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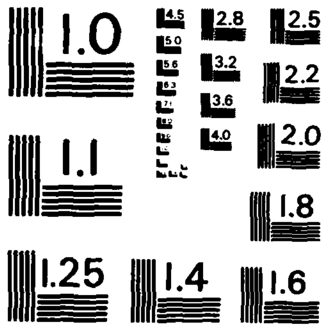

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STRATEGIC OPTIONS IN LOGISTIC SYSTEMS

by

Phillip E. Miller

A Dissertation submitted to the faculty of
The University of North Carolina at Chapel Hill
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the School of Business Administration.

Chapel Hill

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1985

Approved by:

Harry M. Wagner
Adviser

Ann E. Marucheck
Reader

Reader

PHILLIP E. MILLER. Strategic Options In Logistic Systems
(Under the direction of HARVEY M. WAGNER.)

There is a general lack of understanding the effects that implementation of logistic strategies have on systemwide performance measures.

This thesis develops a model of a multi-echelon inventory system that is comprised of three bases and a centralized repair facility. Each base has a specific level of aircraft. An aircraft is grounded if part A or part B fails and there is no immediate replacement. Part A may be repaired at base level; part B, however, can only be repaired at the depot. Both parts are repaired in the same labor constrained depot shop.

The model provides a tool to analyze alternative logistics strategies. The issues that we investigate include increasing spare levels of parts A and B, increasing repair capability at depot and base level, redesigning part A to reduce mean time between failures, and decreasing transportation time between the bases and depot. These strategies assess the merits of three redistribution rules. Additionally, these strategies are analyzed in the following two ways (1) one at a time and (2) in combination with a partial factorial design.

We believed apriori that the dynamic redistribution rule would outperform the static rule. Although a statistically significant difference was found using the

Wilcoxan signed rank test between the static and dynamic rules, any test done on a single experiment results in no difference between the rules. Looking at results from a manager's point of view, it is obvious that the different strategy combinations result in a much greater change for the performance measures than did the redistribution rules.

From the base manager's point of view, the strategies that offer the greatest impact at base level are (1) reducing transportation pipeline time and (2) altering spare levels. These strategies would be extremely expensive and would undergo close scrutiny during Air Force planning and budgeting processes.

From the viewpoint of the depot manager, the strategies that offer the greatest impact at depot level are (1) altering repair capacity at depot or base and (2) redesigning part A. The redesign of a part is a very time consuming and expensive strategy that results in minimal changes at base and depot. Additionally, the redesign and base repair strategies only affect part A with little or no effect on part B.

The strategy that increases the depot worker resource is the only one that positively affects the performance measures at both depot and base. This is the only strategy that significantly increases flights flown and reduces both parts' backorder days.

ACKNOWLEDGEMENTS

Receiving a doctorate is a major milestone in my Air Force career, as well as, my life. I certainly wish to thank many people who were instrumental in helping me achieve this milestone.

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Raymond Carroll was always available to answer questions dealing with statistical analysis. He has the ability to make the hardest concepts easy to understand and simple to accomplish.

Lou Moore was a source of information and problem-solving in my simulation development. If he had not been available to guide the direction of the simulation, many valuable hours would have been lost.

I would also like to thank Fritz Russ and Rich Ehrhardt, the last members of my committee, for being team players and important assets to a smoothly working committee.

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Last, but certainly not least, I must thank my family, Patty, Valerie, and Cindy. I could not have completed the dissertation without you. I love you all, although on many occasions I spent more time with my Sanyo computer than with you. So I thank you all for providing the loving support I needed.

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CHAPTER ONE

OVERVIEW

INTRODUCTION

Congress, the Department of Defense, and the military services have recognized the importance of relating resources and policies to logistic system performance. But they also have recognized the difficulty of establishing that relationship. Charles W. Groover, Deputy Assistant Secretary of Defense (Program Intergration), stated his belief that, "we have a fair understanding of how the logistic system operates to support our weapon systems and equipment; however, the specific functional relationships between resources and policies applied and the resulting system performance is incredibly complicated [6]." To achieve an understanding of these relationships, techniques are needed that give consistent measures across different resource groups, and consider the important interactions among resources and strategic policies at all levels of the logistics system.

During the past three decades, a substantial number of mathematical models have been developed pertaining to various aspects of component repair and resupply. These models attempt to solve some of these problems by setting specific policies and then measuring their direct effect on spare allocation and system performance. Several early models [11, 19, 20] calculated the required resource levels by using steady state, or time-averaging, techniques that do not account for surges in demand or variations in logistics support and policy decisions. This resulted in the development of a model that uses dynamic queueing equations to describe the complex behavior of the logistics system.

STEADY STATE MODELS

The METRIC (Multi-Echelon Techniques for Recoverable Item Control) model was initially developed by Craig Sherbrooke in 1966 to determine stock levels in a two-echelon (base-depot) inventory system for reparable items [21]. When reparables fail, they are repaired and returned to service rather than scrapped. Typically, these items are expensive, and their individual demand rates are low. Their proper management is extremely important to the Air Force, since over 70 percent of the total investment in spares is concentrated in reparable items.

Subsequently, John Muckstadt in 1971 developed a model for the control of a multi-item, multi-echelon, multi-indenture reparable item inventory system [16, 17, 18]. This model, called MOD-METRIC, extends Sherbrooke's METRIC model and explicitly considers a hierarchical parts structure. The model describes the logistics relationship between components and the final assembly; it then computes base and depot spare stock levels for all items. Muckstadt also developed an algorithm for finding an optimal solution to the redistribution problem. The algorithm is based on Sherbroke's marginal analysis procedure; it reduces the number of required calculations, but may find only a local optimum [17].

Nearly simultaneously, Bruce Miller formulated a Transportation Time Look Ahead policy as a simple real-time decision rule that redistributes newly available reparable items coming out of repair to a base having the greatest immediate need [12, 14]. In this case, the dynamic decision rule is optimal for a multi-state variable dynamic programming problem. Miller's heuristic rule was first developed as the Real Time METRIC (RTM) in 1968.

TIME-DEPENDENT MODEL

In 1980 the Rand Corporation developed new analytic methods for studying the transient behavior of component repair/inventory systems under time-dependent operational demands and logistics decisions. By 1982 these methods led to the development of the Dyna-METRIC model by R. Hillestad [11]. This model uses dynamic queueing equations to determine appropriate levels of system performance such as aircraft availability, fill rate, and expected backorders. Dyna-METRIC was developed primarily as a readiness assessment tool, but can determine the level of spare parts required to satisfy a given level of aircraft availability. The measure of aircraft availability is used instead of expected backorders, which was used in the previous steady-state models.

MODEL DESCRIPTION

We take as the setting for our analysis a hypothetical model of a multi-echelon system comprised of three bases and a centralized depot facility. For purposes of our discussion in this chapter, we assume that a single item is removed for repair. Figure 1.1 illustrates the flow of components from the aircraft, through all levels of supply and repair, and finally returning back to the aircraft. Additionally, key policies are identified that must be considered by the model.

COMPONENT FLOW

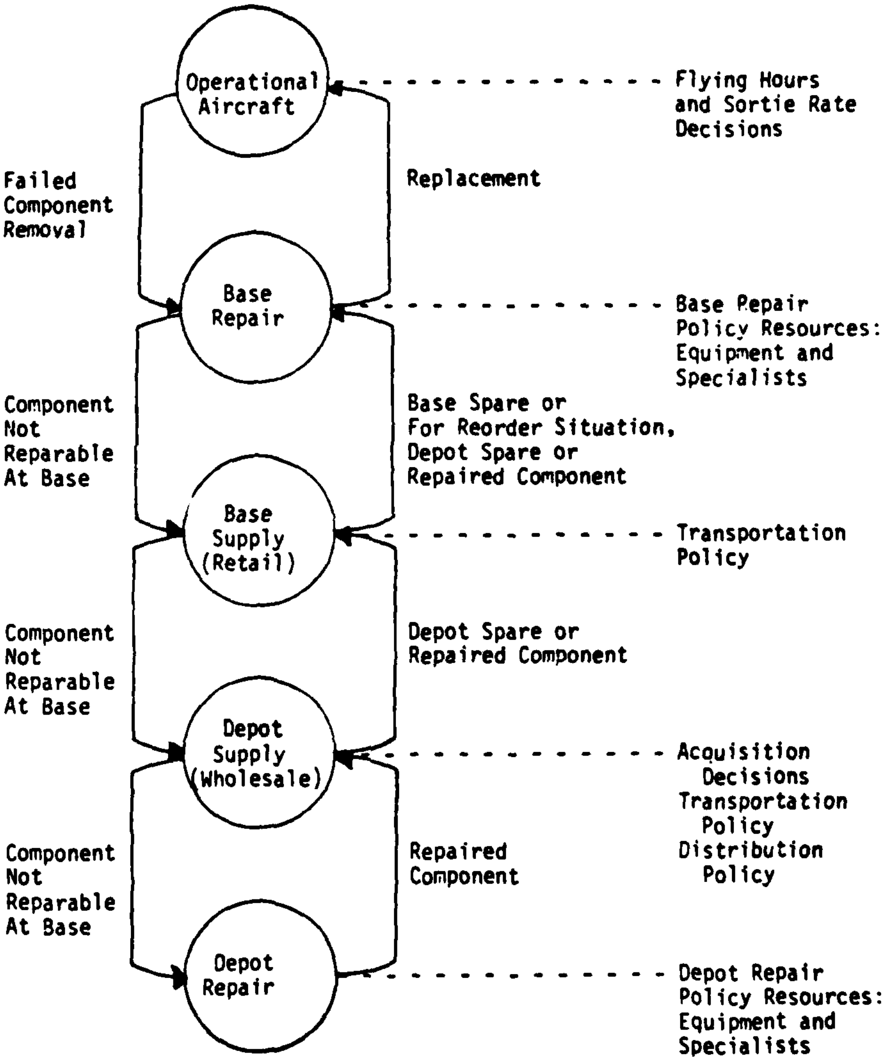


FIGURE 1.1

During normal maintenance, periodic inspection, or after inflight problems, a failed unit is removed from an aircraft. In real life, occasionally more than one unit is removed. For purposes of our multi-echelon model, however, suppose only a single reparable item is removed. After removal the unit is inspected for possible repair at base level, and then it is turned into base supply. If a serviceable is available in base supply spare stock, it is issued; otherwise, a backorder occurs.

If the unit is reparable at base level, it goes to a maintenance shop where the repair is accomplished. The serviceable is returned to base supply to clear a backorder or replace issued spare stock. If the unit cannot be repaired at base level, the reparable is packaged and shipped to depot. If a serviceable is available at depot in spare stock, it is sent to base and the reparable is placed in depot repair. When depot repair is completed, the unit is returned to depot spare stock. When the reparable arrives at depot and depot spare stock is zero, then the unit goes directly in depot repair. When the repair is completed, the serviceable is returned to the base of origin. This verbal description of the multi-echelon model underlies the mathematical model described below.

Each base j has an associated mean component failure or demand rate (λ_j) and a number of spares

(s_j) initially allocated to it. Assume that with probability r_j the unit demanded can be repaired at base level and with probability $1-r_j$ it must be shipped to the depot for repair. The round trip transportation time from base j to the depot (including administration time) is O_j. The mean base repair rate is μ_j, where D represents the mean depot repair rate. Finally, the number of spares available at base j at time t is $s_j(t)$. A simplified flow diagram of this system is shown in Figure 1.2.

The model described above can influence decisions about system-wide allocations and serviceable dispatching. The model parameters reflect strategic policy choices concerning resources assigned to repair, spares, and transportation. The next section summarizes previously published literature that is appropriate to such a system.

METRIC MODEL [21]

METRIC determines both requirements and distribution of reparable items in a two-echelon inventory system. The objective is to find base and depot spare levels that minimize total expected base level backorders. By definition, a backorder exists when demand for an item is left unsatisfied at base level. The model is not explicitly interested in depot

MODEL DIAGRAM

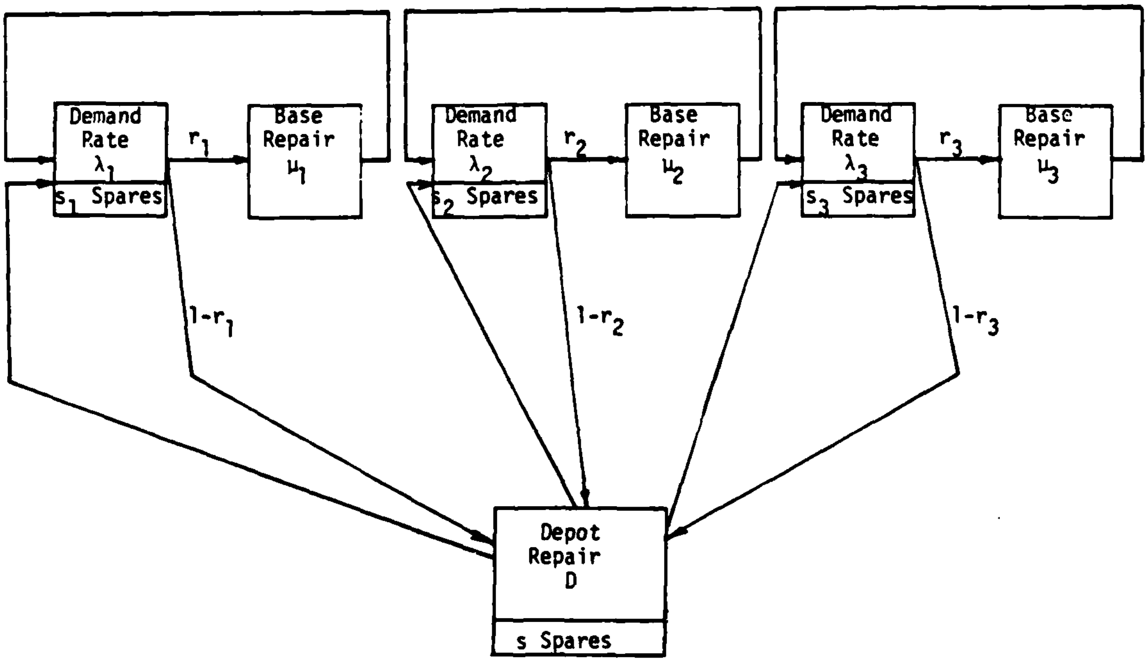


Figure 1.2

backorders, which are important only in their overall effect on base backorders.

The probability distribution for the number of units demanded by base j from the depot per unit time is Poisson with mean equal to $\lambda_j(1-r_j)$. Thus, the expected number of demands arriving at depot per unit time from all three bases (Fig. 1.2) is

$$\lambda \equiv \sum_{j=1}^{3} \lambda_j(1-r_j) \quad . \tag{1}$$

On arrival at depot, a key factor in the METRIC model is an "ample server assumption": units to be repaired go into service immediately and never wait in a queue [3]. Statistically, this means that repair turn around times are independent. This assumption allows the use of Palm's Theorem from queueing theory. This states that if demand is Poisson, and if there are ample servers, then the number of units in repair at steady state is also Poisson, regardless of the repair distribution. The Poisson state probabilities can be completely described by the mean of the repair distribution. Letting x represent the number of demands outstanding, λ the mean depot demand arrival rate, and D the mean depot repair time, the steady state probability that x units are in repair at the depot is

$$p(x|\lambda D) = \frac{(\lambda D)^x e^{-\lambda D}}{x!} \quad . \tag{2}$$

Note that λD represents the mean number of units in repair at the depot.

It is necessary to determine appropriate spare stockage levels for each base and the depot. The following solution to this multi-echelon problem is developed by Feeney and Sherbrooke [2, 18, 19]. Let s be the depot spare stock level for an item. Then the expected number of depot backorders, referred to as the depot backorder function, is

$$B(s|\lambda D) = \sum_{x-s+1}^{\infty} (x-s)p(x|\lambda D) \quad , \tag{3}$$

where x is the quantity demanded, and $p(x|\lambda D)$ is the Poisson probability density, given by (2).

With the depot backorder function specified, the average number of backorders for each base can be calculated, given base spares s_j. We present the METRIC algorithm for this computation below.

SOLUTION PROCEDURE

1) First compute the average number of units backordered per demand at the depot (3) divided by the expected number of demands per unit time, λ . Thus, the average number of units backordered per demand at the depot is

$$\sum_{x=s+1}^{\infty} \frac{(x-s)p(x|\lambda D)}{\lambda} = \delta(s)D \quad , \tag{4}$$

where

$$(5) \qquad \delta(s) = \sum_{x=s+1}^{\infty} \frac{(x-s)p(x|\lambda D)}{\lambda D} = \frac{B(s|\lambda D)}{B(0|\lambda D)} .$$

The quantity δ(s) can be interpreted as the fraction of time that the depot has no available spares.

2) Next compute the expected response time at base j given the depot stock level s and the base stock level s_j. When the depot has one or more spares on hand, the average depot response time to base j is the average administrative and total transportation time, O_j, for base j. When the depot has no spare on hand, the average depot response time to base j is $O_j + D$, since the model [18] assumes that the spare sent to depot for repair is returned to the same base. Thus, the average depot response time is between O_j and $O_j + D$ and depends on s. Therefore, at base j the expected number of units on backorder is given by

$$(6) \qquad B_j(s_j|\lambda_j T_j) = \sum_{x-s_j+1}^{\infty} (x-s_j)p_j(x|\lambda_j T_j) ,$$

where

$$(7) \qquad T_j = r_j \mu_j + (1-r_j)\ (O_j + \delta(s)D) ,$$

μ_j is the average base repair time, and $p_j(x|\lambda_j T_j)$ is a Poisson demand distribution with mean $\lambda_j T_j$.

3) For each level of depot stock s and total base stock S $(=s_1 + s_2 + s_3)$, determine an optimal allocation of stock s_j to the bases. Thus, the optimization problem is

$$\min \sum_{j=1}^{3} B_j(s_j|\lambda_j T_j)$$

subject to

$$s_1 + s_2 + s_3 = S$$
$$s_j = 0, 1, 2, \ldots \quad .$$

This optimization is accomplished by marginal allocation. At each step of the marginal allocation process, add a unit of stock to that base where it produces the largest reduction in expected backorders. Let $A(s, S)$ be the resulting optimal value of the objective function.

4) Compute the expected total backorders at all bases as a function of depot stock s and total base stock S under optimal allocation (Table 1). For each level of total system stock, $s + S$, (represented by all the entries along a diagonal in the table), select the combination that gives the minimum expected number of total backorders. Record the actual optimum allocation of stock between bases and depot of each $s + S$.

Given s + S spares in the entire system, an optimum solution can be obtained by simply locating the smallest entry on the diagonal corresponding to (s + S).

EXPECTED BACKORDERS

DEPOT STOCK	TOTAL SPARE STOCK AT ALL BASES				
	0	1	...	S	...
0	A(0, 0)	A(0, 1)	...	A(0, S)	...
1	A(1, 0)	A(1, 1)	...	A(1, S)	...
.	.	.	...	.	...
.	.	.	...	.	...
.	.	.	...	.	...
s	A(s, 0)	A(s, 1)	...	A(s, S)	...
.	.	.	...	.	...
.	.	.	...	.	...
.	.	.	...	.	...

TABLE 1

SUMMARY

The METRIC model can determine both requirements and distribution of reparable items in a two-echelon inventory system. Sherbrooke's and Feeney's METRIC uses a compound Poisson distribution for item demand which is a generalization of the simple Poisson discussed above. The compound Poisson assumes that base demands arrive in batches rather than individually; however, in both cases the interarrival times between demands (batch or individual) are exponentially distributed. In addition the model can be broadened to achieve a multi-item solution with the inclusion of additional marginal analysis. The model does not compare different provisioning or dispatching rules. Two major assumptions that are present in METRIC are (1) no lateral supply and (2) no condemnations. Cannibalization also is ignored in the METRIC model.

MUCKSTADT'S REDISTRIBUTION ALGORITHM [19, 20]

Muckstadt's algorithm [20] simplifies the calculations required to solve METRIC. Specifically, it relies on the marginal analysis procedure described in Sherbrooke's solution steps [21], and uses the properties of the backorder function. Instead of calculating all of Table 1, as Sherbrooke does, Muckstadt substantially limits the search. The reduced computation is important when there are hundreds of units of a particular item in spare stock. This algorithm significantly reduces the number of required calculations, but it may find only a local optimum.

BRUCE MILLER'S HEURISTIC RULE [12, 14]

The applicability of dynamic programming as a computational technique is limited in that many sequential decision models require an extremely large number of states. The reparable item inventory system is an excellent example of a sequential decision model with an astronomically large state space. Miller developed a heuristic dynamic decision rule, called the Transportation Time Look Ahead Policy, to analyze the complex inventory system problem [12, 14].

In Miller's model, each base j is described by two parameters: λ'_j the Poisson demand rate in items per day, and Q'_j the deterministic transportation time in days between the depot and base. The repair time in days at the depot for each item is independent of the repair time of other items in repair and is exponentially distributed with a mean of $1/D'$. Miller assumes that the exact number of installed items at base j never enters the model explicitly. The installed items only generate demands for a spare item when they fail.

There are several basic differences between the METRIC models and Miller's model. In all models, when a demand occurs, if a spare item is available at that base, it replaces the failed item. In Miller's model, there is no base repair and, thus, the fraction of units that are base j reparable is zero ($r_j=0$). Upon completion of repair at depot, an item is shipped to a base that generally is different from the one where that item failed. The METRIC model returns the serviceable item back to the same base, as discussed earlier in this chapter. Miller does not consider how many inventory items should be procured. His model's objective is to find a redistribution rule that minimizes the average expected number of backorders at all the bases.

To model the system, Miller use a discrete time formulation with minuscule time increments $(\Delta t=10^{-6}$ days). For notational ease, let $Q_j = Q'_j/\Delta t$, $\lambda_j=\lambda'_j\Delta t$, and $D = D'\Delta t$. Therefore, λ_j is the probability of a demand at base j during a microday of length Δt. Assume that at most one demand and one repair take place in the system during a microday.

Although Miller formulates a dynamic programming model, the crux of his model is his heuristic rule, the Transportation Time Look Ahead Policy. He states that this rule represents a rare case where a myopic decision policy is optimal for a multi-state variable dynamic programming problem [12]. Miller's heuristic rule, which was first developed as the Real Time METRIC (RTM) [14], will be discussed in detail.

At a time t, when a newly repaired unit becomes available at the depot, the Transportation Time Look Ahead Policy is used to evaluate the expected number of backorders at each base j over the next Q_j microdays. The policy allocates the newly repaired unit to the base that will yield the greatest marginal decrease in the number of expected backorders. The Transportation Time Look Ahead Policy combines two concepts that have been used in standard inventory models. First, the relevant inventory level at base j equals the number of units on hand plus the number of units that will be arriving in the next Q_j microdays. Second, the relevant demand at base j is the cumulative demand over the next Q_j microdays.

Thus, the number of units at base j that will be available in Q_j microdays is $s_j(t) - R_j$, where $s_j(t)$ is the number of spares on hand plus in transit to base j at time t, and R_j is the random demand that occurs at base j in the next Q_j microdays. The variable R_j has a Poisson distribution with a mean of $\lambda_j Q_j$. Let

$$P\{R_j = v\} = p_j(v|\lambda_j Q_j) = \frac{(\lambda_j Q_j)^v e^{-\lambda_j Q_j}}{v!} \quad . \tag{8}$$

Letting $s_j(t) = i$, then the expected backorder Q_j microdays in the future is

$$B_{ij} = \sum_{v=i+1}^{\infty} (v-i) p_j(v|\lambda_j Q_j), \quad \text{and} \tag{9}$$

$$\begin{aligned} G_j(i) &= B_{ij} - B_{i+1,j} \\ &= \begin{cases} 1 - \sum_{v=0}^{i} p_j(v|\lambda_j Q_j) & \text{for } i>0 \quad . \\ 1 \quad \text{for } i<0 \quad . \end{cases} \end{aligned} \tag{10}$$

$G_j(s_j(t))$ is the marginal decrease in backorders due to allocating an additional unit to base j. When a unit comes out of depot repair, the Transportation Time Look Ahead Policy is applied by calculating $G_j(s_j(t))$ for each base j and sending the serviceable unit to a base associated with the maximum of this quantity. When base j has a backorder with no spares on hand or in transit, then i is represented by a negative number. Since a negative spare condition can be present at more than one base, ties are broken by examining total spares needed by the base and number of microdays in this status $(i<0)$.

THE DYNA-METRIC MODEL [11]

In 1978 researchers at the Rand Corporation developed new analytic methods using dynamic queueing equations to study the transient behavior of component repair/inventory systems under time-dependent operational demands and logistics decisions similiar to those that might be experienced in wartime. In 1981 these methods were published as the Dyna-METRIC mathematical model [11].

The model represents the logistics system as a network that corresponds to the states and processes a unit can be in, such as, attached to an aircraft, in repair at a base, in transit from base to depot, in depot level repair, or on the shelf at base or depot in serviceable condition. Dyna-METRIC emphasizes the retail part of the logistics system, which includes the base level repair and supply activities. The theoretical development of the dynamic queueing equation by Hillestad and Carrillo is described below.

Classical steady-state inventory theory provides a model that describes how many components will be in the various echelons of a component repair/inventory process when the component demand rates are driven by a stationary probability distribution. Time-dependent flying scenarios cannot be studied with this approach. Dyna-METRIC relieves steady-state assumptions by letting the daily demand rate be a function of time, $\lambda(t)$. Instead of using an average repair time, the dynamic model uses the probability that a component entering repair at time z is still in repair at time t. This probability, called the repair function, is denoted by $F(t,z)$.

The Dyna-METRIC model combines the repair and demand functions to determine the average number of units in repair at the depot. Consider only those components that arrive in an interval of time Δz. If the number of demands arriving in the interval Δz is independent of the number of demands arriving in similar intervals centered at times other than z and the repair probability function is independent of the probability distribution generating the demand rate, the contributions of all intervals can be summed to obtain

$$(11) \qquad m_{\Delta}(t) = \sum_{z<t} \lambda(z)F(t,z)\Delta z$$

The limit as Δz approaches 0, is

$$(12) \qquad m(t) = \int_0^t \lambda(z)F(t,z)dz \quad ,$$

which represents the average number of components in repair at the depot at time t. Hillestad and Carrillo [11] show that, with the additional assumption that the component demand probability distribution is Poisson, $m(t)$ is the mean of a nonhomogeneous (time varying) Poisson process. Therefore, the probability that x components are in depot repair at time t is

$$(13) \qquad P\{x|m(t)\} = \frac{m(t)^x e^{-m(t)}}{x!} \quad .$$

The average number of depot backorders at time t is similar to Sherbrooke's depot backorder function. Let $s(t)$ be the depot spare stock level at time t. Assume that at time t the average number of components in depot repair is $m(t)$. Then the expected number of depot backorders at time t is

$$(14) \qquad B(s(t)|m(t)) = \sum_{x=s(t)+1}^{\infty} (x-s(t))p(x|m(t)) \quad ,$$

where x is the quantity demanded, and $p(x|m(t))$ is the Poisson probability density, given by (13).

Using (14), at time t the average number of backorders for each base, given base spares $s_j(t)$, can be calculated. The calculation is identical to the first two steps in the METRIC algorithm. Thus, up to this calculation the Dyna-METRIC model is actually the same as METRIC with time-dependent variables. The major difference occurs after the average number of backorders for each base is calculated. METRIC uses an optimization problem that minimizes backorders by marginal allocation. The Dyna-METRIC model's optimal determination of spares does not depend on this backorder calculation. The Dyna-METRIC model's optimization problem is presented next.

DYNA-METRIC'S ALLOCATION OF SPARES

For Dyna-METRIC, base level aircraft available to fly is of primary interest, and is a constraint in the model that determines the optimal spares level. The constraint is expressed as a probability of not exceeding a given number of aircraft that are unable to fly at a specified point in time. For example, a commander wishes to be 90 percent confident of flying eight of the ten aircraft positioned at the base. This means that the number of grounded aircraft cannot exceed two. In determining the spares level, the model provides enough spares to give the desired confidence at lowest cost. Thus, the objective function is the total cost of spares at the base.

For each level of depot spare stock s and total base spare stock S $(=s_1 + s_2 + s_3)$, the model determines an optimal allocation of stock s_j to the bases. Let c represent the unit cost of the spare and be the desired confidence level. Let K be the number of grounded aircraft (aircraft unable to fly because a spare is unavailable) that must not be exceeded. Finally, let $p(i|s_j)$ be the probability that the number of grounded aircraft is i given a stock level s_j. Then, the optimization problem is

$$\min \sum_{j=1}^{3} cs_j$$

subject to

$$\prod_j \left(\sum_{i<K} p(i|s_j) \right) \geq \omega$$

$$s_j \geq s_{jo} \quad \text{for each } j,$$

$$s_j \quad \text{non-negative integer.}$$

where s_{jo} is the input base j stock level for the component. This optimization can be accomplished by marginal allocation [8]. At each step of the marginal allocation process, a unit of stock is added to that base where it produces the largest increase in the probability measure at the lowest cost. This process continues until the given confidence level is achieved.

LITERATURE SUMMARY

Despite the important research findings described above, there is a need for a new tool to evaluate alternative logistic strategies for multi-echelon inventory systems, especially during periods of increased flight activity. Most of the work discussed above only addresses single strategies during normal flight operations. Additionally, assumptions are made that eliminate many important strategic issues. For example, Bruce Miller's research addresses the redistribution issue, but assumes that base repair is zero. Also, the number of workers at depot level is assumed to be infinite. Sherbrooke's research investigates initial allocation of spares at base and depot, but uses a static redistribution rule to access system performance. Lastly most literature has used backorder days as the only measure of system performance.

As illustrated in Figure 1.1, many different policies can be addressed in multi-echelon inventory system. These different policies can significantly affect system performance during periods of sustained high flight activity. Muckstadt has shown that spare parts levels determined with steady state models can seriously understate the requirements during peak periods of activity [15]. The development of time-dependent variables in Dyna-METRIC treats surge problems; however, spare part levels must be calculated after the fact, and dispatching of items is not considered at all. These are actually symptoms of a more serious problem--the general lack of understanding the impact of logistic strategies on the entire system. For example, a strategy developed at one level of the repair process can seriously affect repair decisions at all levels of the logistics system. Additionally, this strategy will affect spares levels throughout the system. Research has been very limited in addressing these system-wide problems.

LOGISTIC STRATEGIES

In considering logistic strategies, we must remember the problems in a multi-echelon inventory environment. Logistic strategies and operational policies can improve the systems performance measures; however, strategies generally require a larger capital commitment and a longer time for approval and implementation than do operational policies. Changes in operational policies can be undertaken by lower level managers who redirect personnel to alter day to day activities. Figure 1.3 summarizes answers for

MULTI-ECHELON PROBLEMS, STRATEGIES AND OPERATIONAL POLICIES

PROBLEM	STRATEGIES	OPERATIONAL POLICIES
Long delays in depot repair	Increase depot capacity Increase spares inventory	Hire workers Shift workers from other areas
Large percentage of aircraft grounded	Redesign product Increase spares inventory	Redistribute spares Alter distribution rule
Transportation delays	Change routes or procedures	Expedite high priority shipments
Large percentage of items sent to depot for repair	Redesign product Increase base repair capacity	Change technical data tolerances
Low supply service level	Redesign product Increase spares inventory	Redistribute spares Alter dispatching rule

FIGURE 1.3

multi-echeon inventory problems by strategies and operational policies.

Long delays in depot repair can be decreased by increasing depot capacity or increasing depot spares inventory. Both of these strategies requires long time frames for budget approval at the highest levels of management. Since the only requirement on depot managers is to meet end of year manpower levels, hiring of repairmen can be accomplished at the depot without prior budget approval. This operational policy of hiring personnel in effect increases the depot's capacity. By increasing depot capacity, the queue of parts awaiting repair is reduced and spares are made available to the base in a shorter period of time.

Another problem finds local base commanders with too large a percentage of aircraft unable to fly. One strategy looks at increasing reliability by redesigning the part. With the larger mean time between failure, fewer parts break and less aircraft are grounded. Another strategy increases the level of spares in inventory. This strategy decreases the level of grounded aircraft, but increases the level of maintenance that must be performed in the system. The corresponding operational policy can redistribute the current spares to the bases that need them the most or completely alter the method used to redistribute spares coming out of depot repair. Both of these policies may improve the level of flyable aircraft, but significantly reduce other system performance measures.

If more items are arriving for depot repair than forecasted from the bases, then an increase in base repair capacity or a change in technical data tolerances could be accomplished. The increase in base repair capacity will require additional equipment and/or personnel. A change in tolerances in the technical data can be accomplished by engineers at the depot. These tolerance changes allow base personnel to repair more of the items. In either case, the parts that have no base repair possible, but are repaired in the same depot repair shop, can affect the system in a manner that may be unexpected by system managers.

Finally, if transportation shipments are expedited, the total time that an aircraft must wait at base level can be reduced significantly. By decreasing the shipment time, however, the resulting increased sortie rate at base level also increases the depot awaiting repair queue.

Obviously, a strategy developed at one level of the repair process can seriously affect repair decisions at all levels of the logistics system. Additionally, this strategy will affect spares levels throughout the system. Research has been very limited in addressing this total systems problem.

PROPOSED TOOL

This dissertation develops a simulation tool to aid upper-level managers in the analysis of alternative logistic strategies. We develop the model shown in Figure 1.4. The model evaluates the impact of various strategies on depot redistribution rules using base and depot performance measures. In addition, sensitivity analysis is accomplished on pairs of strategies to evaluate significant interaction effects.

The model is comprised of six operational areas. The function of the areas are described in brief below. A complete description is given in Chapter 2.

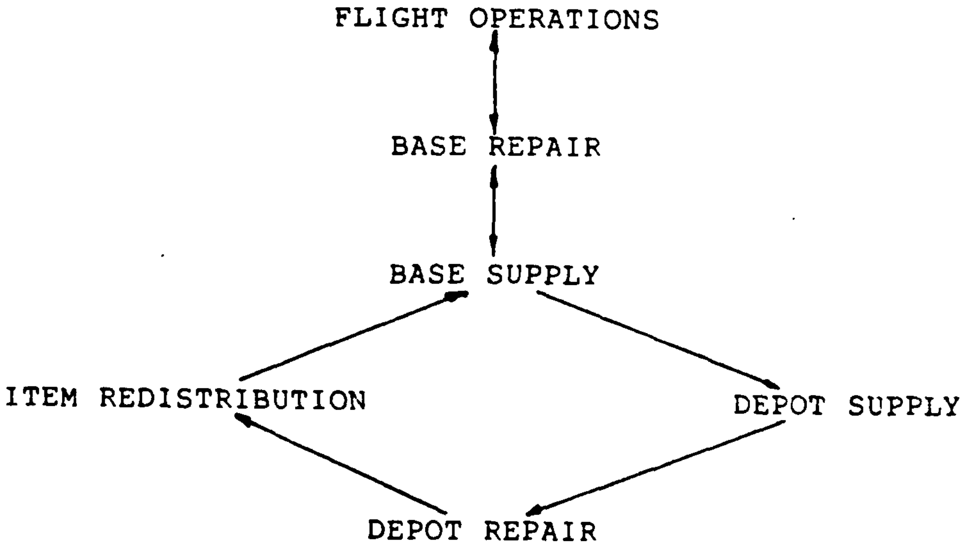


FIGURE 1.4

FLIGHT OPERATIONS - schedules a specific number of aircraft for daily flights at each base. An aircraft may be logging flight hours, grounded awaiting repair, or being repaired.

