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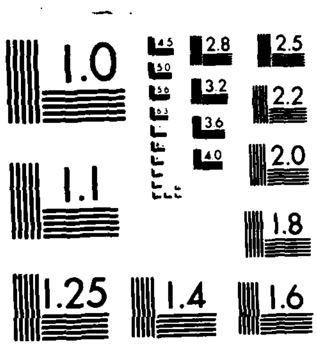

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THESIS

A RETAIL LEVEL INVENTORY MODEL FOR NAVAL AVIATION REPAIRABLE ITEMS

by

Mark Leonard Mitchell

March, 1983

Thesis Advisor: F. Russell Richards

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The inventory model used by the U. S. Navy for aviation repairable items was analyzed and found to be deficient in two major areas. The method in which input data is used is found to be overly conservative. The underlying theoretical model was identified as an M/M/oo queueing model. The assumption of unlimited repair capacity in this model is not valid for application to Navy maintenance activities.

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Simulation with data obtained from the USS RANGER 1983 deployment supports the contention that the proposed model does a superior job of estimating inventory requirements.

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A Retail Level Inventory Model
for
Naval Aviation Repairable Items

by

Mark Leonard Mitchell
Lieutenant Commander, Supply Corps, United States Navy
B.S., Massachusetts Institute of Technology, 1972

Submitted in partial fulfillment of the
requirements for the degree of

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March, 1983

Author: Mark Leonard Mitchell

Approved by: F. R. Richards
Thesis Advisor

Alan W. McMasters
Second Reader

K. T. Washburn
Chairman, Department of Operations Research

K. T. Marshall
Dean of Information and Policy Sciences

ABSTRACT

The inventory model used by the U. S. Navy for aviation repairable items was analyzed and found to be deficient in two major areas. The method in which input data is used is found to be overly conservative. The underlying theoretical model was identified as an $M/M/\infty$ queueing model. The assumption of unlimited repair capacity in this model is not valid for application to Navy maintenance activities.

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Simulation with data obtained from the USS RANGER 1983 deployment supports the contention that the proposed model does a superior job of estimating inventory requirements.

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A. SUPPORTING NAVAL AVIATION AT THE RETAIL LEVEL

1. Repairable Items are the Key to Success

Twenty four hours a day, in most corners of the world, aircraft of the United States Navy are being launched and recovered as they undertake their missions in support of national objectives. The effective accomplishment of each mission is dependent upon having sufficient numbers of aircraft ready to fly and to perform at their fullest capability. To support this goal, the Navy has built an extensive system of maintenance facilities and supply points. Their only purpose is to ensure that the readiness of the Naval Air Force is kept high.

The key concept in minimizing the downtime of degraded aircraft is the philosophy of "remove and replace". This program is designed to maximize the availability of aircraft by quickly identifying any malfunctioning unit, removing it, and rapidly installing another unit that has been positioned at the support base for that purpose. The malfunctioning unit may then be disposed of or repaired, as appropriate.

As technology has advanced, the level of complexity (and the associated cost) of the avionics and weapon systems has been increased. This has led system planners and designers to the decision to repair as much of each unit as can possibly be done, and to support this repair at the maintenance organization closest to the operating site.

The repair of the repairable malfunctioning units (henceforth called "NRFI repairables", meaning "not ready for issue" repairable units) becomes a critical task.

identifying the fault, fixing or replacing subunits, and certifying the item RFI (ready for issue) before it is needed to replace an item on another aircraft becomes a challenging logistics task. If the repair takes too long, or if parts needed to repair it are not available, the next failure on an aircraft may cause the entire aircraft to be left in a degraded mode, and the capability to perform a mission may be denied. Providing an adequate support system for repairing the NRFI repairables, and for maintaining sufficient RFI inventories to meet expected demands, is the key to mission readiness.

2. Surges, Cycles, and Forecasting

The system today has some significant problem areas that periodically cause concern at various levels of management. Each ship and air station supporting Naval Aviation has experienced situations in which the available support has seemed inadequate. These periods may be characterized by the occurrence of many inventory shortages and backed-up repair lines. Fleet exercises, sudden unanticipated commitments, or new surveillance targets have all caused increased demand that seems to strain the system to the limit. As the duration of this heavy demand period lengthens, more extraordinary measures are undertaken: cannibalization of downed aircraft and of NRFI items becomes necessary, and extra quantities of critical items are demanded from other support activities. It becomes extremely distressing to those in command when this situation exists, especially when they realize that the new mission, exercise, or task at hand may be a close realization to the level of commitment required by the operating forces if they had to mobilize for a war.

