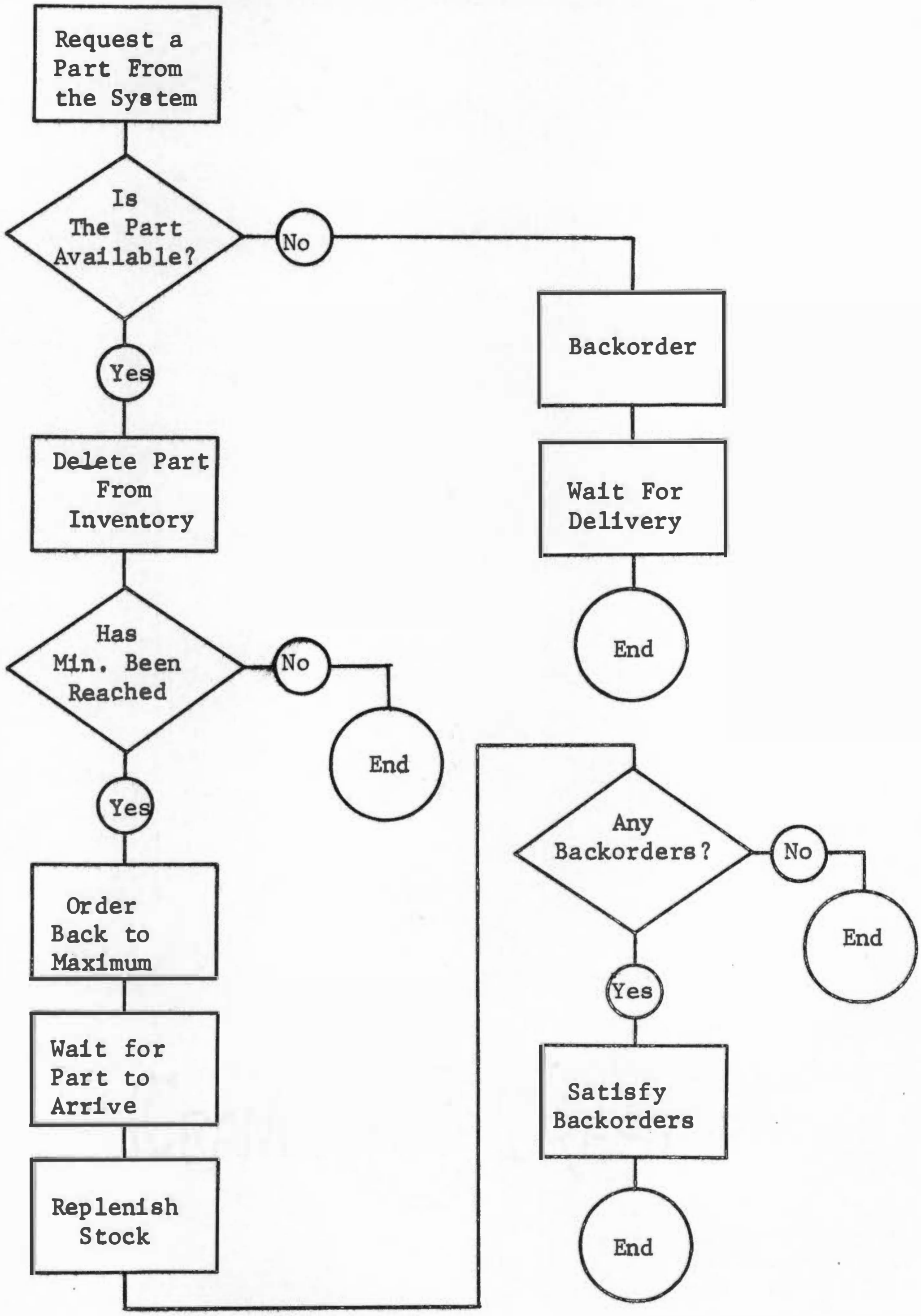

FIGURE 4

FLOW DIAGRAM OF INVENTORY SIMULATOR

rectangular distribution. Since, as previously stated, sufficient data was not available to obtain a finite demand distribution form, a rational basis for the adoption of a preconceived demand distribution form could not be developed. Consequently, a rectangular distribution was selected to introduce demands on the system randomly throughout the year. Having selected the annual usage parameter, the rectangular distribution was used to randomly select the days of the year in which the demand would occur. Through the use of a rectangular distribution a demand had equal probability of occurring on any day during the year thus providing the random occurrence of demand desired. Upon entering a request, a test for part availability is made; if a negative answer results, a stockout is recorded and the part is backordered. If the part is available, the inventory level is decremented by one. Following this, a test for order status is made to determine if an order should be placed. If not, the transaction is terminated; but if the minimum point has been reached or the inventory level is below the minimum an order quantity is placed according to the following formula:

$N = MIL - PIL - PQ$ Where:

N = Number of Items to be Ordered

MIL = Maximum Inventory Level

PIL = Present Inventory Level

PQ = Present Quantity Ordered.

Consequently, the occurrence of a multiple order being outstanding is possible.

Following the placement of an order, a lead time value is selected from a rectangular distribution of a specified range of time. The logic for the selection of a rectangular distribution to introduce lead time variability into the system was identical to that used in the development of the demand distribution. It was determined that each day of the lead time range should have equal probability for the selection of the lead time value. As the simulation continues, the order is received and the stock is replenished along with filling all back orders. This system was simulated for a total cycle of 500 years with the clock acknowledging the beginning of each new year; however, continuity in terms of demands and lead time was uninterrupted. At the completion of the simulated cycle the values of average inventory, average number of orders placed per year, and the average number of stockouts occurring per year were recorded. These values were calculated based on data over the entire simulated period, consequently the total number of orders placed and the total number of stockouts which occurred were divided by the number of years simulated in order to obtain a simple average. The average inventory level was calculated as a simple average of the inventory levels recorded at the end of each day during the simulated period.

IV. EXPANSION OF THE INVENTORY MODEL

Since each simulation cycle provided results from only one combination of annual usage, max-min points, and lead time range, the total model was expanded to include these factors as input variables. For purpose of analysis the values for each of these variables were

selected as shown in Table III. Annual usage of six or less was felt to be the most applicable since along with usage above this value, the classical models seem to provide realistic control. The expanded simulation model followed the logic depicted by the flow diagram in Figure 5. Incorporating the basic logic as depicted in Figure 4 (page 19), an initial lead time distribution, annual usage, and max-min set was simulated through the entire cycle, and after tabulating the results, the max-min set would be changed while the initial lead time distribution and annual usage remained the same. The simulation was continued on this cycle until all max-min sets were used; then the annual usage was increased, and the entire cycle was repeated. As can be seen in Figure 6, the average number of stockouts per year increased for a given max-min set as the annual usage increased. Also, since a larger minimum provides additional protection, the average number of stockouts per year decreases as the max-min points increase. Similarly, the average number of orders placed per year, Figure 7, increased as the annual usage increased. This value is effected directly by the order quantity; consequently, as the difference between the max-min points increased the average number of orders placed per year decreased. Figure 8 depicts the simulated values of the average inventory level resulting at each max-min and annual usage level. These values result as average values over the simulated period and are dependent on a combination of the minimum point and order quantity since the minimum provides a specified recorder level and the order quantity dictates the turnover rate of an item.

TABLE III

INPUT VARIABLES SELECTED FOR SIMULATION ANALYSIS

Annual Usage	Max-Min Points	Lead Time Ranges (weeks)
1, 2, 3,	1-0, 2-0, 2-1,	0-2, 2-4, 4-8,
4, 5, 6	3-1, 4-1, 4-2,	8-12, 12-16
	5-2, 6-2, 7-2,	
	5-3, 6-3, 7-3,	
	8-3	