BASE REPAIR - accomplishes minor repairs on reparables and repair grounded aircraft when serviceables are available.

BASE SUPPLY - warehouses spare parts and initializes requisitions for replacement serviceables, either through base or depot repair cycles.

DEPOT SUPPLY - is a centralized receiving point for reparables from all bases. Breaks down palletized shipments and sends reparable to proper depot repair shop.

DEPOT REPAIR - accomplishes major repairs and overhauls on reparable items.

ITEM REDISTRIBUTION - determines which base will receive the serviceable part coming from depot repair.

The model can address these questions of interest from managers at all levels of the multi-echelon system:

- How much spares inventory is needed to meet flight requirements?
- How many workers are needed in depot repair?

- How does decreased transportation time affect the system?
- How do increased flight requirements affect the system's performance?
- What are the tradeoffs among system performance measures?
- What is the impact of maintenance accomplished at base or depot level?

ORGANIZATION OF REMAINING CHAPTERS

We have presented an outline of a computer simulation model for analyzing the impact of logistics stategies on a multi-echelon system's performance. The design specifications are described in Chapter 2. Issues regarding the evaluation of alternatives and statistical accuracy are investigated and resolved in Chapter 3. Chapter 4 assesses three redistribution rules to determine which rule performs best in an increased flying hour program. Additionally, the partial factorial design that is used for this research is explained. One-at-a-time strategies are analyzed in Chapter 5 using the closed system view. Then a linear model derived from the partial factorial design assesses the impact on each performance measure of varying resource levels. Chapter 6 addresses the effect of strategies on different organizational levels within the multi-echelon system and presents future research topics.

CHAPTER TWO

MULTI-ECHELON SYSTEM MODEL

In this chapter, the general multi-echelon model is described and parameters used to initialize the model are presented. The block structure of the simulation model developed to perform the experiments is also discussed.

MODEL SPECIFICATIONS

The model that this dissertation uses is shown in Figure 2.1. It represents a multi-echelon system comprised of three bases at the lowest level of operation and a centralized depot repair facility.

The three bases represent possible actual situations. First, there is an operational base in the Continental United States (CONUS). The term operational means that the base is capable of flying a wartime scenario with personnel who are fully trained. This training occurs at a CONUS training base, which makes up the second type of base in the model. The third type of base is operational in an overseas location. This base has the same mission and flight requirements as does the CONUS base; the only major difference is the distance from the centralized depot facility.

The two operational bases (CONUS and overseas) have an aircraft wing consisting of one aircraft squadron, each with 10 aircraft. The training base's wing consists of two squadrons. This larger number of aircraft is required at the training base because more flights are required for training of personnel than to keep them current at the operational bases.

For the purposes of the model, the parts requirements for each aircraft are scaled down. The model simulates two parts, A and B. Each aircraft contains an A and a B; if either of these parts fail, the aircraft is grounded until the part is replaced.

Part A has a mean time between failure (MTBF) of 300 hours. This part can be repaired at base level with probability shown in Figure 2.2, or at the depot. Part B has a higher MTBF of 550 hours, but cannot be repaired at a base. Both parts are repaired in the same shop at depot, which has 12 repairmen available to work.

A phase inspection is scheduled every 1000 hours for each aircraft. During phase the aircraft is grounded and not available for flight for 20 days.

The model rolls forward daily and simulates flying activity, parts failures, phase downtime, supply and repair actions, and depot redistribution decisions. Parts are repaired to satisfy actual customer requirements at base level. We explain below the operational areas shown in Figure 2.1.

The arrows indicate the flow of parts from one area to another. The system is dynamic, so that the system's state at one day influences the state of the system the next day. For example, the number of aircraft grounded on one day reduces the level of aircraft available to fly the next day. The inventory of spares available at base level is a function of beginning inventory, requirement demands, repair rates, and transportation time. It is the dynamics of the model that make it complex. A change of strategy in one area ripples through the system, and impacts other operational areas.

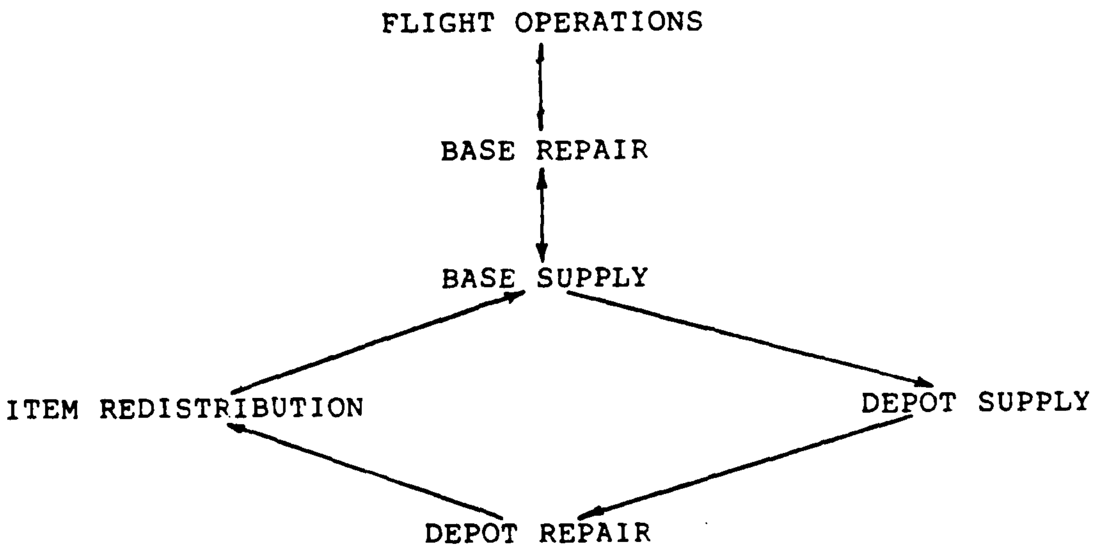


FIGURE 2.1

FLIGHT OPERATIONS

Flight operations consist of scheduling aircraft for flights and providing personnel to fly the mission. In this model, we assume that personnel are always available to fly and that increased flight requirements will be matched with an increased crew force size.

Each day aircraft are scheduled to fly from the pool of available aircraft at each base. These aircraft are flown for a length of time which is normally distributed with mean 10 hours and standard deviation 1. When the aircraft lands, the flight time is subtracted from the time remaining until part failure and aircraft phase. If none of these times are zero, the aircraft is serviced and becomes available for flight requirements the next day.

If an aircraft is grounded, it is removed to a hangar to await a serviceable part or to complete the phase inspection.

BASE REPAIR

When a part is removed from an aircraft, it is inspected for possible base repair. Only part A can be repaired at base level. The base repair percentages and repair time are shown in Figure 2.2. Additionally, there is an infinite number of repairmen available at base level.

	BASE 1	BASE 2	BASE 3
Number of Aircraft	10	20	10
Number of Spare A Items	3	6	3
Number of Spare B Items	3	6	3
Percent of Base Reparable	25%	10%	25%
Scheduled Number of Sorties Per Day	4	8	4
Days of Transportation Time Between Base & Depot	7	7	14
Depot Repair Rate for Spare A	- 3 days + exponential with mean of 4 days		
Depot Repair Rate for Spare B	- 7 days + exponential with mean of 7 days		
Base Repair Rate for Spare A	- 1 day + exponential with mean of 4 days		

FIGURE 2.2

BASE SUPPLY

After a part is inspected for possible repair at base level, it is turned into base supply. If a serviceable part is available in base supply spare stock, it is issued; otherwise a backorder occurs. If the unit is reparable at base level, it goes to a maintenance shop where the repair is accomplished. The serviceable is returned to base supply to clear the backorder or replace issued stock. If the unit cannot be repaired at base level, supply ships the reparable to depot.

On return from depot, a serviceable item can either clear an outstanding backorder or replace issued spare stock. If more than one aircraft has been grounded, the one grounded the longest received the part. If no aircraft is grounded, base supply spare stock is incremented by the serviceable part.

DEPOT SUPPLY

Depot supply is a centralized receiving point for parts arriving from any base. The parts are released from supply to depot repair on request. We assume no condemnations of parts in the system. Every reparable eventually returns to base level as a serviceable item. An important decision is which base receives the serviceable part? We test the effects of three redistribution rules on system performance measures.

ITEM REDISTRIBUTION

Redistribution in a multi-echelon inventory system is performed by an item manager. This manager combines a specific redistribution rule and knowledge of the existing spare situation in the system to make the decision. A commonly used rule, which we designate as the static rule, distributes a serviceable out of depot repair to the base turning in that unit for repair.

In addition to the static rule, we examine two dynamic redistribution rules. First, Bruce Miller's Heuristic rule is tested. This rule distributes a serviceable out of depot repair depending on each base demand rate, pipeline transportation time, and the number of spares in base stock plus in transit. The second dynamic rule enhances Miller's Transportation Look Ahead Policy by including the expected number of serviceables coming from base repair during the base-depot pipeline time.

DEPOT REPAIR

Depot repair is the highest level of repair possible in the Air Force maintenance system. Parts can be completely rebuilt or overhauled at depot. Extensive repairs are accomplished which base level maintenance cannot handle.

In our model, parts A and B have a common depot repair shop, and a workforce of 12 repairmen are available to repair both parts. When a repairman is not available for an entering reparable, the item is placed into a queue. The first available repairman removes the item at the front of the repair queue. The repair rates for both parts are shown in Figure 2.2.

BLOCK STRUCTURE

The conceptual model described in the first section of Chapter 2 is programmed in SIMSCRIPT II.5. The code for the simulation consists of routines and processes shown in Figure 2.3. We start with an overview.

The MAIN routine schedules the initial process called NEWDAY and the two events called RESET and CLOSING. On a daily basis, NEWDAY schedules the FLIGHT process for a specified number of aircraft at each base. If an aircraft lands in flyable status, it is returned to the NEWDAY process. If either part A or B is broken, the aircraft is grounded and the part is sent to the REPAIR process. After a repair is completed, the DISPATCH routine determines proper redistribution of the serviceable part. The serviceable part is returned to the proper base in the FLIGHT process, and if an aircraft is grounded for this part, it is returned to flyable status.

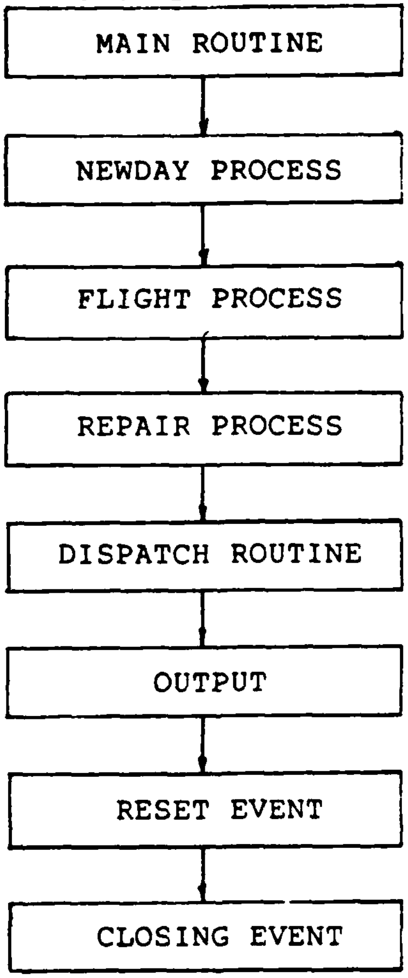


FIGURE 2.3

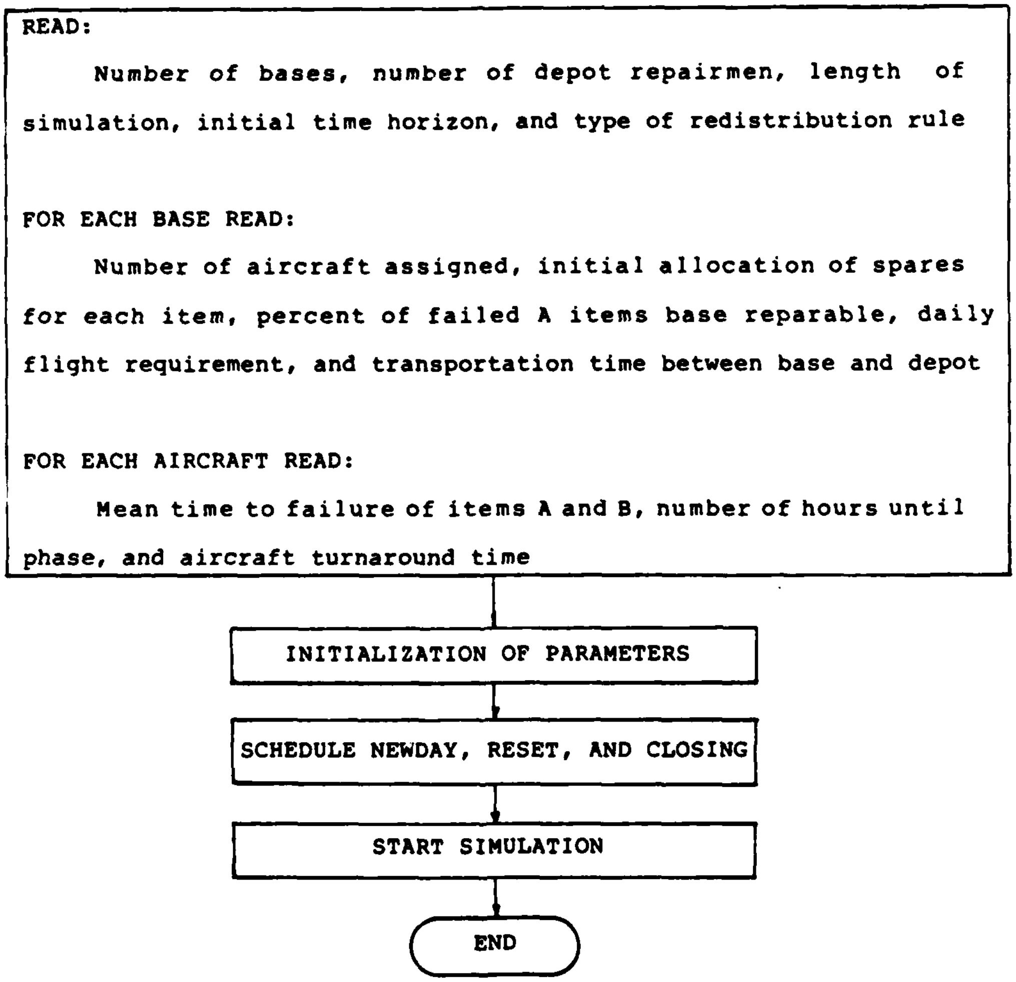
The RESET event resets all accumulated statistical totals to zero and reinitializes counters. Additionally, RESET activates the PRINTOUT process at the end of a one year run length. The PRINTOUT process writes the performance measures into a predetermined file and schedules a RESET. PRINTOUT also calls an ACCOUNT routine, which builds an array and calls the BATCH.MEANS.METHOD routine. Finally, the CLOSING event is called at the end of the total simulation time. Each routine and process is described in more detail in the remainder of this chapter.

MAIN ROUTINE

The primary focus of the MAIN routine is to read the input data, initialize parameters, and schedule processes and events to start and stop the simulation. A flowchart of the activities in the MAIN routine appear in Figure 2.4. MAIN reads the data used to construct the base and aircraft parameter sets.

For each aircraft a turnaround time of eight hours is set. The turnaround time is the amount of time required to service the aircraft and repair minor maintenance problems prior to the next flight. Additionally, the mean time to failure for parts A and B are 300 hours and 500 hours, respectively. The time to next failure is initialized using exponential distributions with these means. Finally, the time left to phase for each aircraft is input. A phase is scheduled every 1000 hours; however, only one aircraft is normally phased every month in a 10 aircraft wing. The phase inspection consists of a teardown of critical areas for inspection and repair, such as landing gear, flight control surfaces, and engines.

MAIN ROUTINE



READ:

Number of bases, number of depot repairmen, length of simulation, initial time horizon, and type of redistribution rule

FOR EACH BASE READ:

Number of aircraft assigned, initial allocation of spares for each item, percent of failed A items base reparable, daily flight requirement, and transportation time between base and depot

FOR EACH AIRCRAFT READ:

Mean time to failure of items A and B, number of hours until phase, and aircraft turnaround time

Figure 2.4

Figure 2.5 shows the number of assigned aircraft, the initial allocation of spares for both parts, the percent of base reparables for part A, the number of scheduled sorties per day, and the transportation time between the depot and each base.

	BASE 1	BASE 2	BASE 3
Number of Aircraft	10	20	10
Number of Spare A Units	3	6	3
Number of Spare B Units	3	6	3
Percent of Base Reparable	25%	10%	25%
Number of Sorties Per Day	4	8	4
Days of Transportation Time Between Base and Depot	7	7	14

Figure 2.5

NEWDAY PROCESS

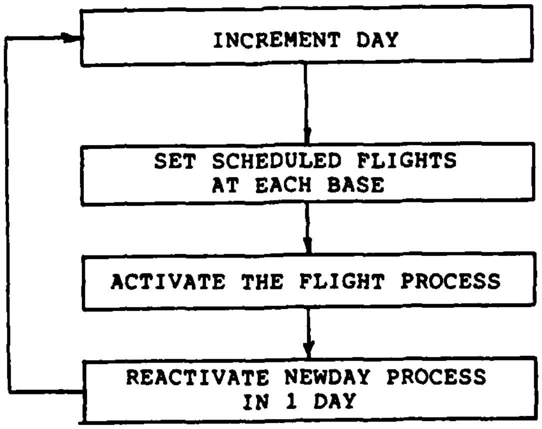


Figure 2.6

NEWDAY PROCESS

The NEWDAY process, shown in Figure 2.6, sets the scheduled flying requirements for each base and activates the FLIGHT process. NEWDAY is reactivated every day and increments the simulation to the next day.

FLIGHT PROCESS

For each base, the scheduled number of aircraft is flown if resources are available. If fewer resources are available than the scheduled number of flights, all available aircraft are flown. The difference between scheduled and actually flown is accumulated to measure the base's ability to meet scheduled flights. If more resources are available than the scheduled number of flights, all scheduled sorties are flown and the difference is accumulated as idle operationally ready aircraft.

After a flight, the time to failure clock for each item is decremented by the flight time. Also, the time left to phase is decremented by the same amount. The clock is then checked to see if a failure has actually occurred (time is less than zero). Since most failures will occur during flight, we assume the failure will not cause the flight to be terminated early. If a part has failed, it is removed from the aircraft. If a spare is available from base supply, it is given to the aircraft and the supply level is decremented. The failed part is then sent to the REPAIR process.

If the base supply spare level is zero or negative, the aircraft is suspended and placed in a hangar queue awaiting a serviceable unit from the REPAIR process. When a serviceable unit is available, the aircraft is reactivated and removed from the queue. Also, the time to failure clock is reinitialized. After a maintenance and turnaround delay, an aircraft is available for flight in NEWDAY.

When an aircraft is ready for phase inspection, it is suspended and placed in a hangar queue for a period of 20 days. After the phase, the aircraft is reactivated, removed from the queue, and rescheduled for 1000 flight hours until the next phase. The aircraft is available for flight in NEWDAY. The FLIGHT process flowchart is in Figure 2.7.

REPAIR PROCESS

When a part enters the REPAIR process, shown in Figure 2.8, it is checked to see if base repair is possible. If the item is base reparable, it is sent to base repair, and after being repaired, it is returned to base supply. We assume no transportation delay between base repair and base supply. If no aircraft is waiting for the part, base spare stock is incremented. If aircraft are in the hangar queue awaiting a part, the first one in the queue receives the part.

FLIGHT PROCESS

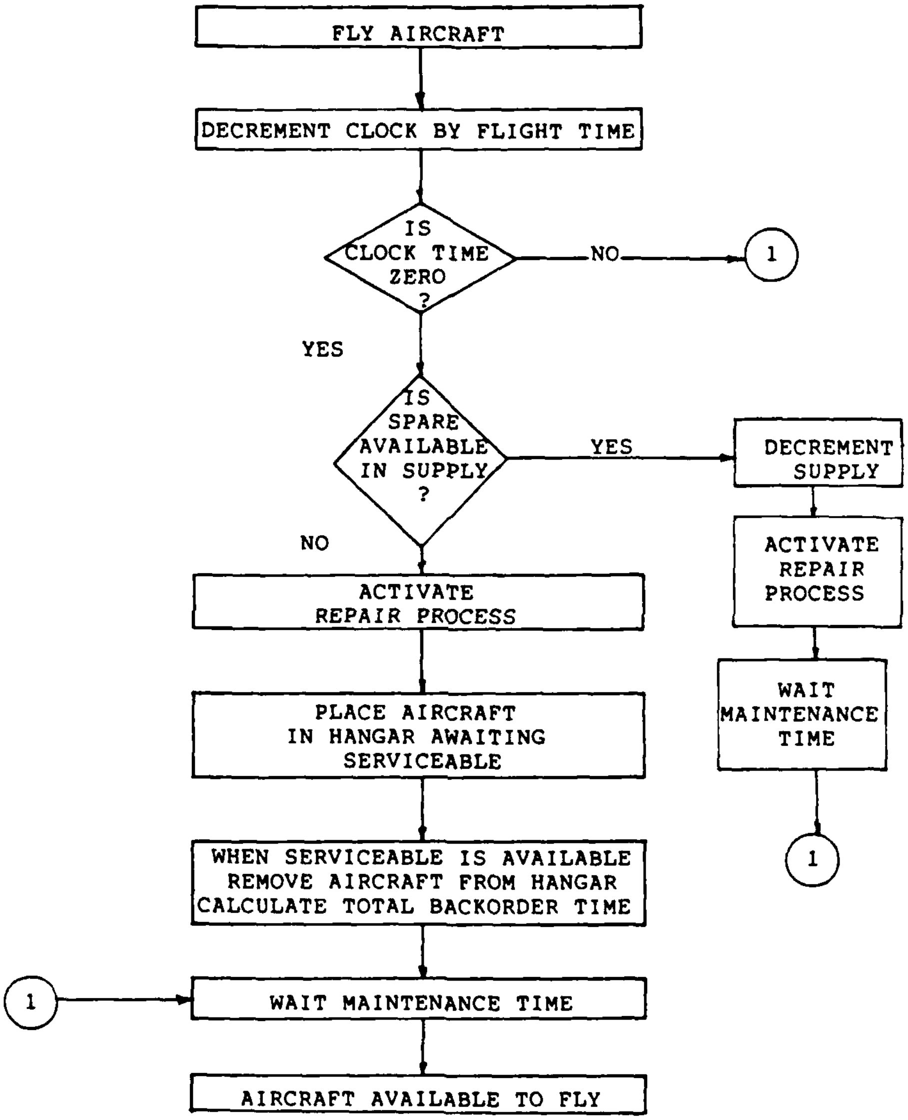


Figure 2.7

If the item is not base reparable, it is shipped to the depot using the transportation delay time shown in Figure 2.5 for the particular base. At the depot, the failed part goes into the repair shop if a repairman is available. Otherwise, the part is placed in an awaiting repair queue for the first available repairman. After a repair is completed, the DISPATCH routine determines the redistribution of the serviceable item.

REPAIR PROCESS

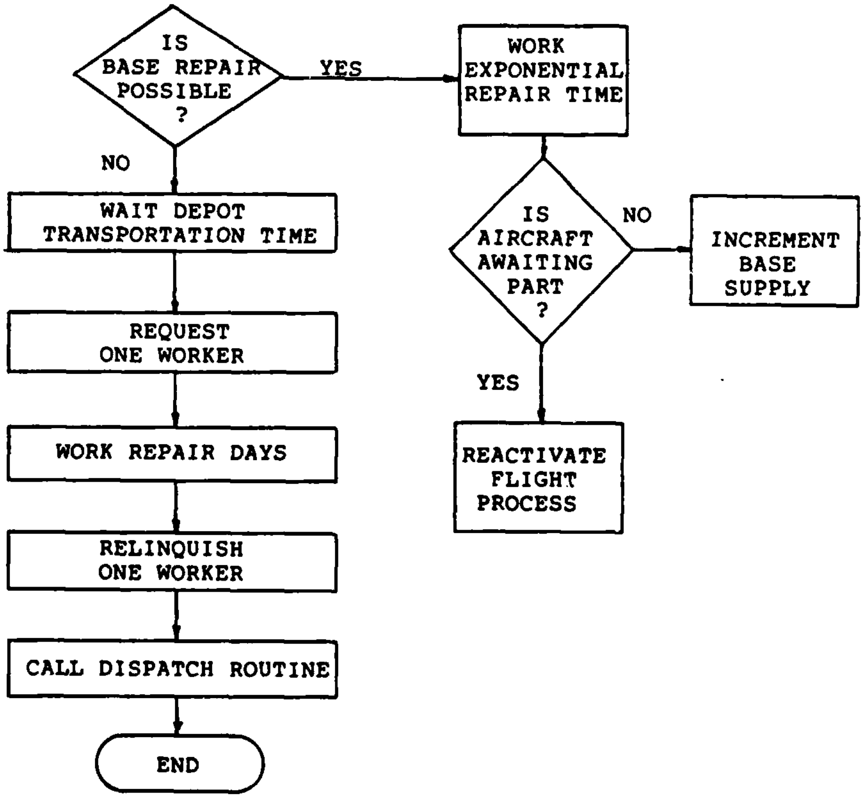


Figure 2.8

DISPATCH ROUTINE

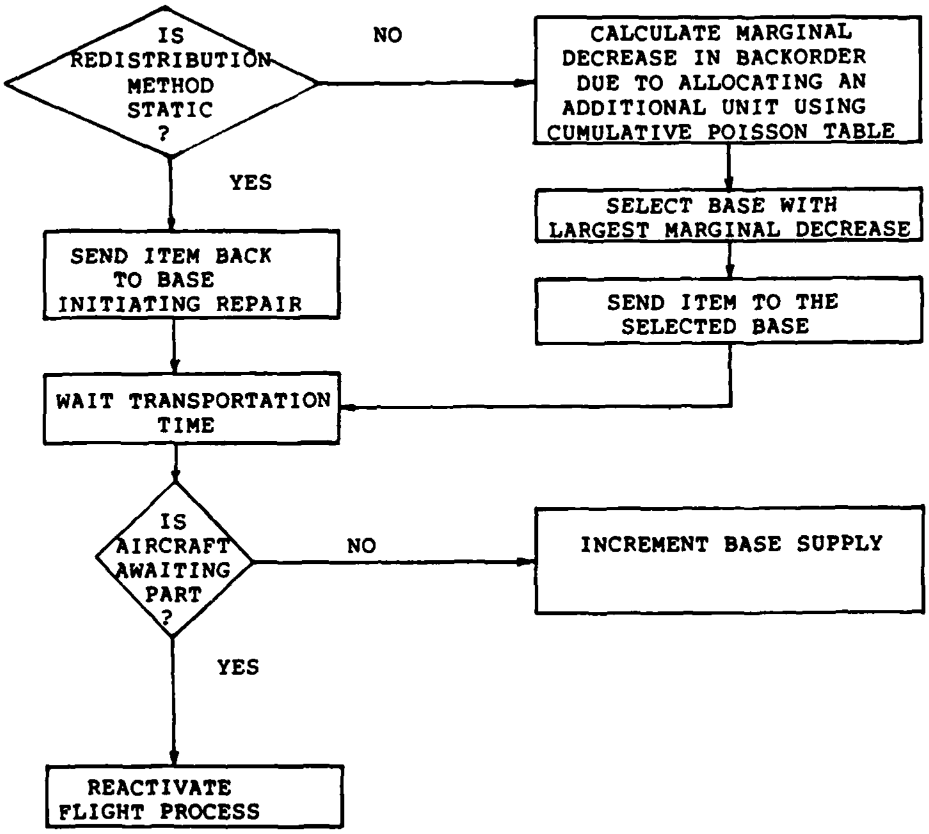


Figure 2.9

DISPATCH ROUTINE

The DISPATCH routine shown in Figure 2.9 decides which base receives a repaired item. A static or dynamic redistribution policy is specified in the MAIN routine for each simulation run. The static redistribution policy sends the part back to the base from which it came. If no grounded aircraft is waiting for the part, base spare stock is incremented. If aircraft are waiting in the hangar queue, the first one in the queue receives the part, is removed from the queue, and reactivated.

The dynamic redistribution policy is Bruce Miller's Transportation Look Ahead Policy, as described in Chapter 1. A marginal decrease in backorders due to allocating an additional unit is calculated for each base. The bases are prioritized by this value in a POLICY queue, where the base with the maximum is put first. Thus, when a unit comes out of depot repair, it is sent to the first base in this queue. A new marginal value is calculated for this base, and all bases are reprioritized in the POLICY queue. After the transportation delay, the serviceable unit increments base spare stock if no aircraft are grounded. If aircraft are suspended in the hangar queue, the first one in the queue receives the part, is removed from the queue, and activated.

A third redistribution rule uses the same procedures as described in the previous dynamic rule, but also includes the actual number of serviceable units coming from base repair during the transportation time. This redistribution rule is referred to as the enhanced dynamic rule.

PRINTOUT PROCESS

The PRINTOUT process, shown in Figure 2.10, records the performance measures for the bases and the depot. Additionally, the ACCOUNT routine is called, and the RESET event is scheduled.

ACCOUNT ROUTINE

The ACCOUNT routine, shown in Figure 2.11, takes a mean of a performance measure accumulated during the simulation and places it into an array. The performance measure is specified in the PRINTOUT process. The simulation length is 32 years with each year comprised of 365 days. After the 32 observed means are arrayed, the BATCH.MEANS.METHOD routine computes interval estimation for the population mean.

BATCH.MEANS.METHOD AND STUDENT.T ROUTINES

The BATCH.MEANS.METHOD routine, shown in Figure 2.12, allows for interval estimation for the population mean, and uses Fishman's batch means method program [7]. This routine estimates a mean, the variance of the sample mean, and determines the number of degrees of freedom.

PRINTOUT PROCESS

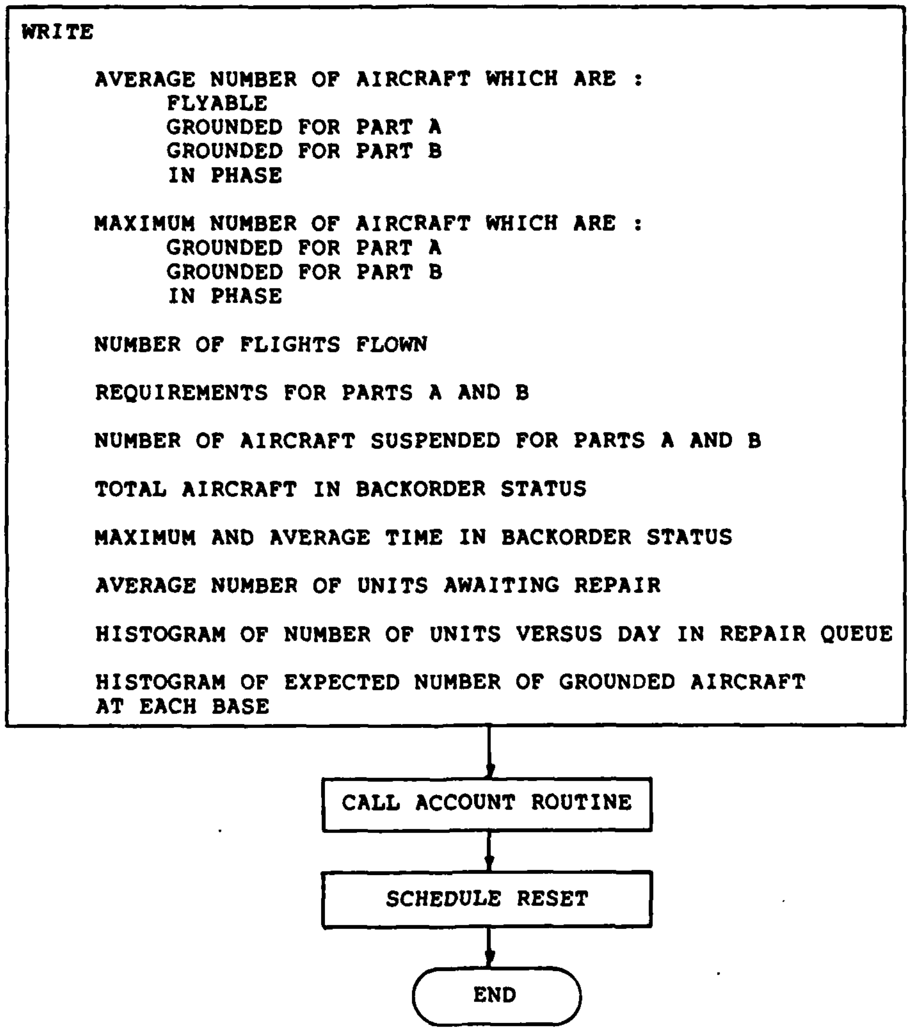


FIGURE 2.10

ACCOUNT ROUTINE

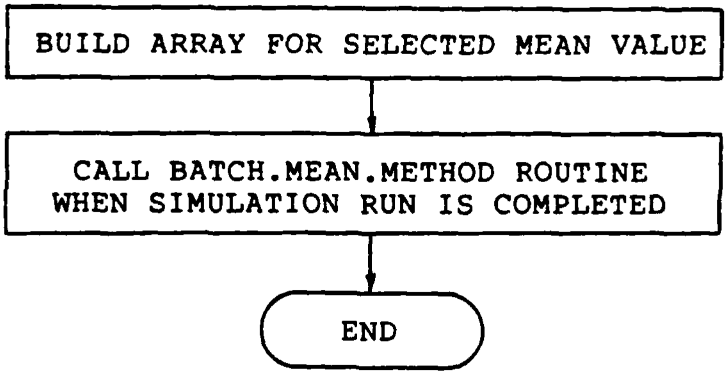


FIGURE 2.11

BATCH.MEANS.METHOD ROUTINE

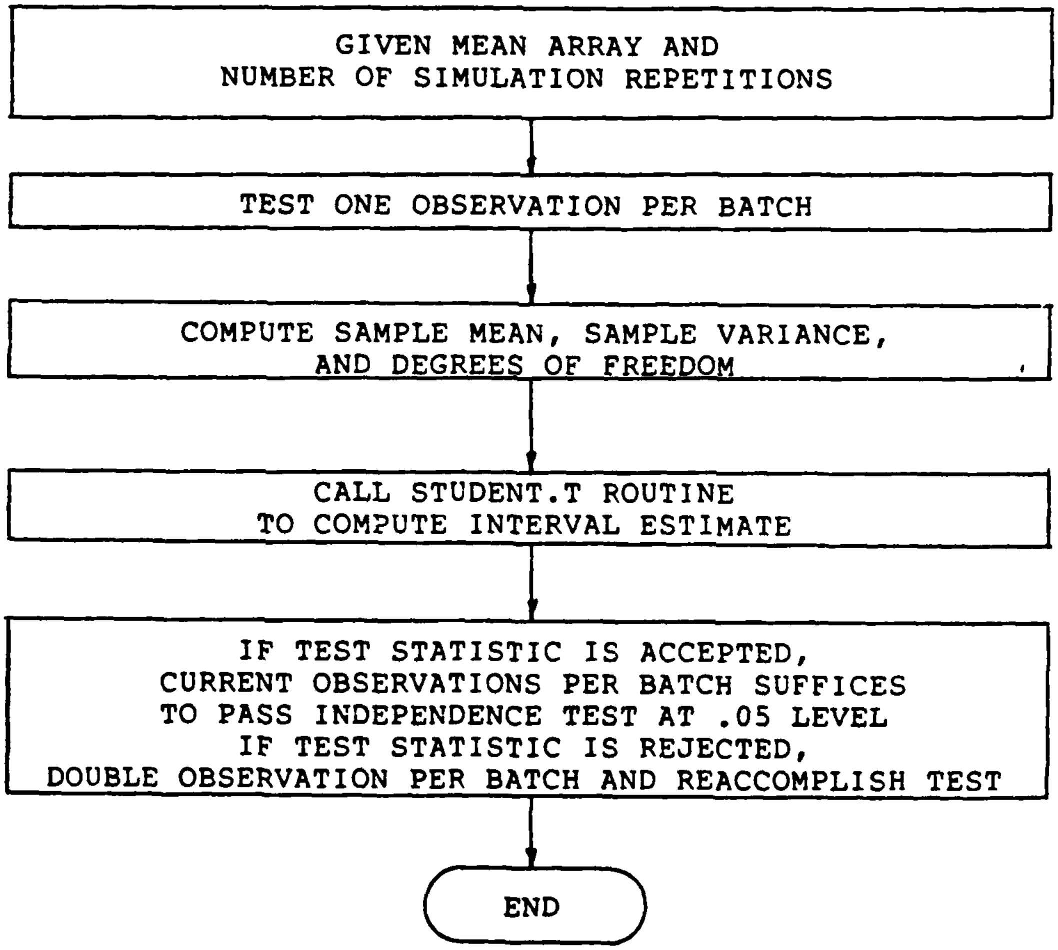


FIGURE 2.12

The STUDENT.T routine, shown in Figure 2.13, uses these quantities to compute an interval estimate using the t distribution. The results of these routines will be discussed in Chapter 3.