The inventory level and repair capability is supposedly designed to support full mobilization operations. The shortcomings displayed when actually required to approach that operational tempo are cause for serious concern. The inability to anticipate demand, and to adequately provide a system to meet this demand, exists to some extent in any military logistics system. Failures are random, and the ability to forecast accurately is the subject of considerable research. However, the surge problem is not one of predicting failures for any given item, but rather of anticipating increased demand across the entire inventory, and thereby providing enough maintenance capacity (with associated sub-units and piece parts) or an expanded inventory so that the aircraft can be kept flying and the missions fulfilled for the duration of the heavy demand period.

B. HOW MUCH INVENTORY?

1. Repairable Inventory System Objectives

As the current system has evolved, management of the repair facilities and the supporting supply points has become increasingly more complex. Costs of inventories, test facilities, technical documentation, and the training and retention of maintenance personnel have all been growing with the costs of the systems to be supported. Each of these areas has to compete with each other and with other programs for funding in a scarce resource environment. It is absolutely vital then that planners and analysts be able to make tradeoff decisions between the various logistic elements requiring funds and to build the overall system to provide the needed support at the lowest cost.

Analysis techniques for evaluating level of repair [Ref. 1], and logistics support [Ref. 2], have been established by the Department of Defense. In such a planned system estimates must be made of inventory requirements and maintenance capabilities long before the first system is operational in the fleet. Significant problems can arise, however, if the planning assumptions for funding or manpower are incorrect, or if the operators of the system are ignorant of the planning and do things their own way. Both of these situations affect the current method for maintaining the repairables inventories so vital to mission success.

The current procedures used for establishing the allowances of repairable items to be stocked at a given support site do not consider the capacity or configuration of the maintenance activity, the levels of sub-components and piece parts being stocked, or any cost-tradeoff plan for determining what is the best mix for adequate support. Despite these shortcomings, the existing system has been made to work through the dedicated efforts of many supply and maintenance personnel, both military and civilian. These personnel have had to cope with periodic severe material shortages, extraordinary expediting, and numerous stopgap measures in order to provide support. It is mandatory that those who design the system recognize the shortcomings and work towards improvement. Just such an effort has been underway for the last five years.

2. RIMSTOP

In 1974, the then Deputy Secretary of Defense, W. P. Clements, directed that a study be undertaken to examine the stockage policies that had evolved within the various services and the Defense Supply Agency. That study was issued in 1976 and became known as RIMSTOP, an acronym for the DOD Retail Inventory Management and Stockage Policy. Its purpose was to examine the way that retail level support was actually being provided by the military services, and to attempt to set some overall guidelines that should be followed for these inventories. Out of RIMSTOP came specific policy guidance in the form of DOD Directive 4140.44, and DOD Instructions 4140.45 (for consumable items) and 4140.46 (repairable items). Some of the recommendations for repairable inventories, as listed in DODI 4140.46 [Ref. 3], were:

> Levels of reparable items shall be determined as a function of maintenance replacements and shall be tailored to individual item characteristics related to conditions existing at the individual intermediate level supply point....
>
> The following levels will be computed for each reparable item to be stocked at the intermediate level on a demand-supported basis:
>
> (1) Repair Cycle Level (RCL)
>
> (2) Order and Shipping Time Level (OSTL)
>
> (3) Safety Level (SL). The SL is a function of the probabilities that the repair cycle time will be exceeded, the order and shipping time will be exceeded, the maintenance replacement rate will be higher than forecasted, and a number of maintenance replacements, anticipated for repair at the activity, will require resupply from external sources. The SL considers the degree of risk of stockout and is computed as
>
> $$SL = t \times s(RLD),$$
>
> where: t = safety level parameter
>
> $s(RLD)$ = Standard deviation of maintenance replacement during the leadtime which is the weighted average of RCT (repair cycle time) and OST (order and shipping time).
>
> The safety level parameter t will be selected by the DoD Component concerned, and may not exceed three standard deviations of maintenance replacement during leadtime.
>
> (4) Operation Level (OL)
>
> (5) Replenishment

The Navy has used this guidance as a springboard for examining current inventory support procedures and has been successful in obtaining funding through the Program Objectives Memorandum (POM) process for initiatives based upon this review. The basic approach, however, has been to put additional band-aids on the current system in attempts to make it work better, rather than starting over from scratch to try to develop a system that will do a better job of estimating the system needs. The purpose of this thesis was to take the latter approach, searching for a better method to do the job.