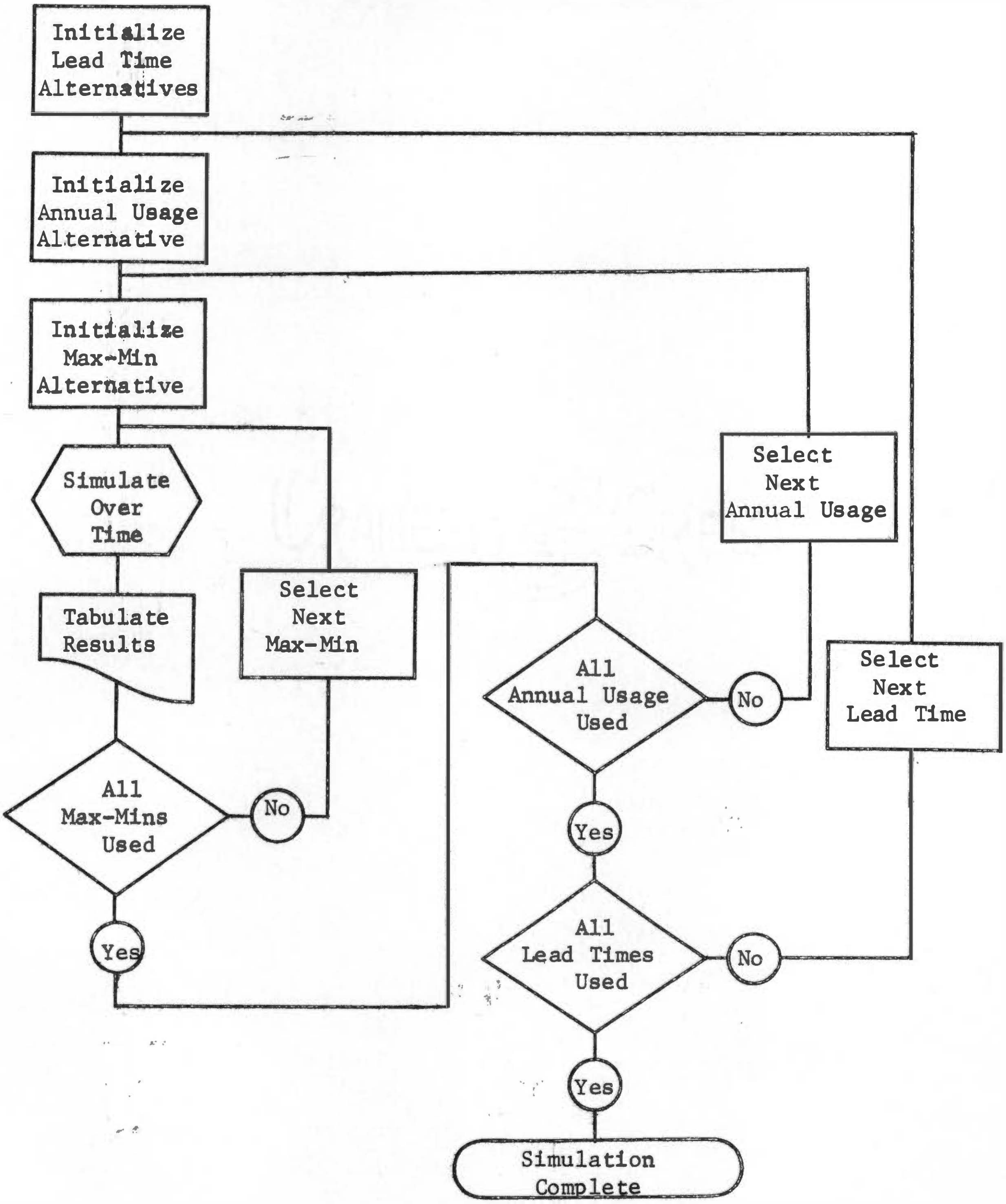

FIGURE 5

EXPANDED SIMULATION MODEL

Annual Usage

Max-Min Points

	1	2	3	4	5	6
1-0	0	.11	.32	.67	1.07	1.58
2-0	0	0	.16	.23	.55	.66
2-1	0	0	0	.01	.09	.22
3-1	0	0	0	.02	.05	.08
4-1	0	0	0	0	.05	.07
4-2	0	0	0	0	0	0
5-2	0	0	0	0	0	0
6-2	0	0	0	0	0	0
7-2	0	0	0	0	0	0
5-3	0	0	0	0	0	0
6-3	0	0	0	0	0	0
7-3	0	0	0	0	0	0
8-3	0	0	0	0	0	0

FIGURE 6

AVERAGE NUMBER OF STOCKOUTS PER YEAR WITH LEAD TIME OF 2-4 WEEKS

Annual Usage

Max-Min Points	1	2	3	4	5	6
1-0	1.00	2.00	3.00	4.00	5.00	6.00
2-0	.50	1.00	1.58	2.13	2.80	3.39
2-1	1.00	2.00	3.00	4.00	5.00	6.00
3-1	.50	1.00	1.58	2.13	2.80	3.39
4-1	.33	.68	1.00	1.47	1.92	2.36
4-2	.50	1.00	1.58	2.13	2.80	3.39
5-2	.33	.68	1.00	1.47	1.92	2.36
6-2	.25	.50	.83	1.00	1.46	1.77
7-2	.20	.40	.64	.96	1.04	1.48
5-3	.50	1.00	1.58	2.13	2.80	3.39
6-3	.33	.68	1.00	1.47	1.92	2.36
7-3	.25	.50	.83	1.00	1.46	1.77
8-3	.20	.40	.64	.96	1.08	1.48

FIGURE 7

AVERAGE NUMBER OF ORDERS PLACED PER YEAR WITH LEAD TIME OF 2-4 WEEKS

Annual Usage

Max-Min Points

	1	2	3	4	5	6
1-0	.942	.888	.836	.789	.741	.702
2-0	1.478	1.525	1.355	1.406	1.316	1.287
2-1	1.942	1.884	1.828	1.770	1.713	1.659
3-1	2.478	2.525	2.349	2.399	2.301	2.268
4-1	2.916	2.958	3.037	2.781	2.768	2.773
4-2	3.478	3.525	3.349	3.399	3.300	3.266
5-2	3.916	3.958	4.037	3.781	3.768	3.772
6-2	4.517	4.537	4.446	4.547	4.236	4.375
7-2	4.883	4.889	4.943	4.731	4.933	4.650
5-3	4.478	4.525	4.349	4.399	4.300	4.266
6-3	4.916	4.958	5.037	4.781	4.768	4.772
7-3	5.517	5.537	5.446	5.547	5.236	5.375
8-3	5.883	5.889	5.943	5.731	5.918	5.650

FIGURE 8

AVERAGE INVENTORY WITH LEAD TIME OF 2-4 WEEKS

CHAPTER IV

APPLICATION OF ECONOMIC PARAMETERS

I. DETERMINATION OF SYSTEM COST

Following the simulation and the tabulation of the results, attention was given to establishing the optimum solution for each set of parameters. In order to evaluate the equation presented in Table II (page 18), it was necessary that additional information be obtained in order to complete the calculations. In order to calculate the carrying cost the value of K, the carrying cost factor, must be determined. In the context of the equations K is defined as a percent of inventory investment and calculated by the equation:

$$K = \frac{C_{io}}{C_{iv}}$$

Where C_{io} = Annual Cost of Inventory Operations

C_{iv} = Investment in Inventory

The cost of inventory operation includes obsolescence, interest on required working capital, storage costs, and similar factors. Carrying cost, defined by VandeMark, is made up of the associated average percentages presented in Table IV (34).

Some managers take the point of view that the carrying cost is merely one of the policy variables in the control system (2). It makes it possible to balance between the cost of investment on the one hand and the out-of-pocket expense on the other. Consequently when management

TABLE IV

ANALYSIS OF COST OF INVENTORY OPERATION

Elements of Cost	Percent of Inventory Value
Depreciation and Obsolescence	5
Finance	5
Handling	4
Storage	2
Insurance and Taxes	1
Total	17

feels that inventory investment is excessive or should be minimized, a high carrying cost can be used thereby minimizing the inventory investment. On the other hand, inventories can be increased by using a low carrying cost. The difficulty of obtaining the total cost of inventory operation lends credence to this type of appraisal however a finite cost can be determined. Although the relationship shown in the calculation of K indicates a continuous function, it is clearly recognizable that the true relationship, as with most operational cost, is a step function increasing incrementally with segments of inventory. For this analysis, it was assumed that the carrying cost could be defined as a fixed ratio and could be expected to occur on an annual basis. For the purpose of these calculations a value of 15 percent was chosen as the K value. This value is very similar to the percentage tabulated by VandeMark (34).

In addition, the procurement cost equation requires the determination of the cost to place an order. This is generally realized to be a step function based on the number of orders placed and received at a particular facility; however, a general rule of thumb often applied results in an accumulation of cost from purchasing, receiving and inplant handling of orders spread out over the number of orders placed.

This approach assumes that only one item is entered on an order thereby accrediting all of the order cost to one item. Analysis of present practice reveals that several items may be on one order; consequently, the cost of ordering should be distributed. Using this approach, the normal cost per purchase order would be divided over the expected number of line items per order thereby resulting in a more realistic

cost per order per part which could be used in the analysis. Based on this procedure of calculation the value of \$3 per line item was calculated to be the expected cost per line item.

As with other cost elements which enter into explicit solutions, the stockout cost is a measure which is very difficult to obtain and at best is hazily definied (19). This cost, however, is essential to the evaluation of the annual stockout cost which occurs under each alternative. Even more difficult, if not impossible, is establishing a stockout cost which would be representative for a total spare parts inventory. As mentioned earlier, a stockout is considered to occur when a request is made for an item and the request is not filled. Often a stockout is referred to as the occasion when the inventory level goes to zero. It is the contention of the author that a stockout cost cannot be incurred until a request is made. Rarely is the stockout cost of spare parts a constant in its own right since the cost is usually a variable which is subject to time. In general, it is felt that the stockout cost for a given item follows a cost distribution as shown in Figure 9. As can be seen, the total cost of a stockout is represented by the expression:

$$C_{stk} = C_f + (C_v)\ (t_n)$$

where a fixed cost, C_f is incurred per stockout occurrence and a varible cost, C_v, usually the cost of pounds of production lost per unit time, is incurred proportional to the amount of time a production unit is down. The variable cost portion of the curve can range from a small insignificant value with a slope of zero to one which varies exponentially over time.

