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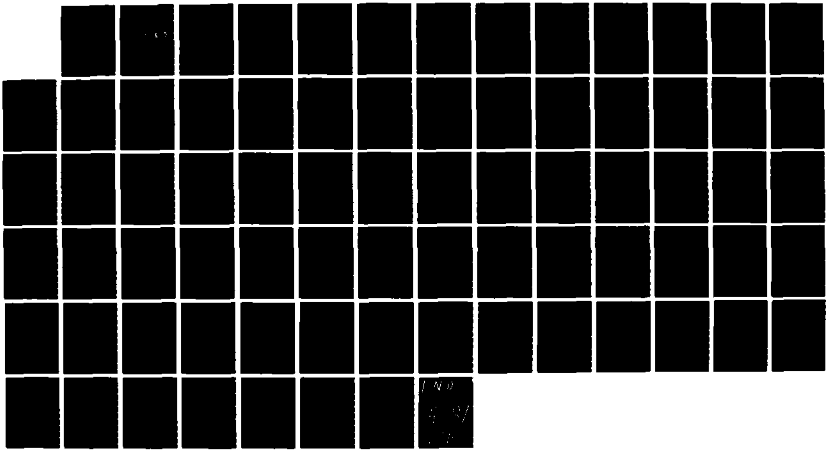

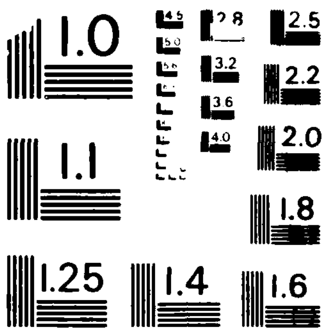

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THESIS

OPERATING HOURS BASED
INVENTORY MANAGEMENT

by

James L. Lewis

December 1986

Thesis Advisor Willis R. Greer, Jr.
Co-Advisor F. R. Richards

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Operating Hours Based Inventory Management

by

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requirements for the degree of

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ABSTRACT

Inventory management models based on operating hours are examined and discussed. Traditional demand based models incorporating risk and shortage costs are developed. The two major components of an operating hours model, operating hours and procurement lead-time are reviewed and discussed. Data for both operating hours and procurement lead-time for the LM-2500 Gas Turbine Engine, and operating hours for the U. S. Air Force are reviewed and tested to determine accuracy. Some time series models are tested to determine if operating hours forecasting can be improved. The role of the item manager in an operating hours based model is discussed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Inventory Management of spare and repair parts in the U. S. Military requires the expenditure of huge sums of money. In Fiscal Year 1987, the annual amount in the Presidental Budget for Operations and Maintenance for the Department of Defense was $85.773 billion. A large proportion of these monies will be expended on direct support materials and repair parts. With expenditures of this magnitude, it is incumbent upon the military business managers to utilize the funds in the most efficient and effective manner possible. Furthermore, it should be realized that the wealth of a nation does not reside solely in the money or in the treasury. This concept was addressed as early as 1677 by A. Pappilon [Ref. 1].

> The stock of riches of the kingdom doth not only consist in our money, but also in our commodities and ships for trade, and in our ships for war, and magazines furnished with all necessary materials.

It is the goal of this thesis to review the underlying assumptions, models and accuracy of one method of inventory management. This method is an inventory model based on unit or system operating hours.

A. BACKGROUND

In 1980, the U. S. Navy introduced a new shipboard propulsion system. This was the LM-2500 Marine Gas Turbine Engine. The LM-2500 is a marinaized version of the Air Force TF-56 engine used in the C-5A and the C-10 cargo aircraft. The engine is also used commercially in the DC-10 and the Lockheed L-1011. The engine was developed by General Electric, Evandale, Ohio on a research and development contract with the Department of the Air Force.

Since the marinaized engine, LM-2500, was intended solely for shipboard use, the initial inventory management process was to be one of normal Uniform Inventory Control Point[1] procedures based on historical demand observations.

[1]The Inventory Control Points or ICPs are the central agencies that control and maintain the inventory of U. S. Navy requirements. The two major elements are the Navy Ships Parts Control Center (SPCC) and the Aviation Supply Office (ASO). Inventory procedures are controlled by the Fleet Material Support Office (FMSO).

It soon became apparent that normal demand forecasting was not sufficient to support the system efficiently. The system had grown in population by 240% in two years (1980-1982). The growth in the operating hours of the system was even more dramatic. During the same 1980-1982 period, operating hours increased by 1,222%.

Clearly an inventory model based on more than historical demand was required if the LM-2500 program were to be sufficiently supported. This was an operating hours based model known as Program Data Expansion (PDE).

B. METHODOLOGY

The basic methodology of this research began with the collection of actual and projected operating hours. These data were then tested to determine the accuracy of the predictions. This discussion is contained in Chapters Two and Three.

Data for another major element of the operating hours inventory management model were collected. This is data on the procurement lead time. The data collection is discussed and the data tested in Chapter Four. Finally, the effect of changes in operating hours on the inventory model and some forecasting techniques are addressed in Chapter Five. Conclusions and recommendations are contained in Chapter Six.

II. BASIC INVENTORY MANAGEMENT

The necessity to maintain an inventory of goods has been recognized since the beginning of the industrial revolution. An inventory of raw and finished materials, parts, and supplies is required to support the goals of industry, merchants, and the military. However, an inventory cannot simply be a collection of every item that could possibly be needed. Nor could the inventory be maintained in unlimited quantities. Some model must be found that can be used to optimize the inventory system.

There are three factors with competing interests in the inventory process. These factors are described by Enrick [Ref. 2], and become the basis for optimizing the inventory process. The factors are:

- Financial: the comptroller will desire relatively low levels of stock because funds tied up in inventory are unproductive
- Requirements: the users of the material will desire that every item possible be carried in the largest quantity possible
- Production: the manufacturers will want inventories carried in such a manner that production runs are the most efficient.

Clearly each of these individual goals could only be achieved at the expense of the others. These problems are properly identified by Prichard [Ref. 3]. He also indicates a solution is achieveable.

> Inventory managers have long recognized that some of the foregoing objectives conflict with others; they are now coming to understand that a balance can be achieved, within limits, among specific objectives so as to satisfy the broader aims of inventory management.

It is the job of inventory management to balance these factors and ensure optimal utilization of money, material, and manpower.

A. NORMAL (DEMAND BASED) INVENTORY MANAGEMENT

The goal of any inventory model is to answer two specific questions: how much to order and when to order. To begin discussion of demand-based inventory models, the simplest model will be reviewed. The most basic model assumes demand is known and constant over time. It also assumes inventory replenishment is instantaneous. The model also assumes all material will be used, and backorders are not allowed.

Under these assumptions, there are two major considerations in operating an inventory system - ordering costs and holding costs. Ordering costs are minimized by ordering all the inventory required at one time in one order. This could be many years worth but would result in placing only one order. This would minimize ordering cost but would result in drastically high holding costs. The second method is to maintain no stock and order only when material is required. This method results in zero holding costs, but large expenditures on ordering costs.

The two cost elements in the basic demand inventory model are ordering cost and holding cost. Ordering costs are simply the costs of placing an order. If A is the administrative cost of placing an order, Q is the order quantity, and D is the quarterly demand, then the annual ordering cost is given by equation 2.1.

$$\text{Order Cost} = (4*D/Q)*A \qquad \text{(eqn 2.1)}$$

Holding costs are the costs associated with warehousing, insurance, and the time value of money. This cost can be expressed as a dollar amount or as a percentage of the inventory held. The Navy Ship Parts Control Center (SPCC) basic model uses a percentage. The holding cost rate, variable I, includes consideration of investment cost, storage, obsolescence and losses. The values for variable I are set at 0.23 for a consumable item and 0.21 for a repairable item.

Since demand is assumed constant, the average inventory on hand is Q/2. At the beginning of the demand period the amount of inventory on hand would be Q, since the material was just received. The amount of material on hand at the end of the demand period should be zero to minimize holding costs. The average inventory on hand is therefore Q/2. If C is the replacement cost of the item, then the average annual holding costs are given by equation 2.2.

$$\text{Holding Cost} = (Q/2)*I*C \qquad \text{(eqn 2.2)}$$

The average annual total cost for management and operation of the basic inventory model can now be calculated. The total cost for the model would be the sum of equation 2.2 and equation 2.1. This results in the total cost function given by equation 2.3. The value of Q which minimizes equation 2.3 is found by differentiating with respect to Q, and setting the resulting equation equal to zero, and solving for Q. This optimal order quantity is given by equation 2.4.

$$\text{Total Cost} = (Q/2)*I*C + (4*D/Q)*A \qquad \text{(eqn 2.3)}$$

$$Q_{optimal} = \sqrt{(8*A*D/I*C)} \qquad \text{(eqn 2.4)}$$

The first part of the inventory problem has now been answered. Equation 2.4 sets the optimal reorder quantity. When to order is the next question to be addressed. In the model discussed above this is decided by determining that level of stock at which an order should be placed so that the stock on hand when an order arrives will be zero. This level, called the reorder level, is a function of the demand during a lead-time. In the case of a known deterministic demand rate D and a constant lead-time L, the optimal reorder level would be exactly the lead-time demand, D*L. If either the demand rate or the lead time is not constant, the reorder level is D*L + Safety Stock, where D is the expected demand rate and L is the expected lead-time. The safety stock is addressed later. In the case of random demand or random lead-times, uncertainty enters the problem and stockout risks must be considered. The calculation of risk and a safety level for protection from that risk is the subject of the next section.

1. The Basic Inventory Model with Variability

The previous model assumed known, constant lead-times and demand. The demand for an item is almost never a constant. Variability of demand can be caused by varying usage levels and simple random failures. The variability in the procurement lead-time can be attributed to the randomness of shipping and handling times and variability in the actual production time. As a result the actual lead-time demand is a random variable. This results in consideration of an additional element in the total cost function. In addition to ordering and holding costs, a shortage cost must now be included.

During an inventory cycle there will be a random number of items ordered. Holding costs will be affected since the cycle begins with a net inventory that is also a random variable. Define an inventory cycle to be the interval between the placing of two consecutive orders. There will be a constant number of Q units used in each cycle. If the mean rate of demand per unit time is D, there will be an average of D/Q cycles per unit time. If the administrative order cost is A, the ordering cost per unit time will be (A*D)/Q.

Define safety stock as the expected value of the stock on hand at the end of a cycle. Let x be the number of demands in a cycle. Let μ be the expected lead-time demand. Let r be the beginning inventory position. The stock on hand at the end of the cycle will be the expected value of the function given by equation 2.5.

$$\begin{cases} 0 \text{ if } x > r \\ r-x \text{ if } x \leq r \end{cases} \qquad \text{(eqn 2.5)}$$

If f(x) is the probability of x demands, then the expected value of equation 2.5, the safety stock, is given by equation 2.6.

$$s = \sum (r - x) f(x) , x \leq r \qquad \text{(eqn 2.6)}$$

This can be re-expressed as equation 2.7.

$$s = r - \mu + \sum (x - r) * f(x) , x \geq r \qquad \text{(eqn 2.7)}$$

Define holding cost to be the expected unit years of stock on hand times the cost of holding one item. Consider a single cycle. At the beginning of the cycle there will be, on average, s + Q items on hand. At the end of the cycle there will be s items. The average number of items on hand during the cycle will therefore be:

$$(s + Q + s) / 2 = s + Q/2$$

If the holding cost for one item per unit time is IC then the holding cost per unit time is:

$$\text{Holding Cost} = (s + (Q / 2)) * IC$$

Denote $\sum (x - r) f(x), x \geq r$, as $\eta (r)$. Substituting equation 2.7 into the holding cost equation results in equation 2.8.

$$\text{Holding Cost} = (r - \mu + \eta (r) + Q/2) * IC \qquad \text{(eqn 2.8)}$$

The annual ordering cost will be the administrative cost A times the number of orders placed. This is:

$$\text{Ordering Cost} = A\,(\,4\,D\,/\,Q\,)$$

Define the cost of a stockout as π . The number of stockouts in a cycle will be given by:

$$\begin{cases} 0 & \text{if } x \le r \\ x - r & \text{if } x > r \end{cases}$$

The expected number of stockouts per cycle will therefore be:

$$\sum (\,x - r\,)\,f(x),\;\; x \ge r$$

The stockout cost per year will then be given by equation 2.9.

$$\text{Stockout Cost} = (\,4\,D\,/\,Q\,) * \pi * (\,\sum (\,x - r\,)\,f(x)),\;\; x \ge r \qquad \text{(eqn 2.9)}$$

Total inventory cost per year is the sum of ordering cost, holding cost, and shortage cost. The total cost function is given by equation 2.10.

$$\begin{aligned} \text{Total Cost} &= A\,(\,4\,D\,/\,Q\,) \\ &IC\,(\,(\,Q\,/\,2\,) + r - \mu + \eta\,(r)\,) \qquad \text{(eqn 2.10)} \\ &+ (\,(\,\pi\,4\,D\,)\,/\,Q\,) * \eta\,(r) \end{aligned}$$

Taking the partial of equation 2.10 with respect to Q results in equation 2.11.

$$\begin{aligned} \partial\,TC\,/\,\partial\,Q &= -(\,4\,D\,A\,/\,Q^2\,) \\ &+ IC\,/\,2\; - (\,(\,4\,D\,\pi\,)\,/\,(\,Q^2\,) * \eta\,(r) \qquad \text{(eqn 2.11)} \end{aligned}$$

Setting equation 2.11 equal to zero and solving for Q results in equation 2.12.

$$Q = \surd\,(\,(\,8\,D\,(\,A + \pi\,(\,\eta\,(r)\,)\,)\,/\,IC\,) \qquad \text{(eqn 2.12)}$$

Taking the partial of equation 2.10 with respect to r results in equation 2.13.

$$\partial TC / \partial r = IC + IC (\partial \eta (r) / \partial r) + ((\pi 4 D) / Q) * (\partial \eta (r) / \partial r) \qquad \text{(eqn 2.13)}$$

Where $\partial\eta / \partial r$ is given by:

$$\sum -f(x), \; x \geq r$$

which we denote by H(r).