STUDENT.T ROUTINE

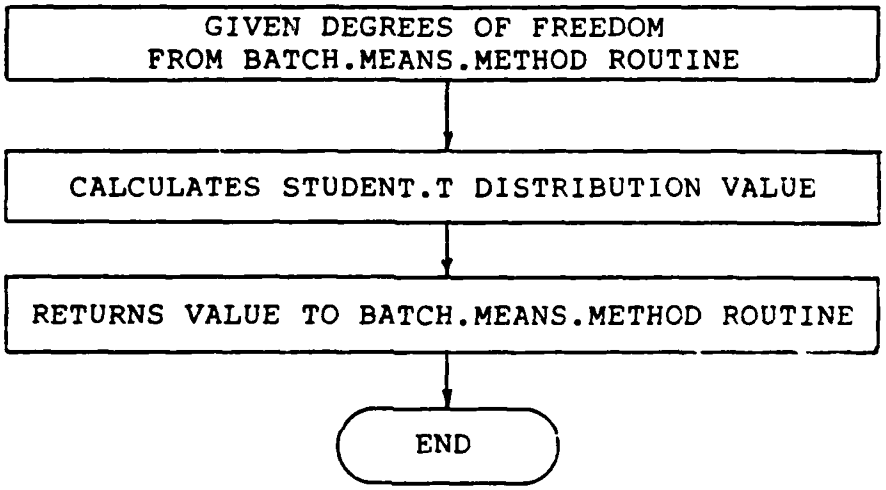


FIGURE 2.13

CLOSING EVENT

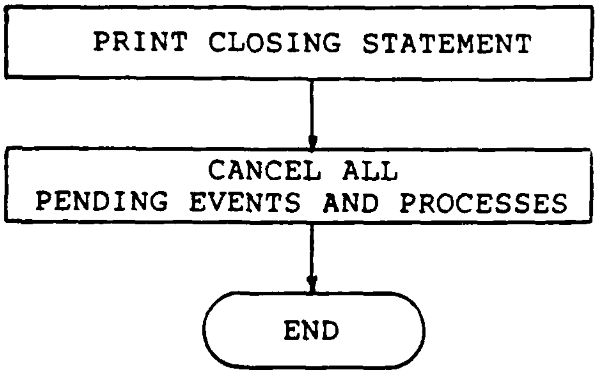


FIGURE 2.14

CLOSING EVENT

The CLOSING event, shown in Figure 2.14, is called by the MAIN routine to stop the simulation and to cancel any pending events in an orderly fashion.

CONCLUSION

This chapter presented the general multi-echelon model and the parameters used to initialize the model. Additionally, the block structure of the simulation model developed to perform the experiments was discussed. Chapter 3 examines the data from the simulation test runs to determine the proper data analysis design. This includes autocorrelation, batch size, sample size, and model validation.

CHAPTER THREE

DESIGN OF DATA ANALYSIS

In this chapter, the performance measures used to evaluate the redistribution rules are presented. The data from the simulation test runs are examined for autocorrelation. A technique for dealing with autocorrelation is described and implemented. Next, we evaluate the sample size needed for estimation of confidence intervals. Finally, validation of the model is discussed.

PERFORMANCE MEASURES

In Chapter 2, we described our model of a system comprised of three bases and a centralized depot facility. The operation of this multi-echelon system is monitored by five performance measures for each time period. The performance measures are used to analyze the operations of the system under various logistic strategy scenarios.

The five performance measures are calculated daily and accumulated as model statistics. After a year (365 days) of operation, a mean of each performance measure is output. The performance measures are described below.

- PERCENT OF FLIGHTS FLOWN - the number of flights flown divided by the total number of scheduled flight for 365 days for each base.
- BASE SUPPLY STOCKAGE EFFECTIVENESS - percent of requisitions filled by supply immediately through base spare stock for both parts.
- MEAN BACKORDER DAYS - average number of days a grounded aircraft spends awaiting a spare from the supply system.
- MEAN UNITS AWAITING DEPOT REPAIR - the average number of reparables awaiting entry into the depot repair shop.
- WORKER UTILIZATION - the fraction of time the depot worker is busy.

AUTOCORRELATION

Many statistical tests assume that the observations in the data set are independent and normally distributed. Each of the performance measures in the simulation model that is tabulated daily is neither normally distributed nor independent from day to day.

In order to accommodate this autocorrelation, we group successive observations into batches and calculate a mean for each batch. For example, suppose the batch size is 8 and there are 256 data elements. Then the average of the first 8 data elements becomes the first observation, the average of the second set of 8 data elements becomes the second observation, and so forth. This approach would construct a new data set of 32 observations.

As the batch size gets larger and larger, the correlation between the means of batched observations diminishes. We must determine the batch size needed in our model in order to achieve independence among the observations.

BATCH SIZE

To determine the batch size, we use Fishman's Batch Means Method [5]. In the Batch Means Method, sequentially larger batch sizes are used to construct sets of observations from a data set. For each set of observations, the hypothesis that correlation is equal to zero is tested. If the hypothesis is rejected, the batch size is doubled and the hypothesis retested.

The test runs produced 256 monthly means for each performance measure. The means were arrayed and sent to the BATCH.MEANS.METHOD routine within the simulation program. The results of the batch size test are summarized in Figure 3.1.

From the initial runs, 32 eight month batches pass the test of independence at the .05 level of significance. Since eight month batches are not commonly used, a one year batch size for all performance measures was chosen and tested.

PERFORMANCE MEASURES	PASSES TEST OF INDEPENDENCE AT .05 LEVEL
Percent of flights flown	128 - two month batches
Mean backorder days	32 - eight month batches
Mean units awaiting depot repair	64 - four month batches
Base stockage effectiveness	128 - two month batches
Worker utilization	128 - two month batches

FIGURE 3.1

SAMPLE SIZE

The sample size of 32 was determined using Stein's two-sample procedure [25]. A starting sample size of 32 years (n_1) was obtained from an initial simulation run. The sample variance was caluclated from this data and used as one variable in the determination of the appropriate sample size. Another variable was the desired length of the confidence interval about the population mean. This length, L, was set equal to ten percent of the sample mean for each performance criteria [26]. This value, the sample variance, and the appropriate t-statistic were then used to compute N with the following formula [25]

$$N = (4t^2(n_1 - 1)\ s^2/L^2) + 1 \quad .$$

The maximum of N and n_1 is used as the sample size. This procedure was applied to the performance measures for several different experimental conditions. Figure 3.2 contains examples of the values obtained from this calculation.

PERFORMANCE MEASURE	n	s^2	$\bar{x}$	N
MEAN BACKORDER DAYS	32	2.461	12.1	982
PERCENT OF FLIGHTS FLOWN	32	.0050	.780	31.4
MEAN UNITS AWAITING DEPOT REPAIR	32	.7969	1.78	2177
BASE STOCKAGE EFFECTIVENESS	32	.0012	.292	19.4
WORKER UTILIZATION	32	.0016	.878	9.85

FIGURE 3.2

It was unrealistic to increase the sample size for the mean backorder days and mean units awaiting depot repair performance measures to the level indicated by Stein's procedure because of the computation time this would require. The simulation runs made with a sample size of 32 required 25 to 30 CPU minutes. The effect on the analysis of using a smaller sample size than indicated by Stein's procedure is that the confidence interval about the population mean is larger than specified ($t_{.05} = 1.645$).

INITIALIZATION

The starting condition for the simulation places all queues and facilities empty and idle. Initial runs found that both parts were broken on all aircraft in 260 days. Additionally, all aircraft had been through the Phase Inspection in the first year. Thus, any action that is possible for an aircraft has happened in the first year of the simulation. Therefore, we have elected to truncate the first 365 days of data in order to avoid any possible influence from initialization.

MODEL VALIDATION

Validating the simulation model is a crucial step in any research project that utilizes simulation. Here are the approaches that were used for internal validation of the simulation model.

Subjective methods of verification were used during the formulation stages of the model and upon completion. These methods included detailed review of program logic and individual testing of subroutines. Error routines built into the SIMSCRIPT package were also used in the debugging process.

During several test runs of the simulation model, a variety of aircraft, part, queue, and repair shop information was printed at each event occurrence. This information was printed for the first 120 days. The simulated movement of the aircraft and parts within the system was analyzed. From the analysis it was determined that the processes and routines which flew the aircraft, sent parts to base and depot repair, and selected the proper base for redistribution were functioning properly. This was done for situations involving both static and dynamic redistribution rules.

As a safeguard against making unintentional alterations to the code, we made a test run to check the output against a previous test run, any time the code was modified or altered.

CHAPTER FOUR

ASSESSMENT OF REDISTRIBUTION RULES

In this chapter, a closed system view of our model is presented. This viewpoint is taken in assessing the three redistribution rules to determine which rule performs best in an increased flying hour program. Additionally, the partial factorial design that is used for this research is explained.

CLOSED SYSTEM VIEW

Our model consists of three basic resources, the levels of which remain constant during a simulation run. These resources are parts A and B, base-assigned aircraft, and depot workers. During the simulated timespan, the resources move to different locations in the system or become busy or idle, but they are never removed from the system. This conservation of resources allows us to track and locate the quantities in the system on a daily basis. The closed system view gives insights into where and how much each resource is affected by changes in the system.

First, consider parts A and B. They can be located in flight ready aircraft that are flying or idle.

Alternatively, the parts can be in aircraft grounded for maintenance or phase inspection. The parts also can be in reparable status in base or depot repair (including intransit to depot). Finally, the parts can be in serviceable status in the supply system. This may mean that they are in base supply or intransit between base and depot. The total number of units equals the sum of the initial system spares and units assigned to aircraft.

Next, consider aircraft. They can be flying, grounded, or idle. If an aircraft is grounded, it can be because parts A or B or both have been removed, or the aircraft is in phase inspection. If an aircraft is capable of flying and is not scheduled, the aircraft is considered idle.

Finally, consider the depot worker resource. A worker is either busy, working on a reparable unit, or idle, awaiting a reparable. Worker utilization measures the number of days in a year that workers are busy. Specifically, we define total workdays per year as 365 times the number of workers. For example, if the number of workers is 12, the total workdays is 4380. Let

$$x_{ij} = \begin{cases} 1 \text{ if worker } i \text{ is busy in day } j \\ 0 \text{ otherwise.} \end{cases}$$

Then, for a given year,

$$(4.1) \qquad \text{worker utilization} = \frac{\sum_{i,j} x_{ij}}{\text{total workdays}} .$$

When using the closed system view of the resources, remember that the results represent time averages. This view of the multi-echelon system closely approximates the base capability measurement program in use presently in several operational Air Force commands.

PEACETIME TO HOSTILITY--BASE CASE SETTING

The peacetime base case setting described in Chapter 2 results in each base flying virtually all scheduled sorties. Department of Defense managers must plan, however, for situations of increased flight requirements. These situations may be as common place as upcoming special missions or as rare as open hostilities against a foreign country. In either case, the increased flight requirements can significantly degrade both base and depot performance measures.

In our hostility scenario, each base's daily flight requirement is doubled. This results in the CONUS and overseas bases having an eight sortie requirement and the training base having a 16 sortie requirement daily. The effect on the base case performance measures is examined using the closed system viewpoint and the aggregate performance measures.

BASE CASE PERFORMANCE

We first compare the peacetime environment prior to doubling the sortie rate to the base case to show the effects of a surge on the multi-echelon system. Then we compare the impact of the three distribution rules. In the next chapter, we show the effects a single resource strategy can have on the system.

We start with a discussion of our performance measures. The percent of flights flown is the number of flights flown divided by the scheduled flights for each base during the year. This performance measure is relevant to all managers because it relates the capability of the base to fly the required aircraft sorties.

Base supply stockage effectiveness is the percent of requisitions filled by base supply immediately through base spare stock for each of the parts A and B. This performance measure is only relevant to base level supply managers, and is considered less important to upper level managers than the next performance measure.

Mean backorder days is the average number of days a grounded aircraft spends awaiting a spare from supply. This performance measure is similiar to the percent of flights flown in its importance to managers at all levels of the multi-echelon system. If the number of days that an aircraft is grounded increases, then fewer scheduled sorties can be flown. Therefore, the mean backorder days measures the capability of a base to have sufficient operationally ready aircraft to fly scheduled sorties.

The next performance measure is the mean units awaiting depot repair. This measures the average number of reparables awaiting entry into the depot repair shop. This figure can indicate to the depot item manager a need for additional spares. Additionally, it acts as an indicator to the maintenance manager for increased manpower in the depot shop.

Finally, worker utilization is the total number of days workers are busy divided by the total number of workdays (see 4-1 above). This performance measure indicates to the depot maintenance manager that changes may be needed in manpower in depot shop.

The data used for the closed system comparison of performance measures are the results of 32 years of simulated time in our computer model. Each performance measure's mean is used to calculate the percent of resources available in specific areas of the system.

The performance measure comparison of peacetime to hostile environments shows the effect of doubling the sortie rate on the system (Figure 4.1). The average number of days which an aircraft waits for a part increases from 4.6 to 7.9 for part A, and from 6.1 to

12.1 for part B. This increase in backorder days coupled with a decrease in percent of flights flown shows that the level of spares available in the system is not adequate. This conclusion is reinforced by looking at the depot worker utilization measure, which increases from 57% to 87%. During hostilities, depot workers are still not fully utilized, even though the sortie rate is low and the backorder days are high.

PERFORMANCE MEASURE	PEACETIME	HOSTILITY
Percent of flights flown	99%	78%
Part A stockage effectiveness	54%	20%
Part B stockage effectiveness	61%	29%
Part A backorder days	4.6	7.9
Part B backorder days	6.1	12.1
Units awaiting depot repair	.05	1.8
Depot worker utilization	57%	88%

FIGURE 4.1

The percent of flights flown decreases from 99% to 78%. This decrease is dramatic. Note, however, the total number of sorties flown has actually increased from 5839 sorties during peacetime to 9102 sorties during hostilities.

These aggregate performance measures provide valid information to managers at all levels. They must be supplemented, however, with additional information to avoid confusion on effects that logistic strategies have on the system. The closed system view, which is discussed next, serves as an alternative to using simple aggregate measures.

The closed system view looks at the effects on the bases and depot individually. Additionally, the effects on the resources of parts A and B, aircraft, and depot workers are examined in more detail.

The bar chart in Figure 4.2 shows the difference between peacetime and the hostile environment on part A. The percent of units in idle aircraft at base level decreases from 37 percent to 2 percent. This change makes cannibalization infeasible at base level during a hostility. Additionally, this information shows why during peacetime cannibalization becomes an alternative to poor supply performance at base level. Figure 4.2 shows the percent of units available in phase or idle aircraft for possible cannibalization is 53 percent, while the percent of units available intransit to or on the shelf in base supply is only 20 percent.

Another point of interest is the change in units intransit (both reparables and serviceables) between the depot and bases. These intransit units increase from 14 percent to 20 percent, a rise of 50%. This means that on the average 3.2 more units are not available for use in an hostile environment. To a base commander, these units

PEACETIME VERSUS HOSTILITY
FOR
PART A RESOURCE

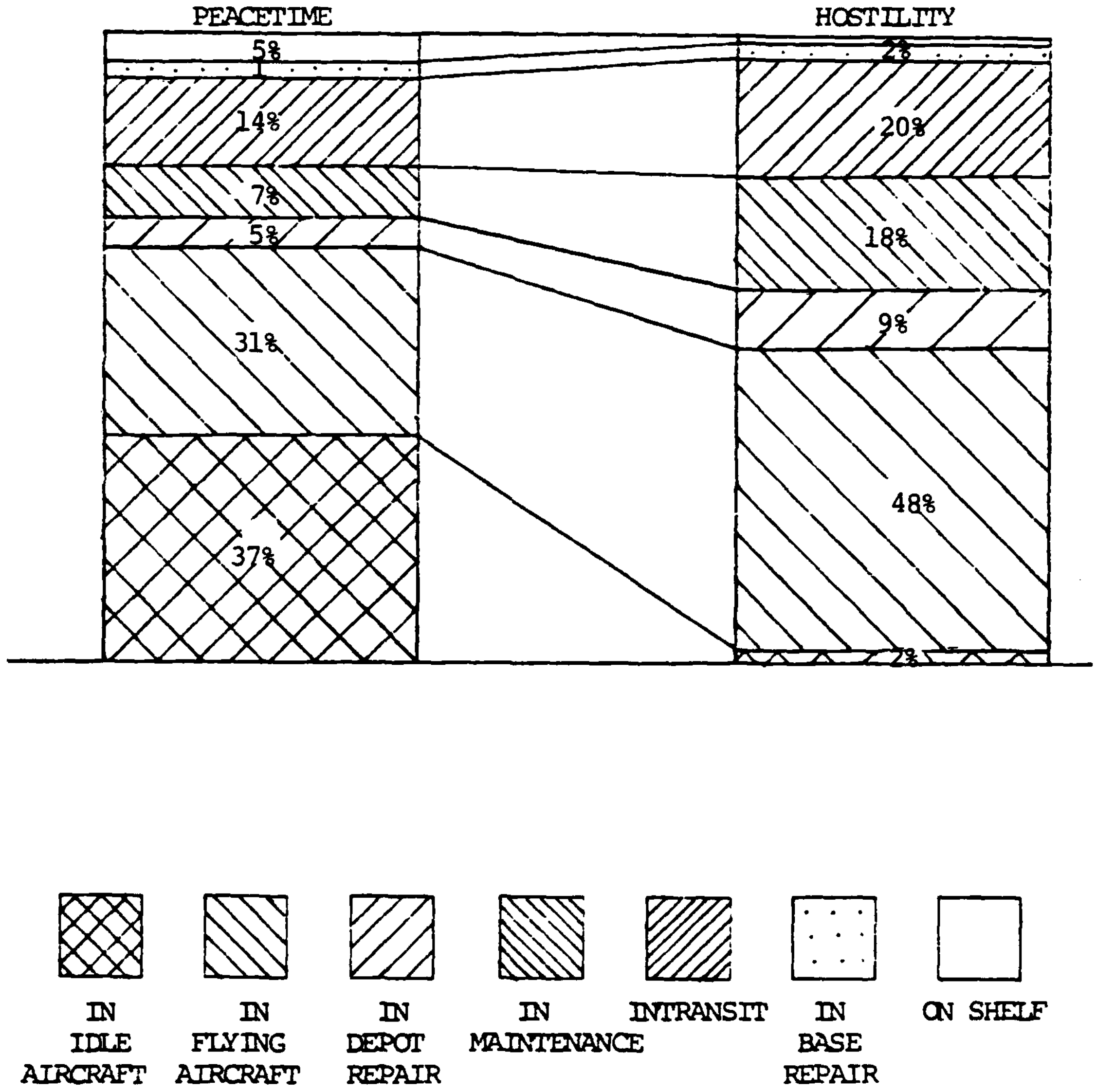


FIGURE 4.2

PEACETIME VERSUS HOSTILITY
FOR
PART B RESOURCE

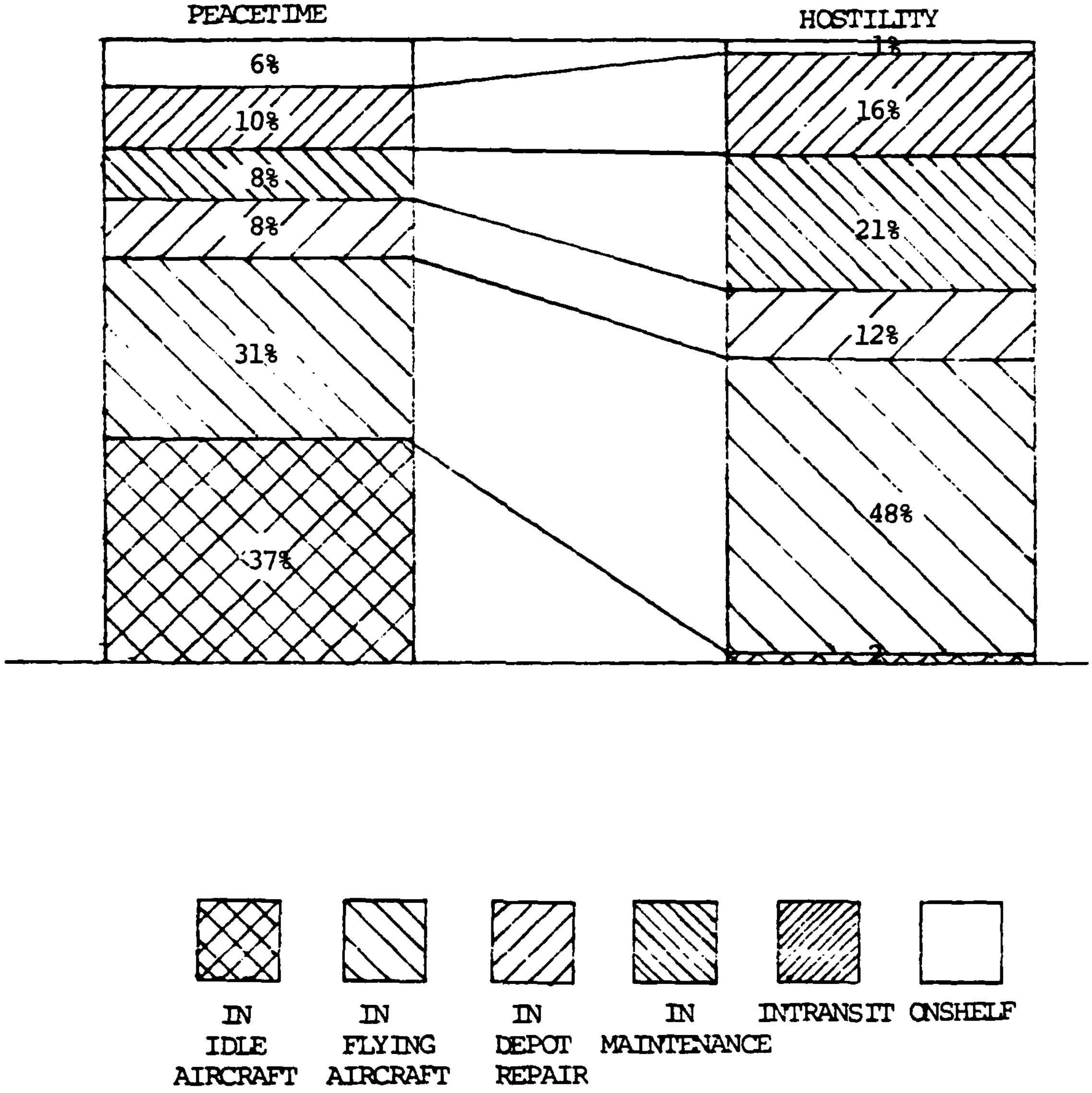


FIGURE 4.3

PEACETIME BASE CASE

	PART A			PART B		
BASE	1	2	3	1	2	3
ON SHELF	5%	3%	10%	7%	4%	11%
IN BASE REPAIR	1%	1%	1%	---	---	---
INTRANSIT	11%	12%	20%	9%	9%	15%
IN PHASE	7%	7%	6%	7%	8%	7%
IN GROUNDED A/C	2%	2%	1%	2%	2%	1%
IN FLYING A/C	34%	34%	28%	35%	35%	30%
IN IDLE A/C	40%	41%	34%	40%	42%	36%

HOSTILE BASE CASE

	PART A			PART B		
	1	2	3	1	2	3
ON SHELF	1%	1%	2%	1%	1%	3%
IN BASE REPAIR	3%	2%	2%	---	---	---
INTRANSIT	19%	19%	30%	14%	15%	24%
IN PHASE	12%	11%	14%	12%	12%	13%
IN GROUNDED A/C	4%	9%	7%	11%	10%	14%
IN FLYING A/C	58%	56%	46%	58%	60%	45%
IN IDLE A/C	3%	2%	1%	4%	2%	1%

FIGURE 4.4

PEACETIME VERSUS HOSTILITY
FOR
AIRCRAFT RESOURCE

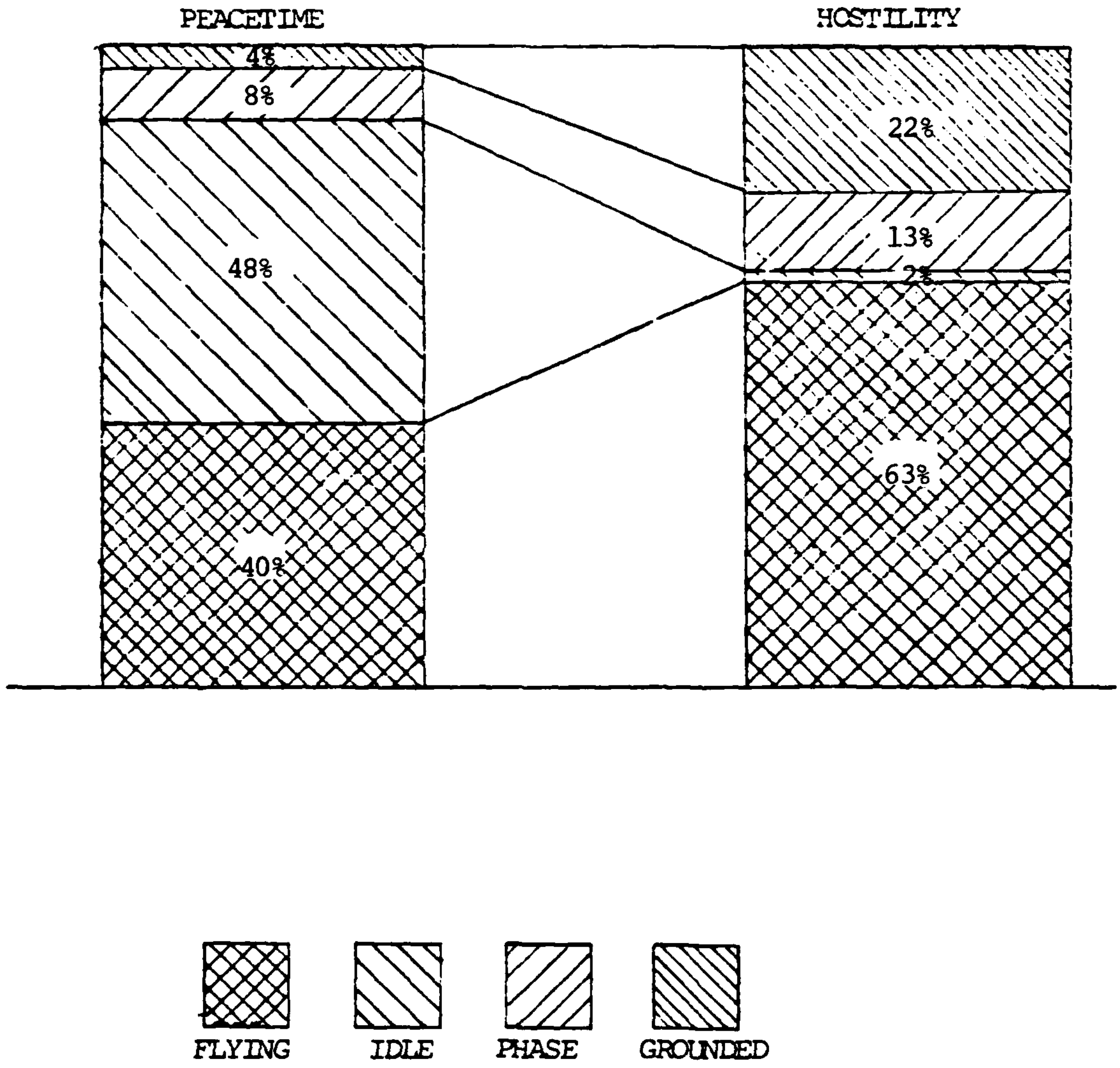


FIGURE 4.5

would permit three more aircraft to fly.

The same type of bar chart shows the aggregate information for part B (Figure 4.3). The changes from peacetime to hostility are very similar to those for part A (Figure 4.2). The major difference is that part B does not have a base repair capability and has no representation on the bar chart.

The closed system view also shows the same information for each base separately (Figure 4.4). The overseas base (base 3) has a greater number of parts intransit than either of the other bases. This is due to the dynamic redistribution rule dispatching more serviceables to the most distant base with the highest demand rate. Although both bases schedule the same number of flights, the overseas base has a greater number of aircraft grounded than the stateside operational base. This difference is primarily caused by the transportation time being doubled between the depot and an overseas base. This results in more unmet demands placed in base supply and therefore more grounded aircraft.

The bar chart, shown in Figure 4.5, shows percentages for the aircraft resource. The decrease of idle aircraft from 48 percent to 2 percent can be explained by the increase of flying aircraft by 23 percent and the increases in both the percent grounded and the percent in phase. If the bases flew all required flights, the percent of aircraft flying would be 80 percent; however, due to the limited resources available only 63 percent can be flown. The difference of 17 percent appears in increased numbers of grounded and phase aircraft.

The depot worker resource is shown in Figure 4.6. The increase of 63 percent of days in which 10 to 12 workers are busy is of particular interest. After doubling the sortie rate, almost 76 percent of the time between 10 and 12 depot workers are busy.

The information provided by the closed system view expands considerably on the basic performance measures available to the system managers at all levels. For this reason, in Chapter 5 the closed system view is used to discuss the comparison of different strategic resource options.

EFFECTS OF REDISTRIBUTION RULES ON THE HOSTILITY BASE CASE

The main issue in this chapter is to assess the redistribution rules to find if one gives the greatest improvement in our performance measures. First, we examine the effects of the three redistribution rules on the hostility base case. Then, we discuss the fractional factorial design that is used to compare these rules for alternative resource strategies.

We start with a discussion of our redistribution rules. The static rule distributes a serviceable out of depot repair to the base turning in that unit for repair. The dynamic rule uses Bruce Miller's Transportation Look

PEACETIME VERSUS HOSTILITY
FOR
DEPOT WORKER RESOURCE
(PERCENT OF DAYS)

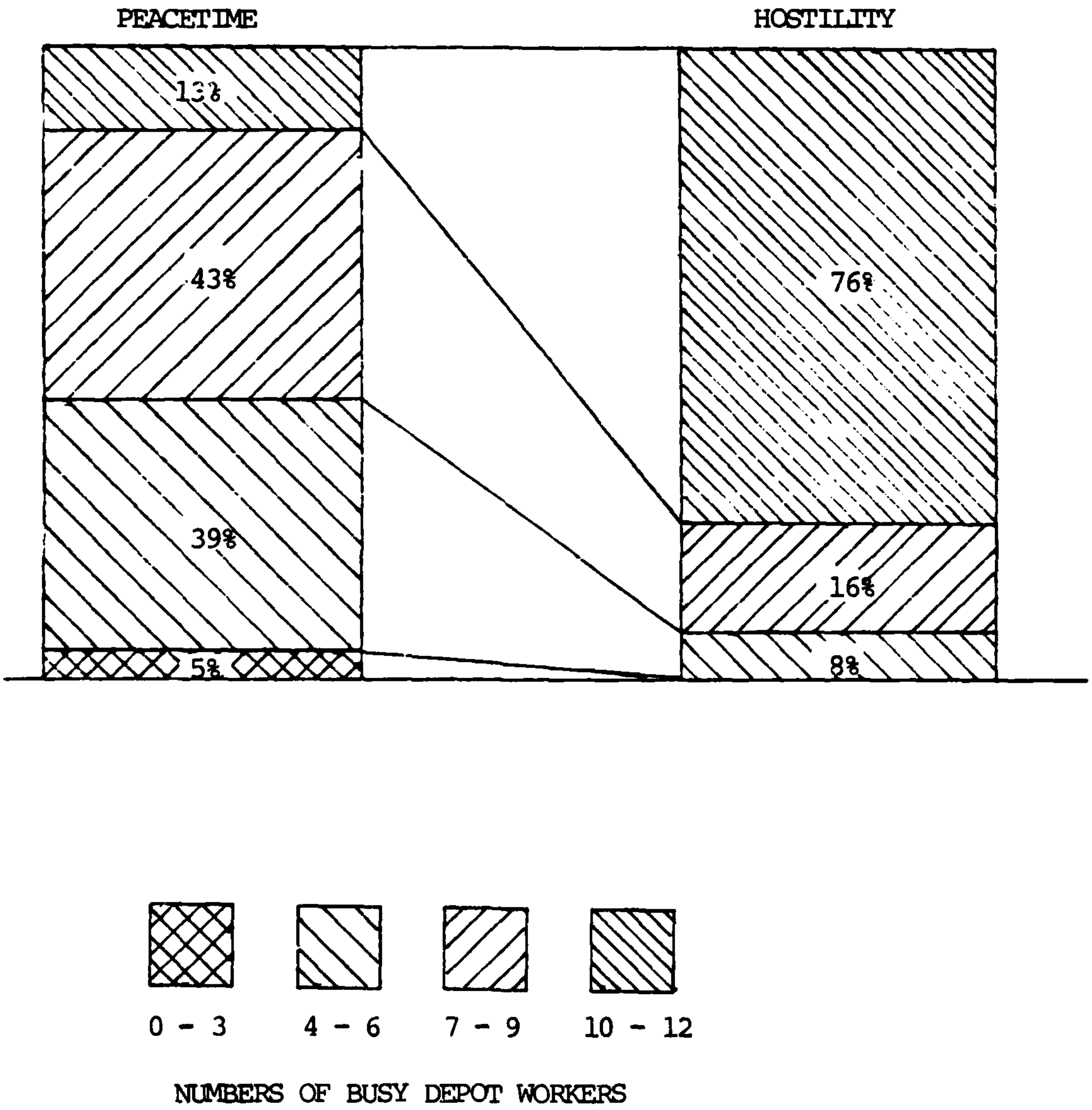


FIGURE 4.6

Ahead Policy to distribute a serviceable to a base by comparing each base's demand rate, pipeline transportation time, and the number of spares in base stock plus in transit. The second dynamic rule enhances the Transportation Look Ahead Policy by including the expected number of serviceables coming from base repair during the base-depot pipeline time.