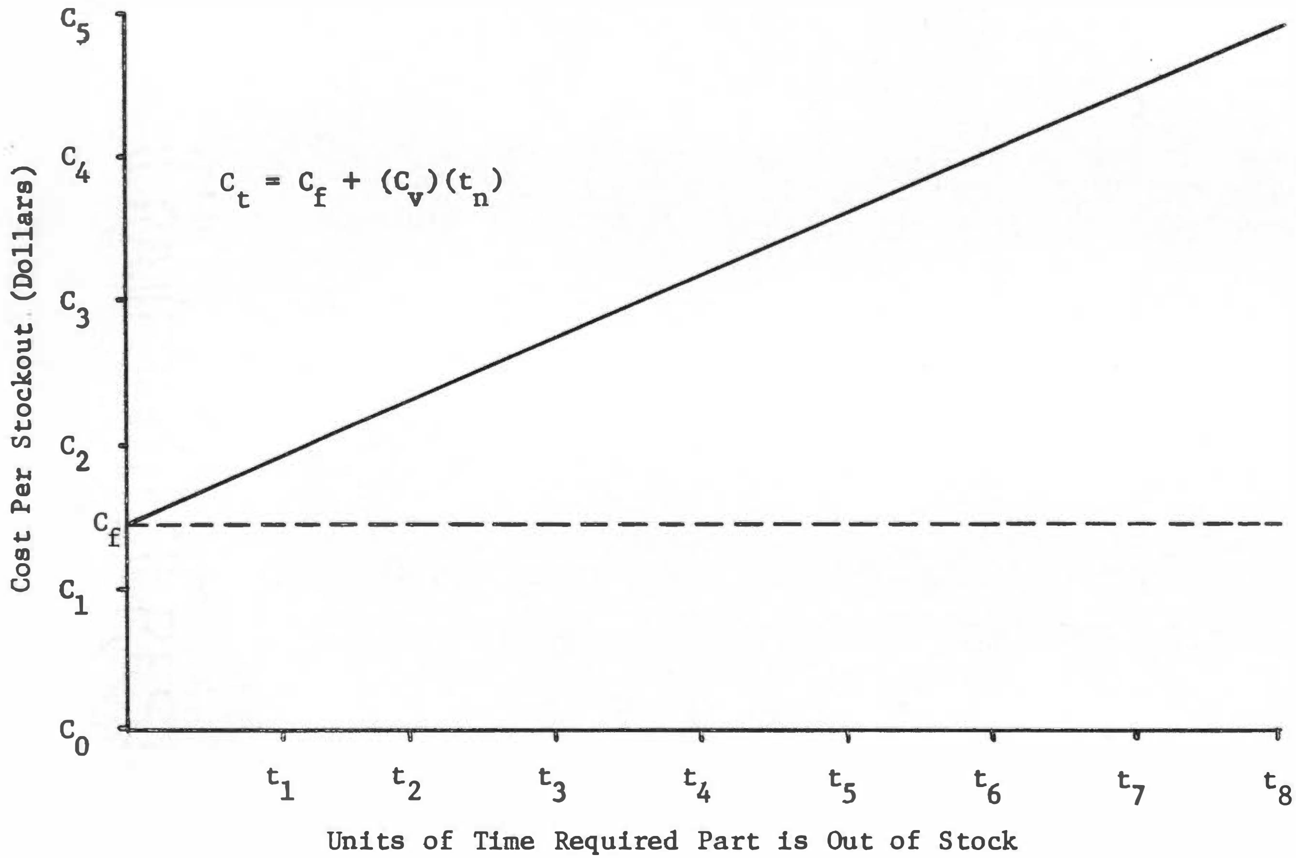

FIGURE 9

CHARACTERISTIC DISTRIBUTION OF STOCKOUT COST

II. INITIAL EXPERIMENTATION WITH COST DATA

As an initial comparison, data from the simulation of an annual usage of three with a lead time distribution of 4-8 weeks was selected. This data, Table V, was analyzed through the use of the total variable cost equation presented in Table II, page 18. As can be seen in Table VI, the evaluation was made with a unit cost of \$100 and an initial stockout cost of \$5. Evaluating the total variable cost equation for each max-min point resulted in the determination of 1-0 as the optimum max-min policy when experiencing these parameters. In order to test the significance of other stockout cost, the unit cost was held constant at \$100, and the evaluation was repeated for a stockout cost of \$50 and \$500, respectively. As indicated, the optimum max-min point at a stockout cost of \$50 is 2-1 while the optimum at \$500 is 3-1. Consequently, the application of varying stockout costs alters the optimum max-min point dramatically. In order to test the effect of unit cost, a similar analysis was conducted holding a constant stockout cost and varying the unit cost. The results of this analysis are shown in Table VII. A stockout cost of \$50 was selected, and the initial evaluation was made with a unit cost of \$10. This evaluation resulted in an optimum max-min of 4-1 while with a unit cost of \$100 the optimum is 2-1, and with a unit cost of \$200 the optimum is 2-0. Once again, changes in the value of unit cost alter the policy which provides optimality of the total cost. These experiments led to the assumption that some method could be developed to represent these relationships by selecting given

TABLE V

EXAMPLE RESULTS OF THE SIMULATION

Test No.	Maximum	Minimum	Number Orders Per Year	Number Stockouts Per Year	Average Inventory
37	1	0	3.00	.65	.690
38	2	0	1.67	.34	1.245
39	2	1	3.00	.02	1.657
40	3	1	1.67	.01	2.226
41	4	1	1.03	0	2.840
42	4	2	1.67	0	3.225
43	5	2	1.03	0	3.840
44	6	2	.87	0	4.291
45	7	2	.72	0	4.722
46	5	3	1.67	0	4.225
47	6	3	1.03	0	4.840
48	7	3	.87	0	5.291
49	8	3	.72	0	5.722

Note: Annual Usage = 3.

Lead Time Range = 4-8 weeks.

TABLE VI

ECONOMIC EVALUATION OF RESULTS WITH VARIED STOCKOUT COST AND CONSTANT UNIT COST

Unit Cost = $100 Stockout Cost = $5			Unit Cost = $100 Stockout Cost = $50			Unit Cost = $100 Stockout Cost = $500		
Max	Min	Total Annual Cost	Max	Min	Total Annual Cost	Max	Min	Total Annual Cost
1	0	$22.60	1	0	$51.85	1	0	$344.35
2	0	25.68	2	0	40.68	2	0	193.68
2	1	33.96	2	1	34.86	2	1	43.86
3	1	38.45	3	1	38.90	3	1	43.40
4	1	45.69	4	1	45.69	4	1	45.69
4	2	53.39	4	2	53.39	4	2	53.39
5	2	60.69	5	2	60.69	5	2	60.69
6	2	66.98	6	2	66.98	6	2	66.98
7	2	72.99	7	2	72.99	7	2	72.99
5	3	68.38	5	3	68.38	5	3	68.38
6	3	75.69	6	3	75.69	6	3	75.69
7	3	81.98	7	3	81.98	7	3	81.98
8	3	87.99	8	3	87.99	8	3	87.99

Annual usage = 3.

Lead time = 4-8 weeks.

TABLE VII

ECONOMIC EVALUATION OF RESULTS WITH VARIED UNIT COST AND CONSTANT STOCKOUT COST

Unit Cost = $10 Stockout Cost = $50			Unit Cost = $100 Stockout Cost = $50			Unit Cost = $200 Stockout Cost = $50		
Max	Min	Total Annual Cost	Max	Min	Total Annual Cost	Max	Min	Total Annual Cost
1	0	$42.54	1	0	$51.85	1	0	$ 62.60
2	0	23.88	2	0	40.68	2	0	53.35
2	1	12.49	2	1	34.86	2	1	59.72
3	1	8.85	3	1	38.90	3	1	72.29
4	1	7.35	4	1	45.69	4	1	88.29
4	2	9.85	4	2	53.39	4	2	101.77
5	2	8.85	5	2	60.69	5	2	118.29
6	2	9.05	6	2	66.98	6	2	131.35
7	2	9.24	7	2	72.99	7	2	143.82
5	3	11.35	5	3	68.38	5	3	131.75
6	3	10.35	6	3	75.69	6	3	148.29
7	3	10.55	7	3	81.98	7	3	161.35
8	3	10.74	8	3	87.99	8	3	173.82

Annual usage = 3.

Lead time = 4-8 weeks.

combinations of unit cost and stockout cost and evaluating the total variable cost equation for each of the max-min points.

III. EXPANSION OF COST ANALYSIS

In order to evaluate the various alternatives, a computer program was developed which followed the logic of the flow diagram in Figure 10. Utilizing the values of number of orders placed, number of stockouts, and average inventory, the objective of this program was to determine the optimum max-min points for a range of unit costs and stockout costs. Since a wide but realistic range of cost was desired, a range of \$5 to \$500 was selected for both the unit cost and stockout cost. In addition, increments of \$5 were chosen in order to provide sufficient data points without cluttering the results with redundancy. In order to handle the data expediently in the calculations, parameter values were coded to represent each of the five lead time distributions, six annual usage values, and thirteen max-min control points. The assignment of these parameter values are shown in Table VIII. Data from the simulation runs, i.e., number of stockouts, number of orders placed, and average inventory, was accumulated into three 3-dimensional arrays labeled STOCK (I,J,K), ORDER (I,J,K) and AVG (I,J,K), respectively. Consequently, the average number of stockouts which occurred per year with a lead time of 0-2 weeks (I = 1), an annual usage of one (J = 1), and a max-min of 1-0 (K = 1), could be introduced as the variable:

STOCK (I,J,K) or STOCK (1,1,1).