Substituting the above into equation 2.13 and setting equal to zero, results in the value of H(r) that is given in equation 2.14.

$$H(r) = (I C Q) / (I C Q + \pi 4 D) \qquad \text{(eqn 2.14)}$$

Equations 2.12 and 2.14 are the optimal solutions for order quantity and reorder level, respectively. However, the optimal solution for Q is in terms of r, while the optimal solution for r is in terms of Q. This problem can be overcome by iteratively solving the two equations until no significant changes in the value of Q and r occur from one iteration to the next.

The solution begins by setting

$$Q_0 = \sqrt{(4 A D / IC)}$$

Then by using this Q_0 in equation 2.14, an initial reorder level, r_0 is calculated. The initial r_0 is then entered into equation 2.12 and a new value for Q_1 is calculated. These iterations continue until convergence is achieved.

2. **Setting Levels by the SPCC D01 Program**

Above we derived expressions for the optimal values of Q and r assuming no constraints and known costs. Now let us see how the UICP model modifies the above expressions to accommodate some real world constraints.

We saw in the classical procedure that one must iteratively solve for r and Q for each item. Since the UICP model is applied to hundreds of thousands of different items it was not computationally feasible, when the model was developed, to do this search for all items. Consequently, to simplify the procedure the UICP model decoupled the determination of the reorder quantities from the determination of the reorder levels. It did this by eliminating the η (r) term from equation 2.12 making the value of Q the same as what is used in the deterministic EOQ model. This value of Q is then subjected to a filtering process.

The basic order quantity is first constrained by the length of time represented by the order quantity. Equation 2.15 is the filter used to constrain the order quantity. The variables are defined as follows:

- D = average quarterly demand
- G = average quarterly repair regenerations
- K_o = minimum quarters of material ordered
- Q = the initial order quantity

$$Q_{constrain} = MIN(12(D\text{-}G), MAX(K_o (D\text{-}G), 1, Q) \qquad \text{(eqn 2.15)}$$

The Q represents the inventory model's calculated order quantity that provides the minimum cost at an acceptable level of risk. The 1 places a floor of one reorder quantity in the constraint. The element K_o also sets a floor level. The K_o can be set at 1, 2, 3, or 4 depending upon how many quarters of demand will be bought as a minimum. The maximum of K_o *(D-G), 1, or Q is selected. Setting K_o at 2, for example, will ensure at least two quarters of attrition demand is procured. This results in a specified floor value. Then the maximum of the floor values is compared with 12(D-G). This is the ceiling value and represents 12 quarters or 3 years of attrition demand. These are policy parameters. The filter ensures no more than three years and no less than one quarter attrition demand is procured.

The order quantity is constrained due to shelf life considerations. In equation 2.16 the previously constrained order quantity ($Q_{constrain}$) is compared to four quarters attrition demand times the shelf life. The shelf life factor, H, is the shelf life of the item in years. This filter ensures the order quantity does not exceed the item shelf life in years of attrition demand. If this constraint were not employed the inventory model could recommend buying many years of demand for an item with a one year shelf life.

$$Q_{order} = MIN(Q_{constrain}, 4H(D\text{-}G)) \qquad \text{(eqn 2.16)}$$

After the value of Q is determined for each item, the reorder level, r, is computed from equation 2.17.

$$H(r) = D*I*C/(D*I*C + \lambda *E*F) \qquad \text{(eqn 2.17)}$$

where

D = Average Quarterly Demand

I = Investment cost

C = Item Unit Cost

λ = Lagrange Funding Feasibility Parameter

E = Military Essentiality

F = Quarterly Requisitions Received (Requisition Frequency)

H(r) is used for setting the reorder level. The distribution to be used in setting the reorder level based on the risk becomes the next important decision to be made. Basically, the D01 program at SPCC assumes a Poisson distribution if the average quarterly demand is less than 0.25 units. In that case the risk is set equal to 1.0 minus the value generated in equation 2.17. The Poisson distribution is then utilized to establish the reorder level (RL) to achieve the established level of risk. For average quarterly demands between 0.25 and 5.0 the negative binomial distribution is used. Finally, if the average quarterly demand is greater than 5.0 the demand is assumed to be normal. For the normally distributed demand the safety level is set at $t \times \sigma$, where t is the z-value from the normal table for the risk generated in equation 2.17, and σ is the standard deviation of the procurement lead-time demand.

Compare this expression to equation 2.14. We see that the Q value in equation 2.14 is replaced by the mean quarterly demand, the quarterly demand in equation 2.14 is replaced by the mean requisition frequency F, and an essentiality parameter is added, and the parameter λ replaces the shortage cost parameter π. These changes to the optimal model have been incorporated for simplicity of implementation. Although the parameter λ replaces the shortage cost π, it is used in the UICP model as a control parameter to guarantee funding feasibility.

The process used to determine the λ value is to set λ at an estimated level and solve for the reorder levels. These reorder levels would then result in a given budgetary requirement. If the resulting budgetary requirement was less than the fixed budget, the λ values could be increased causing higher reorder levels and resultingly higher budget requirements. If a given λ value resulted in requirements higher than the fixed budget, the λ values were reduced resulting in lower reorder levels until the budget requirements were reduced to the level of the fixed budget. The λ values are frequently refered to as the "knob settings" in the U. S. Navy inventory system.

As with the reorder quantities, the reorder levels also are subjected to a filtering process. The filtering process is described below.

The constrained reorder level is achieved by a three phase procedure. First, the inventory model recommended reorder level is compared with the number of policy receivers. A policy receiver is a supply center that will, by policy, carry at least one each of the item. The maximum of R and the number of policy receivers is chosen. This is R_1. In the second phase, the shelf life constraint is compared with R_1. As in $Q_{constrain}$ this establishes a ceiling to ensure shelf life requirements are not exceeded. In the third and final phase the previously constrained reorder level (R_2) is compared to zero (a negative reorder level is not allowed) and the Navy Stockage Objective (NSO).[2] These steps are summarized below.

$$R_1 = \mathrm{MAX}(R, \text{Number of Policy Receivers}) \qquad \text{(eqn 2.18)}$$

$$R_2 = \mathrm{MIN}(4H(D-G)-K_0\,(D-G)\,,\ R_1\,) \qquad \text{(eqn 2.19)}$$

$$R_{constrain} = \mathrm{MAX}\,(\,0,\ \mathrm{NSO},\ R_2\,) \qquad \text{(eqn 2.20)}$$

The resulting order quantities and reorder levels are the values actually recommended by the UICP model for inventory replenishment at SPCC and ASO.

Sigma is replaced by a UICP term, the Procurement Problem Variable (PPV) which is an approximation of the variance of lead-time demand based on the Mean Absolute Deviation (MAD). The MAD value is estimated, in general, using equation

[2]The NSO is an ICP set value for low demand items that ensures a minimum stockage level.

2.21. This equation can be used for demand or procurement lead-time. For a ***normally distributed consumable*** at SPCC, the formulation of the PPV is given by equation 2.22, where PCLT is the mean procurement lead time, MAD_d is the mean absolute deviation of the past demands, D_m is the mean demand and MAD_{pclt} is the mean absolute deviation of the procurement lead-time. An excellent discussion of MAD generation and use is given in [Ref. 4] by Sullivan.

$$MAD = (\sum | X\text{-}X_i |) n \quad \text{for } i=1 \text{ to } n \qquad \text{(eqn 2.21)}$$

$$PPV = (PCLT (1.25MAD_d)^2)+((D_m)^2(1.25MAD_{pclt})^2) \qquad \text{(eqn 2.22)}$$

The formulas for the above levels are not the same at SPCC and the Aviation Supply Office (ASO).[3] The formulas also differ and are assigned different parameters depending on whether the item is a repairable or a consumable. For a detailed treatment of the formulas and parameters see [Ref. 5].

3. Forecasting Based on D01 Levels

Now that uncertainty and risk have been considered and incorporated into the D01 model, the model must forecast the lead-time demand. The system first considers the calculation of the mean quarterly demand. The simplest computation of mean demand is an arithmetic average. This is the sum of the quarterly demand observations divided by the number of observations. However, this method does not consider trends in the data. If the data are trending either upward or downward, the model should consider the most recent observations more heavily.

The SPCC D01 program does in fact consider trending data. First, however, an initial or seed value must be generated. This is computed using equation 2.23. This is the seed value the D01 program utilizes for future trend testing.

$$D_5 = (\sum D_i)/4 \quad \text{for } i=1 \text{ to } 4 \qquad \text{(eqn 2.23)}$$

[3] ASO utilizes both the demand based model and the operating flying hours based model.

At period five the D01 program shifts from an average demand computation to an exponential smoothing model.

The general form for exponential smoothing is shown in equation 2.24. Through algebraic manipulation equation 2.24 can be compressed to equation 2.25, where D_{n+1} is the next period forecast, D_{fore} was the forecast for this period, and D_{act} was the observed demand for this period.

$$D_{n+1} = \alpha(D_n) + \alpha(1-\alpha)(D_{n-1}) + \alpha(1-\alpha)^2(D_{n-2}) \ldots \qquad \text{(eqn 2.24)}$$

$$D_{n+1} = \alpha(D_{act}) + (1-\alpha)(D_{fore}) \qquad \text{(eqn 2.25)}$$

TABLE 1

TREND TOLERANCES FOR SPCC AND ASO

	Maximum	Minimum
ASO	1.50	0.99
SPCC	1.10	0.90

The trend test is shown as equation 2.26. The trend estimate is twice the sum of the two most recent observations divided by the sum of last four observations. A trend is said to be established if the estimated trend is outside of the range of values given in Table 1.

If a trend is indicated, the α value for equation 2.25 is increased as shown in Table 2.

$$\text{Trend} = 2(D_n + D_{n-1}) / (D_n + D_{n-1} + D_{n-2} + D_{n-3}) \qquad \text{(eqn 2.26)}$$

The next forecast required is for the procurement lead-time (PCLT). The forecast for PCLT differs from demand in that there can be many observations per quarter for PCLT vice a single quarterly observation for demand. The first step in

TABLE 2

SMOOTHING WEIGHTS FOR SPCC AND ASO

	Trending	Not Trending
ASO	0.4	0.2
SPCC	0.4	0.2

forecasting the PCLT is to take a quarterly average of all PCLTs if there is more than one observation. This is accomplished by equation 2.27, where $PCLT_{ave}$ is the average quarterly procurement lead-time, $PCLT_i$ is the ith observation, and m is the total number of observations during the quarter. Notice the total $PCLT_i$ is divided by 91. This is required to translate the PCLT from days to quarters.

$$PCLT_{ave} = (\sum PCLT_i) / 91(m) \quad \text{for } i = 1 \text{ to } m \qquad \text{(eqn 2.27)}$$

TABLE 3

PCLT ALPHA VALUES FOR SPCC AND ASO

	Time Since Last Observation		
	1 - 2 Qtrs	2 - 4 Qtrs	4+ Qtrs
ASO	0.5	0.5	0.5
SPCC	0.2	0.5	1.0

The forecast for PCLT is done using exponential smoothing in a manner similar to that for demand. There is, however, no trend test. Instead the α value is derived based upon the length of time since the last PCLT observation. These α values are contained in Table 3 for both ASO and SPCC. Note that, at SPCC, if the last observation of PCLT is in excess of four quarters, the model sets α to 1.0 causing the PCLT forecast to be the most recent observation.

B. OPERATING HOURS BASED MODELS

Now that demand based models have been discussed, attention can be turned to operating or flying hours models.[4] Operating hours models are based upon actual observations for specified periods and program data for future use. Program data is generated by the operational commands based upon desired levels of utilization or a mobilization criteria.

1. How the Models Operate

The operating hours model is based on the gross requirements observed over a period of known operating hours. The gross requirements consist of many different types of specific requirements. These quantities can consist of actual operating stock, safety levels, pipeline requirements, and war reserve and other levels. Operating requirements are the failures or actual demands experienced for a specific item or component. This becomes the requirements of the item and establishes basic levels for a consumable and the basic level and repair effort for a repairable. The safety level applies in a manner similar to that discussed in the demand model. The safety level is a function of the uncertainty or risk of a stock-out for a given item. The pipeline requirements are the levels necessary to cover transportation times and delays due to handling and receiving. War reserve material provides levels for demand during a specific period of wartime activity. This period is generally 90 days for SPCC managed items.

The actual operating stock requirement is a simple calculation. The model begins by calculating the replacement factor. The replacement factor for an item is an estimate of the number of failures (demands) per operating hour. It is, therefore, a failure rate estimate. It is computed simply by dividing the observed number of failures (demands) in a period by the total number of operating hours during the period.

Define the following variables:

- CD_i = Current Demand for period i
- COH_i = Current Operating Hours for period i
- POH_j = Projected Operating Hours for period j
- PCLT = Item Procurement Lead Time

[4]The term operating hours and flying hours will be used interchangeably throughout this paper.