A number of areas of investigation are explored in this thesis. The current model for computing inventory levels assumes that there will not be any capacity constraint. An alternate model is proposed to attempt to explicitly deal with capacity constraints. The current system uses only a small number of data elements available in the aviation 3-M data collection system, and what it is allowed to use is censored rather severely. The effects of censoring such data is examined, and the use of other available data elements is explored.

The following sequence will be used in presenting the analysis in the rest of the thesis. Chapter II discusses the present system and the underlying model at some depth and analyzes the theoretical assumptions of the model. Chapter III proposes an alternate model. Chapter IV compares the existing and proposed models, and includes some examples of how they behave. Chapter V presents a simulation using real data obtained from the USS RANGER (CV-61). Chapter VI provides a summary of results, conclusions, and recommendations for continued research.

II. THE CURRENT MODEL

A. ALLOWANCE DETERMINATION

Allowances of material to be stocked at any given aviation support point are largely determined through a process called AVCAL (Aviation Consolidated Allowance List), which is managed by the Navy Aviation Supply Office (ASO), Philadelphia, Pennsylvania. The process of generating a complete AVCAL is quite complex, but the basic underlying model used for repairable items is fairly straightforward.

1. Forecasting Usage

First, all available maintenance and supply data on repairable usage for the previous support period are gathered. This data may come from a variety of sources. In the case of an aircraft carrier, for example, analysis will include gathering and comparing data from the Aviation 3-M data base (maintained by the Navy Maintenance Support Office (NAMSO), Mechanicsburg, Pennsylvania), supply usage data provided by the ship, and usage rates that have been developed for specific items as the result of various logistic conferences. Once this data has been accumulated and validated, it is converted into aggregate usage rates by dividing total demand by the total number of flying hours that generated the demand. These rates are then used to forecast demand for the next support period by multiplying them by the total number of flying hours that WSPD's (Weapon System Planning Documents) call for. Separate forecasts are generated by this process for the expected number of successful repairs (Equation 2.1) and for actions where repair has been declared beyond the capability of the local maintenance activity (BCM) (Equation 2.2).[1]

Let

- NR = actual number of successfully repaired units, from the reporting period data base;
- NB = actual number of units declared BCM, from the reporting period data base;
- FH = flying hours accomplished during the reporting period;
- FH' = flying hours forecast for a future support period;
- NR' = repair forecast, in number of units; and
- NB' = BCM forecast, in number of units.

Then

$$NR' = NR \cdot \frac{FH'}{FH}\,, \tag{2.1}$$

and

$$NB' = NB \cdot \frac{FH'}{FH}\,. \tag{2.2}$$

----

[1]Variable notation will use the following format: "N " will indicate a count of some action; for example, "NR" is the count of the number of repairs during an interval. "P " is the expected number in a process (also called the expected pipeline quantity); "PR" is the expected number of units in the repair pipeline. "Q " indicates an allowance quantity that provides an appropriate degree of safety level protection to a process: "QR" is the protected quantity computed by an inventory model to support a specified repair pipeline quantity at a given safety level. "N " and "P " variables super-scripted with a prime (') indicate that the variable represents a forecast, rather than an observation.

2. Repair Turnaround Time

In the case of repairs, additional data is gathered on the average length of time that an item is in the repair cycle. This is also done through the use of the 3-M data base, with data elements collected as shown in Figure 2.1 . Data for each of these is taken from the Aviation 3-M Visual Information Display System/Maintenance Action Form (VIDS/MAF), the basic source document for most aviation maintenance data reporting. All of the time data for measuring the repair cycle turnaround time (TAT) is collected as an integer number of days, simply by noting the difference in julian dates between key events in the repair process. Total TAT for each repair action is simply the sum of the four element times. Each of the four TAT element limits is applied to each repair action in the data base; the limit for total TAT is applied against the average TAT for all actions of a given item.[2]