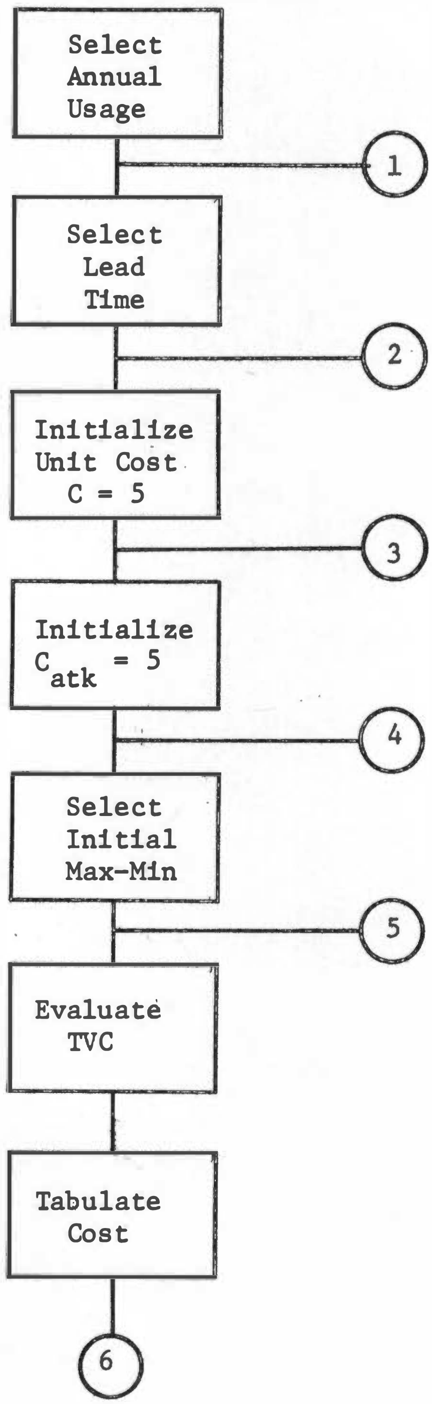

FIGURE 10

ECONOMIC EVALUATION OF POSSIBLE ALTERNATIVES

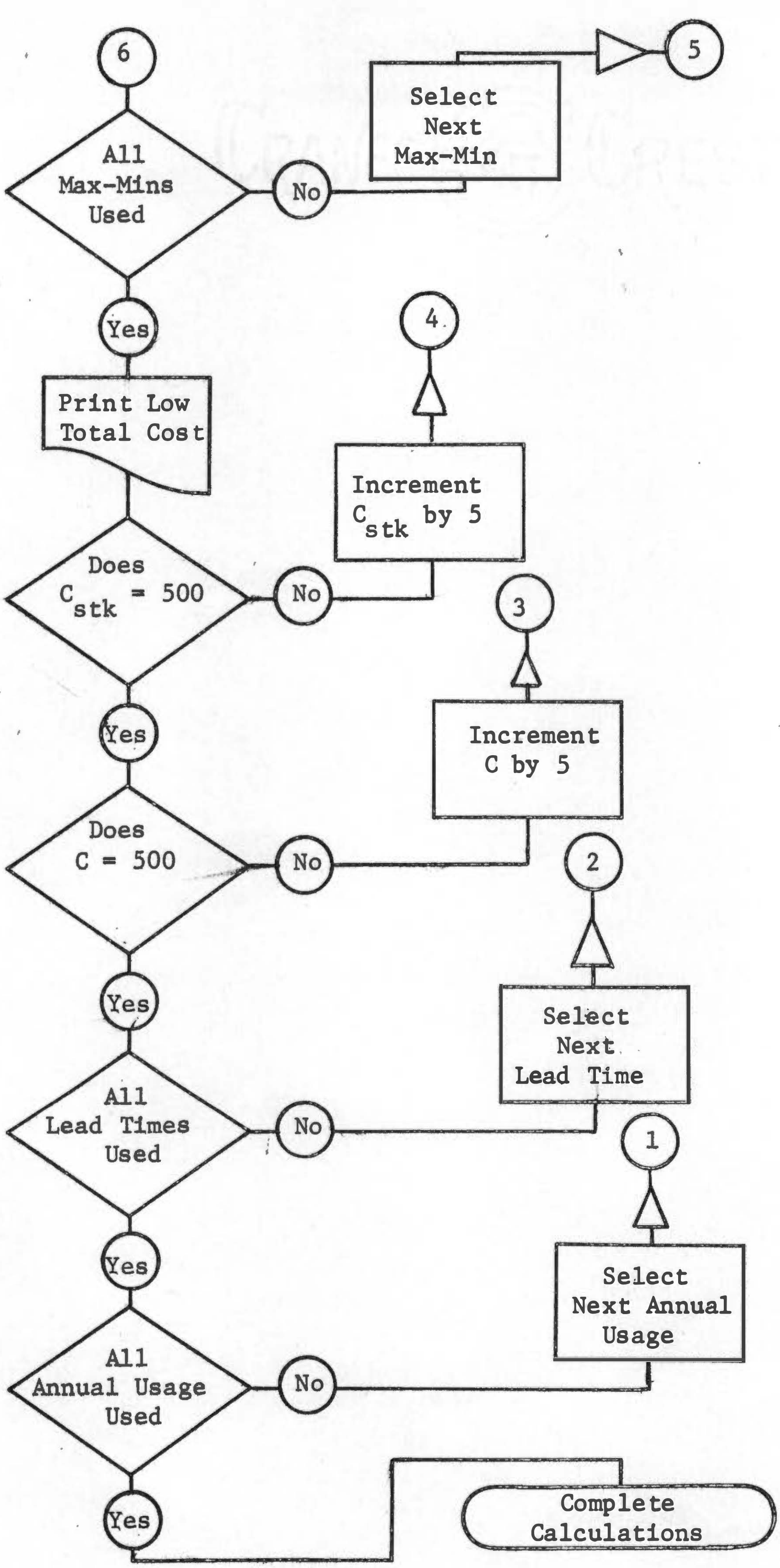

FIGURE 10 (continued)

TABLE VIII

ASSIGNMENT OF PARAMETER VALUES TO INPUT VARIABLES

Lead Time Weeks		Annual Usage		Max-Min Values		
Range	Parameter	Value	Parameter	Max	Min	Parameter
0-2	I = 1	1	J = 1	1	0	K = 1
2-4	I = 2	2	J = 2	2	0	K = 2
4-8	I = 3	3	J = 3	2	1	K = 3
8-12	I = 4	4	J = 4	3	1	K = 4
12-16	I = 5	5	J = 5	4	1	K = 5
		6	J = 6	4	2	K = 6
				5	2	K = 7
				6	2	K = 8
				7	2	K = 9
				5	3	K = 10
				6	3	K = 11
				7	3	K = 12
				8	3	K = 13

Corresponding values for average inventory and number of orders placed per year were entered as: AVG (1,1,1) or ORDER (1,1,1), respectively.

To order the calculations and organize the results, the optimization was begun by initializing the annual usage (J = 1) as the beginning control variable. The second control variable, lead time range, was entered and initialized at I = 1. Based on the initial parameters of the calculation procedure, unit cost was initialized at $5 with a stockout cost of $5. The remaining control variable, max-min point, was initialized at K = 1 and the total variable cost equation was calculated as follows:

$$TVC_K = (C_{stk})\ (STOCK\ [I,J,K]) + (K)\ (C)\ (AVG\ [I,J,K]) + (C_{ord})\ (ORDER\ [I,J,K])$$

Following the calculation, the value of K is incremented by one and the cycle repeated until K = 13. Having a value for each value of K holding I and J constant, the minimum value, TVC_{MIN}, is selected based on the minimum value of TVC_K where I = 1, J = 1, and K = 1 to 13, hence the max-min point corresponding to the value of K where $TVC_{MIN} = TVC_K$ is tabulated and the cost of a stockout is incremented by $5 to reevaluate each alternative under a new cost criterion. The cycle continues in this fashion until all possible combination of unit cost C_{unit} = $5 to $500 and stockout cost C_{stock} = $5 to $500 are calculated and the minimum cost is determined.

IV. DEVELOPMENT OF OUTPUT CONTROL

As shown in the diagram, the results of the calculations are printed at this point in the analysis. Since at this point 10,000 optimum max-min points have been selected, a need for an output code for printing purposes is evident. As indicated in Table IX, a coded symbol was chosen for each max-min point for the sake of clarity. The output format was chosen to be a two-dimensional array using unit cost and stockout cost as coordinates. Substituting the character code for the optimum max-min, corresponding to each set of C_{unit} and C_{stock} coordinates, printed output similar to that in Figure 11 resulted. Since this array corresponded only to values of I = 1 and J = 1, I is incremented by one, the entire cycle is repeated, and a resultant chart is printed for I = 2, J = 1. This continues for all values of I until such time the annual usage J increases to two and the analysis begins anew. Repetition of this cycle resulted in thirty diagrams which each diagram based on a unique set of values for annual usage and lead time range. A sample set of these charts utilizing a lead time range of 0-2 weeks and annual usage values of one to five can be found in the Appendix. As can be seen in Figure 11, this chart depicts the optimum max-min point for any part with a unit cost ranging from five to five hundred, a stockout cost of five to five hundred dollars, an annual usage of 1, and a lead time of 8-12 weeks. Similarly, the other charts depict like information for parts having a different annual usage or lead time.