The replacement factor is therefore equation 2.28.

$$RF = (CD_i : COH_i) \qquad \text{(eqn 2.28)}$$

The operational commanders are then asked to provide projections of operating hours into future quarters, POH_j . Finally, the expected lead-time demand is computed by multiplying the replacement factor, the expected lead-time, and the projected operating hours.

$$LTD = RF * POH_i * PCLT \qquad \text{(eqn 2.30)}$$

$$LTD_i = CD_i * PCLT \qquad \text{(eqn 2.29)}$$

Observe that if the operating hours were a constant K each period, the estimate for LTD given by the operating-hours model would be the same as the estimate given by the demand-based model since $RF*POH_j = RF*K$. This is simply an estimate of the average quarterly demand D.

2. Three Operating Hours Based Models

The discussion thus far has provided the background for many operating-hours based models. There are a plethora of models that are based on program data. The use of program elements for predicting future requirements for spare parts is fairly widespread in the military services. The following are three recent models that utilize program operating hours in lead-time demand prediction.

The ORACLE Model (Oversight of Resources And Capability for Logistics Effectiveness) was developed by Bigelow, [Ref. 6], of the Rand Corporation, in June 1984. The model combines flying hours projections and the number of installations with replacement factors and repair rates to forecast demands.

Similarly, the METRIC Model (Multi-Echelon Technique for Recoverable Item Control) was developed by Sherbrooke [Ref. 7] in 1966 at the Rand Corporation. The model is applicable to a base depot resupply system. The model uses flying hours in a Bayesian forecasting model to predict demands for repairable items in a multi-echelon inventory system. The model accomplishes three purposes: optimization, redistribution, and evaluation.

The dynamic nature of operations and the manner in which inventory systems respond was discussed by Muckstadt [Ref. 8]. The central issue is that operating hours increase rapidly as a new system is introduced and decrease in a similar manner as the system is phased out. Muckstadt developed a model that utilizes flying hours to predict rapid increases in demand and provide necessary support.

The basic operating hours model has been addressed. Three operating hours based models have been discussed. The models fail to address an important central issue. This is the *accuracy* of the forecast of the future operating hours.

III. THE IMPORTANCE OF OPERATING HOURS PREDICTION

Previous discussion has centered on operating-hours-based inventory models. Almost all operating-hours-based models, and the three specific models addressed, have four components or issues in common. These issues are demand, procurement lead-time, operating hours, and risk or uncertainty. This paper will not address risk and uncertainty. These issues are covered extensively by previous references. This paper also will not address the demand phase of the inventory cycle. The demand issue has been throughly covered by others.

This paper does analyze the two remaining issues in the operating hours inventory model - the operating hours and the procurement lead-times. This chapter addresses the forecasting of operating hours and the resulting effect on the demand forecast. This is accomplished by direct observation of historical data and by statistical testing.

Two basic questions need to be answered. The first is how operating hours are forecast. The second is how accurate are the forecasts.

A. BASIS OF OPERATING HOURS PREDICTIONS

There are many methods that can be used to forecast future requirements. Many forecasting methods rely on historical data, an expert opinion, or a combination of the two. Some forecasting methods based upon historical data were discussed Chapter Two. These methods require the observation and collection of actual data. The data are reviewed and scrubbed to ensure that the data are appropriate for inclusion in the data base. The use of historical data are especially accurate when the system is in a static or steady state condition. If demand for an item has been X units per quarter for the past Y quarters, it would be reasonable to assume that demand for the next quarter will be X units.

Other methods of forecasting can be based on the expert opinion. The Delphi technique is one such method of forecasting which uses a group of decision makers with a feedback mechanism. The expert opinion forecast is used in many inventory systems. Consider as an example a seller of soda at a fair. A seller might believe that on a hot, sunny day he will sell more soda than on a cool, overcast day. The seller uses his expert opinion to make his inventory decisions. The expert opinion can be used on a large scale. A businessman whose expert opinion indicates a certain model product will be well received by the buying public may issue inventory guidance contrary to the recommendation of the inventory model. The businessman has supported or substantiated his expert opinion if the venture is successful.

Additional forecasting models can be based on a combination of expert opinion and historical data. The SPCC filters and constraining functions contained in Chapter Two are examples. The inventory forecasting model cannot be allowed to just set the reorder level and quantity that generates the least total cost. One reason is an item with a limited shelf life. An item with a shelf life of 4 quarters should not have a procurement of 5 or more quarters of material. This would be an unwise expenditure.[5] The requirements of the real world are used to filter or modify the forecasts. This is the job of the decision maker. The decision maker must review the data and use his expert opinion to arrive at a decision.

B. OPERATING HOURS PREDICTIONS

This section is concerned with actual predictions of future operating hours. There are two sets of data to be considered in this section. The first set of data consists of forecast operating hours for the LM-2500 Marine Gas Turbine Engine. The second set consists of Air Force flying hours for various types of engines and aircraft.

1. LM-2500 Operating Hours Predictions

The LM-2500, a marine gas turbine engine, is currently installed on 219 ships in the U. S. Navy. The LM-2500 is the main power plant on the DDG, CG, FFG, DD, PHM class of ships. There is also a single LM-2500 installed at a hot plant test site. The predicted operating hours data are contained in Appendix A. The operating hours predictions were received from the Main Propulsion Systems Division (Code 0512) of SPCC. The operating hours forecasts are for the 40 month period of November 1982 to January 1986.

Figure 3.1 shows the predicted LM-2500 operating hours. The forecasts increase in a fairly constant linear manner. The predictions of operating hours appear to be based on a modified Delphi technique. The engineers of the Naval Sea Systems Command (NAVSEA) meet with the operating experts from the Office of the Chief of Naval Operations (OPNAV). Together they estimate the operating hours for each class of ship containing the LM-2500. The forecast hours are totaled and become the

[5] Unless the discount rate for procurement of the material in an economic lot size is greater than that of the spoilage cost.

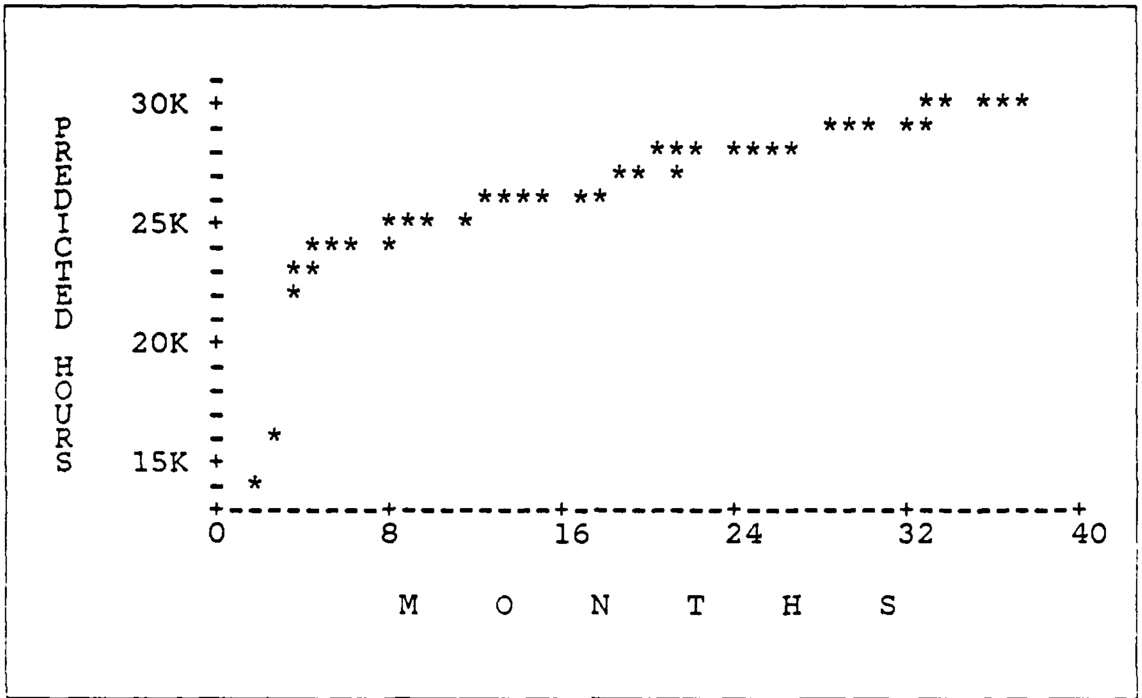

Figure 3.1 LM-2500 Predicted Operating Hours with Respect to Time.

basis for demand forecasting at SPCC. This is an example of an expert opinion method of forecasting. Actual operating hours data are not explicitly considered in the future predictions.

2. **Air Force Operating Hours Prediction**

The Air Force uses a forecast method that appears to combine expert opinion with historical operating hours observations. Planning data for future periods can be based on data from similar past operations. Operating hours for a future exercise can be based on a past exercise that was similar in nature. The forecast operating hours remains an expert opinion that has a basis in historical observations.

Hoffmayer, Finnegan, and Rogers [Ref. 9] discuss the problem of forecasting operating hours. In addressing the requirement to forecast operations they indicate that ". . . operations are dependent on theater of activity rather than force wide . . . ." The operational commanders can influence the program data by including their expert opinion in the forecasting process.

Forecast operating hours data for Air Force aircraft were also described by Hoffmayer, Finnegan, and Rogers [Ref. 9]. The predictions of operating hours are contained in Appendix A. A graphical representation is contained in Figure 3.2. A downward trend is noted. This is believed to be the result of budgetary constraints during the period.

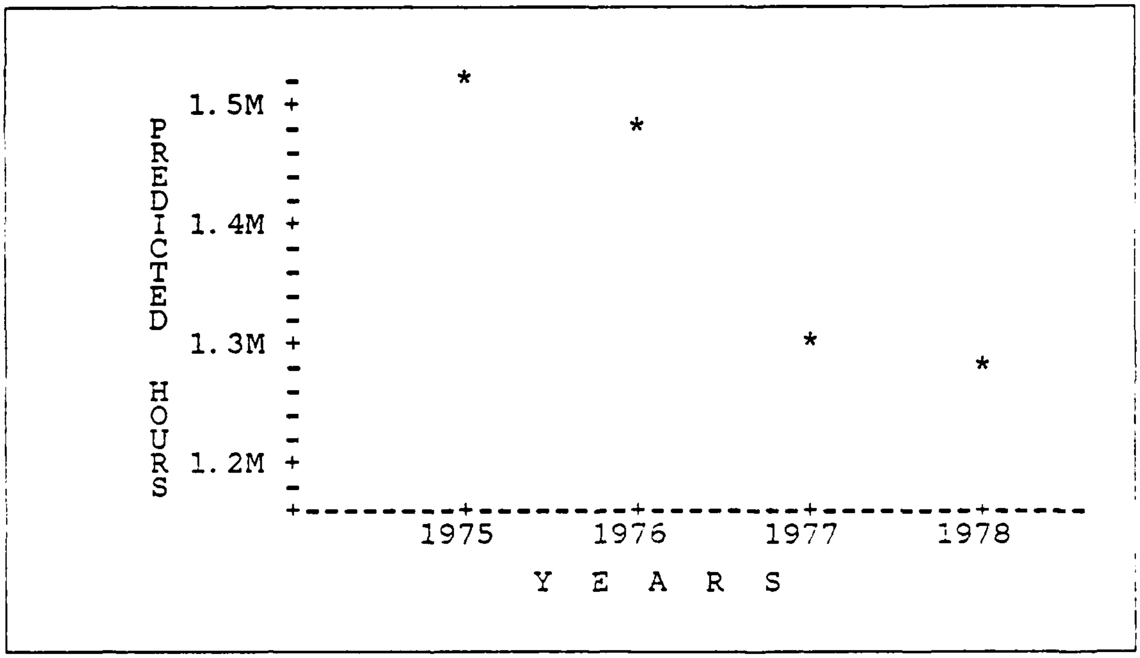

Figure 3.2 Air Force Predicted Operating Hours with Respect to Time.

C. ACTUAL OPERATING HOURS

This section addresses actual operating hours. The compilation of actual operating hours for any system requires the observation, collection, and correlation of data from operational units or other reporting commands.

1. LM-2500 Operating Hours

Actual operating hours data for the LM-2500 are compiled by the Naval Sea Systems Command (NAVSEA) in Washington, DC. The data were received at NAVSEA from all operating units in the Monthly Steaming Report. The report contains information concerning the number of times each engine was started, the total operating hours per engine, and the fuel and lubricants consumed. The operating hours are consolidated by NAVSEA into class of ship and operating location. The total operating hours are accumulated. The total hours become the basis of the D01 Levels Program that forecasts lead-time demand.

The actual operating hours for the LM-2500 are contained in Appendix A. The data were received from the Navy Ship Parts Control Center (SPCC). A graphical representation of the data is contained in Figure 3.3.