The main issue is to decide if one redistribution rule is best when resources are added in the hostility scenario. We vary the six logistic factors shown in Figure 4.7. Each may be set to a low (base case) level or higher value.

LOGISTIC FACTORS	LOW			HIGH		
BASE	1	2	3	1	2	3
PART A SPARE LEVEL	3	6	3	6	12	6
PART B SPARE LEVEL	3	6	3	6	12	6
A REDESIGN	300*			400*		
BASE REPAIR FRACTION	.25	.10	.25	.25	.10	.25
DEPOT WORKERS	12*			15*		
TRANSPORTATION TIME	7	7	14	3	3	7

* - Value is the same for all three bases.

FIGURE 4.7

The base case values are consistent with values presently used by the United States Air Force.

The high values are set by looking at each factor separately. Each value results in about a five percent increase in the percent of flights flown over the figure for the hostility base case. This technique ensures that one factor does not overpower other factors in the experiment. The results of setting the high values for each strategy are shown in Figure 4.8.

Since each simulation of this model requires 25 to 30 CPU minutes, it is not economical or feasible to collect data on all 2^6 factorial combinations that are implied by a full factorial design on the six strategic factors. Statisticians have developed experimental designs called fractional factorials [2, 10]. In using this kind of design, not all of the factorial combinations are tested. The design, shown in Figure 4.9, requires only 16 experiments for each redistribution rule. It allows estimation of all main effects of the factors and seven two-factor interactions. We assume that the other two-factor and higher interactions involving three or more factors are negligible and can be ignored.

STATISTICAL APPROACH

After completing a 32 year simulation run for each of the 16 experiments in the fractional factorial design, a mean and variance are calculated for each performance measure. Since the three redistribution rules are tested in this part of the analysis, each performance measure

COMPARISON OF SINGLE STRATEGIES

PERFORMANCE MEASURES	BASE CASE	INCREASE WORKERS	INCREASE BASE REPAIR	INCREASE SPARE A	INCREASE SPARE B	REDESIGN A	REDUCE TRANSPORT DAYS
PERCENT OF FLIGHTS FLOWN	78% (3%)	84% (1%)	84% (2%)	83% (3%)	83% (3%)	81% (2%)	82% (3%)
PART A BACKORDER DAYS	7.9 (1.6)	7.5 (1.4)	5.8 (.6)	5.9 (1.3)	8.3 (1.6)	7.3 (1.1)	6.3 (1.3)
PART B BACKORDER DAYS	12.2 (1.6)	10.5 (1.0)	11.1 (1.0)	12.7 (1.6)	8.7 (1.7)	12.2 (1.6)	9.0 (1.0)
UNITS AWAITING DEPOT REPAIR	1.8 (.9)	.2 (.1)	.80 (.4)	2.3 (1.3)	4.8 (2.3)	1.5 (.7)	4.2 (1.9)
DEPOT WORKER UTILIZATION	88% (4%)	74% (3%)	83% (4%)	93% (2%)	92% (2%)	83% (4%)	93% (2%)
PART A STOCKAGE EFFECTIVENESS	19% (3%)	32% (3%)	39% (3%)	72% (4%)	10% (3%)	38% (3%)	35% (3%)
PART B STOCKAGE EFFECTIVENESS	25% (3%)	36% (4%)	30% (3%)	20% (4%)	76% (2%)	23% (4%)	39% (3%)

NOTE: STANDARD DEVIATION IN PARENTHESIS.

FIGURE 4.8

PARTIAL FACTORIAL DESIGN

	LOGISTIC FACTORS:					
EXPERIMENT	A SPARE LEVEL	B SPARE LEVEL	PART A REDESIGN	BASE REPAIR	DEPOT WORKERS	TRANSP TIME
1	L	L	L	L	L	L
2	L	L	L	H	H	L
3	H	L	H	L	L	L
4	H	L	H	H	H	L
5	H	L	L	H	L	H
6	H	L	L	L	H	H
7	L	L	H	H	L	H
8	L	L	H	L	H	H
9	L	H	L	H	H	H
10	L	H	L	L	L	H
11	H	H	H	H	H	H
12	H	H	H	L	L	H
13	H	H	L	L	H	L
14	H	H	L	H	L	L
15	L	H	H	L	H	L
16	L	H	H	H	L	L

L : base case level (low)
H : higher level

FIGURE 4.9

has a 48 cell comparison of experiments and redistribution rules. The means for percent of flights flown are shown in Figure 4.10.

The Wilcoxon signed rank test is used to test the differences among the three redistribution rules for 7 performance criteria [22]. This test is the nonparametric analog of the parametric paired t-test for matched samples. For each case, the static rule is tested against both dynamic rules. Then the dynamic rules are tested for difference at the .05 significance level.

Here are the Wilcoxon signed rank calculations for the measure percent of flights flown. First, we calculate the difference between the static and dynamic rule. These signed differences are ranked from numerically lowest value to highest. The lowest difference is assigned a value of one and the highest a value of 16. A statistic T is calculated indicating the sum of only the positive rank values, that is, the ranks where the underlying signed difference is positive. The minimum possible T value is 0 and the maximum is 136. For sample sizes larger than 10, the T statistic is approximately normally distributed, with mean

$$\mu_T = \frac{n(n+1)}{4}$$

and standard deviation

$$\sigma_T = \sqrt{\frac{n(n+1)\ (2n+1)}{24}}\ .$$

In our experimental design, n=16 so that $\mu_T=68$ and $\sigma_T=19.38$. Then

$$z = \frac{T - \mu_T}{\sigma_T}$$

is a standardized normal deviate. This value is compared to a table value at the significance level of .05 ($z=1.96$).

For our example, the statistic T equals 135. This results in a z calculation of 3.46, which implies a significant difference between the static and dynamic rules. A summary of the critical Wilcoxon T values and test results is shown in Figures 4.11 and 4.12.

The results show a statistically significant difference exists between the static redistribution rule and either of the dynamic rules. There appears to be no difference, however, between the two dynamic rules tested.

Although the Wilcoxon test results show a statisticaly significant difference, a visual inspection of Figure 4.10 shows only small numerical differences in rules for each experiment. In fact, if a t-test is

PERCENT OF FLIGHTS FLOWN

(100% = 11,680 FLIGHTS PER YEAR)

EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	77.9%	77.9%	78.4%
2	83.8	84.2	84.3
3	86.0	86.6	86.7
4	88.3	89.0	88.4
5	91.6	93.2	92.6
6	92.9	93.6	93.9
7	91.8	92.7	92.8
8	91.7	92.9	92.8
9	94.1	95.2	95.0
10	86.0	86.8	85.7
11	97.3	98.4	98.3
12	95.0	96.1	96.0
13	93.0	94.7	94.4
14	93.6	95.0	95.2
15	89.5	90.6	91.0
16	92.0	93.0	93.2

FIGURE 4.10

CRITICAL WILCOXON T VALUES FOR
REDISTRIBUTION RULE COMPARISONS

PERFORMANCE MEASURE	STATIC VERSUS DYNAMIC	STATIC VERSUS ENHANCED DYNAMIC	STATIC VERSUS ENHANCED DYNAMIC
PERCENT OF FLIGHTS FLOWN	135	134	65
PART A BACKORDER DAYS	136	136	107
PART B BACKORDER DAYS	136	136	73
UNITS AWAITING DEPOT REPAIR	17	13	62
DEPOT WORKER UTILIZATION	127	134	65
PART A STOCKAGE EFFECTIVENESS	16	19	87
PART B STOCKAGE EFFECTIVENESS	28	30	70

DECISION RULE: Reject hypothesis that means are equal at .05 significance level if T exceeds 106 or is less than 31.

NOTE: Minimum possible T = 0 and maximum possible T = 136.

FIGURE 4.11

COMPARISON OF REDISTRIBUTION RULES

PERFORMANCE MEASURE	STATIC VS DYNAMIC	STATIC VS E.DYNAMIC	DYNAMIC VS E.DYNAMIC
Percent of flight flown	D	E	N
Part A backorder days	D	E	E
Part B backorder days	D	E	N
Units awaiting depot repair	S	S	N
Depot worker utilization	D	E	N
Part A stockage effectiveness	S	S	N
Part B stockage effectiveness	S	S	N

LEGEND: Best rule at an .05 level of significance.

S - static rule.
D - dynamic rule.
E - enhanced dynamic rule
N - no difference between the two rules.

FIGURE 4.12

performed on each of the 16 experiments, the results would show no difference among the redistribution rules. This is because the variance of the yearly mean for the performance measure is relatively large. The distributions of the annual performance measure considerably overlap for the redistribution rules.

For a logistics system, there is really no appreciable difference among the redistribution rules for most of performance measures.

PERFORMANCE MEASURE MEAN
FOR
EACH REDISTRIBUTION RULE

PERFORMANCE MEASURES	STATIC	DYNAMIC	ENHANCED DYNAMIC
PERCENT OF FLIGHTS FLOWN	90%	91%	91%
PART A BACKORDER DAYS	4.5	3.3	3.2
PART B BACKORDER DAYS	8.1	5.2	5.2
UNITS AWAITING DEPOT REPAIR	2.0	2.4	2.4
DEPOT WORKER UTILIZATION	82%	83%	83%
PART A STOCKAGE EFFECTIVENESS	68%	64%	63%
PART B STOCKAGE EFFECTIVENESS	59%	54%	54%

FIGURE 4.13

The results in Figure 4.13 of mean calculations across all 16 experiments show this point clearly. From the manager's point of view, there is virtually no difference in percent of flights flown or depot worker utilization.

The one percent change in flights flown represents approximately 100 additional flights out of a possible 11,680 per year for all three bases. This means that a base manager would see only one additional flight flown every 10th day of operation.

The decrease in backorder days for both parts A and B is important to a manager. More than one day is saved in waiting for a part A and almost 3 days is saved for each part B requisitioned. In a hostile environment, the less time an aircraft is grounded awaiting parts, the more valuable it is as a resource to the base manager.

In a closed system, some performance measures may improve at the expense of other measures. Thus, careful attention must be paid by managers as to which measures should be used to evaluate strategies and operational polices. For example, consider base stockage effectiveness for both parts. In redistributing the level of base spares, bases that are closer to the depot repair facility or have a lower demand receive fewer serviceable units. As a result, fewer demands are met with off-the-shelf units and the base stockage effectiveness is significantly lower for the dynamic rules. Since this performance measure experiences an inverse effect, a manager may want to rely on the other performance measures to appropriately evaluate changes in strategies or policies.

Finally, we note in Figure 4.10 that the performance measure differences among the strategy combinations are much larger than the differences among redistribution rules. Clearly, if limited funds are available to change either the redistribution rules or secure added logistic resources, a manager should concentrate on securing the added resources.

SUMMARY

We have found that using a closed system view allows managers at all levels to receive useful information that is not provided by normal performance measures. This extra information allows each base and the depot to be separately analyzed when strategies are implemented.

The base case resource settings were analyzed for both peacetime and hostile situations. When the flight requirements are doubled, the bases actually fly 50 percent more sorties. The performance measures are degraded, however, since grounded aircraft increase and supply requisition times lengthen due to the increase of failed items in the repair system.

A statistically significant difference appears in the key performance measures in the comparison of the static and dynamic/enhanced dynamic redistribution rules. These differences are derived from the Wilcoxon signed rank test. No statistical difference is found between the dynamic and enhanced dynamic rules.

From a manager's point of view, however, there is hardly any difference between the redistribution rules in all performance measures except the backorder days measure. Securing added logistic resources has a larger effect on the performance measures than changing the redistribution rule.

In examining the 16 experiments, the performance of the static rule is dominated by either one or both of the dynamic rules, but the performance of the two dynamic rules is nearly the same. For our further analyses of strategic options in the next chapter, we have selected the enhanced dynamic rule. Also, since the base stockage effectiveness performance measure does not reflect the true effect of changes on the system, we will not use this measure in the subsequent analyses.

CHAPTER FIVE

EVALUATION OF LOGISTIC STRATEGIES

Throughout this chapter, we use the enhanced dynamic redistribution rule in testing the impact of different logistic strategies. First, one-at-a-time strategies are analyzed using the closed system view. Then a linear model derived from the partial factorial design assesses the impact on each performance measure of varying resource levels.

OVERVIEW

In Chapter 1, we addressed the general lack of understanding the impact of logistic strategies on an entire multi-echelon system. For example, a strategy developed at one level of the repair process can seriously affect repair decisions at all levels of the logistics system. Additionally, this strategy will affect spare levels throughout the system. Logistic strategies and operational policies, shown in Figure 5.1, answer many multi-echelon inventory problems. The question not often answered is what effect does the implementation of a strategy have on systemwide performance measures. The results in this chapter address this question.

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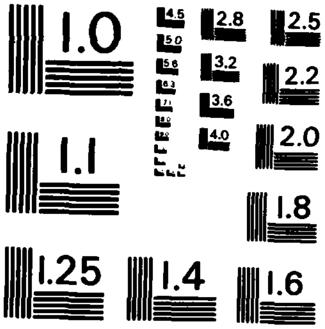

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MULTI-ECHELON PROBLEMS, STRATEGIES AND OPERATIONAL POLICIES

PROBLEM	STRATEGIES	OPERATIONAL POLICIES
Long delays in depot repair	Increase depot capacity Increase spares inventory	Hire workers Shift workers from other areas
Large percentage of aircraft grounded	Redesign product Increase spares inventory	Redistribute spares Alter distribution rule
Transportation delays	Change routes or procedures	Expedite high priority shipments
Large percentage of items sent to depot for repair	Redesign product Increase base repair capacity	Change technical data tolerances
Low supply service level	Redesign product Increase spares inventory	Redistribute spares Alter dispatching rule

FIGURE 5.1

Six strategies are selected for testing. These strategies include: increasing spare inventories for parts A and B, increasing depot and base repair capacities, redesigning part A to lower its failure rate, and decreasing transportation time between depot and base. Our discussion of results groups these into four categories of strategies (1) alter spare levels, (2) alter repair capacity, (3) redesign part A and (4) reduce transportation pipeline time. Each strategy is tested at a low (base case) level or a higher value as shown in Figure 4.7.

The spare levels for parts A and B were initially set to 3, 6, and 3 for the stateside operational base, stateside training base, and overseas operational base, respectively. The increased resource levels are 6, 12, and 6, respectively. The initial quantities allow enough spares to fly virtually all scheduled sorties during peacetime, but leave few serviceables on the shelf in base supply. (The increased spares levels give a five percent increase to the percent of flights flown over the hostility base case.)

The strategy to increase depot capacity increases the number of depot workers available to repair units in the shop. The peacetime level of 12 workers is sufficient at a lower flying rate to maintain adequate spare levels at all bases. Increasing depot workers results in a five percent increase in flights flown over the hostility base case.

The strategy to increase base repair capacity changes the percentage of failed item A units that can be repaired at base level. Recall that part B must be repaired at depot. The increased level of 50 percent for the operational bases and 20 percent for the training base is twice the peacetime percentages.

The redesign of part A would be very time consuming and probably not attempted during hostilities. We assume the design change can be completed prior to hostilities and is available for all units. The redesign changes the mean time between failures (MTBF) from 300 hours to 400 hours. This change allows an average of ten more flights to be flown for each part A.

Finally, the transportation time strategy decreases the days to transport units between bases and the depot. The initial figures of 7 days for stateside bases and 14 days for the overseas base represent the actual times given by the Air Force Supply Manual. We test transportation times of 3 days for stateside bases and 7 days for the overseas base. These decreases result in a five percent increase in flights flown over the hostility base case.

APPROACH

Two techniques are used to test the impact of different logistic strategies. We employ the closed system view to analyze single-factor strategies. We estimate a linear model using the partial factorial design to analyze the 16 strategy combination cases shown in Figure 4.9. Each of these techniques is discussed briefly before we address the logistic strategy results.

Our model encompasses four basic resources, the levels of which remain constant during a simulation run. These resources are parts A and B, base-assigned aircraft, and depot workers. During the simulated timespan, the resources move to different locations in the system or become busy or idle, but they are never removed from the system. This conservation of resources allows us to track and locate the quantities in the system on a daily basis. Since the closed system view gives insights into where and how much each resource is affected by changes in the system, it is invaluable in analyzing the complex interactions of logistic strategies.

LINEAR MODEL

Our partial factorial design is described in Chapter 4. This design tests 16 strategy combinations rather than 64 cases using a full factorial design.

Let M_r represent the estimate of the r^{th} performance measure, and N_r, O_r, P_r, Q_r, R_r, and S_r, be the coefficients of the six strategy factors (A, B, C, D, E, and F), where A = A spare level, B = B spare level, C =

part A redesign, D = base repair, E = depot workers, and F = transportation time. We postulate the linear model

$$M = \text{constant} + N_r A + O_r B + P_r C + Q_r D + R_r E + S_r F + \text{interaction terms} + \text{error}$$

where,

$$A, B, C, D, E, \text{ and } F = \begin{cases} 1 \text{ if strategy is set to high value} \\ -1 \text{ if strategy is set to low value} \end{cases}$$

The fractional factorial design aliases estimates of N_r, O_r, P_r, Q_r, R_r, and S_r with some third and higher order interactions. As we discuss at the end of this chapter, it is reasonable to assume that these higher order effects are negligible. This permits an accurate assessment of the first-order effects. Using the General Linear Model (GLM) procedure in SAS, the data from the simulation runs are analyzed to estimate N_r, O_r, P_r, Q_r, R_r, and S_r. The total number of observations is 512 (16 cases times 32 years). From this analysis, the R^2 for each performance measure is given below:

PERFORMANCE MEASURE	R^2
PERCENT OF FLIGHTS FLOWN	.89
PART A BACKORDER DAYS	.89
PART B BACKORDER DAYS	.87
UNITS AWAITING DEPOT REPAIR	.72
DEPOT WORKER UTILIZATION	.88

ADDITIONAL PART A UNITS

The spare levels for part A were initially set to 3, 6, and 3 for the stateside operational base, stateside training base, and the overseas operational base, respectively. The increased levels are 6, 12, and 6, respectively. This results in 52 units in the system at the low level of part A (40 units on aircraft plus 12 spares) and 64 units at the high level (40 units on aircraft plus 24 spares).

In the fractional factorial design, eight cases are evaluated at the low resource level and eight cases at the high resource level. We can evaluate the impact of increasing part A resource by comparing the averages of the performance measures for the eight low and eight high cases. The difference between the two resource levels also can be assessed by using the linear model coefficient estimated for each performance measure. The results of this comparison are shown in Figure 5.2.

ANALYSIS OF PART A RESOURCE

LOW/HIGH AVERAGES VERSUS LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES			DELTA EFFECT:	
	LOW	HIGH	AVERAGE	LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	89%	93%	4%	4%
PART A BACKORDER DAYS	4.6	1.8	-2.8	-2.8
PART B BACKORDER DAYS	4.9	5.6	.7	.8
UNITS AWAITING DEPOT REPAIR	2.0	2.8	.8	.8
DEPOT WORKER UTILIZATION	81%	85%	4%	4%

FIGURE 5.2

Increasing the part A resources in the system, results in a 4% increase in flights flown. This increase in flights flown is due to reducing backorder days by 2.8 days. Additionally, more part A units in the system results in more units arriving at depot for repair. This means that on the average .8 units more are awaiting depot repair. Increasing units awaiting depot repair results in more busy depot workers and a 4% increase in depot worker utilization.

From the three base managers' point of view this strategy is very beneficial. They see a large decrease in part A backorder days and an increase in flights flown. Perhaps, the most visible advantage to the base managers in implementing this strategy is the increase in units available on the shelf in base supply. Figure 5.3 shows an increase of on-the-shelf units from 4% to 17%. This means an increase of almost 9 units to the base supply managers. The base maintenance managers see a 4% decrease in grounded aircraft with a corresponding increase of 4% in aircraft flying, shown in Figure 5.4. Both idle and in phase aircraft remain unchanged. The only disadvantage at base level is a slight increase of .7 days in the part B backorder days performance measure.

From the depot manager's viewpoint, however, this strategy has a mixed effect on his performance. The number of units awaiting depot repair increases by 40%, but depot worker utilization increases from 81% to 85%.

COMPARISON OF LOW VERSUS HIGH CASES
FOR ADDITIONAL PART A

PART A RESOURCE

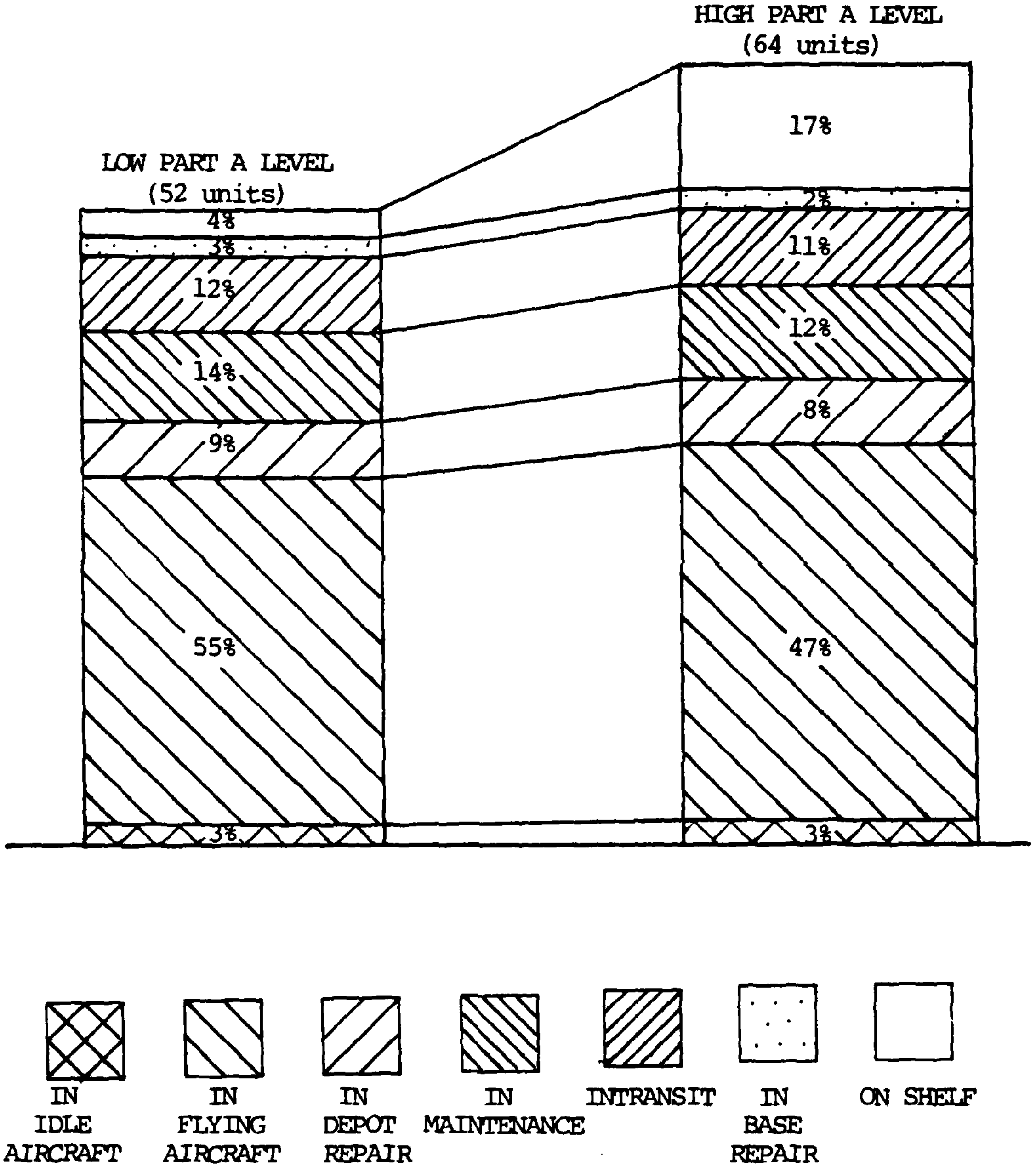

FIGURE 5.3

COMPARISON OF LOW VERSUS HIGH CASES
FOR ADDITIONAL PART A

AIRCRAFT RESOURCE

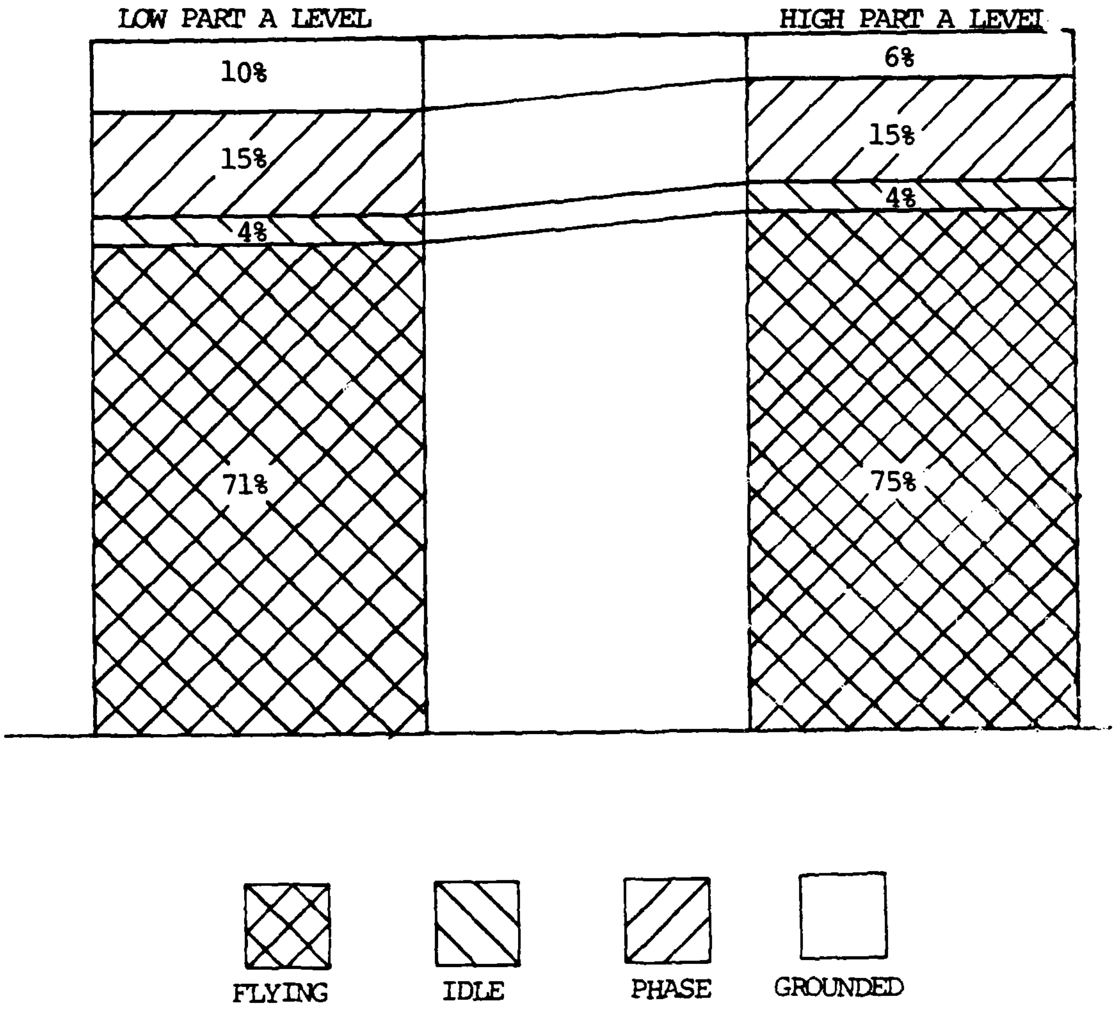

FIGURE 5.4

This increase in utilization is broken down by levels of busy workers in Figure 5.5. This strategy does not warrant additional manpower at depot, since over 50% of the time 3 or more workers are idle.

ADDITIONAL PART B

The spare levels for part B were initially set to 3, 6, and 3 for the stateside operational base, stateside training base, and the overseas operational base, respectively. This results in 52 units in the system at the low level of part B (40 units on aircraft plus 12 spares) and 64 units at the high level (40 units on aircraft plus 24 spares).

The impact of the strategy is evaluated by comparing the averages of the eight low and eight high cases. The results of this comparison are shown in Figure 5.6. Additionally, the difference between the two resource levels is compared to the linear model coefficient for each performance measure.

The percent of flights flown increase by 4% when the part B resource is increased. This increase in flights flown is due to the reduction in part B backorder days by 4.8 days. Additionally, more part B units in the system results in more units arriving at depot for repair. An average increase of 2.4 units is awaiting depot repair. Increasing units awaiting depot repair results in more

COMPARISON OF LOW VERSUS HIGH CASES FOR ADDITIONAL PART A

DEPOT WORKER RESOURCE

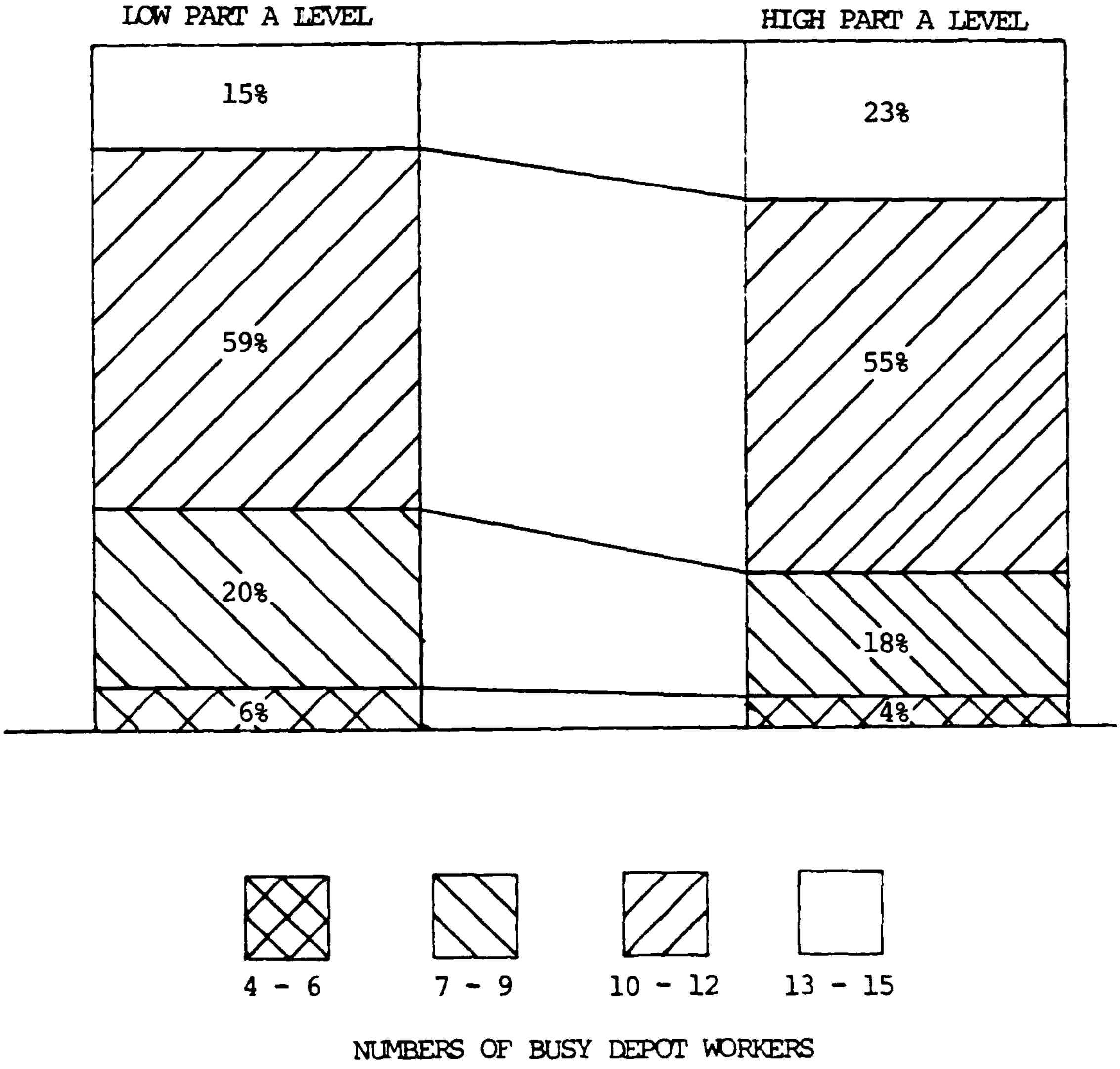

FIGURE 5.5

ANALYSIS OF PART B RESOURCE

LOW/HIGH AVERAGES VERSUS LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES	LOW	HIGH	DELTA EFFECT: AVERAGE	DELTA EFFECT: LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	89%	93%	4%	4%
PART A BACKORDER DAYS	2.9	3.5	.6	.6
PART B BACKORDER DAYS	7.6	2.8	-4.8	-4.8
UNITS AWAITING DEPOT REPAIR	1.2	3.6	2.4	2.4
DEPOT WORKER UTILIZATION	81%	85%	4%	4%

FIGURE 5.6

busy depot workers and a 4% increase in depot worker utilization.

From the three base managers' viewpoint, the advantages of implementing this strategy are overwhelming. The reduction of 4.8 days in part B backorder days coupled with the increase of flights flown by 4% is significant. Again, the most visible advantage to the base supply managers in implementing this strategy is the increase in units available on the shelf in base supply. Figure 5.7 shows an increase of on-the-shelf units from 2% to 13%. This means an increase of over 7 units to the base supply managers. The base maintenance managers see a 6% decrease in grounded aircraft and an increase of 4% in aircraft flying (Figure 5.8). Additionally, both idle and in phase aircraft are increased by 1%. The only disadvantage at base level is a slight increase of .6 days in the part A backorder days performance measure.

This strategy has mixed results for the depot manager. The number of units awaiting depot repair increases by 200% from a low level of 1.2 units to a high level of 3.6 units. Depot worker utilization also increases from 81% to 85%. This increase in utilization is broken down by levels of busy workers in Figure 5.9.