TABLE IX

OUTPUT CODE FOR OPTIMUM MAX-MIN POINTS

Max-Min	Character Code
1-0	0
2-0	+
2-1	.
3-1	*
4-1	-
4-2	X
5-2	@
6-2	T
7-2	#
5-3	H
6-3	$
7-3	K
8-3	Z

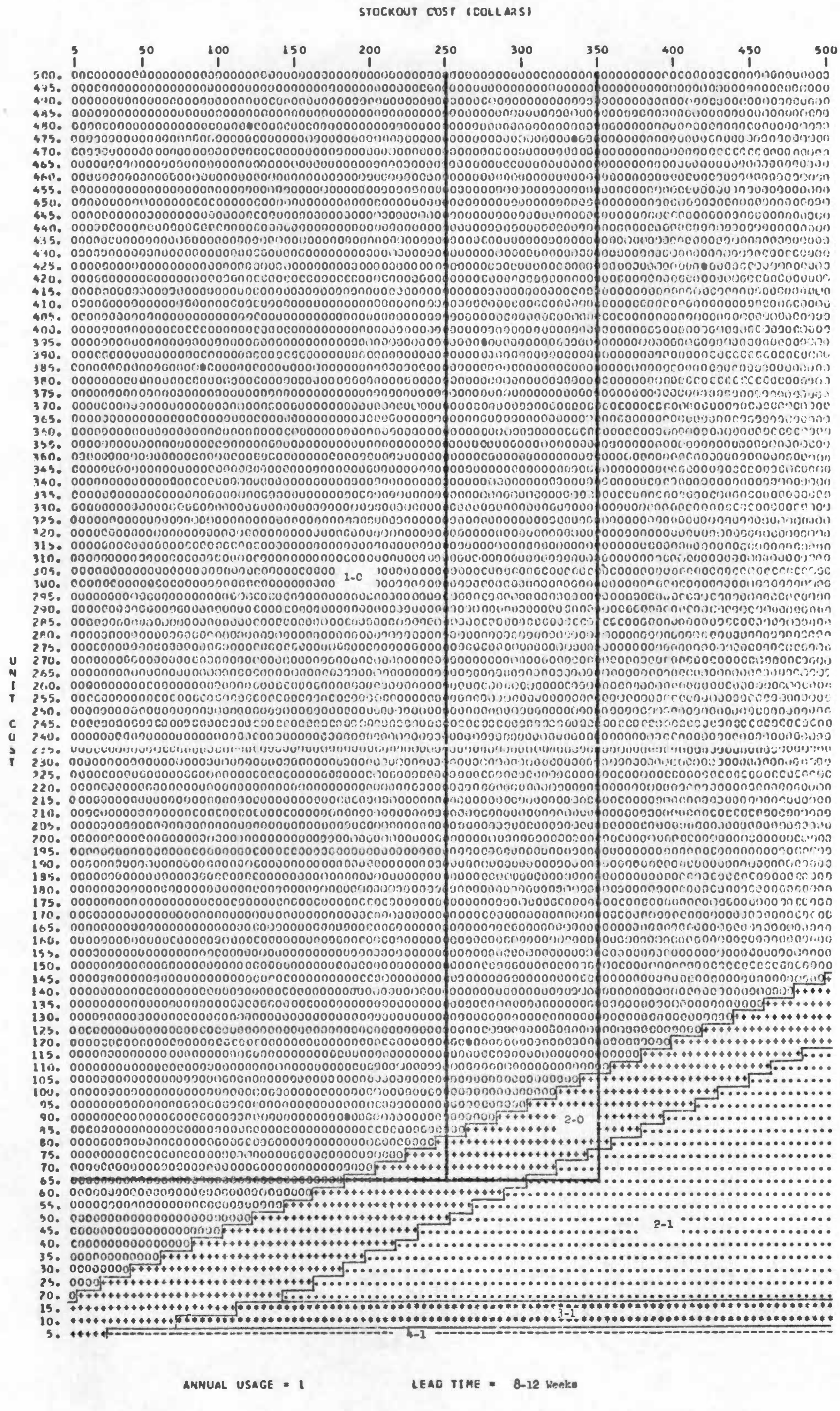

FIGURE 11

SAMPLE OUTPUT CHART

As can be seen in Figure 11, a line has been placed between each change in symbol in order to clearly define regions where one max-min point is optimum.

Since the increments of cost on the axes are in five dollar increments, the interface lines indicate a step function relating unit cost and stockout cost. As could be expected, these lines or region interfaces are actually linear relationships whose slope and intercept can easily be defined. All points on these interfacer lines are points where the cost of stocking policy is equal to that of the adjoining alternative. Using this example marked on the chart, one can see that a part with a unit cost of $65 and a stockout cost of $250 should be stocked with a 2-0 max-min; however, if the stockout cost is $350 the max-min should be 2-1. Thus, this procedure allows an optimum max-min to be determined with ease.

As mentioned earlier, the ease of obtaining stockout cost information is extremely difficult. Normally an estimate can be established within a realistic range but often even this cannot be determined.

Often the maintenance manager will indicate that stockout cost may not be high but he desires a low probability of a stockout occurrence to exist with inventory policies on particular parts. To attack this problem, the relationship between stockout cost and service level was used to establish a basis for determining a low-outage max-min point using the same charts. As pointed out by Herron (15), it is important to recognize that choice of a service level inherently implies a choice of stockout cost. If maintenance management employs a high service

level objective then they inherently employ a high stockout cost. Conversely, if they employ a high stockout cost then they achieve a correspondingly high service level.

Although no attempt is made to quantify this approach, the development can easily be seen. Since each of the interface lines are linear and increases as the value of stockout cost increases, it is intuitively obvious that at some high level of stockout cost, the interface will intersect the horizontal unit cost line of the range from \$5 to \$500. The exception to this of course is the interface line with a zero slope such as that seen between 3-1 and 4-1 max-min range. Applying this logic then to the chart in Figure 11, page 44, the low usage max-min for all parts above a unit cost of \$20 would be 2-1, since at some large value of stockout cost only the alternatives 2-1, 3-1, and 4-1 would be available for possible selection.

CHAPTER V

APPLICATION OF THE MODEL TO SPECIFIC INVENTORIES

I. INITIAL APPLICATION TO SELECTED PARTS

Upon completion of the inventory model, efforts have been made to apply this information to actual items in the maintenance storeroom in order to test the applicability of the concept. In order to ascertain the direct impact the model would have on the inventory, several parts were chosen for initial analysis. Seven parts from this group are shown in Table X to indicate the types of problems which were evident. Item No. 697-82 is a relatively high precision bearing which is a relatively small item but was felt to be important. A review of stockout cost indicated that a minimum of additional cost was incurred when the part was out of stock; consequently, the model indicated a needed change in the max-min from 2-1 to 1-0. Notice, however, the agreement of the model when comparing the low outage max-min with current practice.

Another problem in the opposite sense revealed itself with item number 862-22. Since this valve stem is relatively inexpensive and can be obtained locally, little or no attention had been given to it in the past. The analysis of stockout cost revealed that this valve stem was a part of a system that would cause excessive downtime delays in the shutdown start-up cycle to the extent that a stockout would result in a cost of $2,400 per occurrence. Consequently, the model recommended that

TABLE X

DETAILS OF APPLICATION OF MODEL TO SELECTED PARTS

				Selected Parts				
Item Number	Item Name	Value of Part	Last Year's Usage	Present Inventory Level	Stockout Cost Per Occurence	Current Max-Min	Optimum Max-Min	Low Outage Max-Min
697-82	Bearing	$127	2	2	$ 10	2 1	1 0	2 1
634-75	Bearing	290	3	1	0	4 2	1 0	2 1
862-22	Valve Stem	7	2	1	2,400	1 0	4 1	4 1
904-31	Main Bearing	163	3	7	300	4 2	2 1	3 1
904-52	24" Gasket	23	6	17	300	16 6	4 2	4 2
987-86	Main Bearing	406	1	3	0	4 2	1 0	1 0

the max-min be changed from 1-0 to 4-1. Of additional interest here is the absence of overreaction to this new information. Although the stock-out cost was determined to be relatively high, the simulated results indicated sufficient protection at the 4-1 level. Still another example is item number 904-52, a 24-inch gasket. This item was considered to be in a classification of parts which are normally found in plentiful supply. This is reflected in the present max-min of 16-6. Application of the model indicated a reduction in the max-min point to 4-2 to reflect the optimum cost.

In addition to the initial test, one large group of parts was selected from another inventory type and from that inventory 67 parts were chosen at random which had an annual usage of 1 to 6 and a unit cost range from $2 per item to $728 per item. Each of these items was currently being stocked and had an available inventory for each. Taking each item one by one, the necessary data was obtained from the inventory records and the charts were applied to establish the indicated optimum max-min point. Upon completion of this analysis, the following statistics were summarized: the current inventory level of 67 parts was $18,000, the optimum inventory level indicated by the procedure would be $8,700 with the low usage inventory level being approximately $9,800. These inventory levels were calculated on what was felt to be the expected available inventory level; however, a similar comparison could have easily have been made in considering the maximum inventory level or the minimum inventory level.

II. INTENSIFIED APPLICATION WITH MANAGEMENT INTERFACE

Realizing, of course, that such a drastic change in inventory policy would represent a major change in thinking by the maintenance manager, a simple experiment was designed to test the intuitive realness of the application. Information concerning each part, including max-min points which were already assigned and the optimum max-min points, were listed for management review. In conference with the maintenance manager and his representatives each of these parts were reviewed critically and a max-min point was selected for each based on what the maintenance managers felt to be a practical setup. The average inventory level resulting from the "practical" max-min points was $13,500. This was indicative of the attitude of maintenance management to the protection of their inventories from stockouts; however, for these 67 items this analysis resulted in a reduction in inventory of a minimum of $4,500.

Of significance in this test was the measurement of:

1. The expected resistance to a "model,"
2. The level of protection desired, and
3. The ease of applying the model.

As pointed out, significant progress was established in the initial application; however, it was felt that testing against history was required in order to establish a more finite basis for evaluation. A segment of inventory was selected and optimum max-min points were established for each. Taking each part individually the recent history of the part was relived to determine what would have happened in each

case. Due to the inability to determine if a stockout occurred under the old control points, the same problem occurred when "reliving" the part in the test. Intuitively the stockout results were felt to be the same in either case; however, the average inventory level of the test group could definitely have been 30 percent less had the model been used in the past.