At this point, a few observations about this process are appropriate. In order to develop an effective inventory system, it would seem necessary to measure the period of time between the removal of an RFI item from inventory, and the receipt of a replacement. By using the times from the repair cycle, two important assumptions are being made. First, it is assumed that the removal of the NRFI unit from an aircraft occurs on the same date that the RFI unit is issued. This may be generally true when the supported customer and the supporting supply department are located near each other, and when they adhere to the stated philosophy of "one-for-one" exchange. There are, however, many

----

[2]Procedural guidance provided to the operating forces refers to the TAT limits as "constraints". The limits are not constraints in the technical sense. They are truncation values that are applied so that any TAT element observation greater than the specified limit is reduced to that limit before being used for allowance computation.

A. Key events in the repair process are as follow:

D1 : Date of removal of the NRFI unit from the aircraft.

D2 : Date of receipt of the NRFI unit at the IMA (intermediate maintenance activity).

D3 : Work start date at the IMA work center.

DA1: Date work stops because unit must await the arrival of material before completion of the repair. Unit is declared to be in "awaiting parts" (AWP) status.

DA2: Date unit clears AWP (material received).

D4 : Repair completion date.

B. The repair turnaround time elements are defined by the above dates in the following manner:

TAT element	From date	To date
IP : In-process time	D1	D2
SKD: Scheduling time	D2	D3
RPR: Repair time	D3	D4
less AWP time	DA1	DA2
AWP: Awaiting parts time	DA1	DA2

NOTE: Although AWP time is shown above as being defined by dates DA1 and DA2, in reality a unit may go AWP a number of times; in that event, total AWP time for a unit is computed by summing the times reported for each occurrence of AWP status.

C. Data collected through the aviation 3-M system is limited to a maximum value as follows:

TAT element	Limit (days)
IP : In-process time	1
SKD: Scheduling time	3
RPR: Repair time	8
AWP: Awaiting Parts time	20
TAT: Total time	20 (unit average)

Figure 2.1 Repair Turnaround Time Elements.

instances where this assumption is not valid. Supply departments are frequently called upon for off-station support in which they may be required to send material to activities hundreds or thousands of miles away. In these cases, the removal date and the issue date may be very different, depending on the situation. Additionally, there are classes of items for which the "one-for-one" exchange principle is waived because of the nature of the repair to be undertaken. For example, remain-in-place (RIP) items are specifically exempted.

The second implicit assumption is that a unit will be available from inventory as soon as it is made RFI. Again, this may be valid for many items, but the administrative process of identifying the item to a national stock number, updating records, and storing the unit is not automatic. Unfortunately, the data base does not include these supply times, and the exact extent of the effect is unknown. However, it is fair to assume that the period measured by the repair cycle is a conservative estimate for actual off-the-shelf time experienced by the supply activity.

Existing policy provides that turnaround time elements for every repair action and for every repairable item be compared to limits, or maximum allowable values, before being considered in the allowance determination process. The use of these limits presents a different problem in the development of an effective inventory.

The limits currently in use were shown in Figure 2.1 and were developed at ASO in a study conducted in 1977 [Ref. 4]. In that study, TAT data for a small group of items were collected. The TAT elements were assumed independent, so each element was analyzed separately. An input data censor, or limit, was determined at approximately the ninetieth percentile of the cumulative distribution function for the data element times. The times given in Figure 2.1 were the results.

The reason for the use of limits is not provided in available instructions or other documentation. However, there have been two informal reasons provided in discussions with senior personnel. First, that it is necessary to protect against erroneous values entering the data base and significantly increasing average the TAT. This is a legitimate concern with the 3-M system. The other reason is to "not reward the bad actors". Lack of proper management of aviation repairables could conceivably cause lengthened TAT's, and consequently larger allowances. To what extent the current limits prevent this is unknown.

In either case, however, it is reasonable to question the validity of the current limits as applied to all items. One problem is that intermediate maintenance activities (IMAs) routinely repair items as diverse as engines, avionics, rotor blades, airframes, and instruments. By taking only a small sample of items, and by lumping the data together, it is possible that there are classes of items or certain types of repair processes that are more restricted by the limits than are others.