INCREASED BASE REPAIR

The strategy to increase base repair capacity changes the fraction of failed item A units that can be

COMPARISON OF LOW VERSUS HIGH CASES
FOR ADDITIONAL PART B

PART B RESOURCE

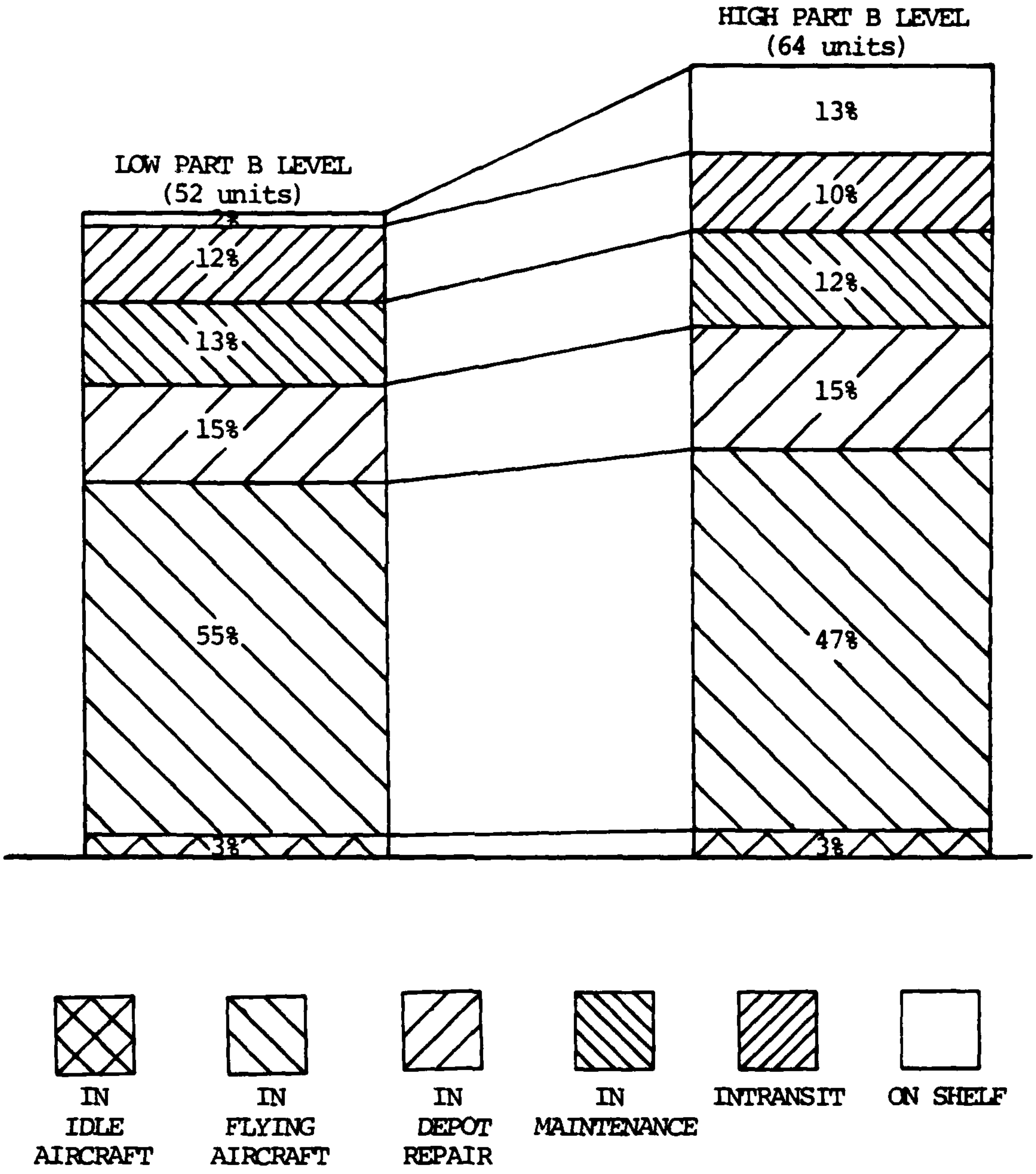

FIGURE 5.7

COMPARISON OF LOW VERSUS HIGH CASES
FOR ADDITIONAL PART B

AIRCRAFT RESOURCE

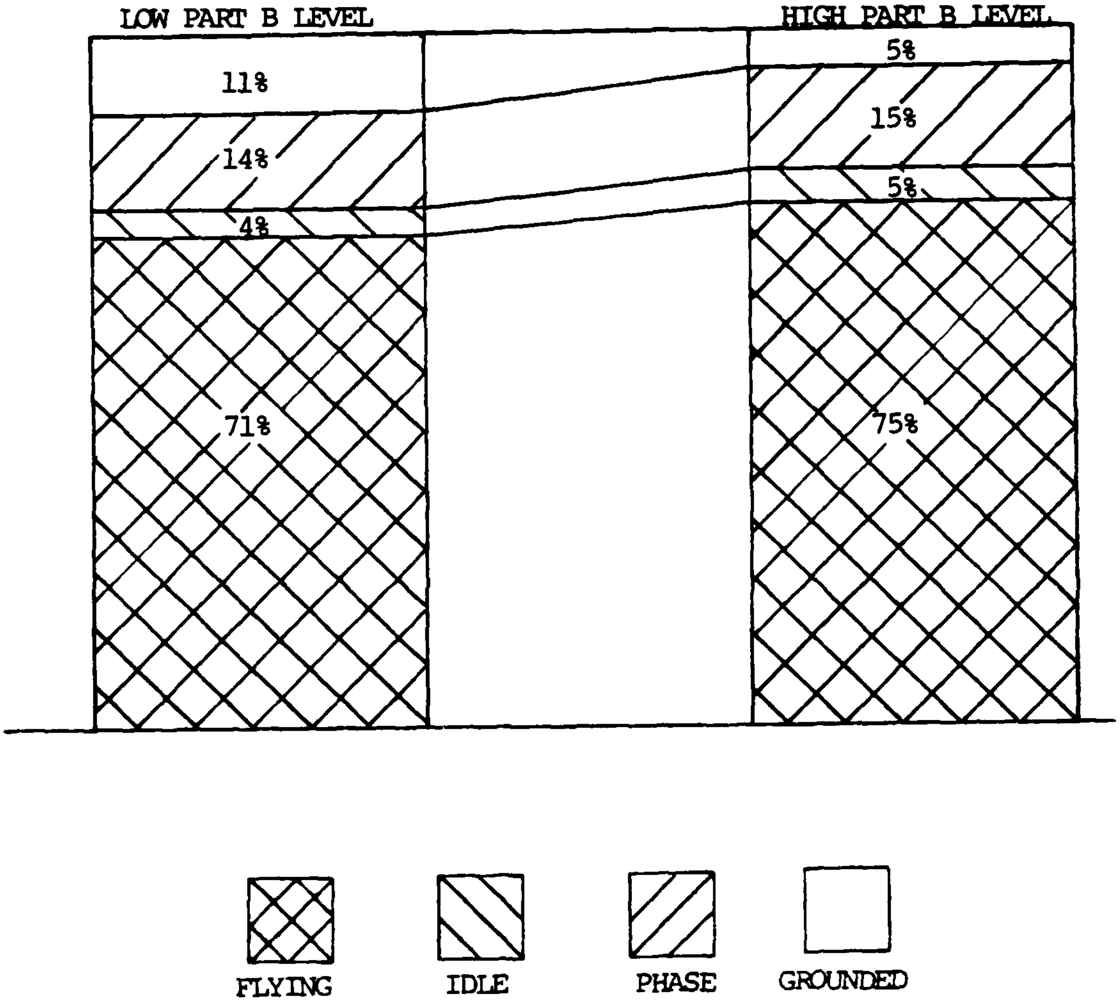

FIGURE 5.8

COMPARISON OF LOW VERSUS HIGH CASES
FOR ADDITIONAL PART B

DEPOT WORKER RESOURCE

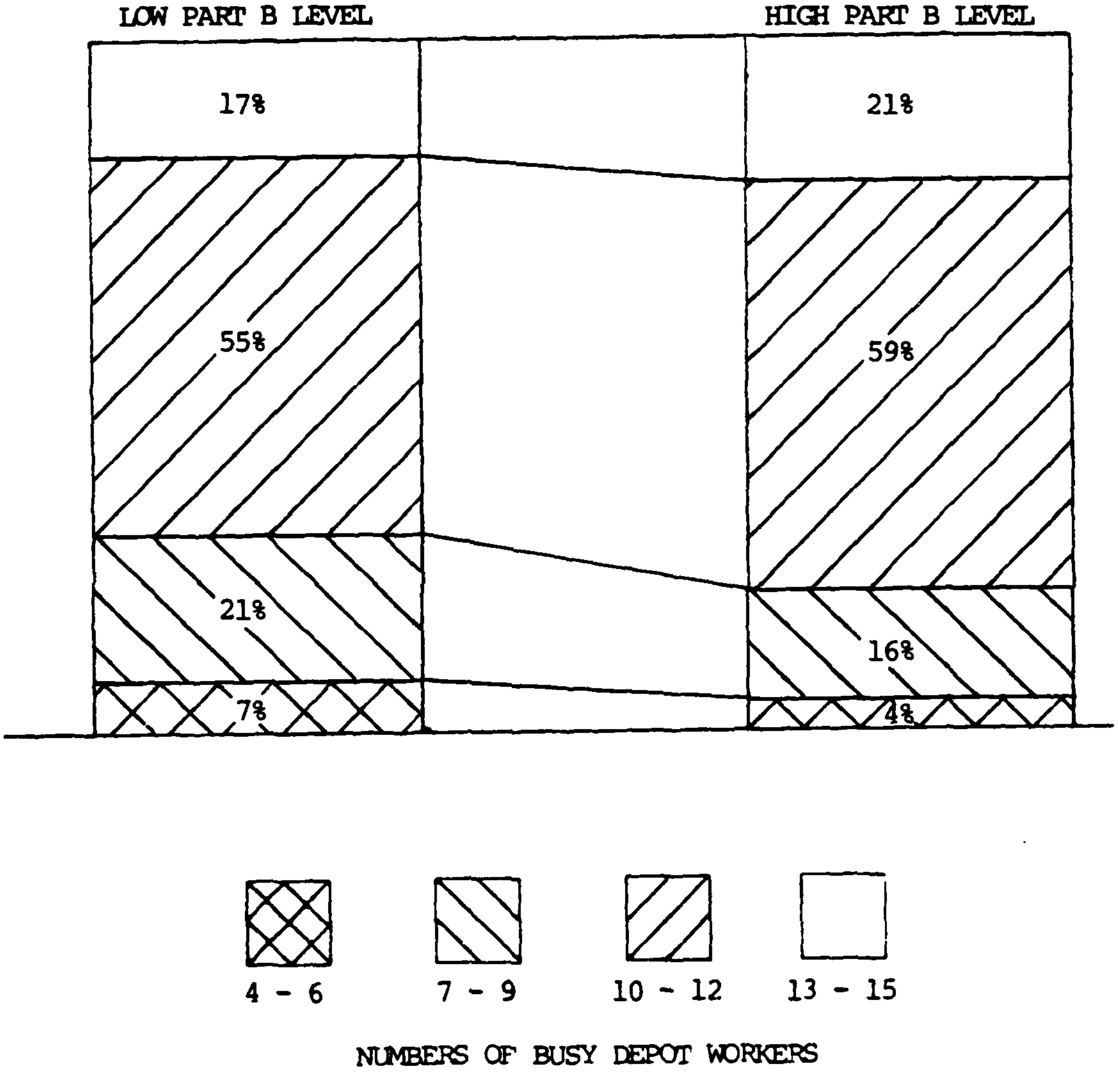

FIGURE 5.9

repaired at base level. The low level for this strategy is .10 for the training base and .25 for both operational bases. The high level is doubled to .20 and .50, respectively. The impact of implementing the strategy can be evaluated by comparing the averages of the low and high cases. The difference between the two base repair levels also can be compared to the linear model coefficient for each performance measure. The results of these comparisons are shown in Figure 5.10.

Increasing base repair capability results in a 2% incease in flights flown. This increase in flights flown is due to reducing backorder days by 1.6 days. These changes in base performance measures are not as large as those associated with increasing the part A and B resource levels. The effect at depot level, however, is much greater. Fewer part A units requiring depot repair result in a decrease of 2.2 units awaiting depot repair. Fewer units awaiting depot repair means more idle depot workers and an 8% decrease in depot worker utilization.

From the three base managers' point of view, the base repair strategy helps, but not as much as increases in part A or B resources. They see a decrease of 1.6 days in part A backorder days and no significant change in part B backorder days. The increase in flights flown is only 2%. Both of these performance measures are approximately 50% of the effect experienced when the part A resource increases. Figure 5.11 shows an increase of

ANALYSIS OF BASE REPAIR CAPABILITY

LOW/HIGH AVERAGES VERSUS LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES			DELTA EFFECT:	
	LOW	HIGH	AVERAGE	LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	90%	92%	2%	2%
PART A BACKORDER DAYS	4.0	2.4	-1.6	-1.6
PART B BACKORDER DAYS	5.3	5.2	-.1	NS
UNITS AWAITING DEPOT REPAIR	3.5	1.3	-2.2	-2.2
DEPOT WORKER UTILIZATION	87%	79%	-8%	-8%

NOTE: NS MEANS THAT THIS COEFFICIENT IS NOT SIGNIFICANT AT .05 LEVEL IN LINEAR MODEL

FIGURE 5.10

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED BASE REPAIR

PART A RESOURCE

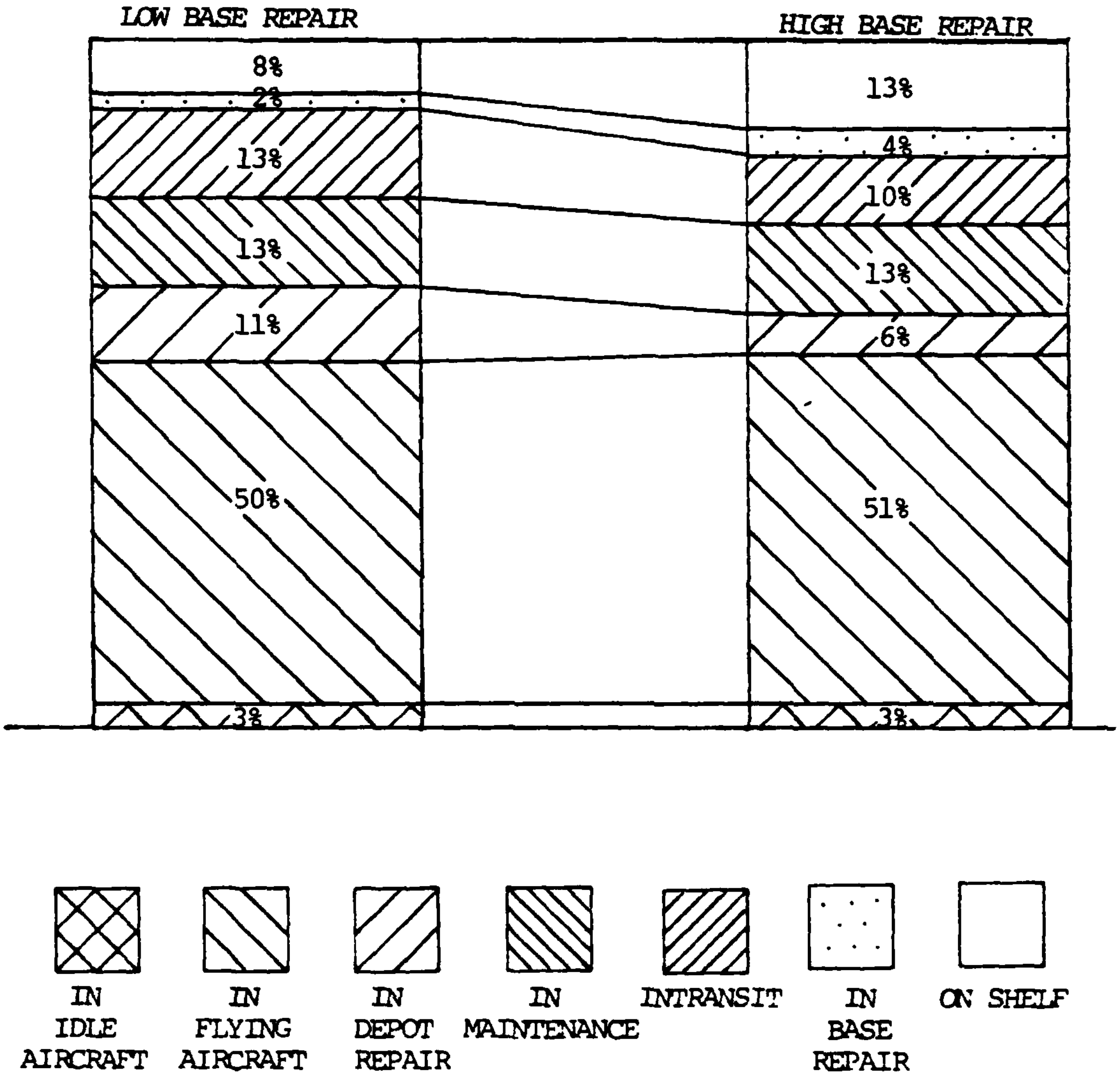

FIGURE 5.11

on-the-shelf units from 8% to 13%. This means an increase of only 2 units to the base supply managers. The base maintenance managers see a 2% decrease in grounded aircraft with a corresponding increase of 2% in aircraft flying (Figure 5.12). Both idle and in phase aircraft remain unchanged.

Implementing this strategy requires the base to add manpower or equipment to their shops. From the results above, consideration must be made to the expense of implementing this strategy, since the impact on performance measures is less than other possible strategies.

From the depot manager's viewpoint, this strategy decreases the number of units awaiting depot repair by 2.2 units, while it also decreases depot worker utilization from 87% to 79%. This decrease in utilization is broken down by levels of busy workers in Figure 5.13. Three depot workers are idle 88% of the time. This means that the depot manager may be able to utilize his workers more profitably by transferring them to understaffed areas.

Implementation of this strategy has an interesting effect on the system. Although the strategy is implemented at base level, the results are really felt more at depot level. Base level performance measures are slightly changed, but not to the degree of depot measures.

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED BASE REPAIR

AIRCRAFT RESOURCE

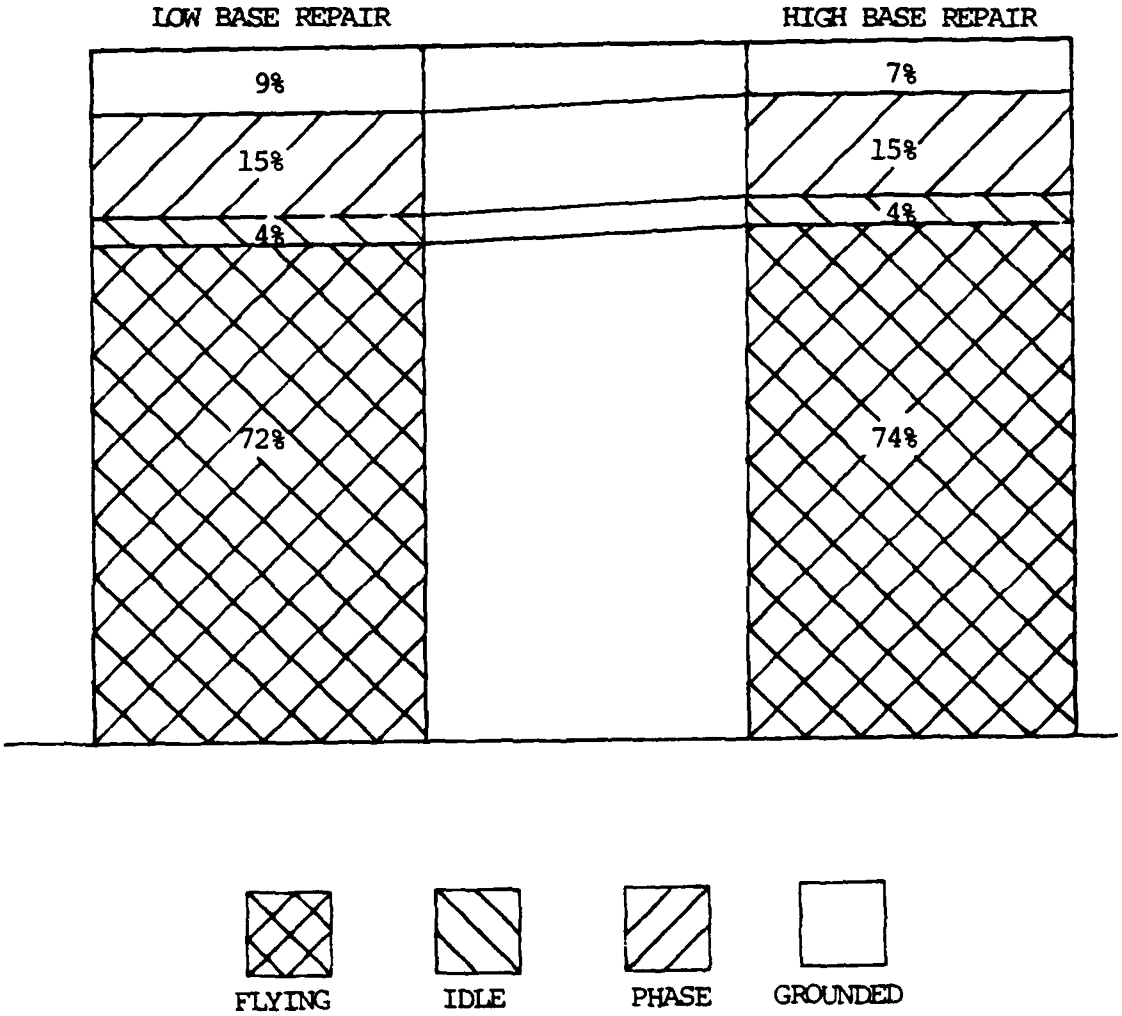

FIGURE 5.12

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED BASE REPAIR

DEPOT WORKER RESOURCE

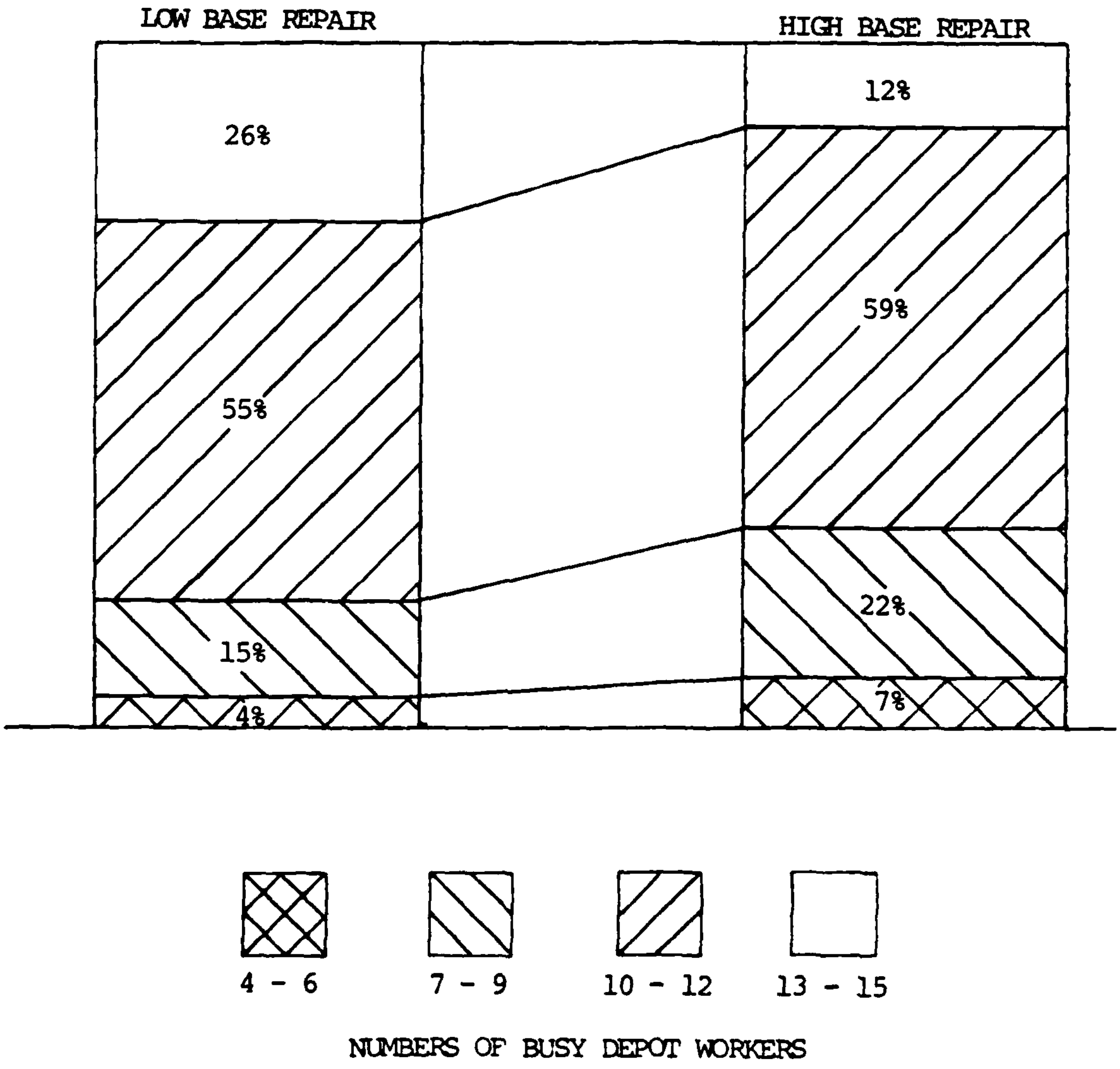

FIGURE 5.13

INCREASED DEPOT REPAIR

The strategy to increase depot capacity increases the number of depot workers available to repair units in the shop. The low level of 12 workers is sufficient to maintain adequate spare levels at all bases during peacetime. During hostilities, the number of workers increases to the high level of 15. We compare the averages of the high and low levels to evaluate the impact of increasing the depot workers. The results of this comparison are shown in Figure 5.14.

Increasing the depot worker resource in the system results in a 2% increase in flights flown. This increase in flights flown is due to reducing backorder days for both parts by 1 day. Increasing workers at depot decreased the number of units awaiting depot repair from 4.3 to .5 units. This means more workers are idle and depot utilization decreases 16%.

The base managers receive little benefit from this strategy. The percent of flights flown increases only 2%, while backorder days decrease about 1 day on each part. The lack of effect at base level on part A and B resources is shown in Figures 5.15 and 5.16. The change in on shelf resources and resources in flying aircraft is only 1%. This means an increase of only .5 units to the base managers. From these managers' point of view, the impact of this strategy is limited. The base maintenance managers see a 2% decrease in grounded aircraft with a

ANALYSIS OF DEPOT WORKER RESOURCE

LOW/HIGH AVERAGES VERSUS LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES			DELTA EFFECT:	
	LOW	HIGH	AVERAGE	LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	90%	92%	2%	2%
PART A BACKORDER DAYS	3.7	2.7	-1	-1
PART B BACKORDER DAYS	5.7	4.8	-.9	-.8
UNITS AWAITING DEPOT REPAIR	4.3	.5	-3.8	-3.8
DEPOT WORKER UTILIZATION	91%	75%	-16%	-16%

FIGURE 5.14

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED DEPOT WORKERS

PART A RESOURCE

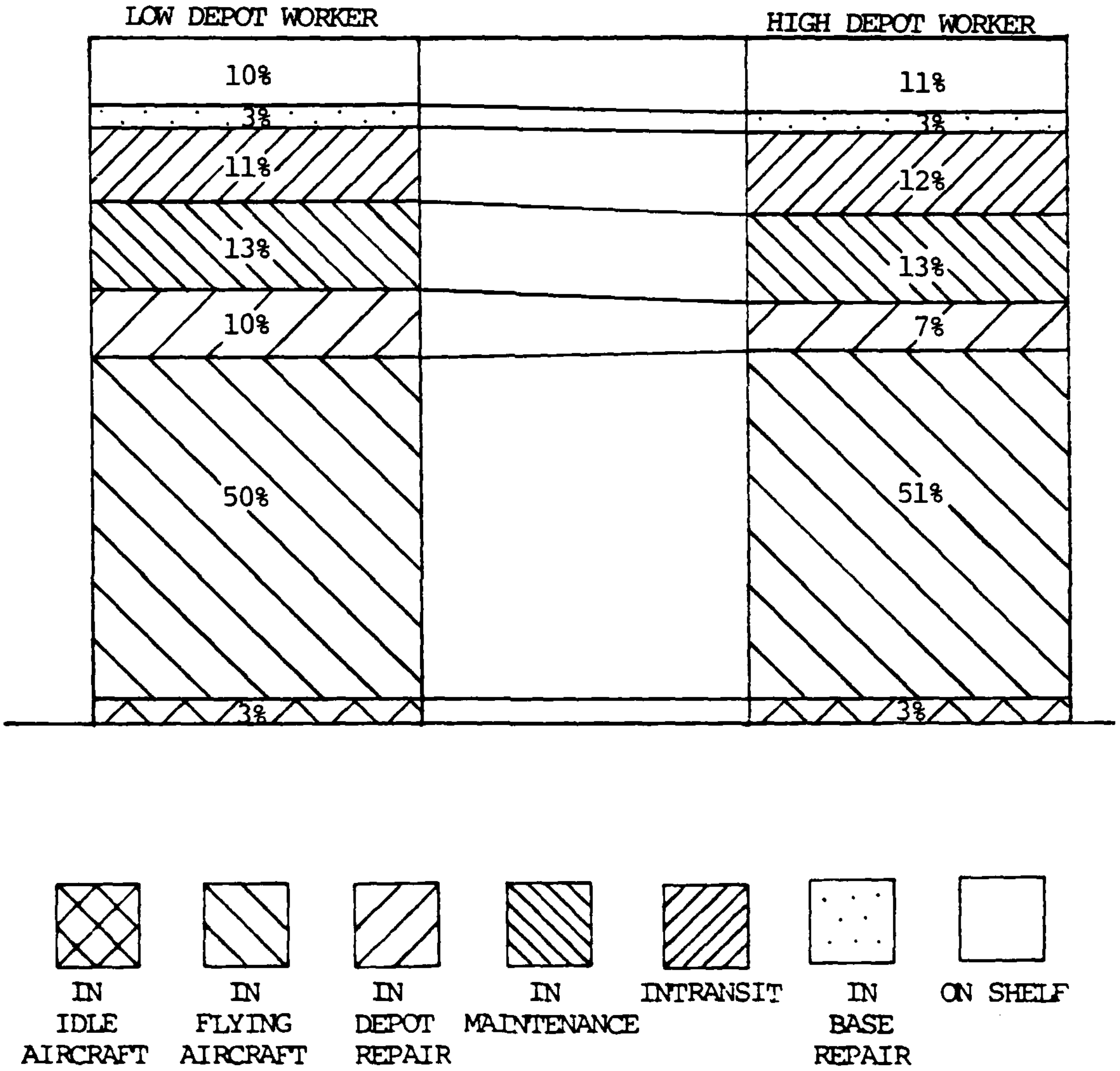

FIGURE 5.15

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED DEPOT WORKERS

PART B RESOURCE

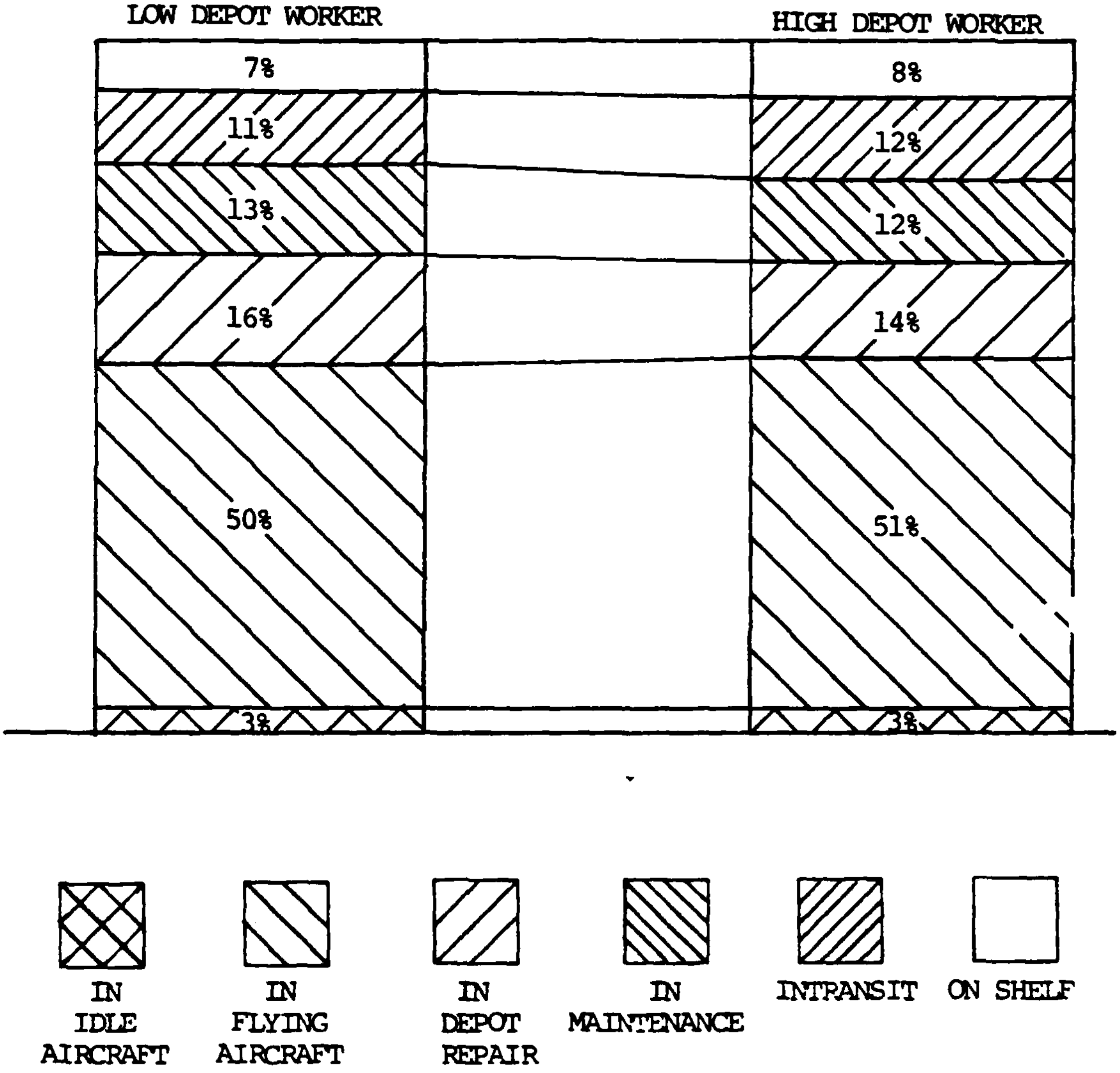

FIGURE 5.16

corresponding increase of 2% in aircraft flying (Figure 5.17). Both idle and in phase aircraft remain unchanged.