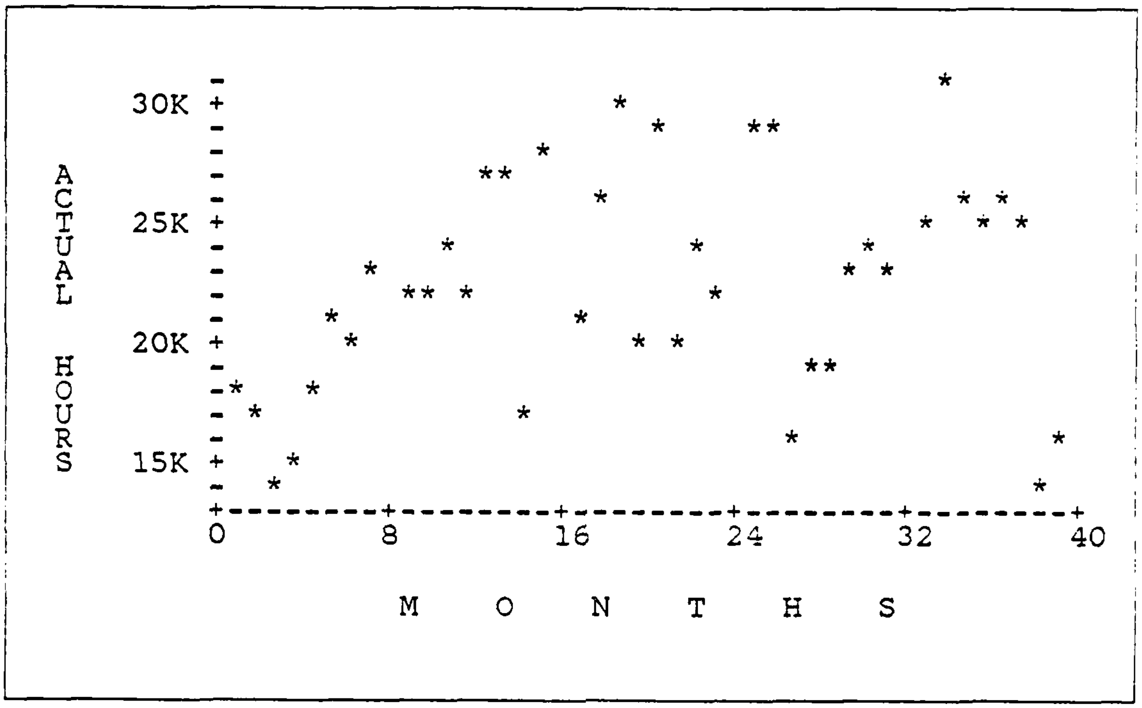

Figure 3.3 Actual LM-2500 Operating Hours with Respect to Time.

2. Air Force Operating Hours

Actual operating hours data for the Air Force were collected in a similar manner. Squadrons and other operating units submit a monthly operations report. The report contains the number of landings, flight hours by type of aircraft, and fuel and lubricants usage.[6] The flying hours are totaled by the Air Force Logistics Center (AFLC). The operating hours are used in the Air Force D041 inventory data base.

The actual annual Air Force operating hours are contained in Appendix A. The observations are for the period of 1975 through 1978. A graphical representation of the total operating hours is contained in Figure 3.4.

[6] The Air Force report contains many additional elements of information. Additional elements include accidents, training and readiness. These elements are not a part of the Navy Monthly Steaming Report.

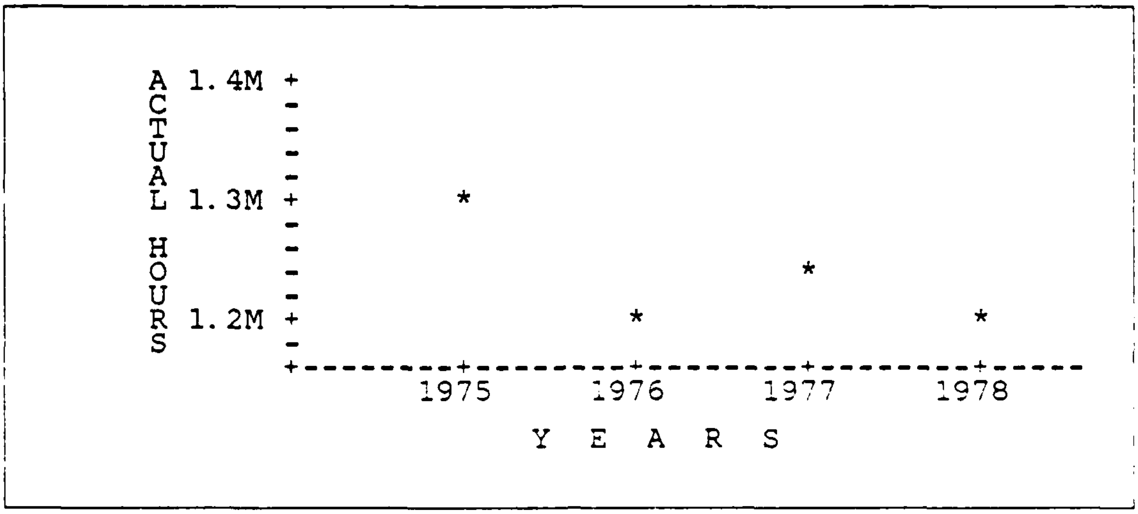

Figure 3.4 Air Force Actual Operating Hours with Respect to Time.

D. HYPOTHESIS TESTING

Hypothesis testing[7] is a mathematical method of determining if actual results agree with a stated assumption. Ott and Hildebrand [Ref. 10] state:

> A statistical test is based on the concept of proof by contradiction and is composed of four parts: a null hypothesis, a research hypothesis, a test statistic and a rejection region.

The first step is to establish the research hypothesis (H_a). The research hypothesis is the statement the tester is trying to demonstrate. A hypothesis test can take the form of questioning whether a population has a certain mean based upon a random sample of the population. Hypothesis testing can be used to determine whether predicted values agree with observed results. After the research hypothesis is formulated the null hypothesis (H_o) can be stated. The null hypothesis is the opposite of the research hypothesis. The next step is to establish the test statistic (T.S.). The test statistic is a value computed from sample data that will be used to accept or reject the null hypothesis.

[7] All hypothesis testing, two sample procedures, time series procedures, t-tests, and regression analysis are based on the output of MINITAB Release 5.1, Minitab, Inc. 1985.

The level of risk is important in setting the rejection region. An increase in the confidence of accepting the null hypothesis will result in an increase in the rejection region. There are two types of errors possible. The first error is rejecting a null hypothesis when it is true. This is a Type I error. It is the largest amount of risk the tester is willing to accept of rejecting a true null hypothesis. The Type I risk is denoted by α. The second error is the Type II error. It is the risk of accepting a null hypothesis when it is false. The Type II error is denoted by β.

1. LM-2500 Hypothesis Testing (Actual versus Predicted)

The LM-2500 data were used to determine how well the predicted operating hours matched the actual operating hours. Any forecasting model which relies on operating hours can be no better than the predictions of operating hours. This test was performed by testing the null hypothesis H_o: Actual hours = Predicted hours.

The predicted and actual data contained in Appendix A are not independent. Since the actual operating hours and predicted operating are naturally paired by the month, the paired t test was used to determine if the mean difference is zero. That is, the null hypothesis H_o: $\mu_a - \mu_p = \mu_d = 0$, was tested versus the two-sided alternative.

This would become:

$H_o : \mu_d = 0$
$H_a : \mu_d \neq 0$
T.S. : $t = (\bar{d}-0)/(s_d/\sqrt{n})$
R.R. : $t > t_{\alpha/2}$ or $t < -t_{\alpha/2}$

where

$\bar{d}$ = the observed mean of the elements in the differences
s_d = the observed standard deviation of the differences
α = .05 (1 - the confidence interval (95%))

The results are contained in Appendix B. The t-value for the test of μ_d equal to zero is 5.15. This t-value is so large that it does not appear on most tables for t-values. The rejection region is a t-statistic greater than 2.704 or less than -2.704. The null hypothesis can be rejected. The rejection of H_o: $\mu_d = 0$ can be made with 95% confidence. The probability of getting a value of the test statistic as extreme as what was observed *when H_o is true* is the p-value. This value is less than 0.0001.

The two sample test procedure is used to determine if the mean of the actual operating hours is equal to the mean of the predicted hours. The test indicates that the true difference is in the range of 2,009 to 5,567 operating hours. The program takes predicted minus actual hours. The mean for predicted hours is 2,009 to 5,567 hours ***more*** than the mean of the actual hours. Predicted hours are greater than actual hours with a level of confidence of 95%.

Figure 3.5 is a graphic representation of the mean of both actual and predicted data.

```
        Individual 95% Confidence Intervals
    for Mean Based on Pooled Standard Deviation
  -----+---------+---------+---------+--
                         (-----*-----)    Predicted
   (-----*-----)                            Actual
  -----+---------+---------+---------+--
    22,000    24,000    26,000    28,000
```

Figure 3.5 Mean of LM-2500 Predicted and Actual Hours.

2. **Air Force Hypothesis Testing (Actual versus Predicted)**

The Air Force predicted and actual data were not in as simple a format as that for the LM-2500. The Air Force data are for seven different types of aircraft, over a period of four years. The hypothesis testing for the data will be on the basis of percent of prediction error. The precent error is calculated by equation 3.1.

$$\text{Percent Error} = (P_i - A_i) / A_i \qquad \text{(eqn 3.1)}$$

The null hypothesis will be supported if $\mu_e = 0$ and contradicted if $\mu_e \neq 0$.

Stated in hypothesis testing terms, the test of Air Force predicted to actual hours would become:

$H_o : \mu_e = 0$

$H_a : \mu_e \neq 0$

T.S. : $t = (\bar{e}-0)/(s_e/\sqrt{n})$

R.R. : $t > t_{\alpha/2}$ or $t < -t_{\alpha/2}$

where

$\bar{e}$ = the observed mean of the elements in the percent error

s_e = the observed standard deviation of the percent error

α = .05 (1 - the confidence interval (95%))

The results are contained in Appendix C. The t-test indicates a t-value of 3.82. The t-value for a confidence level of 95% with 27 degrees of freedom is 2.052. The rejection region is a t-value greater than 2.052 or less than -2.052. The calculated t is within the rejection region. The null hypothesis $H_0 : \mu_e = 0$ can be rejected. The probability of getting a value of the test statistic as extreme as what was observed *when H_0 is true* is the p-value. This value is .0007.

IV. FORECASTING LEAD TIMES

The first factor of lead-time demand has been discussed. Actual operating hours impact on both the order quantity and the reorder level. The length of the procurement lead time is also important in the inventory calculations. The lead-time demand is the quarterly demand rate times the procurement lead-time. Even if the demand rate is correct, an erroneous procurement lead-time will result in an incorrect lead-time demand.

A. IMPORTANCE OF LEAD-TIMES

There are three cases to be addressed in forecasting procurement lead-time. The procurement lead time is over stated, the procurement lead-time is understated, or the procurement lead-time is correct. If the procurement lead-time is overstated, procurement will be in excess of lead-time demand. There will be too much material on hand. Holding cost will be higher than predicted.

If procurement lead-time is understated, insufficient material will be on hand near the end of the lead-time. This will result in backorders. The shortage cost will apply if there are backorders. The inventory system costs will be higher than the optimized levels.

1. LM-2500 Lead Times

Lead-times for the LM-2500 system are generated in the same manner as any other item at SPCC. The system for forecasting lead-times in the SPCC D01 Levels program has two significant shortfalls.

The first problem area is the lack of sensitivity to rapid changes. A radical change in engineering or production could drastically lengthen or shorten the production lead-time. A very large or complex contract could cause prolonged administrative lead-times.

The second problem concerns erroneous data. This could result from errors in the reporting of receipt dates. The timing of the procurement lead-time begins with the issuance of a contract document. This is started by the F01 Procurement Program. The ending point of the procurement lead-time is when the Transaction Item Reporting (TIR) Program processes a document that indicates delivery has been received.

TIR processing is completed on a daily basis. Some material is not processed in a timely manner. Large, bulk items can wait weeks before storage and reporting can be completed. Erroneous data in the TIR program will cause incorrect procurement lead-times.

2. Actual Lead Times

Procurement lead-times for selected LM-2500 components are contained in Appendix D. The actual lead-times range from 14.21 quarters (over three and a half years) to 4.91 quarters. Lead-times include administrative lead-time. Administrative lead-time (ALT) averages approximately two quarters. It can extend up to a year or more for complex contracts.

The actual production lead-time for a component is often a function of the complexity of the item and the contract. Simple items such as bolts and O-rings have a relatively short lead-time. Complex systems such a Main Fuel Control have lead-times more realistically measured in years. The Main Fuel Control has an actual procurement lead-time of almost three years.

Appendix E contains a column headed Diff. This values in this column are the differences between actual and forecast lead-times. The differences in actual and predicted lead-times are plus or minus one half of one quarter. The lead-time errors of Appendix E appear to be relatively small.

3. Item Managers Inputs

Item Managers at SPCC are classified into one of four distinct job categories in the logistics support divisions. In addition to supervisory, administrative, and clerical personnel there are:

- Provisioning: responsible for the initial selection of components to be supported and determination of depth and initial technical specifications
- Procurement Technical: responsible for changes or corrections to the technical specifications of an item and initial preparation of the procurement package
- Program Managers: responsible for the overall supervision of a major component or weapons system
- Item Manager: responsible for the daily business of specific end items.

After initial provisioning the Item Manager provides most of the direct control over the procurement lead-time. The Item Managers are responsible for using the D01 Levels Program and the B01 Supply Demand Review (SDR) to trigger procurements. It is the responsibility of the Item Manager to ensure the procurement lead-time, forecast demand and lead-time demand are correct. There are hundreds of data elements the Item Manager must ensure are correct. None are more important than the procurement lead-time and forecast demand.

The Item Manager can correct data elements directly through system input. Should a Program Manager becomes aware of a problem,[8] he would inform the Item Manager. If the lengthening of a procurement lead-time is the result, the Item Manager can use this knowledge to ***manually*** change the forecast procurement lead-time.