Even if we accept the premise that all items have the same universal mean TAT, there is another way in which these limits inhibit proper support. If the underlying distribution of each TAT element is exponential, acceptance of only the bottom ninety percent of the data has the effect of reducing the mean to 90% of its original value. This point can be easily shown. Let S be the level of data accepted (e.g., 0.90). Then solve for the value T that will provide that level using:

$$S = \int_0^T \lambda e^{-\lambda y}\, dy ,$$

$$= 1 - e^{-\lambda T} .$$

Solving for T gives:

$$T = -\frac{1}{\lambda} \ln(1-s).$$

Next, find the mean of the distribution that is censored at point T as follows:

$$\mu = \int_0^T \lambda y \, e^{-\lambda y} \, dy + (1-s)T;$$

which solves as:

$$\mu = \frac{1}{\lambda}\left[1 - (1+\lambda T)e^{-\lambda T}\right] + (1-s)T.$$

Substituting:

$$e^{-\lambda T} = 1-s,$$

$$1+\lambda T = 1 - \ln(1-s), \text{ and}$$

$$(1-s)T = -\frac{1}{\lambda}(1-s)\ln(1-s),$$

yields:

$$\mu = \frac{1}{\lambda}\left[1-(1-s)(1-\ln(1-s))\right] - (1-s)\ln(1-s),$$

$$\mu = \frac{1}{\lambda}s;$$

and the proportion of the original mean ($1/\lambda$) represented by μ is:

$$\frac{\mu}{1/\lambda} = s.$$

Setting the TAT limits at the 90th percentile has the effect of only accepting data within 1.3 standard deviations of the true mean of the underlying distribution. (The 90th percentile of an exponential distribution occurs at a value approximately 2.3 times the mean, or 1.3 standard deviations greater than the mean, since the mean and standard deviation are the same.)

The RIMSTOP repairable instruction, [Ref. 3], specified that the repair cycle time could be protected at a level no greater than <u>three</u> standard deviations, which would be a little higher than the 98th percentile. It is impossible to do this if the TAT observations for the underlying process are limited using the current values. Again, the current system of developing allowances uses a deliberately conservative approach.

3. Current Range Rules

Various range rules are in use to determine if any allowance for an item is justified. Table I provides these

TABLE I

Existing Allowance Model Range Rules

A. Local Repair Cycle Requirement (LRCR)

To qualify for an LRCR allowance, an item must have a forecast for the expected number of units in the repair cycle of at least 0.111. This translates to a minimum of two repairs per year taking the maximum of twenty days average TAT, or any other combination of repairs x average TAT equal to or greater than 40 days/year (3.33 days/month).

B. Attrition allowance

To qualify for an attrition allowance, an item must satisfy one of the following:

LRCR quantity authorized	Unit price	Minimum forecast BCM rate
Yes	All	1 per 3 months (.333/month)
No	> $5000	1 per 6 months (.167/month)
No	< $5000	1 per 9 months (.111/month)

rules, which are published by ASO [Ref. 5]. Some of the more astute operators in the field have pointed out that these range rules are not always consistent with good support. It has been noted that it is to a customer's advantage to ensure that a moderate demand repairable with low TAT has at least two BCM's during a year in order to assure that an allowance of at least one is maintained at the station. Alternately, it might be to their advantage to lengthen the TAT in some way, again to ensure that an allowance of one is justified. A zero allowance forces every failure to become a situation degrading an aircraft; increased support is provided if an item satisfies the range rule.

B. MODELS USING THE POISSON DISTRIBUTION

1. The Current Model

The following procedure is used for determining the final allowance quantity, given validated input data.

a) A forecast for the expected number of units in the repair cycle at any given time is computed using the forecast from Equation 2.1 as follows:

let

t' = length of forecast period;

NR' = total forecast repairs over $(0,t')$;

TAT = average experienced turnaround time (after limits applied); and

PR' = forecast number of units in the repair pipeline.

Then:

$$PR' = NR' \cdot \frac{TAT}{t'} \tag{2.3}$$

b) This quantity is used as the parameter in a Poisson distribution to find the number of units (QR) that need be stocked so that the CDF of the distribution at QR is closest to the policy safety level (currently set as 0.90).

1) Find the smallest Qu that satisfies:

$$0.90 < \sum_{i=0}^{Q_u} e^{-(PR')} \cdot \frac{(PR')^i}{i!} \qquad (2.4)$$

2) Let Ql = Qu - 1

3) Compute the protection level afforded by Ql and Qu.