From the viewpoint of the depot manager, this strategy dramatically reduces both units awaiting depot repair and depot worker utilization. Increasing depot workers results in a decrease of 3.8 units awaiting depot repair. By reducing the number of units in repair, the number of idle workers increases. Thus, the depot worker utilization decreases from 91% to 75%. Figure 5.18 shows how the decrease in utilization affects the levels of busy workers. Prior to increasing the depot workers the maximum workforce level is busy only 38% of the time. This result is most significant to the depot manager.

This strategy has an interesting effect on the system. The depot implements the strategy and receives the benefit of reduction in two critical performance measures. The bases receive little benefit from increasing the depot workers. Increases are slight and may be unnoticed at base level.

REDESIGN PART A

The strategy to redesign part A changes the mean time between failures (MTBF) from 300 hours to 400 hours. For each part A, this additional 100 hours allows an average of ten more flights to be flown until the part fails. The impact of this strategy is evaluated by comparing the averages of the eight low and eight high cases

COMPARISON OF LOW VERSUS HIGH CASES FOR INCREASED DEPOT WORKERS

AIRCRAFT RESOURCE

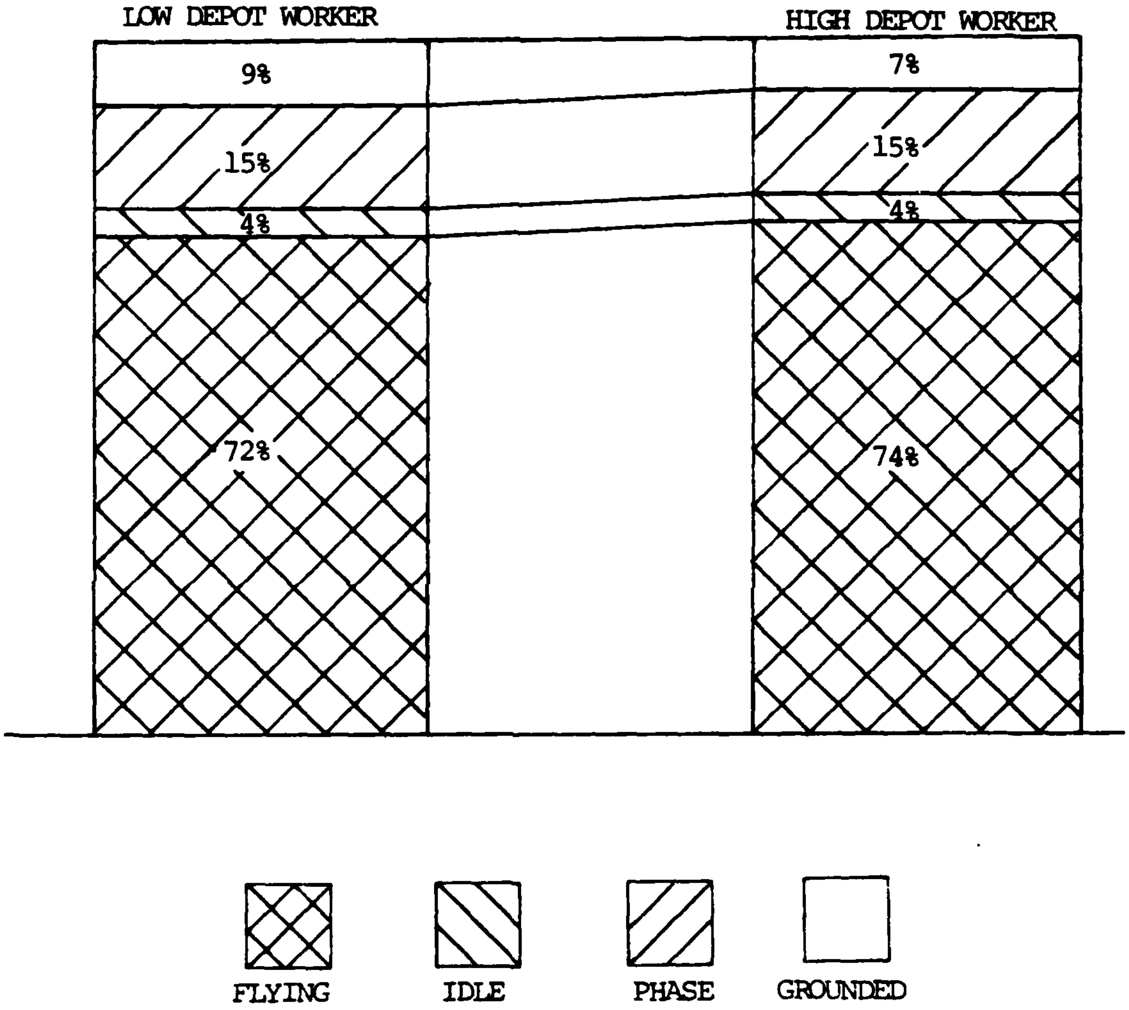

FIGURE 5.17

COMPARISON OF LOW VERSUS HIGH CASES
FOR INCREASED DEPOT WORKERS

DEPOT WORKER RESOURCE

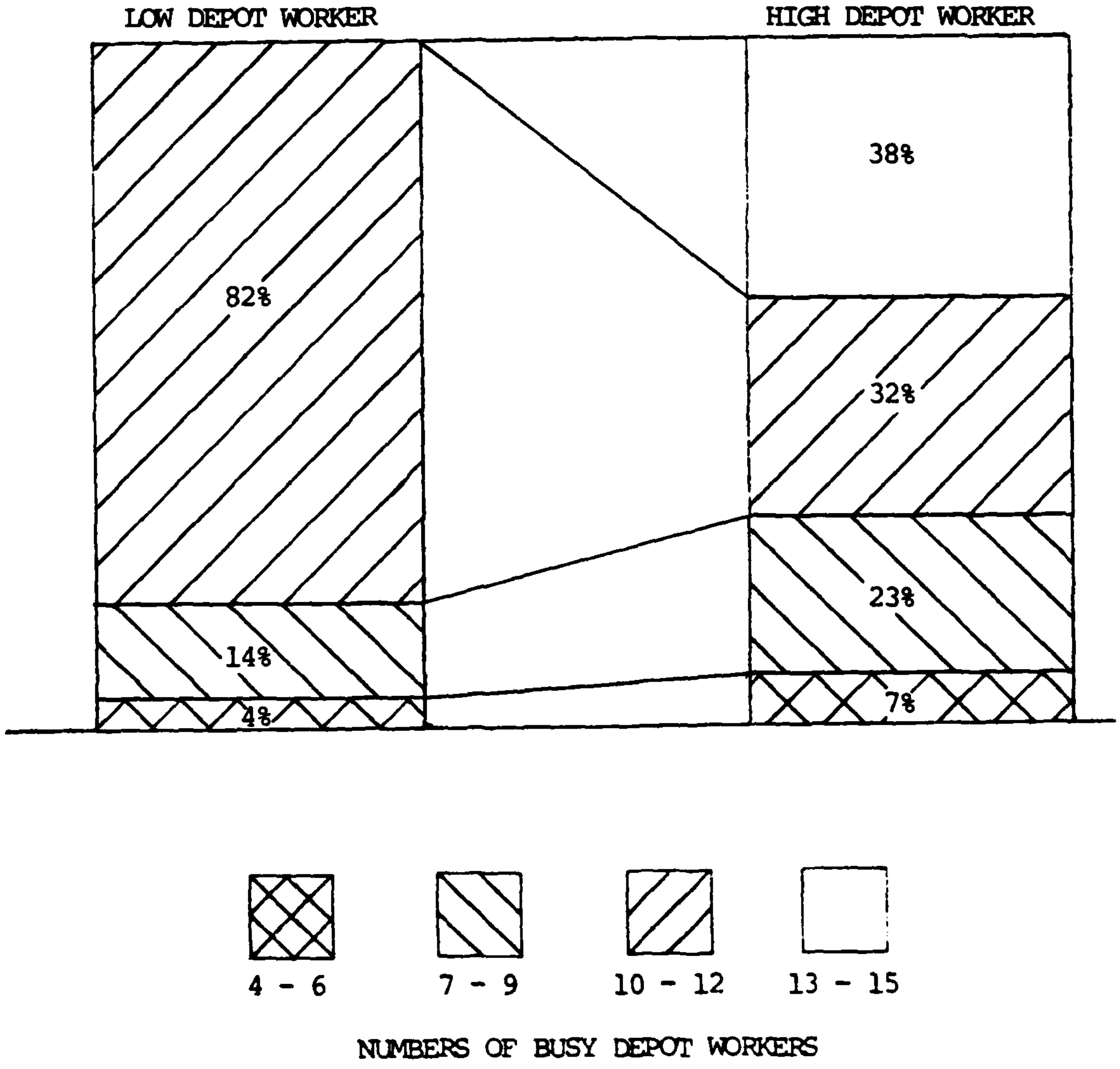

FIGURE 5.18

in our design. The results of this comparison is shown in Figure 5.19.

The percent of flights flown increases by 2% when part A is redesigned. This increase is due to the redesign allowing more flights prior to failure and the part A backorder days being reduced by 1 day. Fewer part A units arriving at depot reduces the units awaiting repair by less than 1 unit. Decreasing units awaiting depot repair results in more idle depot workers and a 5% decrease in depot worker utilization.

From the base managers' viewpoint, the part A redesign helps, but not as much as other strategies. They see a decrease of 1 day in part A backorder days and no significant change in part B backorder days. The increase in flights flown is only 2%. Both of these performance measures are approximately 50% of the effect experienced when the part A resource increases. Figure 5.20 shows an increase of on-the-shelf units from 9% to 12%. This means an increase of only 1.5 units to the base supply managers. The base maintenance managers see a 2% decrease in grounded aircraft with a corresponding increase of 2% in aircraft flying, shown in Figure 5.21. Both idle and in phase aircraft remain unchanged.

From the depot manager's viewpoint, this strategy has a minimal effect. The number of units awaiting depot repair decreases by .8 units, while depot work utilization decreases from 85% to 80%. This decrease in

ANALYSIS OF PART A REDESIGN

LOW/HIGH AVERAGES LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES			DELTA EFFECT:	
	LOW	HIGH	AVERAGE	LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	90%	92%	2%	2%
PART A BACKORDER DAYS	3.7	2.7	-1	-1
PART B BACKORDER DAYS	5.1	5.3	.2	NS
UNITS AWAITING DEPOT REPAIR	2.8	2.0	-.8	-.8
DEPOT WORKER UTILIZATION	85%	80%	-5%	-6%

NOTE: NS MEANS THAT THIS COEFFICIENT IS NOT SIGNIFICANT AT .05 LEVEL IN LINEAR MODEL

FIGURE 5.19

COMPARISON OF LOW VERSUS HIGH CASES
FOR PART A REDESIGN

PART A RESOURCE

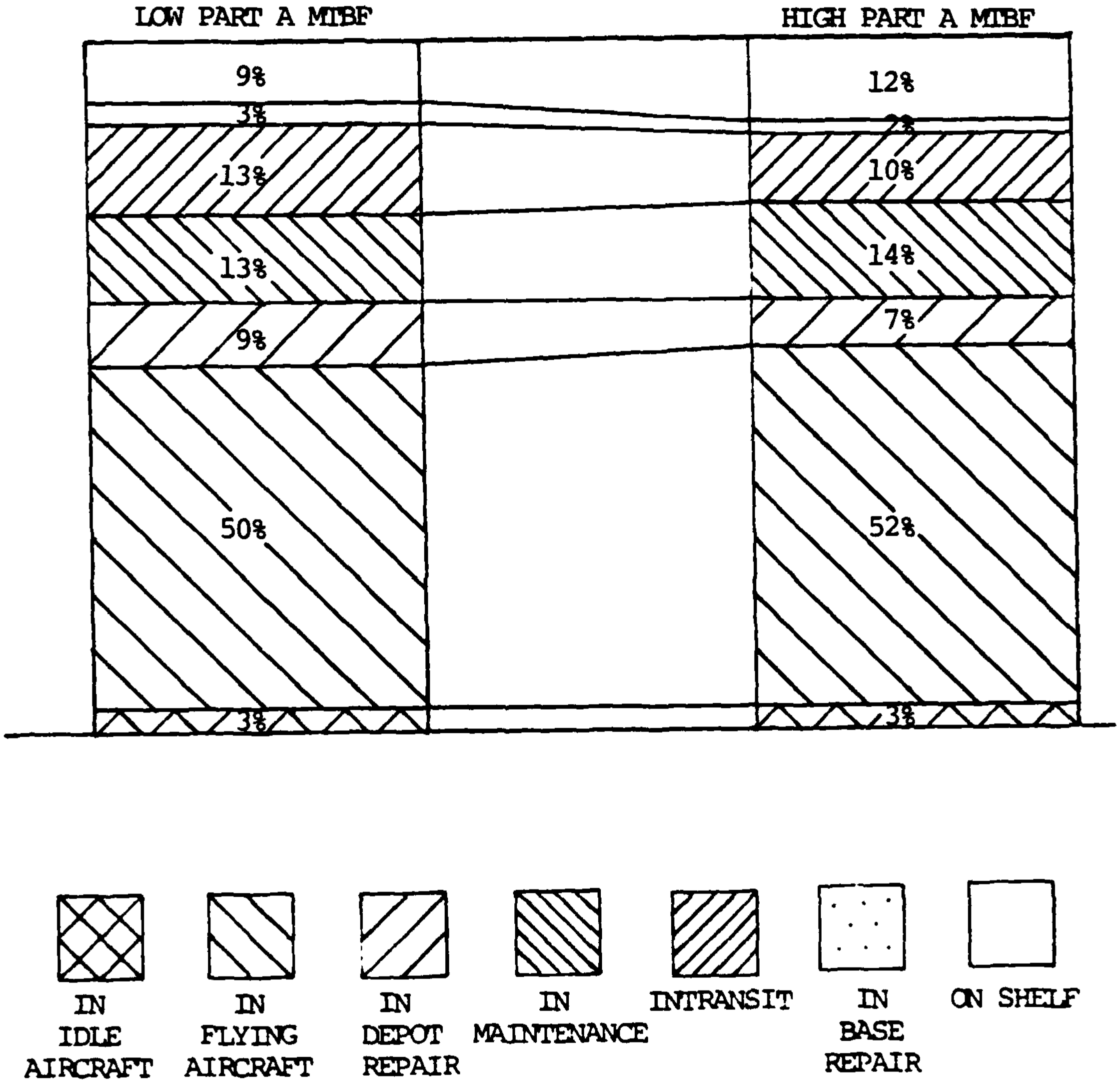

FIGURE 5.20

COMPARISON OF LOW VERSUS HIGH CASES FOR PART A REDESIGN

AIRCRAFT RESOURCE

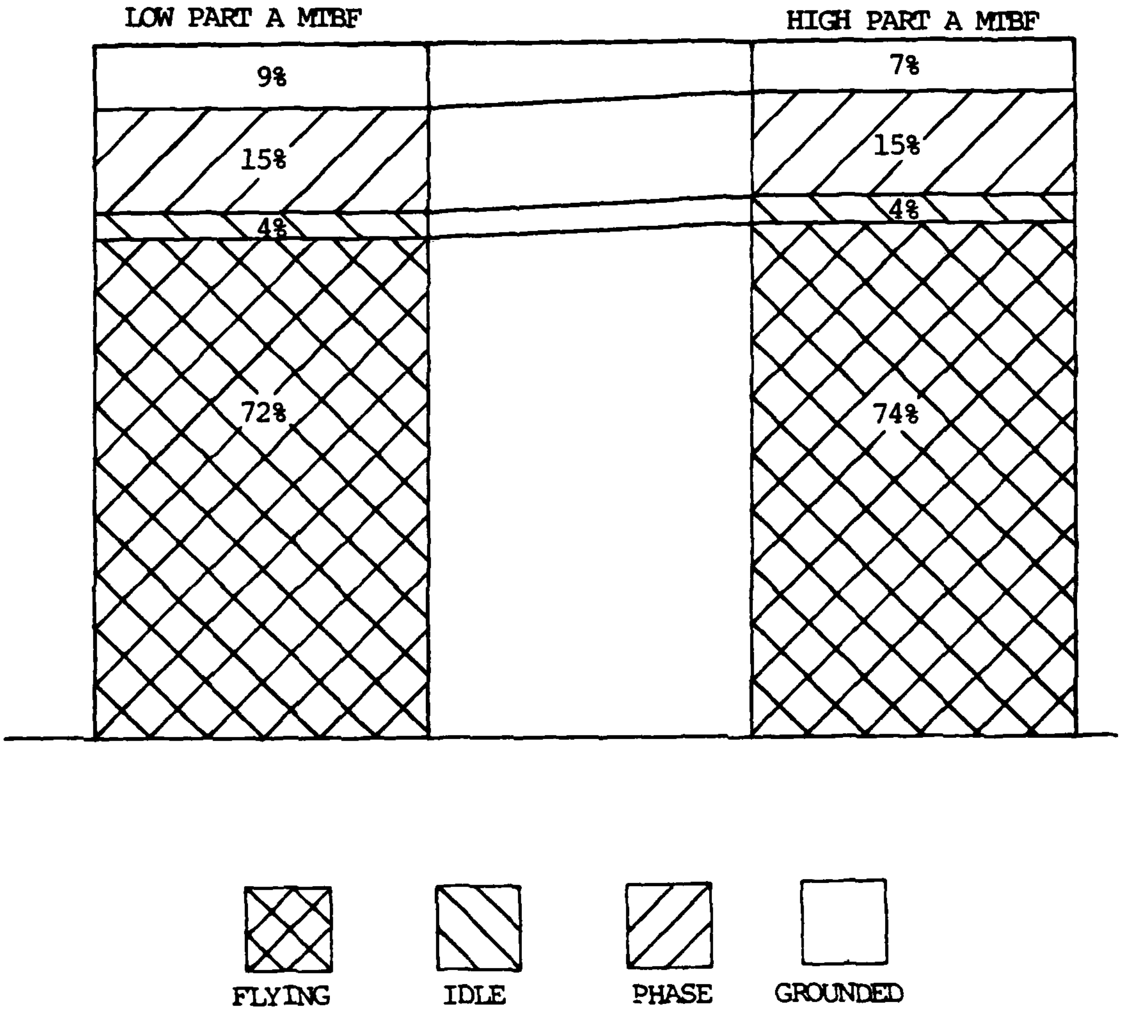

FIGURE 5.21

utilization is broken down by levels of busy workers in Figure 5.22. Three depot workers are idle 83% of the time. This means that the depot shop manager could utilize his workers more profitably in other areas.

Implementing this redesign strategy requires large expenditures of money and a long leadtime. From the results above, consideration must be made to the expense and time required to implement this strategy, since the impact on performance measures is less than other possible strategies.

REDUCED TRANSPORTATION TIME

The transportation time strategy decreases the days to transport units between bases and the depot. The initial value of 7 days for stateside bases and 14 days for the overseas base represent the actual times given by the Air Force Supply Manual. We test transportation times of 3 days for stateside bases and 7 days for the overseas base. We compare the averages of the low and high levels to evaluate the impact of reducing transportation time. The results of this comparison are shown in Figure 5.23.

Decreasing transportation time results in an increase of 4% in flights flown. Both part A and B experience decreases in backorder days. Grounded aircraft wait 1.4 days less for part A and 3.2 days less for part B. Both parts arrive faster at depot for repair with a resulting increase of 2 units awaiting depot repair.

COMPARISON OF LOW VERSUS HIGH CASES
FOR PART A REDESIGN

DEPOT WORKER RESOURCE

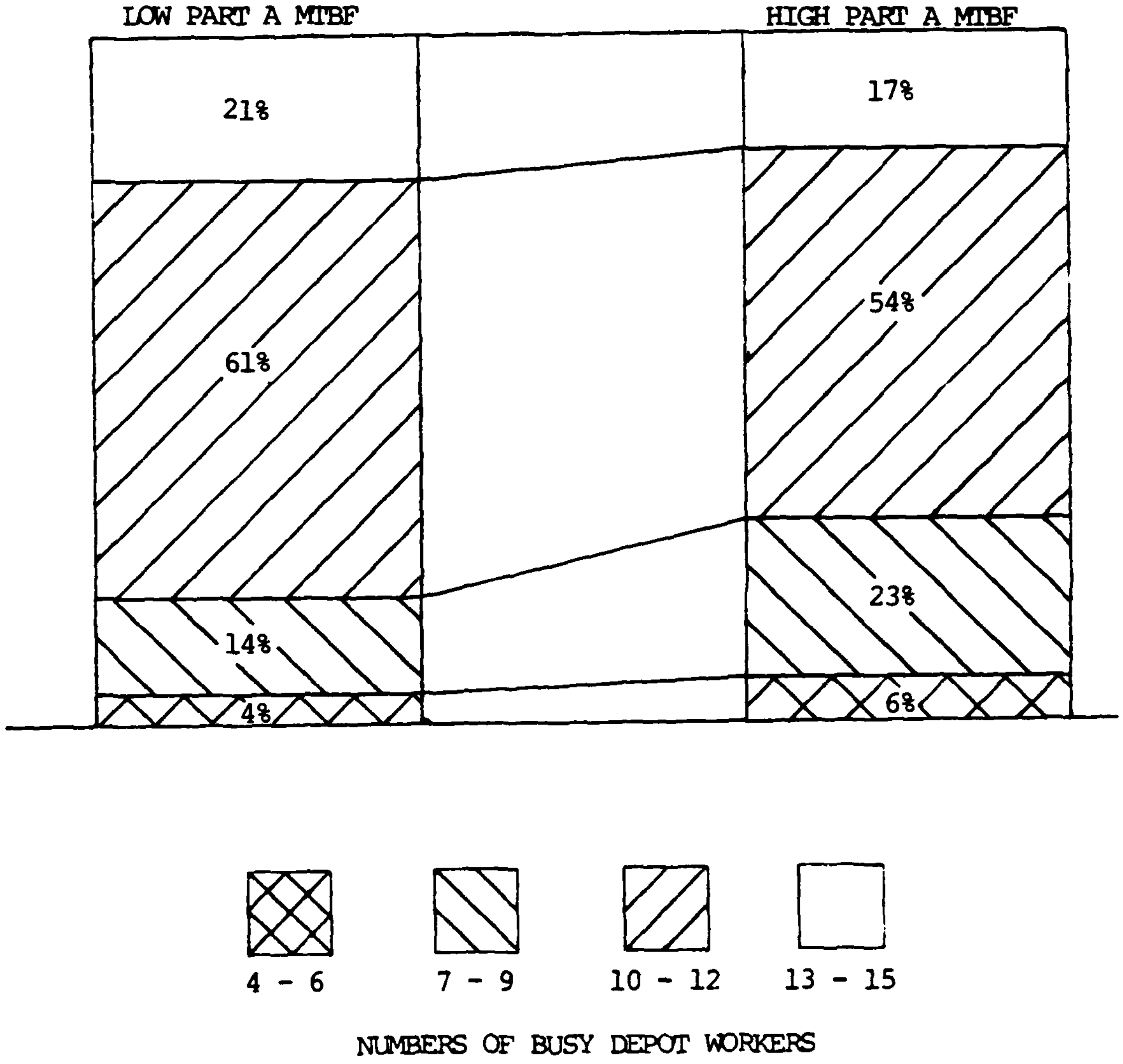

FIGURE 5.22

ANALYSIS OF TRANSPORTATION DAYS RESOURCE

LOW/HIGH AVERAGES VERSUS LINEAR MODEL COEFFICIENT

PERFORMANCE MEASURES	LOW	HIGH	DELTA EFFECT: AVERAGE	DELTA EFFECT: LINEAR MODEL
PERCENT OF FLIGHTS FLOWN	89%	93%	4%	4%
PART A BACKORDER DAYS	3.9	2.5	-1.4	-1.4
PART B BACKORDER DAYS	6.8	3.6	-3.2	-3.2
UNITS AWAITING DEPOT REPAIR	1.4	3.4	2.0	2.0
DEPOT WORKER UTILIZATION	81%	85%	4%	4%

FIGURE 5.23

Increasing units awaiting depot repair results in more busy depot workers and a 4% increase in depot worker utilization.

From the point of view of the base managers, the advantages of implementing this strategy are numerous. The reduction in backorder days for both parts coupled with the increase of flights flown by 4% is extremely significant. The most visible advantage to the base managers in implementing this strategy is the reduction of units intransit and the increase in units available on the shelf in base supply. Figure 5.24 shows a reduction of 7% in units intransit with a 4% increase of on shelf units for part A. This means that 3.6 fewer units are intransit and 2 units more are on the shelf in supply. Figure 5.25 shows that part B's effects on intransit and on-the-shelf units are identical to part A's effects. The base maintenance managers see a 6% decrease in grounded aircraft and an increase of 4% in aircraft flying, shown in Figure 5.26. Additionally, both idle and phase aircraft increase by 1%.

Decreasing transportation pipeline time has a devastating result on the depot. The number of units awaiting depot repair increases by 150% from a low level of 1.4 units to a high level of 3.4 units. Depot worker utilization increases from 81% to 85%. This increase in utilization is broken down by levels of busy workers in Figure 5.27. For the depot manager, there are definitely