This appears to be the case with the predicted and actual lead-times noted in Appendix D. When changes occur the Item Manager completes the necessary corrections. Thus, with this feedback feature, one would expect the forecasted lead-times and the actual lead-times to be very close. The accuracy of the forecasts is tested in the next section.

B. TESTING ACCURACY OF LEAD TIMES

The primary question addressed in this section is the accuracy of the predictions of procurement lead-time. The methods discussed in Chapter Three will be utilized.

1. Hypothesis Testing

Let μ_p be the mean of the population of projected lead-times and let μ_a be the mean of the population of actual lead-times for the selected components of the LM-2500 system. We are interested in determining if these two means are the same. We address this by testing the null hypothesis

$$H_o : \mu_d = \mu_p - \mu_a = 0$$

versus the two-sided alternative

$$H_a : \mu_d \neq 0.$$

We use the paired t-test with test statistic

$$t = (d_{bar} - 0)/(s_d / \sqrt{n})$$

[8] Program Managers have direct interface with commercial production personnel. Changes such as production lead-time, scheduling, material shortages, and other production problems are most often discovered by the Program Manager.

and rejection region

RR: $t > t_{\alpha} 2$ or $t < t_{\alpha} 2$.

Where d_{bar} is the sample mean of the differences in predicted and actual procurement lead-times for the random sample of items selected from the LM-2500 system.

Appendix E provides a listing of the data and the results of the test of hypothesis. The test statistic yields a t-value of 0.09, which strongly supports the null hypothesis. The p-value for this test is 0.93. Therefore, the null hypothesis cannot be rejected. This is expected because the feedback feature, discussed above, has the effect of forcing the forecasted and actual lead-time figures close together.

A 95% confidence interval for the difference in means is (-1.32,1.34). Figure 4.1 gives a graphic presentation of the 95% confidence limits for both the forecasted and the actual procurement lead-times. The substantial overlap in the intervals supports the null hypothesis. Thus, the procurement lead-times for the LM-2500 system appear to be forecasted accurately.

```
Individual 95% Confidence Intervals
   for the Mean Based on Pooled
      Standard Deviation

-----+---------+---------+----------+-
(---------------*----------------)   Predicted
(---------------*---------------)    Actual
-----+---------+---------+----------+-
9.6       10.2      10.8      11.4
```

Figure 4.1 Confidence Intervals for Procurement Lead Times.

C. OTHER LEAD TIME CONSIDERATIONS

This section discusses the characteristics of procurement lead-time. A discussion of the physical attributes of procurement lead-time is provided. The possibility of measuring procurement lead-time in units other than time is discussed.

1. **Lead Times in Operating Hours**

Procurement lead-time is traditionally measured in terms of time. The basic measure of procurement lead-time is generally in quarters. The four quarterly periods, for fiscal year XY, are divided as follows:

- 1st Quarter - 1 October 19XX through 31 December 19XX
- 2nd Quarter - 1 January 19XY through 31 March 19XY
- 3rd Quarter - 1 April 19XY through 30 June 19XY
- 4th Quarter - 1 July 19XY through 30 September 19XY

Procurement lead-time is expressed in terms of the number of quarters required to complete the procurement cycle. The cycle includes administrative lead-time and production lead time. The sum is the procurement lead time.[9] The measurement of procurement lead-time is initially counted in days and then converted to quarters.

Consider the conversion of procurement lead-time to units of operating hours. Assume the following inventory parameters for an item:

F_o = 200 hours = flying hours for the last quarterly period
D_o = 10 units = total demand for the last quarterly period
F_p = 260 hours = average flying hours per quarter through lead-time
D_p = unknown = demand forecast at the next procurement lead-time
P = 6 quarters = the procurement lead-time in quarters
RL = unknown = the reorder level

Assume also that the next six quarterly projected operating hours are:

F_1 = 220 hours, F_2 = 230 hours, F_3 = 250 hours
F_4 = 270 hours, F_5 = 290 hours, F_6 = 300 hours

Because operating personnel may find it more convenient to think of stock in terms of the amount of program that can be supported, it might be useful to convert some of the expressions discussed earlier to units of operating hours of stock. This can be accomplished simply by dividing units of stock by the replacement factor to obtain

[9] At Navy Inventory Control Points, the value of administrative lead-time is not directly measured. The production lead-time is subtracted from the total procurement lead-time. The result is the administrative lead-time.

operating hours of stock. For example, an on-hand stock level of 100 units with a replacement factor of .05 units per hour could be re-expressed as

100 units / 0.05 units per hour = 2000 operating hours of stock.

Similarly, one could express reorder quantities and reorder levels in terms of operating hours of stock. For example, a reorder quantity of 500 and a reorder level of 200 would be equivalent to

500 units / 0.05 units per hour = 10,000 operating hours

and

200 units / 0.05 units per hour = 4,000

operating hours, respectively.

Such figures are likely to be more meaningful to military planners who must schedule future month's operations.

V. CHANGES IN OPERATING HOURS

This chapter is concerned with the impact on the inventory model due to changes in operating hours. These changes will be assumed to be the result of random variations or seasonal changes and not the result of a war time surge. The difference between a mature system and an increasing or declining system will be addressed.

A discussion of time series will be the subject of the second section. Some forecasting techniques will be considered. The models will be a Seasonal Factors with a Trend approach, and the Winters Exponential Smoothing Model with Seasonal Factors.

The final section will be concerned with the financial impact of changes in operating hours. This discussion will center on the financial costs of long supply (over investment) and short supply (under investment). A discussion of the Item Managers role in an operating hours based inventory system will be addressed.

A. PREDICTED VERSUS ACTUAL OPERATING HOURS

This section discusses the effect of changes in operating hours. Two areas will be covered. The first is a discussion of steady state operations. The second is a discussion of a system in a dynamic period. This period could be one of growth or decline caused by program factors.

1. Steady State Operations

This discussion addresses two areas. The first is the magnitude of changes. The second is the presence of a trend.

Operating hours for a system are in steady state when changes in operating hours are relatively insignificant. The changes in hours are small when compared to the mean.

Assume the predicted quarterly operating hours are represented by the following:

$$F_1 = 230 \quad F_2 = 240 \quad F_3 = 140$$
$$F_4 = 170 \quad F_5 = 220 \quad F_6 = 200$$

The initial demand and operating hours are:

F_o = 200 hours = flying hours for the previous quarter

D_o = 10 units = total demand for the previous quarter

The predicted flying hours data has a mean of 200 hours with a standard deviation of 38.47.

The above data were constructed to demonstrate a point. The average quarterly operating hours is 200 hours. This average is the same as the initial operating hours used to develop the replacement factor. The average operating hours per quarter (F_p) would equal 200 hours. The predicted demand per quarter would be:

D_p = (10 demands/200 hours)*(200 hours) = 10 demand per quarter

RL = 10 demands per quarter * 6 quarters = 60 demands

This demonstrates that in a steady state system the lead-time demand is the initial demand times the procurement lead-time.

2. **Dynamic Operations**

Operating hours for a system are dynamic when changes in operating hours are not insignificant. One form this takes is an upward or downward trend.

There are many methods used to determine the existence of a trend. One method, called the "two over four method" multiplies the sum of the two most recent observations and divides by the total of the last four observations. A trend is indicated if this ratio lies outside given tolerances. The SPCC D01 Levels Program for demands uses this type of trend test.

Assume a component in an operating hours system with a procurement lead-time of five (5) quarters. Assume that the previous five observed quarterly operating hours were 220, 240, 240, 260, 270. Assume that the predicted operating hours for the next five quarters are 280, 290, 310, 320 and 340. A trend test for this data could be a two over five test. Past and predicted trends would then be:

Past Trend = (5/2)*(260+270)/(220+240+240+260+270) = 1.077

Future Trend = (5/2)*(320+340)/(280+290+310+320+340) = 1.071

The upward trend is the most important for the inventory control points. Support for an upward trending system is the goal of FOSS (Follow On Supply

Support). FOSSing a system is designed to provide additional material support during the growth to maturity. Projected operating hours can be used during the growth phase to improve material support.

B. TIMES SERIES ANALYSIS

This section explores other time series methods for forecasting. These models are based on historical data. Peterson and Silver, [Ref. 11], state, "Let's face it. There is really no way of judging the future except by the past". Peterson and Silver identify the *forecaster's dilemma* by recognizing the basic problem in forecasting, and the relationship between forecasting and the decision maker:

> Only one thing is certain after such decisions are made - *the forecasts will be in error.* What remains to be determined is the exact size of the resulting errors and whether any past decisions need to be altered in response. Forecasts are at best imprecise, at worst misleading.

1. A Forecast Model with Seasonal Factors and a Trend

A simple time series model is one that allows an overall trend with seasonal dummy variables. This forecasting technique is shown in equation 5.1. The equation consists of a constant, k_1, a linear trend element, k_2, and three seasonal dummy variables. The values of Q_2, Q_3 and Q_4 *are set at zero or one* depending upon the quarter in which the data was collected. Q_1 is stated then in terms of the other variables. Using the LM-2500 operating hours data from Appendix A, a table can be set-up as in Table 4. The quarters selected were divided as follows:

- Quarter 1 = November, December, January
- Quarter 2 = February, March, April
- Quarter 3 = May, June, July
- Quarter 4 = August, September, October

$$h_t = k_1 + k_2{*}t + k_3{*}Q_2 + k_4{*}Q_3 + k_5{*}Q_4 \qquad \text{(eqn 5.1)}$$

This unusual division of the quarters was used to group the holiday months together. The assumption is that operations are depressed during the Thanksgiving, Christmas, and New Year's periods.

TABLE 4

HISTORICAL DATA WITH SEASONALITY

Year	t	h	Q2	Q3	Q4
1983	1	48,013	0	0	0
	2	59,820	1	0	0
	3	66,003	0	1	0
	4	73,007	0	0	1
1984	5	66,064	0	0	0
	6	83,355	1	0	0
	7	69,937	0	1	0
	8	72,635	0	0	1
1985	9	61,809	0	0	0
	10	66,548	1	0	0
	11	78,653	0	1	0
	12	78,008	0	0	1
1986	13	54,368	0	0	0

Least squares regression was used to estimate the five parameters. The results of the regression are contained in Appendix F. Equation 5.2 is the resulting equation. This has an R-squared value of 58.6%. This is better than the regression results previously discussed in Chapter Two. The single variable regression, with respect to time, achieved an R-squared value of only 6.5%.

$$h_t = 52{,}507 + 722*t + 13{,}067*Q_2 + 13{,}967*Q_3 + 16{,}264*Q_4 \quad \text{(eqn 5.2)}$$

There are many models other than the additive model. The multiplicative model could also be used. It takes the form of:

$$F_t * S_t * k_t$$

where F_t is the forecast for time t, S_t is the seasonal trend, k_t is the growth trend.

Exponential smoothing models that utilize seasonal and trend factors directly have been developed by many individuals. The models vary in the manner in which they accommodate the seasonal and trend factors. McClain and Thomas, [Ref. 12], reviewed many common exponential smoothing models. Their review indicated that the models were:

. . . equivalent in the sense that one could achieve identical forecasts if the smoothing constants were selected carefully.

2. Winters Exponential Smoothing with Seasonal Factors

The Winters Exponential Smoothing Model was originally developed by Peter Winters [Ref. 13]. The basic Winters model is shown as equation 5.3 where:[10]

d_t = the exponentially smoothed level at the end of period t

d_{t-1} = the exponentially smoothed level at the end of period t-1

d^t = actual observation during period t

α = the smoothing constant, $0 \le \alpha \le 1$

N = the number of periods in the season

F_{t-N} = the seasonal factor at the end of period t-N

G_{t-1} = the trend for period t-1

$$d_t = \alpha(d_t \; F_{t-N}) + (1-\alpha)(d_{t-1} + G_{t-1}) \qquad \text{(eqn 5.3)}$$

The seasonality factors are updated once each season by equation 5.4, where β is the seasonal smoothing constant, $0 \le \beta \le 1$.

$$F_t = \beta (D^t / d_t) + (1 - \beta) * F_{t-N} \qquad \text{(eqn 5.4)}$$

The trend factor is computed and updated each period using equation 5.5, where γ is the trend smoothing constant, $0 \le \gamma \le 0$, and G_t is the per period additive trend factor. Trend is accounted for in a linear manner.

$$G_t = \gamma (d_t - d_{t-1}) + (1 - \gamma) * G_{t-1} \qquad \text{(eqn 5.5)}$$

The forecast for the next period, or for the j^{th} period is given by equation 5.6 d_{t+j} is the forecast for j periods forward from time t.

$$d_{t+j} = (d_t + j * G_t) * F_{t+j-N} \qquad \text{(eqn 5.6)}$$

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[10]In this model superscripts will indicate actual or observed data, while subscripts will indicate forecasts or estimates.

TABLE 5

INITIAL OPERATING HOURS OBSERVATIONS

Year, i	Quarter	Period, t	Hours
1983	1	-7	48,013
	2	-6	59,820
	3	-5	66,003
	4	-4	73,007
1984	1	-3	66,064
	2	-2	83,355
	3	-1	69,937
	4	0	72,635

The above equations describe the Winters method. Three initial seed values are required to start the model. These are:

d_o = the initial demand forecast
G_o = the initial trend factor
F_i = the initial seasonal factors, $i = 1$ to 4 for annual data.

The Winters method requires two additional initial factors to be calculated. These are V_1 and V_2. V_1 is the average hours over the first N periods (N is assumed to equal 4). If annual figures are used this becomes the initial four observations from Table 5. V_2 is average number of hours over the last N periods.