4) If the protection level at Ql is closer to 0.90 than that at Qu, let QR = Ql; otherwise, QR = Qu.

c) A quantity of one is then added to QR for operating level (OL), and this becomes the LRCR:

LRCR = QR + 1.

d) Separately, a quantity of material to support expected attritions from the repair cycle (BCM's) is computed. This quantity is determined using the BCM forecast for the endurance period (t') from Equation 2.2 (Rounding for all allowances is at the 0.5 level, except for the first unit added in accordance with the range rules.)

Attrition quantity = NB'.

e) The attrition quantity is added to the LRCR quantity to provide the final allowance:

Allowance = LRCR + NB'.

2. The RIMAIR Pipeline Model

As previously indicated, RIMSTOP provided an impetus for examining the existing repairable model, and a number of deficiencies were found. It was recognized that the quantity provided as an attrition allowance, which was theoretically provided to support wartime mobilization operations with resupply delayed or cut off, was in fact supporting the number of items in the wholesale resupply pipeline during normal operations. Additionally, the attrition allowance was being computed deterministically. Consequently, efforts were made starting in 1978 to obtain funding through the POM process; first, to support the number of items actually in the wholesale resupply pipeline so that the endurance level would not be drawn down, and secondly to provide protection to this wholesale pipeline to account for the stochastic nature both of the failures which cause the BCM's, and of the resupply time itself. These efforts to obtain funding coincided with the development of a model to be used in computing allowances under the RIMSTOP guidelines. This model is called the RIMAIR pipeline model.

The RIMAIR pipeline model attempts to alleviate some of the shortcomings recognized in the previous model. It includes the addition of stock to the attrition portion of the allowance to support the expected order and shipping time experienced during peacetime, and the addition of a wholesale resupply pipeline to the repair cycle pipeline for the purpose of providing Poisson protection to the entire pipeline. Investigations into the use of variable range and depth techniques for providing better overall performance for the dollars invested in inventory are also being pursued. As of March 1983, however, none of the RIMAIR additives have actually been added to any activity's AVCAL, and only the attrition portion additives have been approved and funded. Significantly, however, the basic model, with the established limits on TAT observations and the use of the Poisson distribution for the computation of the safety level, has not been changed.

The computations involved with the RIMAIR pipeline model are more complicated than with the current model because of the way that the wartime mobilization requirement is computed. Shortly after the RIMSTOP instructions were published, DoD provided additional guidance on the computation of that mobilization requirement in the form of DODINST 4140.47, [Ref. 6]. The actual pipeline model developed at NAVSUP took this into account, and consequently became considerably more difficult to deal with. For the purpose of this thesis, however, it is the underlying repair process model that is being examined, and the complications of the mobilization additive will be ignored. A greatly simplified pipeline model results, which can be explained as follows.

a) Compute the expected repair pipeline quantity (PR') as in Equation 2.3 above:

$$PR' = NR' \times \frac{TAT}{t'}.$$

b) Compute the forecast wholesale resupply pipeline (PB') as follows:

let

WTAT = expected wholesale resupply time;

then

$$PB' = NB' \times \frac{WTAT}{t'}.$$

c) Define the total forecast pipeline quantity (P') as the sum of these,

$$P' = PR' + PB'.$$

d) Compute the protected pipeline quantity by using P' in Equation 2.4 above. Find the quantity QP that provides protection closest to 0.90.

e) The final allowance (QT) is the quantity QP plus one for operating level (OL), plus any additives that may be allowed for wartime mobilization (QM):

$$QT = QP + OL + QM.$$

This model has explicitly allowed for the wholesale resupply cycle, and provides protection to the entire pipeline, not just to the repair pipeline. Funding to support the allowances that it provides should greatly enhance fleet support.

3. Example Allowances

a. The Current Model

The following example is provided to illustrated how the current system works, followed by the changes made as a result of using the RIMAIR pipeline methodology.