COMPARISON OF LOW VERSUS HIGH CASES FOR PIPELINE TRANSPORTATION TIME

PART A RESOURCE

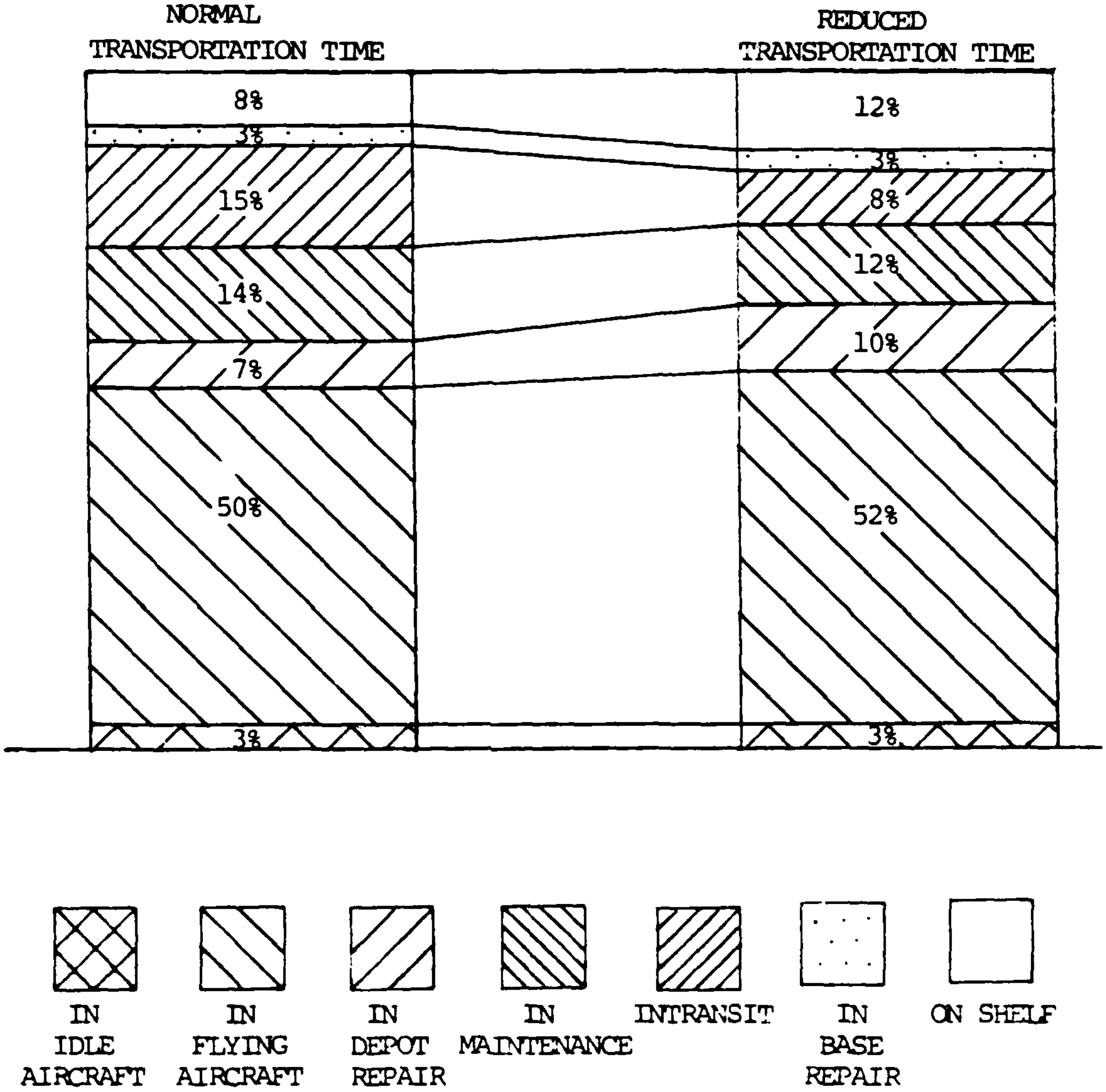

FIGURE 5.24

COMPARISON OF LOW VERSUS HIGH CASES FOR PIPELINE TRANSPORTATION TIME

PART B RESOURCE

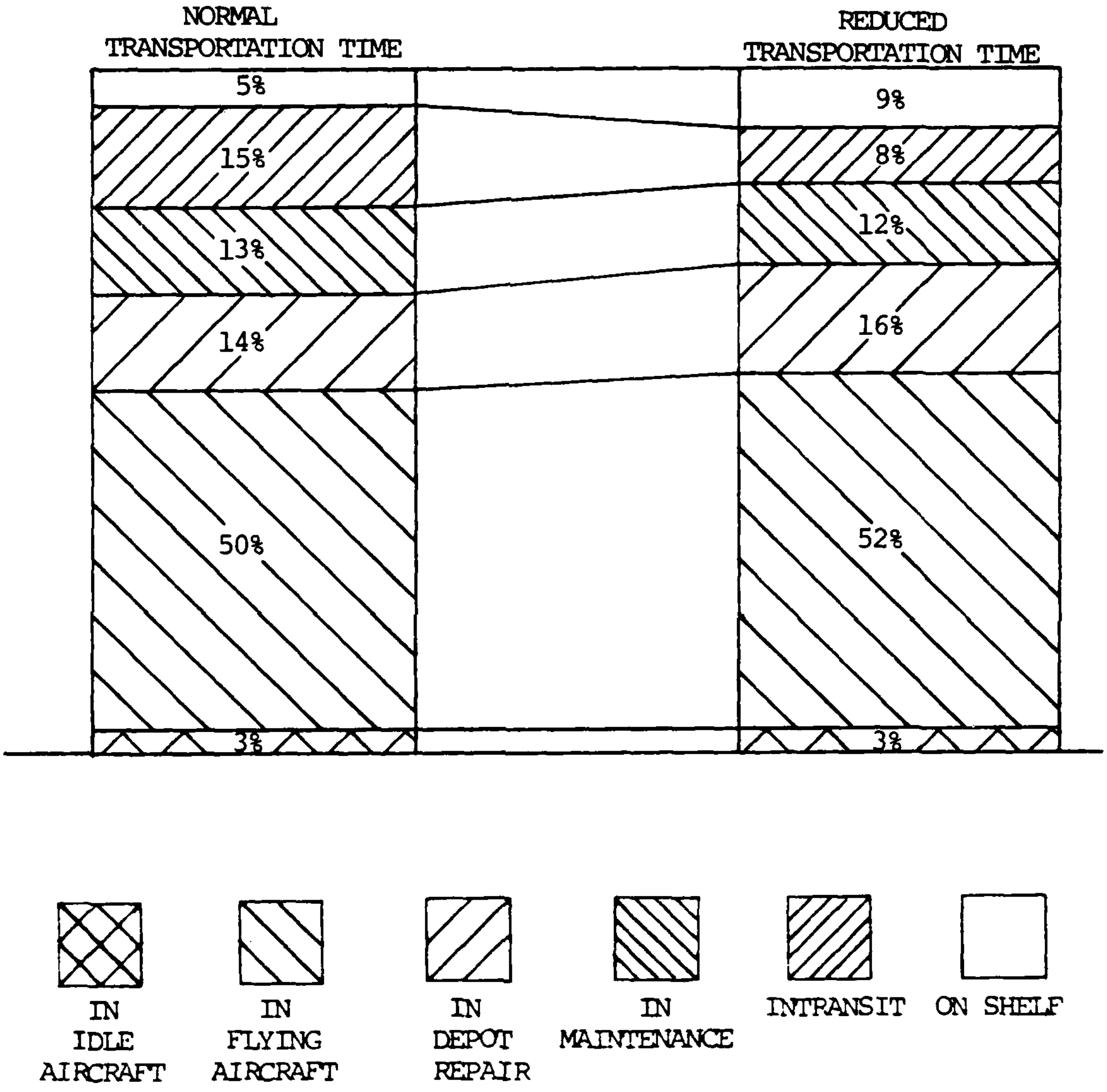

FIGURE 5.25

COMPARISON OF LOW VERSUS HIGH CASES FOR PIPELINE TRANSPORTATION TIME

AIRCRAFT RESOURCE

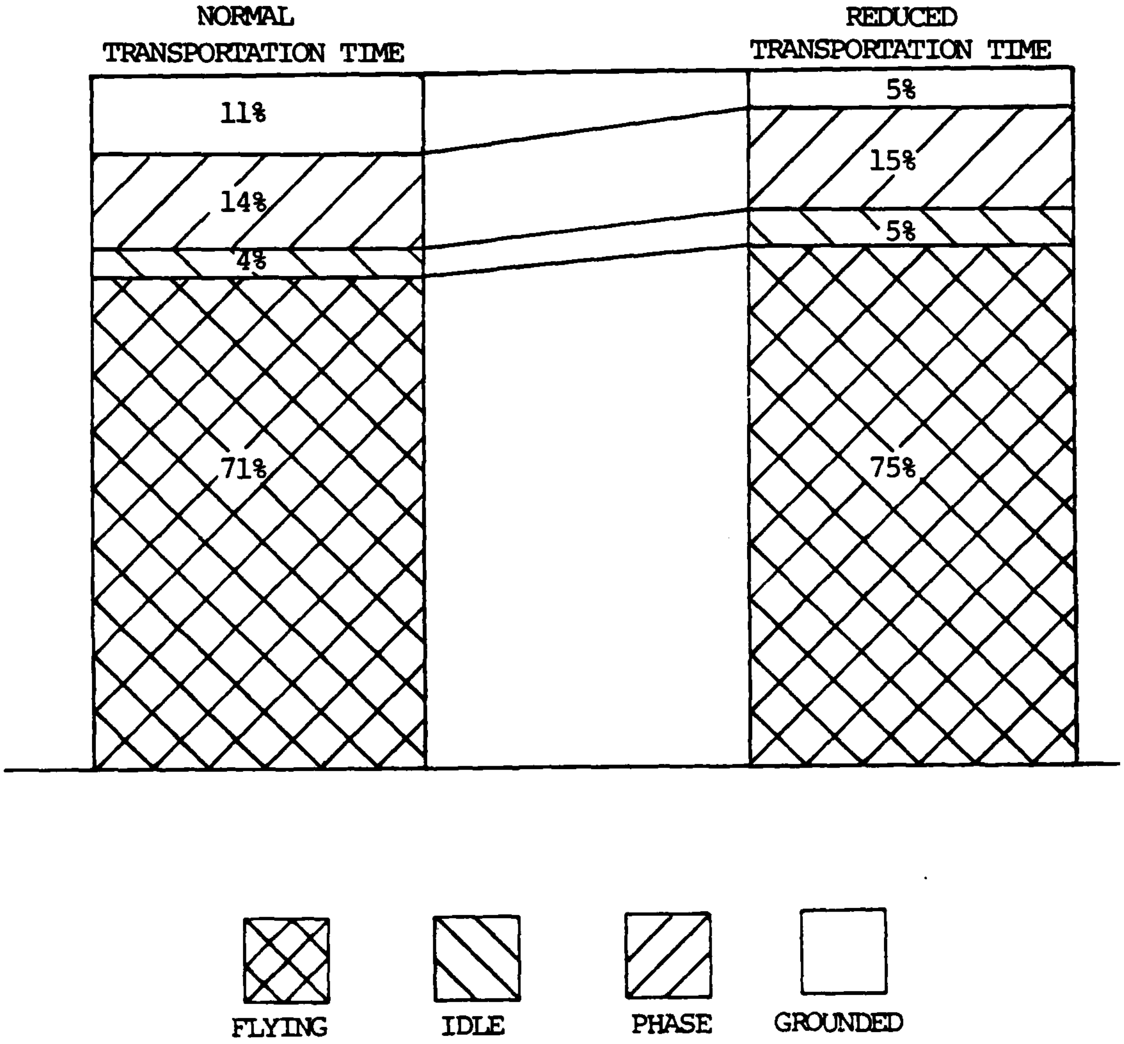

FIGURE 5.26

COMPARISON OF LOW VERSUS HIGH CASES FOR PIPELINE TRANSPORTATION TIME

DEPOT WORKER RESOURCE

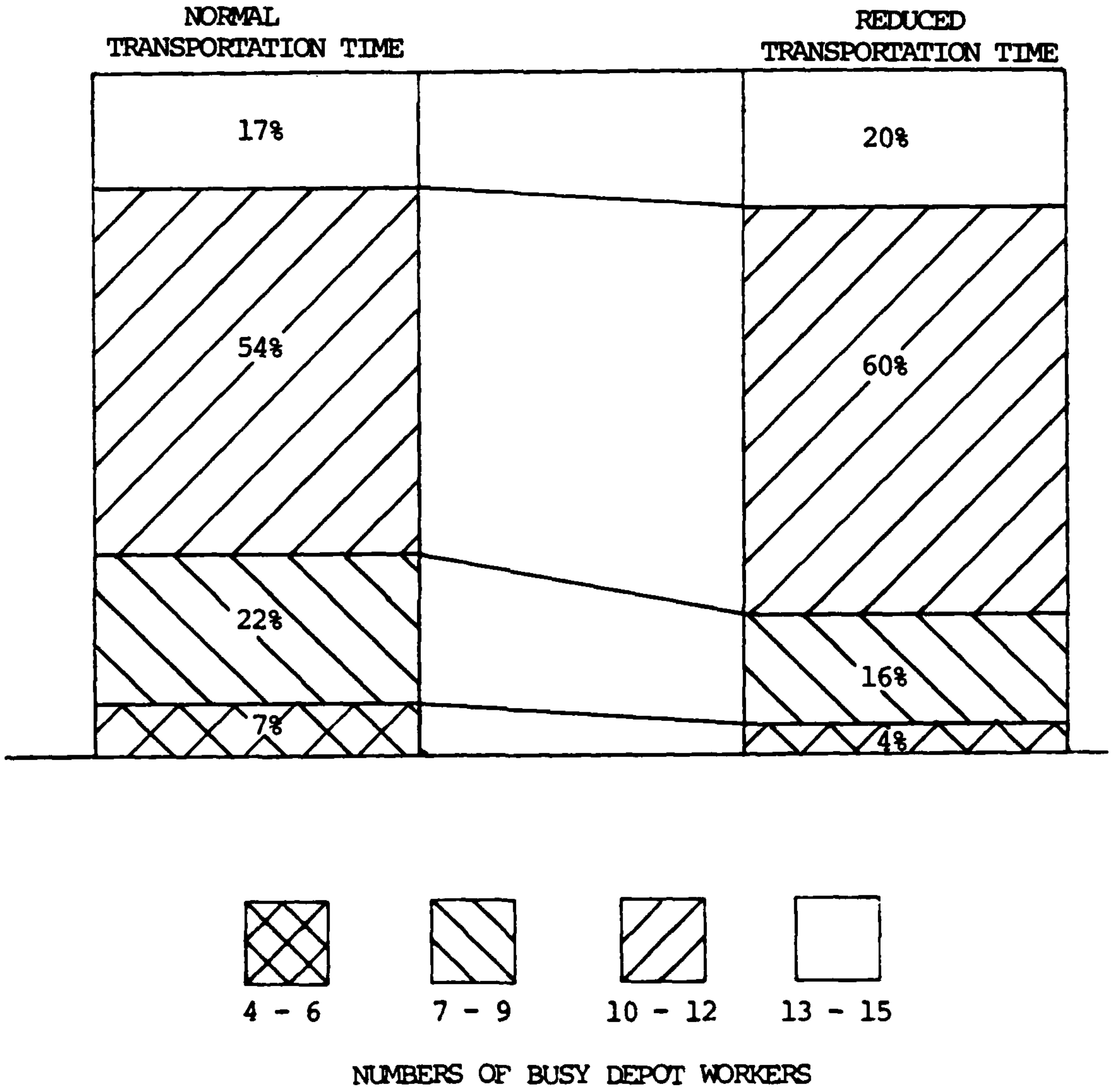

FIGURE 5.27

no advantages to implementing this strategy. More units are awaiting repair and an increase of 9% in the upper two workforce levels is apparent.

SUMMARY

A base manager is in the unenviable position of not being able to control his own destiny. Only the base repair strategy is implemented at base level. All other strategies are implemented at a higher decision making level. Unfortunately, for the base manager, many of these uncontrollable strategies affect base performance measures more than the base repair strategy. From the base manager's point of view, the strategies that offer the greatest impact at base level are (1) reducing transportation days and (2) altering spare levels. These strategies would be extremely expensive and undergo close scrutiny during Air Force planning and budgeting processes.

From the viewpoint of the depot manager, the strategies that offer the greatest impact at depot level are (1) altering repair capacity at depot or base and (2) redesigning part A. The redesign of a part is a very time consuming and expensive strategy. In fact, for the minimal changes at base and depot, this strategy is not worthwhile. Additionally, the redesign and base repair straegies only affect part A with little or no effect on part B. Thus, they would help the depot manager, but would not significantly affect base level performance.

The strategy that increases the depot worker resource is the only one that positively affects the performance measures at both depot and base. The effect at base level is less than at the depot. This is the only strategy, however, that significantly increases flights flown and reduces both part's backorder days. This depot worker strategy is also the easiest to implement. A local depot commander can approve additional manpower, if end of year strength levels are not exceeded. The disadvantage to this strategy is the length of time required to hire and train personnel. This disadvantage can be overcome if rather than hiring new personnel, the workforce is shifted from overmanned shops.

INTERACTIONS

By using a fractional factorial design, we trade off information about some two-factor and all higher order interactions for the convenience and lower cost of constructing and testing fewer experimental combinations. The assumption must be made, however, that these higher interactions are negligible and can be ignored. If these higher order interactions are not negligible, their effects are aliased with those interactions that are measured. Aliased factors are those whose effects are completely correlated. Therefore, we are unable to separate the effect due to one factor from those due to others in the aliased set.

In our design, the main effects are all aliased with three-factor or higher-order interactions. Since almost half of the two-factor interaction terms shown in Figure 5.28 are not significant in the linear model, we feel the assumption of negligible effects from higher order interactions is correct. Thus, the linear model coefficients of the main effects are reliable assessments of increasing resource levels.

On the other hand, Figure 5.28 shows that all estimable two-factor interactions are aliased with other two-factor and higher-order interactions. Many of the aliased interactions cannot be assumed to be negligible. This leads to a tenuous interpretation of the estimable two-factor interactions. For example, the percent of flights flown shows a second order interaction with base repair and depot workers. This interaction is aliased with part B spare level and transportation time. The interpretation of the negative 2% coefficient cannot be attributed with certainty to any particular factor combination in the alias set. Thus, we refrain from interpreting the quantities in Figure 5.28. Chapter 6 addresses dealing with second-order interactions as an area for future research.

We did some testing of two-factor effects, however, relating to part A resource versus part B resource and base repair capability versus depot worker resource. In

PERFORMANCE MEASURE	COEFFICIENTS FOR INTERACTION TERMS OF GENERAL LINEAR MODEL						
	I	II	III	IV	V	VI	VII
PERCENT OF FLIGHTS FLOWN	.4%	-.5%	NS	NS	-1%	-2.1%	.5%
PART A BACKORDER DAYS	NS	.2	NS	NS	.4	.3	-.2
PART B BACKORDER DAYS	NS	-.2	NS	NS	NS	.8	-.1
UNITS AWAITING DEPOT REPAIR	NS	NS	NS	-1.1	NS	.8	-.9
DEPOT WORKER UTILIZATION	NS	NS	-.7%	-.3%	-.7%	-1%	NS

LEGEND:
A = A spare level
B = B spare level
C = Part A redesign
D = Base Repair
E = Depot workers
F = Transportation time

ALIASES:
I AB = CF = BCDE = ADEF
II AE = CD = ABDF = BCEF
III AF = BC = CDEF = ABDE
IV BE = DF = ABCD = ACEF
V CE = AD = BCDF = ABEF
VI DE = AC = BF = ABCDEF
VII EF = BD = ACDF = ABCE

NS MEANS THIS COEFFICIENT IS NOT SIGNIFICANT AT .05 LEVEL IN LINEAR MODEL

FIGURE 5.28

this testing, we only changed the two factors of interest to their high levels and left the other four factors at their low levels. Therefore, the results do not resolve the problem of estimating second-order interactions in the linear model.

Units awaiting depot repair is the only performance measure that shows any interaction effect when parts A and B are increased. Thus, over the values that we tested, the combined effect on percent of flights flown from having additional parts A and B is simply the sum of the separate effects. For depot repair, however, the combined effect is less than the sum of the individual effects. When base repair capability and depot workers are increased, only percent of flights flown reveals a significant interaction; the combined effect is less than the sum of the separate effects. The other measures exhibited additive effects over the range of values tested.

CONCLUSION

In this chapter, the enhanced dynamic redistribution rule was used to test the different logistic strategies. Single strategy analysis and a linear model formulation were accomplished. The results provide important insights to managers at all level of the multi-echelon system. Chapter 6 addresses the effect of strategies on different organizational levels within the multi-echelon system. Additionally, future research topics are presented.

CHAPTER SIX

MAJOR CONCLUSIONS

This chapter summarizes our research and addresses the effect of strategies on different organizational levels within the multi-echelon system. It concludes by suggesting areas for future research.

SUMMARY

We developed a model of a multi-echelon inventory system that is comprised of three bases and a centralized repair facility. Each base has a specific level of aircraft. An aircraft is grounded if part A or part B fails and there is no immediate replacement. Part A may be repaired at base level; part B, however, can only be repaired at the depot. Both parts are repaired in the same labor constrained depot shop.

The model provides a tool to analyze alternative logistics strategies. The issues that we investigated include increasing spare levels of parts A and B, increasing repair capability at depot or base level, redesigning part A to reduce mean time between failures, and decreasing transportation time between the bases and depot. These strategies were used in assessing the merits of three redistribution rules. Additionally, these strategies were analyzed in the following two ways (1) one at a time and (2) in combination with a partial factorial design. Results of this analysis are summarized in the next section.

INSIGHTS AND ORGANIZATIONAL EFFECTS

Given the literature in the multi-echelon area, we believed apriori that the dynamic redistribution rule would outperform the static rule. In addition, since Bruce Miller's model did not include base repair, we thought that added information on base units from our model would enhance the dynamic redistribution rule and give better results.

From the results of Chapter 4, we found no overwhelming difference among the three rules for each of the 16 experiments. By testing all 16 experiments, a statistically significant difference was found using the Wilcoxon signed rank test between the static and dynamic rules. Any test done on a single experiment, however, resulted in no difference between the redistribution rules. Looking at these results from a manager's point of view, it is obvious that the different strategy combinations resulted in a much greater change for the performance measures than did the redistribution rules. Thus, a manager, who must decide between changing redistribution rules or logistic strategies, will probably opt for the logistic strategies. This is especially true if the manager has a limited budget and must get the most "bang from the buck."

In implementing any strategy or combination of strategies, a manager must be aware that what turns out to be an improvement at one level in the system may result in a degradation at another level. For example, by increasing spare B units, more aircraft sorties are flown. As a consequence, there is now no stock of spare A on the shelf at base and an increase in units at depot repair. If spare A units are increased to counter these problems without increasing depot workers, large quantities of reparables arrive at the depot for repair. The constrained work force at depot cannot handle the increase in units. This results in more units awaiting depot repair and a highly utilized and highly disgruntled workforce.

When system-wide impacts are assessed, what problems occur as a consequence? First, there is inevitable organization conflict. At base level, a commander wants to fly all scheduled sorties and have the highest performance measures possible. This makes the maintenance commander concerned over reducing the number of grounded aircraft and decreasing the amount of time that an aircraft remains grounded. The base supply commander's concern is being able to meet demands in a timely manner and keeping his stockage effectiveness high. As our results have shown, there is no single strategy that achieves all of the base level aims. If a strategy is implemented to help one set of performance measures, other performance measures may suffer and organizational conflict will arise.

Organizational conflict is amplified with the depot managers in a multi-echelon system. The item manager is concerned with maintaining a specific level of spares in the system. In most cases, the item manager has a certain percent of spares set aside for wartime emergency use. Base level managers cannot understand why aircraft should remain grounded when these wartime reserve spares are available.

Additionally, the depot maintenance manager can be severely impacted by strategies implemented by the item manager. Increasing spare part levels can result in added workload in the maintenance shop. This increased workload requires additional manpower, but hiring and training depot workers can be a long operation. Thus, increasing spares without a corresponding increase in depot workers can severely impact depot maintenance capability. This is a key point in making a global versus a local optimization decision.

Sometimes a manager implements a strategy that locally optimizes certain key performance measures. The final result of this strategy is sub-optimal systemwide performance. For example, if spares are increased or transportation time decreases without an increase in depot workers, a backlog develops in depot repair. This increase in units awaiting depot repair reduces the overall number of spares available to base level. Thus, in many cases, strategies must be implemented in combination to facilitate system improvements. Implementing strategies one at a time to save money or for planning purposes can be counter-productive and cost more money in the long run.

FUTURE RESEARCH

In this section, we suggest future research that is an immediate extension of this dissertation.

In Chapter 5, we discussed the problems in trying to interpret two-factor interactions. These problems arose due to the estimable two-factor interactions being aliased with other two-factor interactions. Many of these aliased interactions cannot be assumed to be negligible. Reliable interpretation of these interactions would be possible if either a full factorial design or a fractional factorial design with fewer factors were used. Both of these designs result in all two-factor interactions being estimable. This would be an immediate concern for future research.

Further research into condemnation of parts can explore the impact that condemning parts have on the system spare levels. The effects of procuring additional units when specific spare levels are reached also can be analyzed. The complexity of long and erratic procurement leadtimes for some parts can be investigated in this analysis.

We have observed that large quantities of units are also available at base level in phase aircraft or aircraft grounded for other reasons. These units can be removed and used on grounded aircraft. The area of cannibalization of parts needs further research to determine the impact that cannibalization has on spare levels and repair actions in the multi-echelon system.

Out research looked at the effects that specific strategies had on performance measures. Rather than using the changes in performance measures to show the impact of strategies, future research can show the monetary impact of strategies. Two strategies can have the same effect on performance measures, but the costs of implementing the strategies can be completely different. This area of cost/benefit tradeoffs needs further research to establish the best performing and least costly strategies.

There are many opportunities for research in all logistic areas, but the research must consider the entire multi-echelon system. Evidence from this thesis suggests that research in one area without considering the entire system may not show all the critical effects.

APPENDIX A

SOURCE PROGRAM FOR SIMULATION RUNS

```
"MULTI-ECHELON SIMULATION
PREAMBLE
 NORMALLY MODE IS INTEGER
 EVENT NOTICES INCLUDE RESET AND CLOSING
 PROCESSES INCLUDE PRINTOUT AND NEWDAY
     EVERY FLIGHT HAS AN AC
     EVERY REPAIR HAS A SITE
                  AND A REQ
 RESOURCES INCLUDE WORKER
PERMANENT ENTITIES
     EVERY BASE HAS AN ASUPPLY
                AND A BSUPPLY
                AND AN ATOTAL
                AND A BTOTAL
                AND AN AINTRANSIT
                AND A BINTRANSIT
                AND AN AGK.VALUE
                AND A BGK.VALUE
                AND AN ALAST.SUPPLIED
                AND A BLAST.SUPPLIED
                AND A NUM.AIRCRAFT
                AND A OR.REQUIRMT
                AND A DAILY.SCHEDULE
                AND A REPAIR.PERCT
                AND A TRANSPORTATION
                AND A TOTCOUNT
                AND AN IN.REPAIR
                AND OWNS A QUEUE
                AND AN A.HANGAR
                AND A B.HANGAR
                AND A P.HANGAR
                AND BELONGS TO AN APOLICY.Q
                AND A BPOLICY.Q
          EVERY AIRCRAFT HAS A CLOCK1
                    AND A CLOCK2
                    AND A CLOCK3
                    AND A FLT.TIME
                    AND A SUS.TIME
                    AND A CYCLE.TIME
```

```
                    AND A BSUS.TIME
                    AND A BCYCLE.TIME
                    AND A TURNAROUND
                    AND A STATUS
                    AND A FLT
                    AND A TTIME
                    AND AN ASSGND.BASE
                    AND BELONGS TO A QUEUE
                    AND AN A.HANGAR
                    AND A B.HANGAR
                    AND A P.HANGAR
TEMPORARY ENTITIES
     EVERY FORM HAS A PART.TYPE
DEFINE DISPATCH AS A ROUTINE
DEFINE ACCOUNT AND BATCH.MEANS.METHOD AS ROUTINES
THE SYSTEM HAS A METHOD
          AND OWNS AN APOLICY.Q AND A BPOLICY.Q
THE SYSTEM HAS AN APCT.BASE.REPR RANDOM STEP VARIABLE
DEFINE APCT.BASE.REPR AS AN INTEGER STREAM 1 VARIABLE
DEFINE ATABLE AND BTABLE AS REAL, 2-DIMENSIONAL ARRAYS
DEFINE AENTRY AND BENTRY AS REAL, 2-DIMENSIONAL ARRAYS
DEFINE TURNAROUND AS A REAL VARIABLE
DEFINE CLOCK1 AN FLT.TIME AS REAL VARIABLES
DEFINE CLOCK2 AND CLOCK3 AS REAL VARAIBLES
DEFINE RPR.TIME AND THREE AS REAL VARIABLES
DEFINE SUS.TIME AND CYCLE.TIME AS REAL VARIABLES
DEFINE AGK.VALUE AND BGK.VALUE AS REAL VARIABLES
DEFINE BACKORDER AND BBACKORDER AS DUMMY REAL VARIABLES
DEFINE EFF AS A DUMMY REAL VARIABLE
DEFINE STUDENT.T AS A INTEGER VARIABLE
DEFINE COUNTER, YRCOUNT, AND WCTR AS INTEGER VARIABLES
DEFINE ACOUNTER AND BCOUNTER AS INTEGER VARIABLES
DEFINE PCOUNTER AND TOTCOUNT AS INTEGER VARIABLES
DEFINE FCOUNTER, RUN.LEN, AND LEN.SIM AS INTEGER VARIABLES
DEFINE ACTR, BCTR, AND INIT.TIME AS INTEGER VARIABLES
DEFINE QUEUE AS A FIFO SET
DEFINE A.HANGAR, B.HANGAR, AND P.HANGAR AS FIFO SETS
DEFINE APOLICY.Q AS A SET RANKED BY HIGH AGK.VALUE,
      THEN BY LOW ALAST.SUPPLIED
DEFINE BPOLICY.Q AS A SET RANKED BY HIGH BGK.VALUE,
      THEN BY LOW BLAST.SUPPLIED
 DEFINE AVAILABLE TO MEAN 0
 DEFINE FLYING    TO MEAN 4
 DEFINE APART.BROKEN TO MEAN 1
 DEFINE BPART.BROKEN TO MEAN 2
 DEFINE MAINTENANCE TO MEAN 3
 DEFINE PHASE TO MEAN 5
 DEFINE STATIC TO MEAN 10
 DEFINE E.DYNAMIC TO MEAN 15
 DEFINE DYNAMIC TO MEAN 20
```

```
ACCUMULATE VARQ AS THE VARIANCE,
          MEANQ AS THE MEAN OF N.QUEUE
ACCUMULATE AMAX AS THE MAXIMUM,
          AMEAN AS THE MEAN OF N.A.HANGAR
ACCUMULATE BMAX AS THE MAXIMUM,

          BMEAN AS THE MEAN OF N.B.HANGAR
ACCUMULATE PMAX AS THE MAXIMUM,
          PMEAN AS THE MEAN OF N.P.HANGAR
ACCUMULATE WTMEAN AS THE MEAN
AND FREQ (0 TO 31 BY 1) AS THE HISTOGRAM OF N.Q.WORKER
ACCUMULATE AFREQ (0 TO 16 BY 1) AS THE HISTOGRAM OF TOTCOUNT
ACCUMULATE UTILIZATION AS THE AVERAGE OF N.X.WORKER
ACCUMULATE WFREQ (0 TO 16 BY 1) AS THE HISTOGRAM
           OF N.X.WORKER
ACCUMULATE ASMEAN AS THE MEAN OF ASUPPLY
ACCUMULATE BSMEAN AS THE MEAN OF BSUPPLY
ACCUMULATE ATMEAN AS THE MEAN OF AINTRANSIT
ACCUMULATE BTMEAN AS THE MEAN OF BINTRANSIT
ACCUMULATE REMEAN AS THE MEAN OF IN.REPAIR
TALLY BMNCT AS THE MEAN OF BBACKORDER
TALLY NUMBER.OF.AC AS THE NUMBER,
      MAXCT AS THE MAXIMUM
      AND MNCT AS THE MEAN OF BACKORDER
TALLY FMEAN ASA THE MEAN OF EFF
END

MAIN
     LET METHOD = STATIC
     "METHOD CAN BE SET TO ANY OF THREE VALUES AT THIS
     "POINT : STATIC, DYNAMIC, AND E.DYNAMIC
     READ SEED.V(1) USING 84
          LET RUN.LEN = 365
          LET LEN.SIM = 12046
          LET INIT.TIME = 365
     "THE LENGTH OF SIMULATION IS 1 YEAR (365 DAYS).  THE
     "TOTAL RUN IS 32 YEARS WITH A ONE YEAR INITIALIZATION
     "PERIOD.
          LET COUNTER = 0
          LET ACOUNTER = 0
          LET BCOUNTER = 0
          LET PCOUNTER = 0
          LET FCOUNTER = 0
          LET ACTR = 0
          LET BCTR = 0
          LET YRCOUNT = 0
          LET WCTR = 0
     RESERVE ATABLE(*,*) AS 3 BY 20
     RESERVE BTABLE(*,*) AS 3 BY 20
     RESERVE AENTRY(*,*) AS 3 BY 20
     RESERVE BENTRY(*,*) AS 3 BY 20
```

```
                LET N.BASE = 3
                     CREATE EACH BASE
                LET N.WORKER = 1
                     CREATE EVERY WORKER
                "U.WORKER CAN BE SET TO A LOW VALUE OF 12 OR
                "A HIGH VALUE OF 15.
                LET U.WORKER = 12
                LET N.AIRCRAFT = 0
           FOR EACH BASE DO
                READ AUNITS USING 85
                LET ASUPPLY = AUNITS
                READ BUNITS USING 85
                LET BSUPPLY = BUNITS
                READ NUM.ASGND USING 85

                LET NUM.AIRCRAFT = NUM.ASGND
                LET N.AIRCRAFT = N.AIRCRAFT + NUM.ASGND
                LET AINTRANSIT = 0
                LET BINTRANSIT = 0
                LET IN.REPAIR = 0
                LET ALAST.SUPPLIED = 0
                LET BLAST.SUPPLIED = 0
           LOOP
                CREATE EVERY AIRCRAFT
                LET ASGND.SO.FAR = 0
      FOR EACH BASE DO
           READ APCT.BASE.REPR USING 85
           LET NUM.ASGND = ASGND.SO.FAR + 1
                FOR I = ASGND.SO.FAR TO NUM.ASGND DO
                     LET AIRCRAFT = I
                     LET CLOCK1 = EXPONENTIAL.F(300.,1)
                     "CLOCK1 CAN BE SET TO A MEAN OF 300 HOURS
                     "FOR A LOW VALUE OR 400 HOURS FOR A HIGH
                     "VALUE OF MTBF.
                     LET CLOCK2 = EXPONENTIAL.F(550.,1)
                     READ THREE USING 85
                     LET CLOCK3 = THREE
                     LET TURNAROUND = 8.0
                     LET STATUS = AVAILABLE
                     LET ASSGND.BASE = BASE
                     FILE THE AIRCRAFT IN QUEUE
                LOOP
           LET ASGND.SO.FAR = NUM.ASGND
      LOOP
           FOR EACH BASE DO
                READ FLT.PLAN USING 85
           "NOTE: THE NUMBER OF FLIGHTS PLANNED FOR EACH BASE IN
           "      PEACETIME IS 4 FOR OPERATIONAL BASES AND 8 FOR
           "      TRAINING BASES.  DURING HOSTILITIES, THE FLIGHTS
           "      INCREASE TO 8 AND 16 RESPECTIVELY.
                LET DAILY.SCHEDULE = FLT.PLAN
```

```
          READ TRAVEL USING 85
     "NOTE: THE TRANSPORTATION PIPELINE TIME IS SET TO 7
     "      DAYS FOR STATESIDE BASES AND 14 DAYS FOR THE
     "      OVERSEAS BASE.   THE TIME CAN BE REDUCED FOR
     "      TESTING TO 3 DAYS AND 7 DAYS, RESPECTIVELY.
          LET TRANSPORTATION = TRAVEL
     LOOP
FOR EACH BASE DO
     FOR J = 1 TO 20 DO
          READ AENTRY(BASE,J) USING 85
          LET ATABLE(BASE,J) = AENTRY(BASE,J)
          READ BENTRY(BASE,J) USING 85
          LET BTABLE(BASE,J) = BENTRY(BASE,J)
     LOOP
LOOP
     ACTIVATE AN NEWDAY IN 6 HOURS
     SCHEDULE A RESET IN INIT.TIME DAYS
     SCHEDULE A CLOSING  IN LEN.SIM DAYS
          START SIMULATION
END

PROCESS NEWDAY
     "THE NEWDAY PROCESS INCREMENTS THE DAY BY ONE AND
     "SCHEDULES THE PROPER NUMBER OF FLIGHTS FOR EACH
     "BASE.   FOR EVERY OPERATIONAL AIRCRAFT IN QUEUE
     "A FLIGHT PROCESS IS ACTIVATED.   THE NEWDAY PROCESS
     "IS REACTIVATED IN 1 DAY.
     ADD 1 TO DAY
          FOR EACH BASE DO
               LET OR.REQUIRMT = DAILY.SCHEDULE
               FOR EVERY AIRCRAFT IN QUEUE
               ACTIVATE A FLIGHT GIVING AIRCRAFT NOW
          LOOP
     FOR EACH AIRCRAFT DO
          LET TTIME = CLOCK1 + CLOCK2 + CLOCK3
          LET EFF = TTIME
     LOOP
          RESET TOTALS OF EFF
     FOR EACH BASE DO
          LET TOTCOUNT = N.A.HANGAR + N.B.HANGAR +N.P.HANGAR
     LOOP
          ACTIVATE A NEWDAY IN 1 DAY
  END

PROCESS FLIGHT GIVEN AC
  "THE FLIGHT PROCESS ATTEMPTS TO FLY THE REQUIRED NUMBER
  "OF FLIGHTS FOR EACH BASE.   AFTER THE FLIGHT, THE PART
  "A AND B AND PHASE CLOCK ARE DECREMENTED BY THE FLIGHT
  "TIME.   THE CLOCKS ARE CHECKED TO SEE IF ANY ARE BELOW
  "ZERO.   IF CLOCKS ARE POSITIVE, THE AIRCRAFT ARE
  "SERVICED AND PLACED IN THE READY TO FLY QUEUE.   IF
```

```
"CLOCKS ARE ZERO OR BELOW, THE AIRCRAFT IS GROUNDED AND
"THE PART REMOVED FOR THE REPAIR PROCESS.
   LET AIRCRAFT = AC
   LET FLT = FLIGHT
   LET BASE = ASSGND.BASE
        IF OR.REQUIRMT > 0
             REMOVE THE AIRCRAFT FROM THE QUEUE
             LET OR.REQUIRMT = OR.REQUIRMT - 1
             LET FLT.TIME(AC) = NORMAL.F(10.0,1.0,1)
             LET STATUS = FLYING
             WAIT FLT.TIME(AC) HOURS
             LET AIRCRAFT = AC
             LET BASE = ASSGND.BASE
             LET FCOUNTER = FCOUNTER + 1
             LET CLOCK1(AC) = CLOCK1(AC) - FLT.TIME(AC)
             LET CLOCK2(AC) = CLOCK2(AC) - FLT.TIME(AC)
             LET CLOCK3(AC) = CLOCK3(AC) - FLT.TIME(AC)
   IF CLOCK1(AC) < 0 AND CLOCK2(AC) < 0, LET STATUS = BOTH
        IF CLOCK1 < 0., LET STATUS = APART.BROKEN
             LET ACTR = ACTR + 1
             LET REPAIR.PERCT = APCT.BASE.REPR
             IF ASUPPLY > 0
                  LET ASUPPLY = ASUPPLY - 1
                  CREATE A FORM
                  LET PART.TYPE = 1
                  ACTIVATE A REPAIR GIVING
                             BASE AND FORM NOW
             ELSE
                  FILE THE AIRCRAFT IN THE A.HANGAR
                  LET STATUS = -STATUS
                  CREATE A FORM
                  LET PART.TYPE = 1
                  ACTIVATE A REPAIR GIVING
                             BASE AND FORM NOW
                  LET ACOUNTER = ACOUNTER + 1
                  LET SUS.TIME = TIME.V
                  SUSPEND PROCESS
                  LET AIRCRAFT = AC
                  LET FLT = FLIGHT
                  LET BASE = ASSGND.BASE
                  LET CYCLE.TIME = TIME.V - SUS.TIME
                  LET BACKORDER = CYCLE.TIME
                  REMOVE THE FIRST AIRCRAFT
                             FROM THE A.HANGAR

             ALWAYS
                  LET STATUS = MAINTENANCE
                  WAIT 4 HOURS
                  LET AIRCRAFT = AC
                  LET FLT = FLIGHT
                  LET BASE = ASSGND.BASE
```

```
                    LET CLOCK1 = EXPONENTIAL.F(300.,1)
          ALWAYS
IF CLOCK2(AC) < 0.0, LET STATUS = BPART.BROKEN
   LET BCTR = BCTR + 1
          IF BSUPPLY > 0
               LET BSUPPLY = BSUPPLY - 1
               CREATE A FORM
               LET PART.TYPE = 2
               ACTIVATE A REPAIR GIVING BASE AND FORM NOW
          ELSE
               FILE THE AIRCRAFT IN THE THE B.HANGAR
               LET STATUS = - STATUS
               CREATE A FORM
               LET PART.TYPE = 2
               ACTIVATE A REPAIR GIVING BASE AND FORM NOW
               LET BCOUNTER = BCOUNTER + 1
               LET BSUS.TIME = TIME.V
               SUSPEND PROCESS
               LET AIRCRAFT = AC
               LET FLT = FLIGHT
               LET BASE = ASSGND.BASE
               LET BCYCLE.TIME = TIME.V - BSUS.TIME
               LET BBACKORDER = BCYCLE.TIME
               REMOVE THE FIRST AIRCRAFT FROM THE B.HANGAR
          ALWAYS
               LET STATUS = MAINTENANCE
               WAIT 4 HOURS
               LET AIRCRAFT = AC
               LET BASE = ASSGND.BASE
               LET CLOCK2(AC) = EXPONENTIAL.F(550., 1)
     ALWAYS
ALWAYS
     IF CLOCK3(AC) < 0.0, LET STATUS = PHASE
          LET PCOUNTER = PCOUNTER + 1
          FILE THE AIRCRAFT IN THE P.HANGAR
          WAIT 20 DAYS
          LET AIRCRAFT = AC
          LET BASE = ASSGND.BASE
          REMOVE THE AIRCRAFT FROM THE P.HANGAR
          LET CLOCK3(AC) = 1000.0
     ALWAYS
          WAIT TURNAROUND(AC) HOURS
          LET AIRCRAFT = AC
          LET BASE = ASSGND.BASE
          LET STATUS = AVAILABLE
          FILE THE AIRCRAFT IN THE QUEUE
ALWAYS
END

PROCESS REPAIR GIVEN SITE AND REQ
  "THE REPAIR PROCESS SETS UP THE REPAIR TIMES FOR BOTH BASE
```

```
  "AND DEPOT.   FROM DEPOT, AFTER REPAIR THE DISPATCH
  "ROUTINE IS CALLED TO MAKE THE REDISTRIBUTION DECISION.
  LET FORM = REQ
  LET BASE = SITE
     IF REPAIR.PERCT = 0 AND PART.TYPE = 1
          LET IN.REPAIR = IN.REPAIR + 1
          LET RPR.TIME = EXPONENTIAL.F(4.0,1) + 1.0
          WAIT RPR.TIME DAYS
          LET BASE = SITE
          LET FORM = REQ
          LET IN.REPAIR = IN.REPAIR - 1
       FOR EACH AIRCRAFT IN A.HANGAR
                        WITH STATUS = -APART.BROKEN
          FIND THE FIRST CASE
               IF NONE
                    LET ASUPPLY = ASUPPLY + 1
               ELSE
                    REACTIVATE THE FLIGHT CALLED FLT NOW
               ALWAYS
     ELSE
       IF PAR.TYPE = 1
          WAIT TRANSPORTATION DAYS
          LET BASE = SITE
          LET FORM = REQ
          REQUEST 1 WORKER
          WORK EXPONENTIAL.F(4.0,1) + 3.0 DAYS
          LET BASE = SITE
          LET FORM = REQ
          RELINQUISH 1 WORKER
          CALL DISPATCH
       ELSE
          WAIT TRANSPORTATION DAYS
          LET BASE = SITE
          LET FORM = REQ
          REQUEST 1 WORKER
          WORK EXPONENTIAL.F(7.0,1) + 7.0 DAYS
          LET BASE = SITE
          LET FORM = REQ
          RELINQUISH 1 WORKER
          CALL DISPATCH
       ALWAYS
     ALWAYS
END

ROUTINE DISPATCH
  "THE DISPATCH ROUTINE REDISTRIBUTES THE SERVICEABLE
  "COMING OUT OF DEPOT USING EITHER THE STATIC, DYNAMIC
  "OR ENHANCED DYNAMIC RULE.
     DEFINE ACUM.POISSON AS A REAL VARIABLE
     DEFINE BCUM.POISSON AS A REAL VARIABLE
       IF METHOD = STATIC
```

```
     IF PART.TYPE = 1
          WAIT TRANSPORTATION DAYS
          LET BASE = SITE
          LET FORM = REQ
          FOR EACH AIRCRAFT IN A.HANGAR
                   WITH STATUS = - APART.BROKEN
               FIND THE FIRST CASE
               IF NONE
                   DESTROY THE FORM
                   LET ASUPPLY = ASUPPLY + 1
               ELSE
                   DESTROY THE FORM
                   REACTIVATETHEFLIGHT CALLEDFLT NOW
               ALWAYS
     ELSE
          WAIT TRANSPORTATION DAYS
          LET BASE = SITE
          LET FORM = REQ
          FOR EACH AIRCRAFT IN B.HANGAR
                   WITH STATUS = - BPART.BROKEN
               FIND THE FIRST CASE
               IF NONE
                   DESTROY THE FORM
                   LET BSUPPLY = BSUPPLY + 1
               ELSE
                   DESTROY THE FORM
                   ACTIVATE THE FLIGHT CALLED FLT NOW
               ALWAYS
     ALWAYS
ELSE
     IF COUNTER GE 1
          FOR EACH BASE DO
               REMOVE THE BASE FROM APOLICY.Q
               REMOVE THE BASE FROM BPOLICY.Q
          LOOP
ALWAYS
     LET COUNTER = COUNTER + 1
     FOR EACH BASE DO
        LET ATOTAL = ASUPPLY - N.A.HANGAR + AINTRANSIT
        LET BTOTAL  = BSUPPLY - N.B.HANGAR + BINTRANSIT
          IF METHOD = E.DYNAMIC
               LET ATOTAL = ATOTAL + IN.REPAIR
          ALWAYS
          IF ATOTAL < 0
               LET AGK.VALUE = 1.0
               FILE THE BASE IN APOLICY.Q
          ELSE
             LET ACUM.POISSON = ATABLE(BASE, ATOTAL+1)
             LET AGK.VALUE = 1.0 - ACUM.POISSON
             FILE THE BASE IN APOLICY.Q
          ALWAYS
```

```
            IF BTOTAL < 0
               LET BGK.VALUE = 1.0
               FILE THE BASE IN BPOLICY.Q
            ELSE
               LET BCUM.POISSON = BTABLE(BASE, BTOTAL+1)
               LET BGK.VALUE = 1.0 - BCUM.POISSON
               FILE THE BASE IN BPOLICY.Q
            ALWAYS
       LOOP
  IF PART.TYPE = 1
       REMOVE THE FIRST BASE FROM APOLICY.Q
       LET SITE = BASE
       LET ALAST.SUPPLIED = ALAST.SUPPLIED + 1
       FILE THE BASE IN APOLICY.Q
       LET AINTRANSIT = AINTRANSIT + 1
       WAIT TRANSPORTATION DAYS
       LET BASE = SITE
       LET FORM = REQ
       LET AINTRANSIT = AINTRANSIT - 1
       FOR EACH AIRCRAFT IN A.HANGAR
                WITH STATUS = -APART.BROKEN
            FIND THE FIRST CASE
                 IF NONE
                      DESTROY THE FORM
                      LET ASUPPLY = ASUPPLY + 1
                 ELSE
                    DESTROY THE FORM
                    REACTIVATE THE FLIGHT CALLED FLT NOW
                 ALWAYS
  ELSE
       REMOVE THE FIRST BASE FROM BPOLICY.Q
       LET SITE = BASE
       LET BLAST.SUPPLIED = BLAST.SUPPLIED + 1
       FILE THE BASE IN BPOLICY.Q
       LET BINTRANSIT = BINTRANSIT + 1
       WAIT TRANSPORTATION DAYS
       LET BASE = SITE
       LET FORM = REQ
       LET BINTRANSIT = BINTRANSIT - 1
       FOR EACH AIRCRAFT IN B.HANGAR
                WITH STATUS = - BPART.BROKEN
            FIND THE FIRST CASE
                 IF NONE
                      DESTROY THE FORM
                      LET BSUPPLY = BSUPPLY + 1
                 ELSE
                    DESTROY THE FORM
                    REACTIVATE THE FLIGHT CALLED FLT NOW
                 ALWAYS
  ALWAYS
ALWAYS
```

```
RETURN
END

PROCESS PRINTOUT
     WRITE SEED.V(1) AS I 12 USING 86
     REWIND 86
     "TO RECEIVE A PAPER COPY OF PRINTOUT WITH PROPER
     "FORMAT REMOVE THE QUOTATION SIGNS FROM ALL LINES
     "BELOW THIS POINT.
"START NEW PAGE
"PRINT 1 LINE WITH DAY AS FOLLOWS
"THE DAY IS ****
"FOR EACH BASE DO
"    PRINT 8 LINES WITH BASE, MEANQ, VARQ, AMAX, AMEAN, BMAX
"    BMEAN, PMAX AND PMEAN AS FOLLOWS

"    STATISTICS FOR BASE *
"THE AVERAGE NUMBER OF FLYABLE AIRCRAFT IS **.**
"                      WITH VARIANCE **.**.
"THE MAXIMUM NUMBER OF AIRCRAFT GROUNDED FOR PART A IS **.
"THEAVERAGE NUMBER OF AIRCRAFT GROUNDED FORPARTAIS **.**
"THE MAXIMUM NUMBER OF AIRCRAFT GROUNDED FOR PART B IS **.
"THE AVERAGE NUMBER OF AIRCRAFT GROUNDED FOR PART B IS **.**
"THE MAXIMUM NUMBER OF AIRCRAFT IN PHASE IS **
"THE AVERAGE NUMBER OF AIRCRAFT IN PHASE IS **.**
"    SKIP 4 LINES
"LOOP
"PRINT 1 LINE WITH FCOUNTER AS FOLLOWS
"   THE NUMBER OF FLIGHTS FLOWN IS *****
"    SKIP 3 LINES
"PRINT 2 LINES WITH ACTR AND BCTR AS FOLLOWS
"PART A REQUIREMENTS FOR THIS SIMULATION ARE ***
"PART B REQUIREMENTS FOR THIS SIMULATION ARE ***
"    SKIP 3 LINES
"PRINT 3 LINES WITH ACOUNTER, BCOUNTER AND
               PCOUNTER AS FOLLOWS
"THE NUMBER OF AIRCRAFT SUSPENDED FOR PART A IS ****
"THE NUMBER OF AIRCRAFT SUSPENDED FOR PART B IS ****
"THE NUMBER OF AIRCRAFT IN PHASE IS ****
"    SKIP 3 LINES
"PRINT 3 LINES WITH NUMBER.OF.AC, MAXCT, AND MNCT AS FOLLOWS
"**** AIRCRAFT WERE IN BACKORDER STATUS FOR THIS SIMULATION.
"THE MAXIMUM TIME IN BACKORDER STATUS WAS ***.**
"THE AVERAGE TIME IN BACKORDER STATUS WAS ***.**
"    SKIP 5 LINES
"PRINT 2 LINES WITH WTMEAN AS FOLLOWS
"DEPOT
"THE AVERAGE NUMBER OF UNITS AWAITING REPAIR IS **.**
"PRINT 1 LINE AS FOLLOWS
"        HISTOGRAM
"FOR K = 1 TO 60
```

```
"PRINT 1 LINE WITH K - 1 AND FREQ(1,K) AS FOLLOWS
"     *        **
"    SKIP 4 LINES
"PRINT 1 LINE AS FOLLOWS
"               BASE 1           BASE 2           BASE 3
"FOR L = 1 TO 25
"PRINT 1 LINE WITH L - 1 AND AFREQ(1,L), AFREQ(2,L)
"        AND AFREQ(3,L) AS FOLLOWS
"     **          ****             ****             ****
"PRINT 3 LINES AS FOLLOWS
"        AIRCRAFT REPAIR MODEL
"           IS NOW COMPLETE
"          START NEW RUN NOW
"   NOTE: THIS CONCLUDES THE PAPER PRINTOUT OF INFORMATION.
"         THE NEXT COMMENTED LINE BELOW THIS NOTE INITIATES
"         THE ACCOUNT ROUTINE WHICH BUILDS AN ARRAY SO THE
"         FISHMAN BATCH MEANS METHOD CAN BE USED TO ANALYZE
"         THE SIMULATION DATA.
"CALL ACCOUNT GIVEN WTMEAN

"   NOTE: THE NEXT SET OF WRITE STATEMENTS OUTPUTS DATA TO
"         FILES PREVIOUSLY BUILT. THE //G.SIMU87 DD CARD AT
"         THE END OF THE PROGRAM NAMES THE FILE TO WHICH THE
"         DATA IS WRITTEN.
     FOR EACH BASE DO
          WRITE BASE, MEANQ, AMEAN, BNEAN, PMEAN, ASMEAN,
          BSMEAN, ATMEAN, BTMEAN ANDREMEAN AS I 2, AND
          9 D(6,2) USING 87
     LOOP
WRITE FCOUNTER, ACTR, BCTR, ACOUNTER AND BCOUNTER AS 5 I 7
     USING 87
WRITE MNCT AND BMNCT AS 2 D(7,2) USING 87
WRITE WTMEAN AS D(6,2) USING 87
WRITE UTILIZATION/12. AS D(7,3) USING 87
     FOR K = 1 TO 31
          WRITE K - 1 AND FREQ(1,K) AS I 3 AND I 4 USING 87
     FOR L = 1 TO 21
          WRITE L - 1, AFREQ(1,L), AFREQ(2,L) AND AFREQ(3,L)
              AS I3 AND 3 I 4 USING 87
     FOR J = 1 TO 16
         WRITE J - 1 AND WFREQ(1,J) AS I 3 AND I 4 USING 87
SCHEDULE A RESET NOW
RETURN
END

ROUTINE ACCOUNT GIVEN QMEAN
     DEFINE QMEAN AS A REAL VARIABLE
     DEFINE FINAL AND NO.FINAL AS SAVED VARIABLES
     DEFINE X AS A REAL SAVED 1-DIMENSIONAL ARRAY
          IF FINAL = 0
               LET FINAL = 32
```

```
               LET NO.FINAL = 1
               RESERVE X(*) AS FINAL
               LET X(NO.FINAL) = QMEAN
          ELSE
               LET X(NO.FINAL) = QMEAN
          ALWAYS
            IF NO.FINAL = FINAL
               CALL BATCH.MEANS.METHOD GIVING FINAL AND X(*)
            ELSE
               ADD 1 TO NO.FINAL
            ALWAYS
     RETURN
END

ROUTINE STUDENT.T(DF)
     NORMALLY MODE IS REAL
     DEFINE A AND DF AS VARIABLES
     DEFINE SS AS A SAVED INTEGER VARIABLE
     DEFINE I AS AN INTEGER VARIABLE
     DEFINE B AND H AS SAVED, 1-DIMENSIONAL ARRAYS
IF SS = 0
     LET SS = 1
     RESERVE B(*) AS 9 AND H(*) AS 4

     LET B(1) = 1.96
     FOR I = 2 TO 9
          LET B(I)  = B(I -1)*B(1)
          LET H(1)  = (B(3)+B(1))/4.0
          LET H(2)  = (5.0*B(5)+16.0*B(3)+3.0*B(1))/96.0
          LET H(3)  = (3.0*B(7)+19.0*B(5)+17.0*B(3)-
                     15.0*B(1))/384.0
          LET H(4)  = (79.0*B(9)+776.0*B(7)+1482.0*B(5)-
                     945.0*B(1))/92160.0
     ALWAYS
          FOR I BACK FORM 4 TO 1 BY 1
               LET A = (A+H(I))/DF
     RETURN WITH A+B(1)
END

ROUTINE BATCH.MEANS.METHOD GIVING N AND X
     DEFINE I,K,N,NO AND NTILDE AS VARIABLES
     DEFINE C,CRITICAL.VALUE,D,E,HALF.WIDTH,NA,Q AND XBAR
          AS REAL VARIABLES
     DEFINE X AND Y AS REAL 1-DIMENSIONAL ARRAYS
 IF N < 8 PRINT 1 LINE THUS
     SAMPLE SIZE TOO SMALL TO PERFORM TEST FOR INDEPENDENCE
     RETURN
 ALWAYS
     RESERVE Y(*) AS N
     LET NTILDE = N
     LET K = 1
```

```
     FOR I = 1 TO N
          LET Y(I) = X(I)
     FOR I = 1 TO N
          COMPUTE XBAR AS THE MEAN OF X(I)
     SKIP 5 LINES
     PRINT 3 LINES WITH XBAR THUS
          0.95 INTERVAL ESTIMATION----BATCH METHOD

                  SAMPLE MEAN = ..........
     SKIP 3 LINES
     BEGIN REPORT
     BEGIN HEADING
     PRINT 3 LINES THUS
     NO. OF   NO. OF OBS.   SAMPLE VARIANCE        CRITICAL
     BATCHES   PER BATCH     OF SAMPLE MEAN   C      VALUE
     -------  -----------   ---------------   -    --------
     END
     SKIP 1 LINE
     `AAA' FOR I = 1 TO TILDE DO
               COMPUTE D AS THE VARIANCE OF Y(I)
                 IF I < NTILDE
                    COMPUTE E AS THE SUM OF
                    (Y(I)-Y(I+1))*(Y(I)-Y(I+1))
                 ALWAYS
           LOOP
     LET D = D*NTILDE
     LET C = 1.0 - E/(2.0*D)

     LET NA = NTILDE*(NTILDE - 1.0)
     LET CRITICAL.VALUE = 1.645*SQRT.F((NTILDE-2.0)/
                          (NTILDE*NTILDE - 1.0))
     LET HALF.WIDTH= STUDENT.T(REAL.F(NTILDE-1))*SQR.F(D/NA)
   PRINT 1 LINE WITH NTILDE,K,D/NA,C AND CRITICAL.VALUE THUS
   *****      *****            ...............   *.***     *.***
     SKIP 1 LINE
     IF ABS.F(C) <= CRITICAL.VALUE AND NO = 0
          LET NO = NTILDE
     ALWAYS
          IF NTILDE < 16
               SKIP 1 LINE
               IF NO > 0
                    PRINT 1 LINE WITH NO THUS
BATCHES SUFFICE TO PASS TEST OF INDEPENDENCE AT 0.05 LEVEL
                    RELEASE Y
                    RETURN
               ELSE
                    PRINT 1 LINE THUS
NO SUCCESS ON TEST OF INDEPENDENCE
                    RELEASE Y
                    RETURN
          ELSE
```

```
                    LET NTILDE = TRUNC.F(NTILDE/2.0)
                    LET K = 2*K
                    FOR I = 1 TO NTILDE
                         LET Y(I)=(Y(2*I-1)+Y(2*I))/2.0
                    GO TO AAA
                    END
               END

EVENT RESET SAVING THE EVENT NOTICE
     FOR EACH BASE DO
          RESET TOTALS OF N.QUEUE
          RESET TOTALS OF N.A.HANGAR
          RESET TOTALS OF N.B.HANGAR
          RESET TOTALS OF N.P.HANGAR
          RESET TOTALS OF TOTCOUNT
     LOOP
          RESET TOTALS OF BACKORDER
          RESET TOTALS OF N.Q.WORKER
          RESET TOTALS OF BBACKORDER
          RESET TOTALS OF N.X.WORKER
     LET  FCOUNTER = 0
     LET ACTR = 0
     LET BCTR = 0
     LET ACOUNTER = 0
     LET BCOUNTER = 0
     LET PCOUNTER = 0
     REWIND 86
          IF WCTR > 1
               READ SEED.V(1) USING 86
               REWIND 86
          ALWAYS

     LET WCTR = WCTR + 1
     ACTIVATE A PRINTOUT IN RUN.LEN DAYS
     RETURN
END

EVENT CLOSING
     PRINT 1 LINE AS FOLLOWS
     CLOSING
     STOP
END

//G.SIMU84 DD DSN=UNC.BA.S6261.PMILLER.ISEED,DISP=OLD
//G.SIMU85 DD DSN=UNC.BA.S6261.PMILLER.RDATA7,DISP=OLD
//G.SIMU86 DD DSN=UNC.BA.S6261.PMILLER.SEEDN,DISP=OLD
//G.SIMU87 DD DSN=UNC.BA.S6261.PMILLER.WK10,DISP=OLD
//
```