The resulting values for V_1 and V_2 are:

V_1 = 61,711 hours
V_2 = 72,998 hours

The initial trend factor (G_0) is then calculated by equation 5.7. This results in G_0 = 2,822 hours. If G_0 is positive, there is an increasing trend. If G_0 is minus, there is a decreasing trend.

$$G_0 = (V_2 - V_1) / N \qquad \text{(eqn 5.7)}$$

The initial forecast (d_0) is calculated using equation 5.8. The resulting initial forecast value is $d_0 = 77.231$. This represents the smoothed level at the end of the most recent season.

$$d_0 = V_2 + G_0\,((N-1)\ 2) \qquad \text{(eqn 5.8)}$$

TABLE 6

INITIAL SEASONAL FACTORS

Year	Quarter, j	Period, t	Seasonal Factor
1983	1	-7	0.85
	2	-6	0.99
	3	-5	1.05
	4	-4	1.11
1984	1	-3	0.96
	2	-2	1.16
	3	-1	0.94
	4	0	0.94

The initial seasonal factors are calculated using equation 5.9. V_i is the midpoint level of the appropriate year. The results of all eight seasonal calculations can be found in Table 6. The seasonal factors total 4.0 for the quarters 1, 2, 3, and 4, and will always be the number of seasons.

$$F_t = d_t / (V_i - (G_o\,(((N+1)/2)-j))) \qquad \text{(eqn 5.9)}$$

The seasonal forecasts are normalized so that the sum of all F_i is equal to n. The resulting normalized seasonal factors are:

$F_1 = .905 \quad F_2 = 1.075$

$F_3 = .995 \quad F_4 = 1.025$

Equation 5.6 can be used to forecast the next period or periods.

TABLE 7

FORECAST AND ACTUAL DATA USING WINTERS SMOOTHING

Year	Quarter, j	Forecast	Actual
1985	1	72,448	61,809
	2	89,090	66,548
	3	85,268	78,653
	4	90,732	78,008
1986	1	82,664	54,368

The first five quarters forecast and the resulting actual values are contained in Table 7. The seasonal adjusted forecasts are close to the actual data. The forecast for quarter 1 and 5 (November, December, and January) were the two lowest forecasts, and were also the two lowest actual observations. The highest forecast quarter was quarter 4. This was not the largest actual observation but was close. The Winters algorithm appears to handle both trend and seasonality in an excellent manner.

C. FINANCIAL CONSIDERATIONS

There are many financial considerations connected with the selection and implementation of any inventory model. An important question is the amount of over statement or under statement that could be caused by the model. In the austere atmosphere of military spending the costs of an inventory model deserve close attention.

The role played by the item manager in correcting for inventory decisions will be discussed.

1. Long Supply (Over Investment)

The first area of concern is that of long supply or over investment. Long supply occurs when too much of an item has been procured. A drastic example of long supply would be the procurement of a number of units sufficient to support requirements for twenty (20) quarters, when the procurement lead-time is only five (5) quarters. Three times the requirements have been procured and three times the amount of money was invested in the inventory.

There are many costs associated with the over investment. Three of these costs are:

- Holding Cost

- Opportunity Cost
- Time Value Cost

The simplest cost to discuss is the holding cost. Holding costs are the cost of warehousing, security, theft, errors, and obsolescence. The procurement of an over investment will directly increase warehousing and security. An increase in the amount of material on hand will increase space requirements. This could also result in an increase in security personnel. The loses due to theft, errors and obsolescence are more of an indirect cost. The longer an item has to remain in a warehouse or on inventory records, the greater the chance items will be stolen or record keeping errors occur. If large amounts of material are procured and warehoused, there could be a greater chance that the material will no longer be needed and have to be disposed.

The opportunity cost is not a physical cost. The opportunity cost is the cost of foregoing the purchase of some other material. The benefit that could have been derived from buying less of the original item and some amount of another item is the cost that is incurred. Criticality of the items is also important in consideration of the opportunity cost. If the criticality of the initial item is much lower than the foregone item the opportunity cost would be higher.

The time value of money is also a consideration. This concept is central to many cost benefit analysises. The idea that a dollar to be received at a later date is worth less than a dollar today is used extensively in financial management systems. The over investment of a given item in excess of the lead-time demand would need to be discounted back to the end of the procurement lead-time to effectively judge the true cost. The cost savings of putting off the long supply procurement must be discounted into the future to determine that value.

Assume an item with the following characteristics:[11]

Cost = $150 per unit
Procurement Lead Time = 8 quarters
Demand = 10 per Quarter
Discount Rate = 10% (0.10)
Units Procured = 200 each

[11] This example does not include risk or safety levels, transportation time, administrative time, holding costs, and opportunity costs. The example also assumes constant, predictable demand and instantaneous resupply.

Three years over investment has been made. This is calculated by:

200 each-10 demands times 8 quarters =
120 each 10 units per quarters = 12 quarters

Using the standard present value formula given in equation 5.11, the present value of the over investment can be calculated. A_n is the annual dollar amount for year n and i is the discount rate.

$$P.V. = (A_n (1 / (1 + i)^n)) \text{ for all } n \qquad \text{(eqn 5.11)}$$

The results are given in equation 5.12.

$$P.V. = 6000^*(.909) + 6000(.826) + 6000(.751) = \$14,916 \qquad \text{(eqn 5.12)}$$

At the end of the procurement lead-time the same amount of material could be procured for $18,000 ($150*12quarters*10each quarter), assuming no price changes. The value of the over investment at the end of the procurement lead-time in equation 5.12 is $14,916. This appears to be a savings of $3,084. However, the $18,000 value that was needed at the end of the procurement lead-time has been available for other uses for two (2) years. The $18,000 must be also be discounted over the two years.

This results in a value as shown in equation 5.13. This is the future value of $18,000 two years hence or at the end of the procurement lead-time. The difference is the time value of the $18,000, which is $3,780. The time values of both the original over investment and the savings of procurement at the end of the initial procurement lead-time are now compared at the same point in time. The over investment of three years worth of material resulted in a savings of $3,084. The savings of waiting until the end of the procurement lead-time is $3,780. By over investment of three years the inventory cost would be $696 more than if the reprocurement took place at the end of the procurement lead-time.

$$F.V.(18000) = ((1 + 0.1)^2) * 18,000 = \$21,780 \qquad \text{(eqn 5.13)}$$

Of course, this analysis ignores other relevant costs such as ordering costs and stockout costs, the savings of which may exceed the cost of long supply.

2. **Short Supply (Under Investment)**

The total costs of under investment are the result of a number of individual costs similar to that of long supply. Some components of under investment are:

- Shortage Costs
- Less than an Economic Order Quantity (Administrative Costs)
- Premium Pay

The first cost associated with under investment is the shortage cost discussed in Chapter Two. The shortage cost is an artificial estimate of the value of having a given item missing from the system or component. This is the most difficult cost to determine. A redundant item or one whose failure does not cause a system to become inoperative should have a low shortage cost. A component of a non-critical system would also have a relatively low shortage cost. The shortage cost would increase as the criticality of the component to the system increases and or the criticality of the system to the mission increases.

Essential items or systems would be assigned a high shortage cost. A component that is essential to the mission of the ship or squadron would have a shortage cost equivalent to the cost of not performing the assigned mission. The shortage cost is usually assigned subjectively by the expert opinion method of decision making. Shortage costs are often set at the same value for items of differing criticality.

Administrative cost is the physical cost of preparing a procurement. This includes the cost of personnel time to negotiate, prepare, and forward the procurement documentation to the supplier. Additional expenditures of funds will have to be made to procure the needed item if a shortage occurs.

The material that is in short supply could have a sufficient level of criticality that the item is required for immediate use. Emergency procurements of this nature can be completed and the material manufactured in less than the normal procurement lead-time. This could require the producer to tool up, man up, and start up the production line for one item. This would be at a cost higher than a procurement of an EOQ lot size. The urgency of need might force the procuring activity to request accelerated manufacture of the item. This could be accomplished by the use of labor intensive measures and/or overtime operations.

All of the intensive methods discussed above are accomplished by offering the producer some level of premium pay. Premium pay is compensation for rapid completion. This is a real cost that should be included in the shortage cost of material.

3. The Item Manager's Role

There are costs associated with over investment and under investment. Grossly excessive material inventories or large numbers of back orders are cause for concern.

The item manager is responsible for the management of the items, including limiting over and under investment. The item manager's role in maintaining the procurement lead-time was discussed in Chapter Four. The item manager can also change the procurement lead-time to more closely reflect that of the real world. The item manager can change other parameters in controlling the inventory level.

The level of quarterly demand at the inventory control points is set by use of the D01 Levels Program. The majority of items are handled automatically and never reach the attention of the item manager. In certain cases the item manager can change the D01 parameters when it is known that certain outside factors are expected to change demand patterns. An example would be an item that is required for a monthly preventive maintenance program. If the requirement were changed from monthly to weekly, the demand would increase. If the item manager is made aware of the change the demand levels can be increased. This would eliminate the likelihood of short supply. Shortages will likely occur in this case unless the item manager has the information prior to one procurement lead-time from the time of implementation. This is often the case since Integrated Logistics Support (ILS) is available to ensure early identification and subsequent prior planning.

The item manager is also made aware of impending reductions in material requirements. This is most often caused by the retirement or disposal of a system or component. With early notification the item manager can reduce the level of demand and ensure minimum quantities are on hand at the time of system phase out.

VI. CONCLUSIONS AND RECOMMENDATIONS

This study was directed toward investigating operating-hours-based demand forecasting for inventory management. The major components of the model have been discussed and examined with two actual data sets. Two broad areas of discussion have resulted from this study. The first is observations concerning operating hours. The second is future studies and recommendations.

A. OPERATING HOURS BASED MANAGEMENT

The basic operating hours model was discussed. Three models were also presented that incorporate operating hours. These models go beyond the basic forecast of lead-time demand. The models address such problems as risk or uncertainty, calculation of safety levels, repair facilities and repair turn around times, and surges in operating tempo.

There are two central attributes concerning operating hours based management. The first concerns the relationship of operating hours to demand. The second area includes the financial results of an operating hours based model.

1. Relationship of Operating Hours to Demand

Throughout this paper there has been the unstated assumption that a relationship exists between the number of operating hours and the resulting demand for repair parts. This concept seems intuitive to the manager of repair parts. Consider, for example, a taxicab company with a fleet of cars. The cars operate X hours during the last year during which the company required replacements for Y tires. The following year the company expects to operate 2X hours. How many tires can the company expect to use next year? The intuitive response would be 2Y number of tires.

The above example implicitly assumes that tire usage was at a steady state with a constant replacement factor. If the tire usage were at steady state, the operating hours model might provide a good approximation for tire usage. If vehicles and tires had been replaced over many iterations, the assumption of a steady state should apply. The forecast of future operating hours would then lead to a forecast of tire usage over the forecast period.

2. Self-Correcting Inventory Management Procedures

The operating hours algorithm, Program Data Expansion (PDE), was used to demonstrate the accuracy of the model. The results are contained in Table 8. The data were received from the Navy Ships Parts Control Center. The data were used in presentations of the PDE model to the Commanding Officer of SPCC and to the Naval Supply Systems Command (NAVSUP).

TABLE 8

RESULTS OF LM-2500 PREDICTED AND ACTUAL DEMAND

Nomenclature	N. S. N.	Date	Predicted Demand	Actual Demand
Starter	01-205-2517	Jul 83	22.8	23.5
		Dec 83	32.1	35.5
Flame Signal	00-602-6815	Jul 83	6.7	8.0
		Dec 83	8.1	9.5
Valve, Btyfy	00-613-7245	Jul 83	8.2	8.7
		Dec 83	11.2	13.2
Nozzle, Fuel	00-613-7235	Jul 83	46.6	45.5
		Dec 83	42.4	44.5
Valve Assy	01-062-4127	Jul 83	3.6	4.5
		Dec 83	3.8	4.2

The predicted values agree closely with the actual results at the end of the lead-times. It was demonstrated in Chapter Three that the predicted operating hours on the LM-2500 were overstated. The hypothesis that forecast operating hours was equal to actual operating hours was rejected. In Chapter Four the procurement lead-time forecasts were tested. The hypothesis that forecast procurement lead-times were equal to actual lead-times could not be rejected.

If the operating hours element of the forecast for lead time demand is significantly in error, the resulting budget estimates should be incorrect. If the forecast for operating hours is overstated then the forecast for lead-time demand will also be overstated.

There are two inputs, one which is believed to be accurate and one which is believed to be inaccurate. The expected result using these inputs would be a forecast of demand which is not accurate. This is not the case as demonstrated in Table 8. The output appears to be reasonable. This leads to the conclusion that some external forces are acting on the model causing good forecasts. The external force appears to be the item manager. It is the responsibility of the item manager to "scrub" the data elements prior to executing the procurement, levels, or budget programs. This is apparently what occurs.

The item manager reviews items when a demand is experienced, when a repair action is initiated, and at many other instances when various data elements exceed given standards. The item manager can force an exception report by certain coding of the item. This results in the item manager reviewing the item many times between procurements allowing corrections to be made. The result is that the item manager acts as a self-correcting factor when operating hours, procurement lead-time, or demand are over- or understated.

B. PREDICTING OPERATING HOURS

There are two areas in predicting operating hours that deserve attention. The first is a discussion of program data versus forecasting models. The second is predictions based upon forecasting models with expert opinion inputs allowed.