Continuing to test the application of this concept, a special analysis was made of items which had not been used for the past two years. Of particular significance was a series of 28 parts which had been approved for stock but had not been used in some time. These were classic examples of items which were stocked as "insurance" items to protect against expected breakdowns on relatively new equipment. As can be seen in Table XI, the inventory was at a maximum level of $14,700. Using the charts as a guide the parts were reviewed using an expected maximum annual usage as a basis rather than simply providing insurance. As a result of the review, the maximum inventory level was reduced to $7,600 and the parts were shipped to other localities which stocked the identical part but realized a higher usage. Consequently, a reduction of $7,000 was immediately realized from this application. Although the reduction was immediate in this case, it must be recognized that the majority of inventory reductions cannot be brought about immediately, especially when the inventory is primarily low usage items. Consequently, the change in an inventory policy may not be realized for several months or even years after the change is made.

TABLE XI

REVIEW OF SELECTED PARTS WITH ANNUAL USAGE OF ZERO

	Current Policy	Revised Policy
Maximum Point	$14,700	$ 7,600
Minimum Point	$ 7,600	$ 500

Note: The review accomplished a $7,000 reduction in the level at which these 28 parts should be stocked.

III. DEVELOPMENT OF COMPUTER APPLICATION

As use of the model became more widespread and universally used, it was deemed necessary to further enhance its use by adopting the logic and concepts for computer application. Not only would the ease of use be greatly facilitated, but also pure application with provisions for reporting provided a real means for measuring the effectiveness of the approach. A new system was not developed just to apply the model, but rather the model was incorporated into an inventory system designed to provide management information on the maintenance inventories.

The logic of the adaptation followed that presented in the flow diagram in Figure 12. Using the parameter values used in the model calculations, this logic segment picks up data from current files concerning each part. As a part transaction enters this segment it carries with it the current unit cost, the calculated annual usage for the last twelve months, the stockout cost, the order cost, and the calculated lead time currently being experienced. If the annual usage of the part is less than or equal to six, the parts transaction will enter the segment and set the lead time parameter I, followed by the annual usage parameter J. Then beginning with K = 1, each alternative is evaluated and compared until the optimum or lowest cost is established. Once completed, the max-min point selected becomes the control model until the next evaluation or manual resetting.

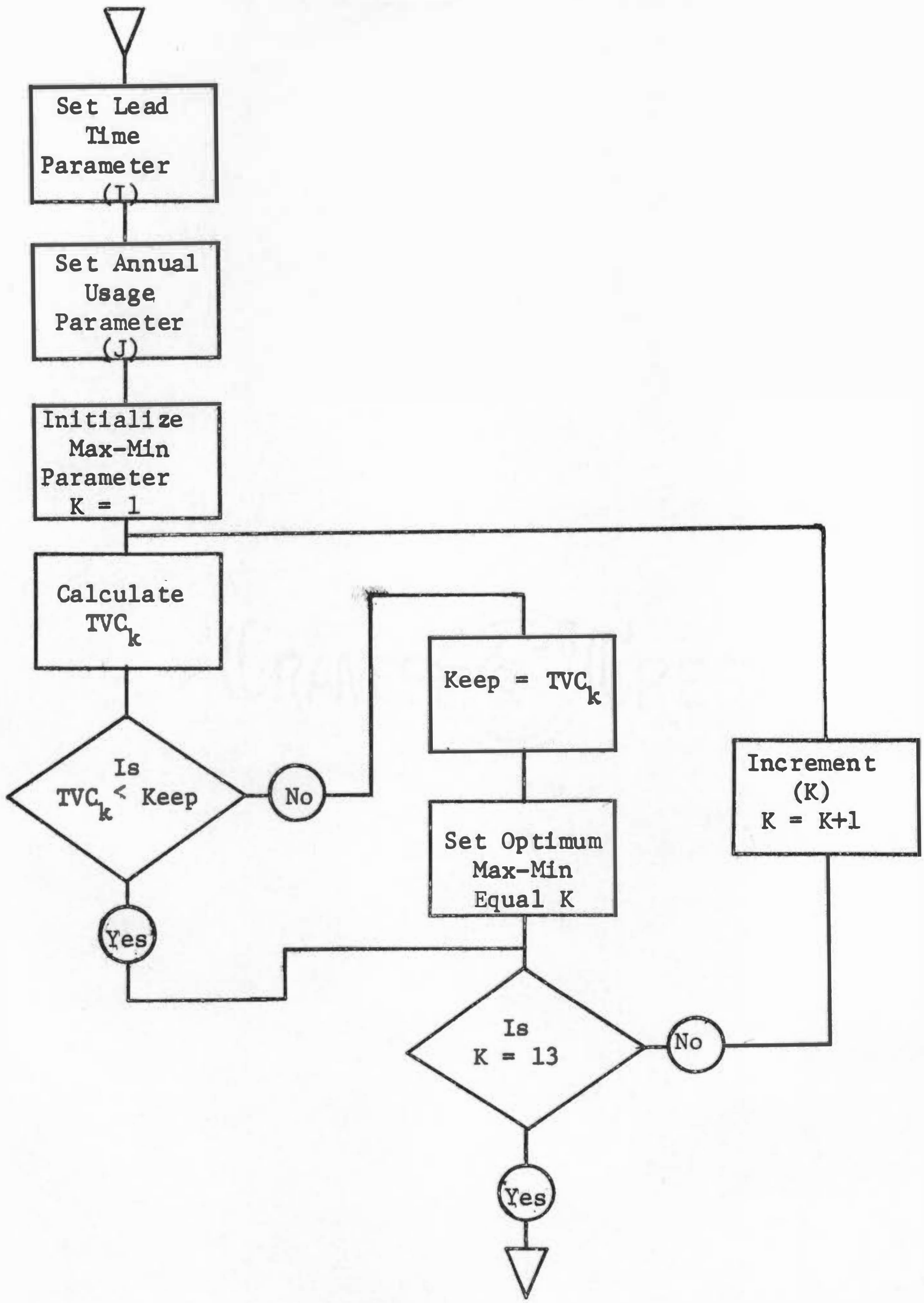

FIGURE 12

COMPUTER ADAPTATION OF INVENTORY MODEL

CHAPTER VI

SUMMARY AND CONCLUSIONS

As stated in Chapter I, the purpose of this study was to develop, test, and implement an inventory control procedure for optimizing the inventory level of low-usage maintenance spare parts. In addition, an objective of simplicity in use of the procedure was also imposed to insure that the model would be more acceptable.

I. SUMMARY

Following a review of the literature, a decision was made to develop a simulation model which would introduce independently the different attributes of annual usage, lead time, and max-min control points. This development and evaluation led to a tabulation of data which provided a basis for economically evaluating different alternatives under a wide range of unit cost and stockout cost. These optimum max-min points were then tabulated in charts which could be used to determine the optimum max-min level when given the unit cost, stockout cost, expected annual usage and lead time.

Evaluation of the policies indicated that optimization could be achieved through the use of the charts without the use of complicated mathematical formulations to discourage the practical application.

Development of the logic for application of the procedure through computer analysis has proven to be the easiest and most comprehensive

means to incorporate this concept in the total inventory control program. Since the model has been in use, the inventory level of this segment of inventory has been decreasing at twice the rate originally expected. At the present rate of decrease, this will amount to a reduction of the inventory level by $100,000 during the first year. Since this measurement only indicates one aspect of the total inventory cost, a measure of the number of stockouts was established to provide a measurement of service level. Defined as the ratio of stock request filled to the total number of stock requests, the service level has maintained an initial level of 95 percent and is beginning to show an increase in some segments of the inventory system.

II. CONCLUSIONS

Based on the method of attack and the results achieved from applying the results of the model, it is the conclusion of the author that the approach provides a realistic appraisal of the inventory system and clearly defines the interactions of the different attributes of the system. Application of the results provides an avenue of spare parts control which heretofore was practically unattainable. This approach is not limited to maintenance spare parts but rather it can be applied to any type of inventory which is characterized by low usage and variable lead time ranges and is somewhat sensitive to the need of having the item in hand when needed.

It is clearly recognized that special cases such as extremely low unit cost and high stockout cost are not covered by this analysis.

In addition, various lead time distributions or more importantly max-min points could be simulated to expand the scope of the concept. Based on the experience with the inventories under investigation, such a continuance was not felt to be justified; however, these areas to remain quantitatively unexplores.