APPENDIX B

This appendix contains means for all performance measures for each of the 16 experiments in the fractional factorial design. This data is also provided for each of the three redistribution rules.

PART A BACKORDER DAYS

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	7.9	7.8	7.5
2	5.1	4.5	4.4
3	5.0	2.3	2.4
4	2.8	1.4	1.3
5	2.5	1.3	1.3
6	3.3	1.5	1.4
7	3.2	2.6	2.4
8	4.1	2.7	2.8
9	3.4	2.7	2.6
10	7.2	6.4	7.0
11	1.3	.8	.4
12	4.1	2.6	2.4
13	5.3	3.1	3.0
14	3.8	2.6	2.5
15	7.4	6.1	5.9
16	5.2	4.4	4.3

PART B BACKORDER DAYS

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	12.1	9.5	9.4
2	11.5	9.3	9.4
3	13.0	11.4	11.3
4	11.7	9.9	10.1
5	8.4	5.8	6.2
6	7.3	5.3	4.9
7	7.9	5.4	5.3
8	7.3	4.8	4.6
9	4.5	1.4	1.2
10	5.0	1.9	2.3
11	4.9	1.0	1.6
12	6.3	3.3	3.1
13	7.0	3.5	3.5
14	8.3	4.3	4.2
15	7.2	3.1	3.1
16	7.5	3.9	3.6

MEAN UNITS AWAITING DEPOT REPAIR

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	1.8	1.8	1.6
2	.1	.1	.1
3	2.0	2.1	2.2
4	.1	.1	.1
5	2.6	2.4	2.9
6	1.0	1.3	1.2
7	1.1	1.4	1.1
8	.3	.3	.4
9	.3	.3	.4
10	7.8	8.6	10.4
11	.2	.3	.3
12	8.2	11.0	10.3
13	1.1	1.5	1.6
14	3.9	4.8	4.0
15	.3	.3	.3
16	1.4	1.6	1.7

DEPOT WORKER UTILIZATION

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	88%	89%	88%
2	65%	66%	66%
3	89%	90%	90%
4	64%	64%	65%
5	90%	89%	90%
6	83%	85%	85%
7	83%	86%	83%
8	74%	77%	76%
9	75%	75%	75%
10	97%	98%	99%
11	70%	71%	71%
12	95%	97%	97%
13	84%	86%	86%
14	92%	94%	92%
15	74%	73%	74%
16	84%	84%	85%

PART A STOCKAGE EFFECTIVENESS

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	20%	11%	10%
2	36%	34%	32%
3	89%	90%	90%
4	96%	97%	98%
5	96%	96%	97%
6	92%	95%	95%
7	76%	71%	72%
8	68%	62%	62%
9	58%	55%	53%
10	25%	17%	12%
11	99%	99%	99%
12	89%	86%	88%
13	70%	64%	60%
14	84%	80%	81%
15	34%	24%	24%
16	50%	43%	41%

PART B STOCKAGE EFFECTIVENESS

	REDISTRIBUTION RULES		
EXPERIMENT	STATIC	DYNAMIC	ENHANCED DYNAMIC
1	29%	18%	20%
2	28%	18%	16%
3	20%	9%	9%
4	23%	12%	11%
5	39%	33%	29%
6	48%	35%	34%
7	43%	33%	36%
8	49%	36%	38%
9	94%	97%	98%
10	82%	93%	90%
11	93%	98%	97%
12	82%	79%	80%
13	81%	77%	78%
14	71%	67%	72%
15	82%	85%	85%
16	78%	78%	78%

APPENDIX C

This appendix contains statistics for each of the 16 experiments in the fractional factorial design. Each experiment has three sections of data. The first section shows the daily average of parts A and B in specific locations in the system. The second section provides the average number of aircraft in flying, grounded, phase, or idle status at the three bases. Finally, the third section shows the number of days that workers remain busy in the depot repair shop. This data was used to produce the bar charts shown in Chapters 4 and 5 of this dissertation.

EXPERIMENT 1

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	.2	.1	.3		.2	.2	.4	
BASE REPAIR	.3	.5	.2		-	-	-	
INTRANSIT	2.1	4.3	4.0		1.6	3.2	3.2	
IN MAINTENANCE	1.8	4.7	2.7		2.6	4.7	3.6	
DEPOT REPAIR				4.9				6.2
IN FLYING A/C	6.6	12.7	6.0		6.6	12.7	6.0	
IN IDLE A/C	.4	.4	.1		.4	.4	.1	

	BASE		
	1	2	3
AIRCRAFT FLYING	6.6	12.7	6.0
AIRCRAFT GROUNDED-			
FOR PART A	1.2	2.2	1.8
FOR PART B	.5	2.2	.9
AIRCRAFT IN PHASE	1.3	2.5	1.2
AIRCRAFT IDLE	.4	.4	.1

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	277
7-9	60
4-6	27
0-3	0

EXPERIMENT 2

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	.4	.3	.9		.2	.2	.4	
BASE REPAIR	.5	1.1	.5		-	-	-	
INTRANSIT	1.5	3.1	3.2		1.7	3.3	3.3	
IN MAINTENANCE	2.2	5.2	2.6		2.0	3.8	1.6	
DEPOT REPAIR				2.6				7.9
IN FLYING A/C	6.8	13.4	6.7		6.8	13.4	6.7	
IN IDLE A/C	.4	.3	.3		.4	.3	.3	

	BASE 1	2	3
AIRCRAFT FLYING	6.8	13.4	6.7
AIRCRAFT GROUNDED-			
FOR PART A	.6	1.2	.4
FOR PART B	.8	2.5	1.4
AIRCRAFT IN PHASE	1.4	2.6	1.2
AIRCRAFT IDLE	.4	.3	.3

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	71
10-12	163
7-9	87
4-6	34
0-3	9

EXPERIMENT 3

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	2.6	3.0	4.0		.1	.1	.2	
BASE REPAIR	.2	.4	.2		-	-	-	
INTRANSIT	1.9	3.5	3.7		1.8	3.5	3.5	
IN MAINTENANCE	2.5	5.2	3.3		1.5	2.8	1.3	
DEPOT REPAIR				4.8				8.5
IN FLYING A/C	7.1	14.0	6.7		7.1	14.0	6.7	
IN IDLE A/C	.4	.5	.1		.4	.5	.1	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.1	14.0	6.7
AIRCRAFT GROUNDED-			
FOR PART A	0	.2	0
FOR PART B	1.0	2.7	1.9
AIRCRAFT IN PHASE	1.5	2.6	1.3
AIRCRAFT IDLE	.4	.5	.1

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	261
7-9	87
4-6	16
0-3	0

EXPERIMENT 4

	PART A				PART B			
	BASE				BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	3.6	4.4	5.6		.1	.1	.2	
BASE REPAIR	.5	.9	.5		-	-	-	
INTRANSIT	1.2	2.5	2.4		1.8	3.6	3.6	
IN MAINTENANCE	2.7	5.0	2.5		1.5	2.9	1.4	
DEPOT REPAIR				2.5				6.9
IN FLYING A/C	6.9	14.4	7.1		6.9	14.4	7.1	
IN IDLE A/C	.4	.7	.4		.4	.7	.4	

	BASE		
	1	2	3
AIRCRAFT FLYING	6.9	14.4	7.1
AIRCRAFT GROUNDED-			
FOR PART A	0	0	0
FOR PART B	1.2	2.1	1.1
AIRCRAFT IN PHASE	1.5	2.8	1.4
AIRCRAFT IDLE	.4	.7	.4

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	49
10-12	102
7-9	151
4-6	62
0-3	0

EXPERIMENT 5

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	3.5	4.4	5.7		.3	.3	.6	
BASE REPAIR	.7	1.2	.6		-	-	-	
INTRANSIT	.7	1.4	1.6		.8	1.6	2.0	
IN MAINTENANCE	2.0	4.5	1.9		1.5	2.8	1.5	
DEPOT REPAIR				4.3				9.1
IN FLYING A/C	7.5	14.8	7.4		7.5	14.8	7.4	
IN IDLE A/C	.5	.7	.6		.5	.7	.6	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.5	14.8	7.4
AIRCRAFT GROUNDED-			
FOR PART A	0	0	0
FOR PART B	.5	1.7	.5
AIRCRAFT IN PHASE	1.5	2.8	1.5
AIRCRAFT IDLE	.5	.7	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	321
7-9	25
4-6	9
0-3	9

EXPERIMENT 6

	PART A BASE 1	2	3	DEPOT	PART B BASE 1	2	3	DEPOT
ON SHELF	3.0	3.7	4.7		.4	.5	.9	
BASE REPAIR	.3	.6	.3		-	-	-	
INTRANSIT	1.1	2.2	2.6		.8	1.6	1.8	
IN MAINTENANCE	2.0	3.9	1.9		1.5	3.1	1.5	
DEPOT REPAIR				5.6				7.8
IN FLYING A/C	7.5	15.0	7.6		7.5	15.0	7.6	
IN IDLE A/C	.5	1.0	.6		.5	1.0	.6	

	BASE 1	2	3
AIRCRAFT FLYING	7.5	15.0	7.6
AIRCRAFT GROUNDED-			
FOR PART A	0	0	0
FOR PART B	.5	.9	.3
AIRCRAFT IN PHASE	1.5	3.1	1.5
AIRCRAFT IDLE	.5	1.0	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	211
10-12	92
7-9	57
4-6	5
0-3	0

EXPERIMENT 7

	PART A BASE 1	2	3	DEPOT	PART B BASE 1	2	3	DEPOT
ON SHELF	1.1	1.4	2.1		.3	.4	.6	
BASE REPAIR	.4	.9	.4		-	-	-	
INTRANSIT	.6	1.1	1.4		.7	1.7	2.0	
IN MAINTENANCE	1.8	4.1	2.0		1.7	3.4	1.5	
DEPOT REPAIR				3.3				8.2
IN FLYING A/C	7.5	14.8	7.5		7.5	14.8	7.5	
IN IDLE A/C	.5	.8	.6		.5	.8	.6	

	BASE 1	2	3
AIRCRAFT FLYING	7.5	14.8	7.5
AIRCRAFT GROUNDED-			
FOR PART A	.2	.3	0
FOR PART B	.3	1.1	.4
AIRCRAFT IN PHASE	1.5	3.0	1.5
AIRCRAFT IDLE	.5	.8	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	260
7-9	95
4-6	10
0-3	0

EXPERIMENT 8

	PART A BASE 1	2	3	DEPOT	PART B BASE 1	2	3	DEPOT
ON SHELF	.8	1.0	1.6		.4	.5	.9	
BASE REPAIR	.2	.5	.2		-	-	-	
INTRANSIT	.8	1.7	2.0		.8	1.6	1.9	
IN MAINTENANCE	1.9	4.0	1.9		1.8	3.4	1.8	
DEPOT REPAIR				4.2				7.7
IN FLYING A/C	7.4	14.9	7.5		7.4	14.9	7.5	
IN IDLE A/C	.5	.7	.4		.5	.7	.4	

	BASE 1	2	3
AIRCRAFT FLYING	7.4	14.9	7.5
AIRCRAFT GROUNDED-			
FOR PART A	.3	.4	.2
FOR PART B	.4	1.0	.3
AIRCRAFT IN PHASE	1.5	3.0	1.6
AIRCRAFT IDLE	.5	.7	.4

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	159
10-12	136
7-9	56
4-6	15
0-3	0

EXPERIMENT 9

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	.7	.7	1.5		3.2	3.8	4.4	
BASE REPAIR	.7	1.2	.6		-	-	-	
INTRANSIT	.8	1.5	1.7		.8	1.6	2.1	
IN MAINTENANCE	1.6	3.2	1.5		1.9	4.0	1.7	
DEPOT REPAIR				4.1				8.1
IN FLYING A/C	7.5	15.2	7.6		7.5	15.2	7.6	
IN IDLE A/C	.6	.8	.6		.6	.8	.6	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.6	15.2	7.6
AIRCRAFT GROUNDED-			
FOR PART A	.3	.8	.2
FOR PART B	0	0	0
AIRCRAFT IN PHASE	1.5	3.2	1.6
AIRCRAFT IDLE	.6	.8	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	70
10-12	152
7-9	109
4-6	33
0-3	0

EXPERIMENT 10

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	.1	.1	.3		2.5	3.2	3.8	
BASE REPAIR	.3	.6	.3		-	-	-	
INTRANSIT	1.0	2.0	2.3		.7	1.5	1.8	
IN MAINTENANCE	1.5	2.7	1.4		2.4	6.0	2.5	
DEPOT REPAIR				10.1				10.6
IN FLYING A/C	7.1	13.7	7.0		7.1	13.7	7.0	
IN IDLE A/C	.5	.4	.5		.5	.4	.5	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.1	13.7	7.0
AIRCRAFT GROUNDED-			
FOR PART A	.9	3.3	1.1
FOR PART B	0	0	0
AIRCRAFT IN PHASE	1.5	2.7	1.4
AIRCRAFT IDLE	.5	.3	.5

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	363
7-9	2
4-6	0
0-3	0

EXPERIMENT 11

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	4.5	5.3	6.5		3.1	3.7	4.3	
BASE REPAIR	.5	1.0	.5		-	-	-	
INTRANSIT	.5	1.2	1.4		.9	1.7	2.1	
IN MAINTENANCE	1.6	3.3	1.6		1.6	3.2	1.6	
DEPOT REPAIR				2.8				8.3
IN FLYING A/C	7.8	15.8	7.9		7.8	15.8	7.9	
IN IDLE A/C	.7	.9	.5		.7	.9	.5	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.8	15.8	7.9
AIRCRAFT GROUNDED-			
FOR PART A	0	0	0
FOR PART B	0	0	0
AIRCRAFT IN PHASE	1.5	3.3	1.6
AIRCRAFT IDLE	.7	.9	.5

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	150
10-12	121
7-9	77
4-6	17
0-3	0

EXPERIMENT 12

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	2.4	3.0	3.9		1.9	2.3	2.8	
BASE REPAIR	.2	.5	.3		-	-	-	
INTRANSIT	.9	1.7	1.9		.8	1.7	2.0	
IN MAINTENANCE	1.7	3.5	1.7		1.6	3.3	1.6	
DEPOT REPAIR				9.4				13.2
IN FLYING A/C	7.8	15.4	7.7		7.8	15.4	7.7	
IN IDLE A/C	.6	1.0	.6		.6	1.0	.6	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.8	15.4	7.7
AIRCRAFT GROUNDED-			
FOR PART A	0	.1	0
FOR PART B	.1	.3	.2
AIRCRAFT IN PHASE	1.5	3.2	1.5
AIRCRAFT IDLE	.6	1.0	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	309
7-9	43
4-6	12
0-3	0

EXPERIMENT 13

	PART A BASE 1	2	3	DEPOT	PART B BASE 1	2	3	DEPOT
ON SHELF	1.6	1.4	2.2		1.9	1.9	2.7	
BASE REPAIR	.4	.6	.3		-	-	-	
INTRANSIT	2.5	5.0	5.0		1.9	4.0	3.7	
IN MAINTENANCE	1.6	2.9	1.5		1.8	3.6	1.8	
DEPOT REPAIR				6.4				8.1
IN FLYING A/C	7.6	15.2	7.6		7.6	15.2	7.6	
IN IDLE A/C	.5	1.1	.7		.5	1.1	.7	

	BASE 1	2	3
AIRCRAFT FLYING	7.6	15.2	7.6
AIRCRAFT GROUNDED-			
FOR PART A	.2	.9	.2
FOR PART B	.1	.1	0
AIRCRAFT IN PHASE	1.6	2.7	1.5
AIRCRAFT IDLE	.5	1.1	.7

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	264
10-12	61
7-9	37
4-6	3
0-3	0

EXPERIMENT 14

	PART A BASE 1	PART A BASE 2	PART A BASE 3	PART A DEPOT	PART B BASE 1	PART B BASE 2	PART B BASE 3	PART B DEPOT
ON SHELF	2.2	2.1	3.5		1.5	1.6	2.3	
BASE REPAIR	.6	1.3	.7		-	-	-	
INTRANSIT	1.7	3.6	3.5		1.9	1.9	3.7	
IN MAINTENANCE	1.6	3.4	1.6		1.6	3.4	1.5	
DEPOT REPAIR				5.3				11.3
IN FLYING A/C	7.7	15.2	7.7		7.7	15.2	7.7	
IN IDLE A/C	.6	1.1	.7		.6	1.1	.7	

	BASE 1	BASE 2	BASE 3
AIRCRAFT FLYING	7.7	15.2	7.7
AIRCRAFT GROUNDED-			
FOR PART A	.1	.3	0
FOR PART B	.1	.2	.1
AIRCRAFT IN PHASE	1.5	3.2	1.5
AIRCRAFT IDLE	.6	1.1	.7

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	333
7-9	32
4-6	0
0-3	0

EXPERIMENT 15

	PART A BASE				PART B BASE			
	1	2	3	DEPOT	1	2	3	DEPOT
ON SHELF	.3	.2	.6		2.1	2.5	3.2	
BASE REPAIR	.2	.5	.2		-	-	-	
INTRANSIT	1.8	3.7	3.7		1.9	3.5	3.6	
IN MAINTENANCE	1.5	3.5	1.4		2.1	4.6	2.1	
DEPOT REPAIR				3.6				7.6
IN FLYING A/C	7.3	14.5	7.3		7.3	14.5	7.3	
IN IDLE A/C	.5	.6	.6		.5	.6	.6	

	BASE		
	1	2	3
AIRCRAFT FLYING	7.3	14.5	7.3
AIRCRAFT GROUNDED-			
FOR PART A	.7	1.5	.7
FOR PART B	.1	.3	0
AIRCRAFT IN PHASE	1.4	3.1	1.4
AIRCRAFT IDLE	.5	.6	.6

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
13-15	127
10-12	116
7-9	99
4-6	22
0-3	0

EXPERIMENT 16

	PART A BASE 1	PART A BASE 2	PART A BASE 3	PART A DEPOT	PART B BASE 1	PART B BASE 2	PART B BASE 3	PART B DEPOT
ON SHELF	.5	.5	1.2		1.8	2.0	2.7	
BASE REPAIR	.5	1.0	.5		-	-	-	
INTRANSIT	1.3	2.6	2.7		1.9	3.7	3.8	
IN MAINTENANCE	1.7	3.4	1.6		1.8	4.0	1.9	
DEPOT REPAIR				3.3				8.9
IN FLYING A/C	7.4	14.9	7.5		7.4	14.9	7.5	
IN IDLE A/C	.5	.7	.5		.5	.7	.5	

	BASE 1	BASE 2	BASE 3
AIRCRAFT FLYING	7.4	14.9	7.5
AIRCRAFT GROUNDED-			
FOR PART A	.4	1.0	.4
FOR PART B	.3	.4	.1
AIRCRAFT IN PHASE	1.4	3.0	1.5
AIRCRAFT IDLE	.5	.7	.5

NUMBER OF WORKERS	NUMBER OF DAYS BUSY
10-12	262
7-9	74
4-6	29
0-3	0

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