1. Program Data versus Forecasting Models

Program data for the LM-2500 is based on expert opinion. The data show little pattern in the actual hours observations, but a steadily increasing prediction of operating hours. The correlation of the actual operating hours to predicted operating hours was less than 6.4%. The results of operations are apparently not being fed back into the program data. The program data does not reflect the real world operations. Without a feedback mechanism the predictions are likely not to improve.

2. Forecasting Models with Expert Opinion

If a forecasting model predicted future events accurately 100% of the time, the job of managing an inventory would be simple. Forecasting models do not provide complete accuracy.

Four models were used to forecast future operating hours. Two of the models, exponential smoothing and moving averages, did not work well with the LM-2500 data. The correlation between the actual and predicted demands was approximately 8%. The White Exponential Smoothing model with a Seasonal Trend provided improved forecasts with a correlation of 20%. The best performing model was the trended forecast with seasonal factors. This model achieved an R-squared value of 58.6%.

C. FUTURE STUDIES

There are many operating hours related subjects that have been left unaddressed. There are three study areas that the writer recommends be undertaken. The first is an investigation of the relationship between operating tempo and actual operating hours. The second would be the hybridization of the operating-hours models with demand-based models. The third is the utilization of operating hours as a basis for performing Follow-On Supply Support (FOSS).

1. The Functional Relationship between Operating Tempo and Actual Operating Hours

Operating tempo of various fleet units impact directly on the number of operating hours. As the tempo increases the demand for both aircraft and shipboard operations will increase.

The relationship of operating hours to tempo is one important relationship. The relationship between operating hours and operating budget is another. The budgeting of aircraft operations at the squadron level is accomplished by the Flying Hours Program. Aircraft have a fairly constant and known average cost per operating hour. This is made up of the cost of maintenance, personnel and facilities. The largest cost is that for fuel. Ships, including gas turbine, steam, and diesel powered, have a known average cost per operating hour.

Can this factor included in an overall model of operational requirements? A model explaining these inter-relationships would be helpful to both the operating hours and demand forecasting methods.

2. Hybrid Based Model (Demand Levels Interfaced with Operating Hours)

The models discussed in this paper have been based on historical operating hours. A model could be developed that relies on both demand and operating hours.

It would be useful to develop a model that utilizes historical operating hours in terms of demand and historical demand patterns. This would be a model that trends and seasonalizes demand patterns while trending and seasonalizing operating hours.

3. Operating Hours Used to Predict Follow-on Supply Support (FOSS)

Follow-on supply support (FOSS) is a method of providing increased levels of support for a new system. Where there is sufficient demand, the D01 Levels Program will forecast requirements and parts will be stocked.

There are no historical demand patterns on a new system. The system must undergo a period of demand development. During this period of approximately two years the actual demands for the component items of the new system are recorded. At the end of the period, requirements are generated the same as with any other system.

The problem is that during the demand development period there would normally be no material or parts to support the system. It is the goal of FOSS to overcome this problem. FOSS uses a Time Weighted Average Month Program (TWAMP) in conjunction with a predicted Technical Replacement Factor (TRF). The TWAMP is the number of units to be operational during any given month. The TRF is an estimate of how many parts will be required per unit per month. The repair parts requirements for each member assembly can then be estimated. The estimates are then entered into the data base as projected future demands.

This lengthy and cumbersome system could be replaced by a system of requirements based on the increasing operating hours of the system. This is what the Program Data Expansion (PDE) model was intended to do for the LM-2500.

The operating hours model used to replace FOSS must be sensitive to low levels of operations. This is due in part to the concept of "infant mortality". This occurs when a system experiences a large number of failures early in the installation and operational period. The failures tend to lessen as the system matures.

Since a large amount of the FOSS/PPR system is checked and loaded into the ICP data base manually, an improvement over the FOSS system would be cost effective.

D. SPECIFIC RECOMMENDATIONS

There are two specific recommendations resulting from this study. The first is a recommendation to the Navy Ships Parts Control Center to establish a method for forecasting LM-2500 operating hours. The second is to put increased emphasis on the Program Data Expansion model.

1. Use of Forecasting Models for Operating Hours

It is recommended that a forecasting model be incorporated in planning for LM-2500 operations and hours. A seasonal model with a trend estimate is recommended.

If it is desired that the models not operate completely independently, expert opinion considerations could be included. This would take the form of modifying (increase or decrease) the forecasts based upon known operational requirements. For example, if it is known that a fleet exercise is planned for sometime in the forecast future, the operating hours could be increased above the model forecasts.

2. The PDE Model

The Program Data Expansion (PDE) model operates well enough to make its application worthwhile. The PDE model forecasts demands relatively well even though the operating hours input to the model is suspect. This is believed to be the result of the efforts of the item managers. Their constant review of items results in "fine tuning" the system.

The PDE model would be even more effective, and less time consuming for the item managers, if the operating hours used to forecast demand were forecast better.

APPENDIX A

PREDICTED AND ACTUAL OPERATING HOURS

LM-2500 Predicted and Actual Operating Hours

Date	Total Hours Predict	Total Hours Actual	DDG-993 Hours Predict	DDG-993 Hours Actual	CG-47 Hours Predict	CG-47 Hours Actual
10/82	14,379	17,452	482	1,103	-0-	-0-
11/82	15,918	17,159	1,332	1,331	-0-	-0-
12/82	22,477	14,677	1,820	1,004	455	884
01/83	22,740	16,177	1,820	1,501	455	-0-
02/83	23,002	17,426	1,820	1,861	455	1,082
03/83	23,457	21,701	1,820	1,730	455	605
04/83	23,540	20,693	1,820	2,046	455	669
05/83	24,065	22,730	1,820	1,341	455	712
06/83	24,328	21,994	1,820	1,598	455	167
07/83	24,328	21,279	1,820	2,008	455	259
08/83	24,590	23,498	1,820	2,196	455	185
09/83	25,115	21,431	1,820	2,186	455	697
10/83	25,365	28,078	1,820	2,673	455	570
11/83	25,365	27,632	1,820	2,795	455	747
12/83	25,628	17,115	1,820	1,012	455	904
01/84	25,890	21,317	1,820	1,451	455	578
02/84	25,890	27,214	1,820	1,408	455	725
03/84	26,153	25,898	1,820	1,750	455	914
04/84	26,153	30,243	1,820	1,584	455	1,342
05/84	26,415	20,616	1,820	1,470	455	87
06/84	27,133	28,620	1,820	1,784	910	378
07/84	27,133	20,701	1,820	1,801	910	576
08/84	27,395	23,791	1,820	1,226	910	394
09/84	27,658	21,405	1,820	1,854	910	624
10/84	27,658	27,439	1,820	2,709	910	694
11/84	27,920	27,503	1,820	1,700	910	153
12/84	27,920	15,257	1,820	501	910	10
01/85	27,920	19,049	1,820	917	910	707
02/85	27,920	19,702	1,820	1,380	910	1,120
03/85	28,183	23,243	1,820	1,753	910	532
04/85	28,708	23,603	1,820	2,112	910	988
05/85	28,708	22,567	1,820	831	910	1,670
06/85	29,163	24,908	1,820	2,345	1,365	540
07/85	29,425	31,178	1,820	3,364	1,365	1,801
08/85	29,425	26,299	1,820	1,821	1,365	1,212
09/85	29,688	25,551	1,820	2,035	1,365	2,573
10/85	29,688	26,158	1,820	1,424	1,365	2,400
11/85	29,950	24,997	1,820	1,407	1,365	1,433
12/85	30,405	13,642	1,820	1,043	1,820	856
01/86	30,405	15,729	1,820	584	1,820	478

Date	PHM-1/3 Hours Predict	Actual	FFG-7 Hours Predict	Actual	Hot Plant Predict	Actual
10/82	10	92	3,564	4,732	-0-	-0-
11/82	22	73	4,404	5,343	-0-	-0-
12/82	252	242	6,300	4,790	-0-	-0-
01/83	252	142	6,563	5,206	-0-	-0-
02/83	252	306	6,825	5,386	-0-	-0-
03/83	252	104	6,825	6,084	-0-	-0-
04/83	252	170	6,825	5,216	83	54
05/83	252	89	7,350	6,979	83	10
06/83	252	143	7,613	7,090	83	16
07/83	252	130	7,613	6,779	83	-0-
08/83	252	225	7,875	7,753	83	8
09/83	252	101	8,400	6,815	83	3
10/83	252	192	8,400	8,737	333	1
11/83	252	377	8,400	8,286	333	49
12/83	252	110	8,663	6,741	333	17
01/84	252	180	8,925	7,481	333	9
02/84	252	308	8,925	9,864	333	11
03/84	252	293	9,188	9,988	333	25
04/84	252	261	9,188	12,160	333	2
05/84	252	221	9,450	7,793	333	10
06/84	252	263	9,713	9,939	333	36
07/84	252	318	9,713	8,340	333	7
08/84	252	394	9,975	9,618	333	4
09/84	252	277	10,238	8,693	333	15
10/84	252	280	10,238	9,235	333	15
11/84	252	423	10,500	9,227	333	8
12/84	252	304	10,500	5,958	333	7
01/85	252	123	10,500	8,221	333	7
02/85	252	99	10,500	7,707	333	7
03/85	252	341	10,763	9,301	333	15
04/85	252	242	11,288	9,680	333	5
05/85	252	223	11,288	10,307	333	10
06/85	252	350	11,288	10,261	333	17
07/85	252	447	11,550	12,078	333	17
08/85	252	484	11,550	12,679	333	20
09/85	252	225	11,813	11,518	333	24
10/85	252	239	11,813	11,461	333	21
11/85	252	368	12,075	11,649	333	11
12/85	252	124	12,075	4,980	333	6
01/86	252	291	12,075	7,028	333	8

Date	DD-963 Hours Predict	DD-963 Hours Actual
10/82	10,323	11,525
11/82	10,160	10,412
12/82	13,650	7,757
01/83	13,650	9,328
02/83	13,650	8,791
03/83	14,105	13,178
04/83	14,105	12,538
05/83	14,105	13,599
06/83	14,105	12,980
07/83	14,105	12,103
08/83	14,105	13,131
09/83	14,105	11,629
10/83	14,105	15,905
11/83	14,105	15,378
12/83	14,105	8,331
01/84	14,105	11,618
02/84	14,105	14,898
03/84	14,105	12,928
04/84	14,105	14,894
05/84	14,105	11,035
06/84	14,105	16,220
07/84	14,105	9,659
08/84	14,105	12,155
09/84	14,105	9,942
10/84	14,105	14,456
11/84	14,105	15,992
12/84	14,105	8,477
01/85	14,105	9,074
02/85	14,105	9,389
03/85	14,105	11,301
04/85	14,105	10,576
05/85	14,105	9,526
06/85	14,105	11,395
07/85	14,105	13,471
08/85	14,105	10,083
09/85	14,105	9,176
10/85	14,105	10,613
11/85	14,105	10,129
12/85	14,105	6,633
01/86	14,105	7,340

Air Force Flying Hours Predicted and Actual

Aircraft: A-7D	1975	1976	1977	1978
Actual Hours	95,802	86,401	109,509	101,040
Predicted Hours	98,318	105,431	99,604	97,716
Aircraft: B-52D,G,H	1975	1976	1977	1978
Actual Hours	151,029	136,076	136,453	133,936
Predicted Hours	182,039	157,702	136,120	136,310
Aircraft: C-5A	1975	1976	1977	1978
Actual Hours	50,522	42,235	49,388	48,281
Predicted Hours	75,236	69,952	41,592	41,288
Aircraft: KC-135A	1975	1976	1977	1978
Actual Hours	206,310	188,709	187,298	192,331
Predicted Hours	236,584	210,278	203,492	204,095
Aircraft: C-141A	1975	1976	1977	1978
Actual Hours	303,009	298,657	291,074	289,763
Predicted Hours	409,738	339,324	286,156	283,864
Aircraft: F-4C,D,E,R	1975	1976	1977	1978
Actual Hours	428,626	406,193	418,316	395,331
Predicted Hours	466,768	513,623	455,037	431,016
Aircraft: F-111A,D,F	1975	1976	1977	1978
Actual Hours	63,397	51,165	52,766	45,452
Predicted Hours	73,359	85,451	72,316	73,019

Totals				
Actual Hours	1,298,695	1,209,436	1,244,804	1,206,134
Predicted Hours	1,542,542	1,481,671	1,294,317	1,267,308

APPENDIX B

LM-2500 REGRESSION AND HYPOTHESIS TESTING

```
REGRESSION OF PREDICTED LM-2500 OPERATING HOURS
-----------------------------------------------

 The regression equation is
 PREDICT = 20868 + 259 TIME

 Predictor        Coef          Stdev     t-ratio
 Constant      20868.3          508.6       41.03
 TIME           259.11          21.62       11.99

 s = 1578         R-sq = 79.1%      R-sq(adj) = 78.5%

 Analysis of Variance

 SOURCE         DF          SS            MS
 Regression      1   357851136     357851136
 Error          38    94654352       2490904
 Total          39   452505344

 Unusual Observations
 Obs.     TIME    PREDICT        Fit Stdev.Fit  Residual    St.Resid
   1       1.0      14379      21127       490     -6748      -4.50R
   2       2.0      15918      21386       471     -5468      -3.63R

 R denotes an obs. with a large st. resid.
```

```
REGRESSION OF ACTUAL LM-2500 OPERATING HOURS
--------------------------------------------

 The regression equation is
 ACTUAL = 20382 + 98.0 TIME

 Predictor        Coef          Stdev     t-ratio
 Constant        20382           1420       14.35
 TIME            98.03          60.36        1.62

 s = 4407         R-sq = 6.5%      R-sq(adj) = 4.0%

 Analysis of Variance

 SOURCE         DF          SS            MS
 Regression      1    51219696      51219696
 Error          38   737935104      19419344
 Total          39   789154560

 Unusual Observations
 Obs.     TIME     ACTUAL        Fit Stdev.Fit  Residual    St.Resid
  39      39.0      13642      24205      1316    -10563      -2.51R
  40      40.0      15729      24303      1368     -8574      -2.05R
 R denotes an obs. with a large st. resid.
```