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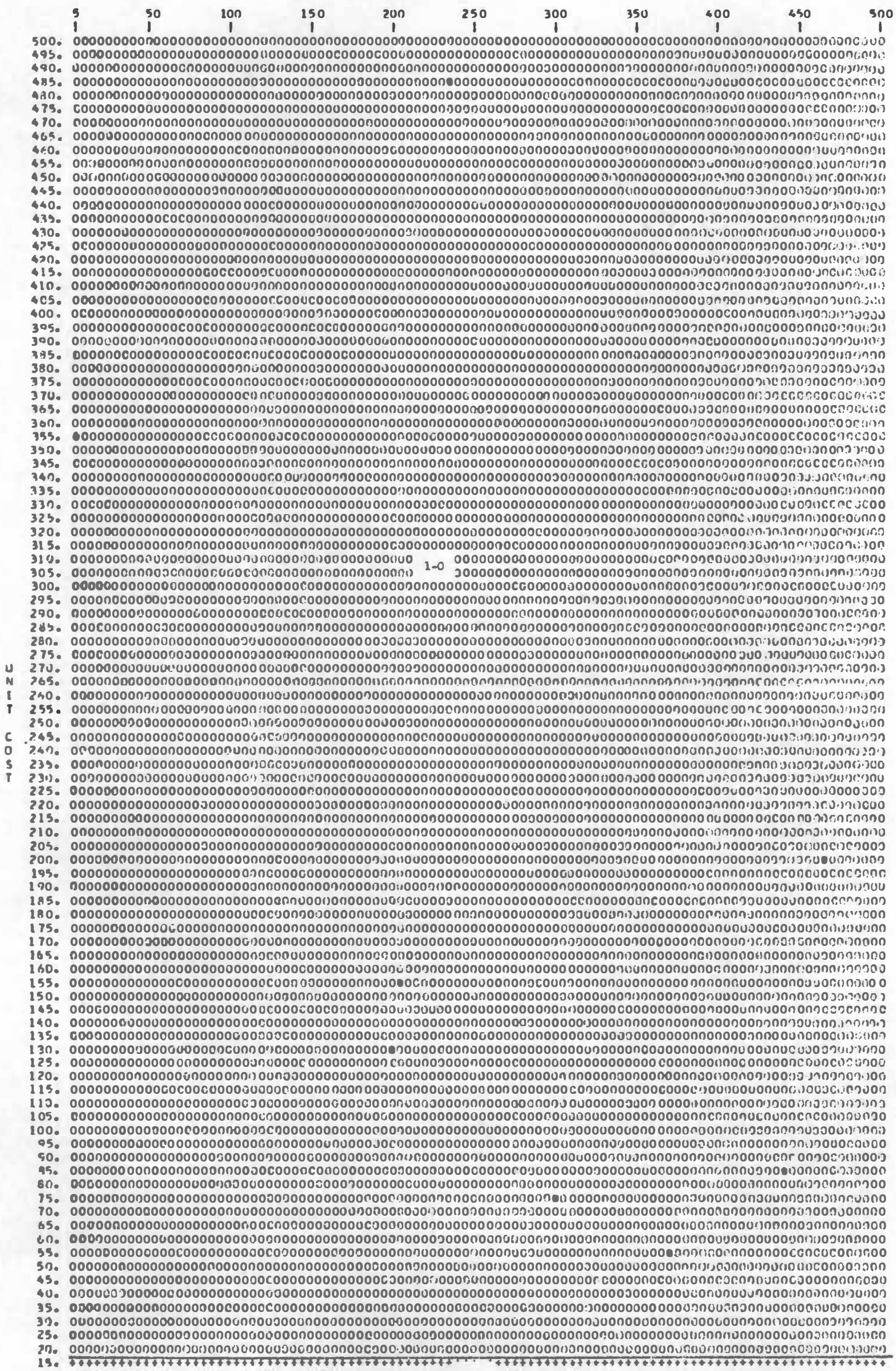
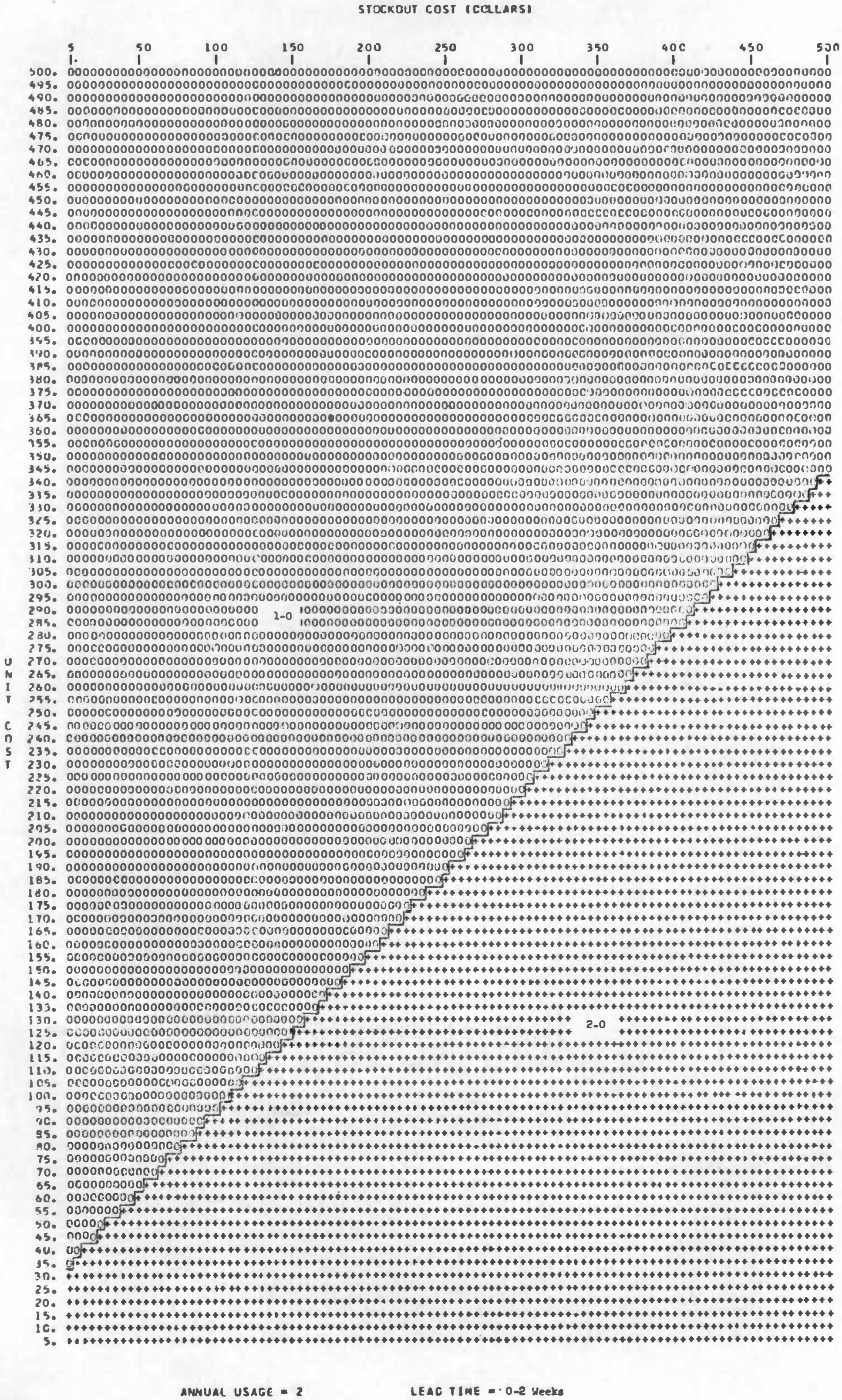
APPENDIX

STOCKOUT COST (DOLLARS)

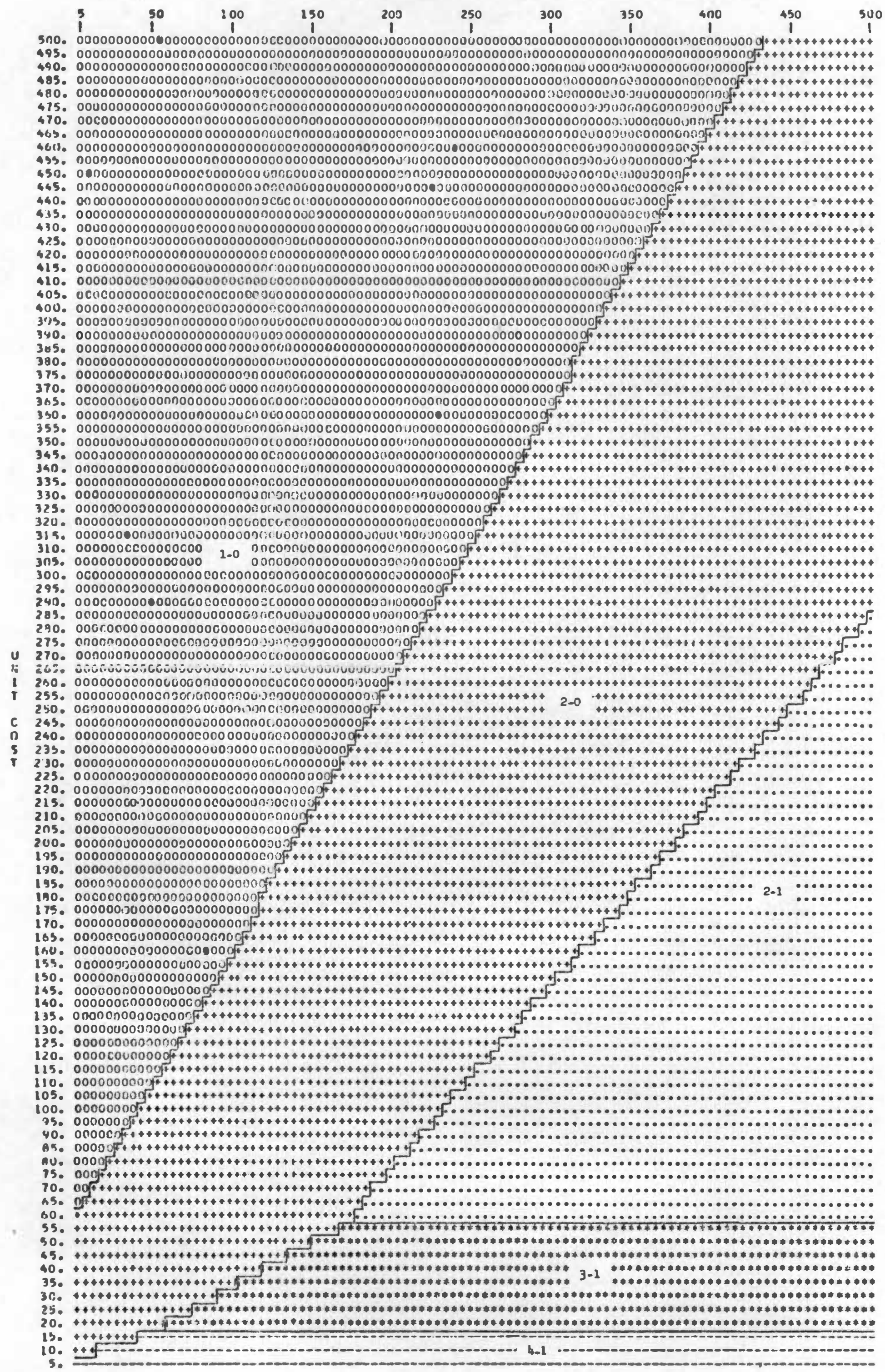


ANNUAL USAGE = 1 LEAD TIME = 0-2 WEEKS



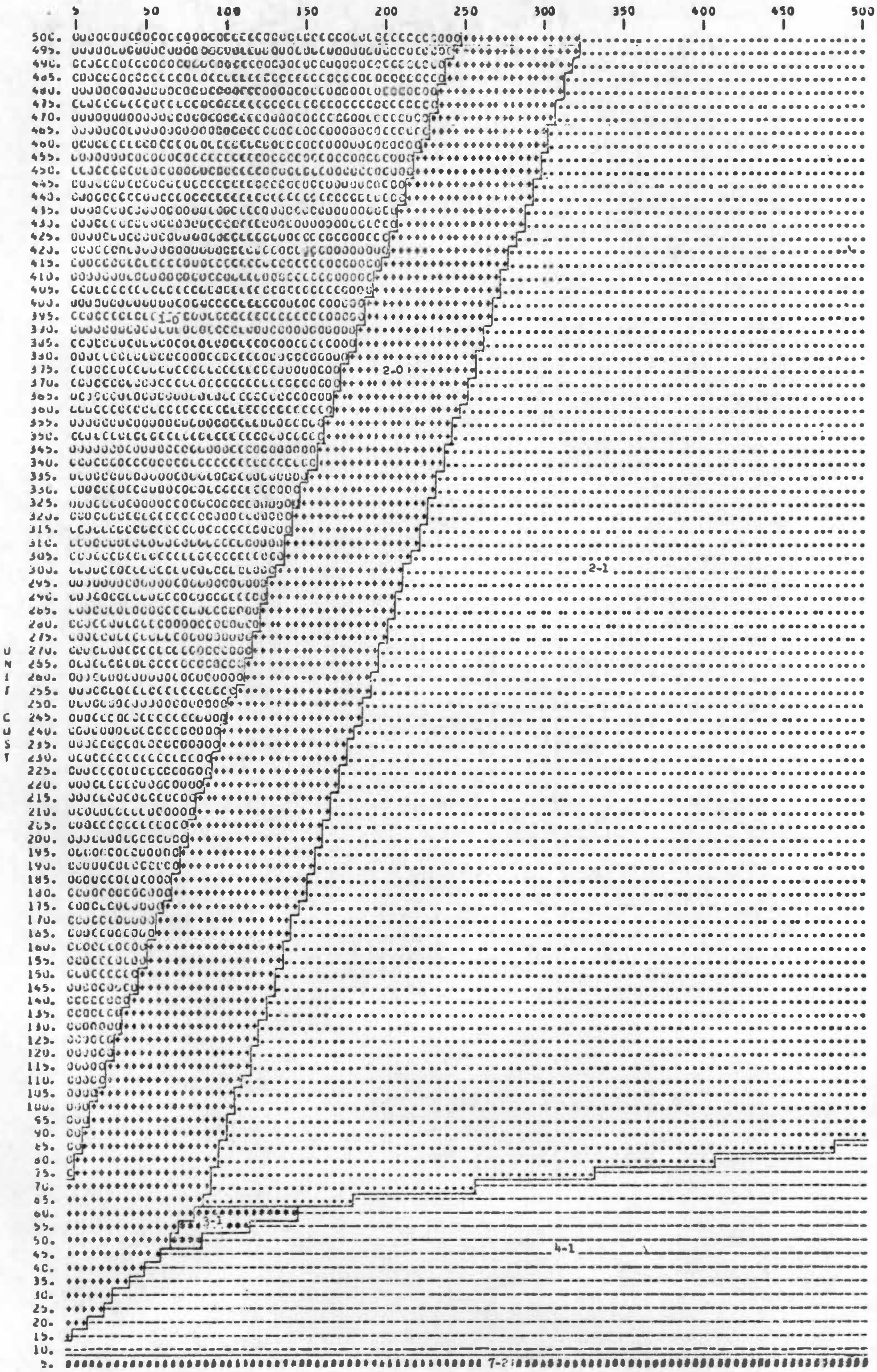
ANNUAL USAGE = 2 LEAD TIME = 0-2 Weeks

STOCKOUT COST (DOLLARS)

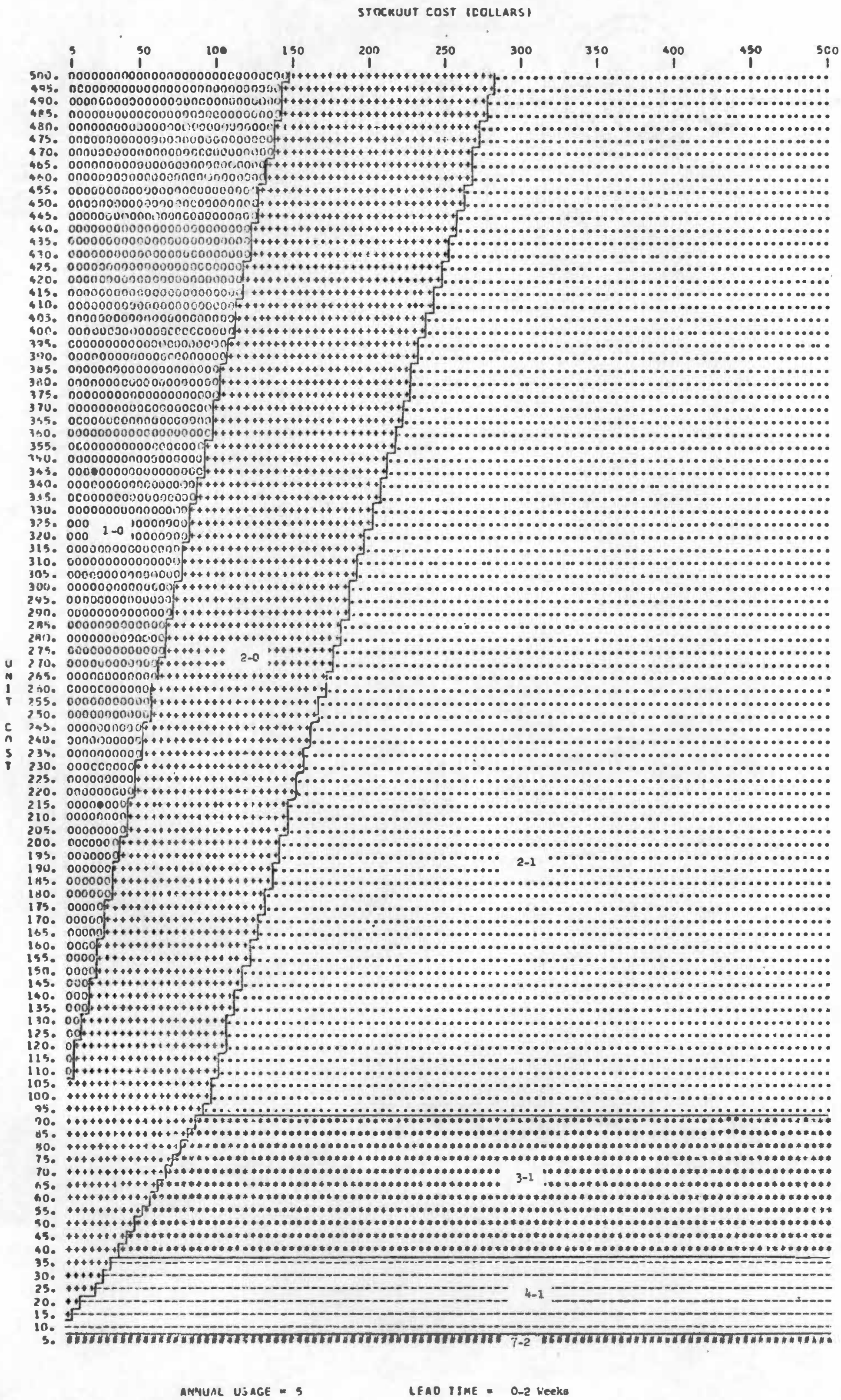


ANNUAL USAGE = 3   LEAD TIME = 0-2 Weeks

STOCKOUT COST (DOLLARS)



ANNUAL USAGE = 4 LEAD TIME = 0-2 Weeks


STOCKOUT COST (DOLLARS)
5 50 100 150 200 250 300 350 400 450 500
UNIT COST
1-0
2-0
2-1
3-1
4-1
7-2
ANNUAL USAGE = 5
LEAD TIME = 0-2 Weeks

VITA

Asa Lee Whitaker, Jr., was born in Knoxville, Tennessee, on September 5, 1941. He attended elementary school in Knox County and was graduated from Karns High School in 1959. Following graduation and one year of study at Auburn University, he owned and operated a private business in the Knoxville area. In September 1963 he entered The University of Tennessee, and in June 1966 he received a Bachelor of Science degree in Industrial Engineering. Following graduation he was employed by Tennessee Eastman Company in Kingsport, Tennessee. In July 1971 he was transferred to the Holston Defense Corporation, also in Kingsport, where he is presently employed. He entered Graduate School, The University of Tennessee, at the Kingsport University Center in September 1966 and received a Master of Science degree with major in Industrial Engineering in August 1972. He is a member of the Alpha Pi Mu and Sertoma International.

He is married to the former Ann Lynette Gilmore of Knoxville, Tennessee, and has one daughter, Amy Leigh.