LISTING OF LM-2500 PREDICTED, ACTUAL HOURS AND DIFFERENCE

ROW	PREDICT	ACTUAL	DIFF
1	14379	17452	-3073
2	15918	17159	-1241
3	22477	14677	7800
4	22740	16177	6563
5	23002	17426	5576
6	23457	21701	1756
7	23540	20693	2847
8	24065	22730	1335
9	24328	21994	2334
10	24328	21279	3049
11	24590	23498	1092
12	25115	21431	3684
13	25365	28078	-2713
14	25365	27632	-2267
15	25628	17115	8513
16	25890	21317	4573
17	25890	27214	-1324
18	26153	25898	255
19	26153	30243	-4090
20	26415	20616	5799
21	27133	28620	-1487
22	27133	20701	6432
23	27395	23791	3604
24	27658	21405	6253
25	27658	27439	219
26	27920	27503	417
27	27920	15257	12663
28	27920	19049	8871
29	27920	19702	8218
30	28183	23243	4940
31	28708	23603	5105
32	28708	22567	6141
33	29163	24908	4255
34	29425	31178	-1753
35	29425	26299	3126
36	29688	25551	4137
37	29688	26158	3530
38	29950	24997	4953
39	30405	13642	16763
40	30405	15729	14676

DESCRIPTION OF THE DATA

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
PREDICT	40	26180	26774	26558	3406	539
ACTUAL	40	22392	22280	22387	4498	711
DIFF	40	3788	3644	3535	4654	736

	MIN	MAX	Q1	Q3
PREDICT	14379	30405	24393	28577
ACTUAL	13642	31178	19212	26093
DIFF	-4090	16763	295	6225

T-TEST OF THE DIFFERENCE IN ACTUAL AND PREDICTED HOURS

TEST OF MU = 0 VS MU N.E. 0

	N	MEAN	STDEV	SE MEAN	T	P VALUE
DIFF	40	3788	4654	736	5.15	0.0000

TWO SAMPLE TEST OF ACTUAL AND PREDICTED OPERATING HOURS

TWOSAMPLE T FOR PREDICT VS ACTUAL

	N	MEAN	STDEV	SE MEAN
PREDICT	40	26180	3406	539
ACTUAL	40	22392	4498	711

95 PCT CI FOR MU PREDICT - MU ACTUAL: (2009, 5567)
TTEST MU PREDICT = MU ACTUAL (VS NE): T=4.25 P=0.0001 DF=72.7

ANALYSIS OF VARIANCE OF ACTUAL AND PREDICTED OPERATING HOURS

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F
FACTOR	1	287020800	287020800	18.03
ERROR	78	1.242E+09	15918614	
TOTAL	79	1.529E+09		

```
                                                 INDIVIDUAL 95 PCT CI'S FOR MEAN
                                                 BASED ON POOLED STDEV
LEVEL        N       MEAN      STDEV   -----+---------+---------+---------+-
PREDICT     40      26180       3406                        (-----*-----)
ACTUAL      40      22392       4498    (-----*-----)
-   -   -   -   -   -   -    -    -    -----+---------+---------+---------+-
POOLED STDEV =      3990               22000     24000     26000     28000
```

APPENDIX C

HYPOTHESIS TESTING OF AIR FORCE OPERATING HOURS

LISTING OF AIR FORCE PREDICTED, ACTUAL HOURS, AND PERCENT ERROR

ROW	PREDICT	ACTUAL	%ERROR
1	98318	95802	0.026262
2	105431	86401	0.220252
3	99604	109509	-0.090449
4	97716	101040	-0.032898
5	182039	151029	0.205325
6	157702	136076	0.158926
7	136120	136453	-0.002440
8	136310	133936	0.017725
9	75236	50522	0.489173
10	69952	42235	0.656257
11	41592	49388	-0.157852
12	41288	48281	-0.144840
13	236584	206310	0.146740
14	210278	188709	0.114298
15	203492	187298	0.086461
16	204095	192331	0.061165
17	409738	303009	0.352230
18	339324	298657	0.136166
19	286156	291074	-0.016896
20	283864	289763	-0.020358
21	466768	428626	0.088987
22	513623	406193	0.264480
23	455037	418316	0.087783
24	431016	395331	0.090266
25	73859	63397	0.165024
26	85451	51165	0.670106
27	72316	52766	0.370504
28	73019	45452	0.606508

DESCRIPTION OF THE DATA

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
PREDICT	28	199497	147006	193501	144216	27254
ACTUAL	28	177110	136264	172623	127505	24096
%ERROR	28	0.1625	0.1023	0.1553	0.2250	0.0425

	MIN	MAX	Q1	Q3
PREDICT	41288	513623	77790	285583
ACTUAL	42235	428626	55424	290746
%ERROR	-0.1579	0.6701	0.0026	0.2534

T-TEST OF THE PERCENT ERROR BETWEEN ACTUAL AND PREDICTED HOURS

TEST OF MU = 0.0000 VS MU N.E. 0.0000

	N	MEAN	STDEV	SE MEAN	T	P VALUE
%ERROR	28	0.1625	0.2250	0.0425	3.82	0.0007

TWO SAMPLE TEST OF ACTUAL AND PREDICTED OPERATING HOURS

TWOSAMPLE T FOR PREDICT VS ACTUAL

	N	MEAN	STDEV	SE MEAN
PREDICT	28	199497	144216	27254
ACTUAL	28	177110	127505	24096

95 PCT CI FOR MU PREDICT - MU ACTUAL: (-50595, 95371)
TTEST MU PREDICT = MU ACTUAL (VS NE): T=0.62 P=0.54 DF=53.2

ANALYSIS OF VARIANCE OF ACTUAL AND PREDICTED OPERATING HOURS

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F
FACTOR	1	7.017E+09	7.017E+09	0.38
ERROR	54	1.001E+12	1.853E+10	
TOTAL	55	1.008E+12		

```
                                          INDIVIDUAL 95 PCT CI'S FOR MEAN
                                          BASED ON POOLED STDEV
LEVEL        N      MEAN      STDEV   ---------+---------+---------+-------
PREDICT     28    199497     144216         (------------*------------)
ACTUAL      28    177110     127505   (------------*------------)
                                          ---------+---------+---------+-------
POOLED STDEV =    136117                     160000    200000    240000
```

APPENDIX D

SELECTED LM-2500 LEAD TIMES

Stock Number	Nomenclature	Forecast Lead Time	Actual Lead Time
7HH 2835-00-596-6273	Thermocouple, Top	12.11	10.76
7HH 2835-00-601-1039	Valve, Gas Turbine	8.41	[illegible]
1HM 2835-00-601-1048	Nozzle, Turbine	12.05	[illegible]
7HH 2835-00-601-1054	Actuater, Power	7.00	[illegible]
7HH 2835-00-601-1236	Sensor, Control	13.98	[illegible]
7HH 2835-00-602-6653	Manifold Assembly	11.58	[illegible]
7HH 2835-00-602-6779	Harness, Thermocou	12.18	[illegible]
7HH 2835-00-602-6786	Thermocouple, Turb	9.72	[illegible]
7HH 2835-00-602-6815	Signal, Flame	11.08	[illegible]
7HH 2835-00-602-6823	Detector, Flame	12.02	[illegible]
7HH 2835-00-602-6836	Detector, Turbine	13.78	[illegible]
1HS 2835-00-602-7089	Blade, Turbine	8.00	[illegible]
1HS 2835-00-602-8050	Transducer, Gas Tu	4.35	[illegible]
7HH 2990-00-611-9596	Starter, Engine	12.00	[illegible]
1HS 2835-01-005-8465	Manifold, Gas Turb	9.00	[illegible]
7HH 2835-01-037-2883	Actuater, Damper	11.73	[illegible]
1HS 2990-01-060-3137	Shaft Assembly	8.30	[illegible]
7HH 2835-01-092-3061	Actuater, Power	7.00	[illegible]
7HH 2835-01-093-1372	Actuater, Power	9.33	[illegible]
1HS 2835-01-107-0765	Blade, Turbine	10.60	[illegible]
1HS 2835-01-108-6297	Blade, Turbine	11.60	[illegible]
1HS 2835-01-116-7313	Blade, Turbine	10.60	[illegible]
1HS 2835-01-117-5564	Blade, Turbine	9.00	[illegible]
7HH 2835-01-205-3244	Main Fuel Control	12.00	11.89
7HH 2990-01-205-2517	Starter, Pneumatic	7.20	6.88
7HH 2990-01-205-7065	Starter, Engine	12.00	12.45

APPENDIX E

LM-2500 LEAD TIME HYPOTHESIS TESTING

Predicted, Actual and Difference Data

ROW	PREDICT	ACTUAL	DIFF
1	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]
5	13.93	14.2?	[illegible]
6	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]
11	[illegible]	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]
13	[illegible]	[illegible]	[illegible]
14	[illegible]	[illegible]	[illegible]
15	[illegible]	[illegible]	[illegible]
16	[illegible]	[illegible]	[illegible]
17	[illegible]	[illegible]	[illegible]
18	[illegible]	[illegible]	[illegible]
19	[illegible]	[illegible]	[illegible]
20	[illegible]	[illegible]	[illegible]
21	[illegible]	[illegible]	[illegible]
22	[illegible]	[illegible]	[illegible]
23	[illegible]	8.47	[illegible]
24	[illegible]	[illegible]	[illegible]
25	[illegible]	[illegible]	[illegible]
26	[illegible]	[illegible]	[illegible]

Description of the Data

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
PREDICT	26	10.255	10.840	10.345	2.346	0.460
ACTUAL	26	10.243	10.935	10.300	2.423	0.475
DIFF	26	0.012	-0.075	-0.007	0.696	0.137

	MIN	MAX	Q1	Q3
PREDICT	4.350	13.980	8.382	12.005
ACTUAL	4.910	14.210	8.407	12.022
DIFF	-1.220	1.690	-0.582	0.507

Results of the t-test

TEST OF MU = 0.000 VS MU N.E. 0.000

	N	MEAN	STDEV	SE MEAN	T	P VALUE
DIFF	26	0.012	0.696	0.137	0.09	0.93

Results of the Two Sample Test

TWOSAMPLE T FOR PREDICT VS ACTUAL

	N	MEAN	STDEV	SE MEAN
PREDICT	26	[illegible]	[illegible]	0.46
ACTUAL	26	[illegible]	[illegible]	0.48

95 PCT CI FOR MU PREDICT - MU ACTUAL: (-1.32, 1.34)
TTEST MU PREDICT = MU ACTUAL (VS NE): T=0.02 P=[illegible] DF=49.9

Results of the Analysis of Variance

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	F
FACTOR	[illegible]	[illegible]	[illegible]	[illegible]
ERROR	[illegible]	[illegible]	[illegible]	
TOTAL	[illegible]	[illegible]		

```
                                          INDIVIDUAL 95 PCT CI'S FOR MEAN
                                          BASED ON POOLED STDEV
LEVEL        N       MEAN      STDEV   -----+---------------+---------------+----------+-
PREDICT     [illegible] [illegible] [illegible]   (---------------*---------------)
ACTUAL      [illegible] [illegible] [illegible]    (--------------*--------------)
                                        -----+---------------+---------------+----------+-
POOLED STDEV = [illegible]                   9.60          10.20           10.80      11.40
```

APPENDIX F

RESULTS OF SEASONAL REGRESSION

The Data Elements Used in the Regression

ROW	t	HOURS	Q2	Q3	Q4
1	1	48013	0	0	0
2	2	59820	1	0	0
3	3	66003	0	1	0
4	4	73007	0	0	1
5	5	66064	0	0	0
6	6	83355	1	0	0
7	7	69937	0	1	0
8	8	72635	0	0	1
9	9	61809	0	0	0
10	10	66548	1	0	0
11	11	78653	0	1	0
12	12	78008	0	0	1
13	13	54368	0	0	0

The Description of the Operating Hours Data

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
HOURS	13	67555	66548	67896	9990	2771

	MIN	MAX	Q1	Q3
HOURS	48013	83355	60814	75507

Results of the Regression

The regression equation is
HOURS = 52507 + 722 t + 13067 Q2 + 13967 Q3 + 16264 Q4

Predictor	Coef	Stdev	t-ratio
Constant	52507	5721	9.18
t	722.4	593.3	1.22
Q2	13067	6040	2.16
Q3	13967	6011	2.32
Q4	16264	6040	2.69

s = 7871 R-sq = 58.6% R-sq(adj) = 37.9%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	4	701979392	175494848
Error	8	495575040	61946880
Total	12	1197554432	

SOURCE	DF	SEQ SS
t	1	109333888
Q2	1	38978576
Q3	1	104574912
Q4	1	449092096

Unusual Observations

Obs.	t	HOURS	Fit	Stdev.Fit	Residual	St.Resid
6	6.0	83355	69908	4544	13447	2.09R

R denotes an obs. with a large st. resid.

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