1) Input data is collected, and the following data is provided for a three month period (parentheses indicate the value used after the TAT limits are applied):

TAT element data, in days

BCMs:	IP	SKD	RPR	AWP	TAT
BCM 1	0	1	1	-	2
BCM 2	0	0	1	-	1
BCM 3	1	1	7	10	19
Repairs:					
Repair 1	0	0	1	-	1
Repair 2	1	0	7	31 (20)	39 (28)
Repair 3	0	2	3	-	5
Repair 4	0	0	0	-	0
Repair 5	1	1	1	-	3
Repair 6	1	2	1	-	4
Repair 7	4 (1)	0	9 (8)	24 (20)	37 (29)
Repair 8	0	5 (3)	0	-	5 (3)
Repair 9	1	1	0	-	2
Repair 10	0	3	2	3	8
Averages:					
Raw	0.8	1.4	2.4	5.8	10.4
Limited	0.5	1.2	2.3	4.3	8.3

Notes: a) Table entries are the number of days reported for the corresponding TAT element and specified action.

b) Averages are based upon repairs only.

c) Dash marks for AWP column mean AWP status did not occur, as opposed to an item going into and out of AWP status the same day.

2) In addition, the following data is provided:

a) Wholesale system resupply time (WTAT) is 26 days.

b) Total flying hours (FH) were 1453 hours.

c) Endurance period (t') is 60 days.

d) Program flying hours are 850/month, therefore FH' is 1700 hours.

3) Compute the LRCR as follows:

$$NR' = NR \times (FH'/FH),$$
$$= 10 \times (1700/1453),$$
$$= 11.7 \text{ units.}$$

$$PR' = NR' \times TAT/t',$$
$$= 11.7 \times 8.3/60,$$
$$= 1.62 \text{ units.}$$

Poisson probabilities for a mean of 1.62 are:

n	f(n)	F(n)
0	0.1979	0.1979
1	0.3206	0.5185
2	0.2597	0.7782
3	0.1402	0.9184*
4	0.0568	0.9752
5	0.0184	0.9936
6	0.0050	0.9986

* n = 3 provides protection closest to 0.90.

Therefore

$$QP = 3 \text{ units; and}$$

$$LRCR = QP + 1,$$
$$= 4 \text{ units.}$$

4) The attrition allowance is computed as follows:

$$NB' = NB \times (FH'/FH),$$
$$= 3 \times (1700/1453),$$
$$= 3.51,$$
$$= 4 \text{ units.}$$

5) The final allowance (QT) is:

$$QT = LRCR + NB',$$
$$= 4 + 4,$$
$$= 8 \text{ units.}$$

b. The RIMAIR Pipeline Model

The procedure presented above is modified when the RIMAIR pipeline model is used. Poisson protection is applied to the attrition pipeline as well as to the repair pipeline. The RIMAIR model procedure is as follows:

1) Collect and limit the input data as in steps a.1. and a.2. above.

2) Compute the repair pipeline (PR') as it was done in step a.3,

$$PR' = 1.62 \text{ units.}$$

3) The number of items expected to be in the wholesale pipeline (PB') are computed as follows, using the BCM forecast developed in step a.4:

$$NB' = 3.51 \text{ units;}$$

$$\begin{aligned} PB' &= NB' \times WTAT/t', \\ &= 3.51 \times 26.0/60, \\ &= 1.52 \text{ units.} \end{aligned}$$

4) Total pipeline allowance (P') is:

$$\begin{aligned} P' &= PR' + PB', \\ &= 1.62 + 1.52, \\ &= 3.14 \text{ units.} \end{aligned}$$

Poisson probabilities for a mean of 3.14 are:

n	f(n)	F(n)
0	0.0433	0.0433
1	0.1359	0.1792
2	0.2134	0.3926
3	0.2233	0.6159
4	0.1753	0.7912
5	0.1101	0.9013*
6	0.0576	0.9589
7	0.0258	0.9848
8	0.0101	0.9949

* n = 5 provides protection closest to 0.90.

Therefore

$$QP = 5 \text{ units.}$$

5) The final allowance (QT) is obtained as follows:

$$\begin{aligned} QT &= QP + OL + QM, \\ &= 5 + 1 + QM, \\ &= 6 + QM \text{ units.} \end{aligned}$$

It can readily be seen that this computation is in agreement with the RIMSTOP guidelines for retail inventory levels quoted in Chapter I. The various levels are equated in Table II For the purpose of this thesis, it will be assumed that any mobilization endurance quantity provided will be the same regardless of whether the underlying peacetime model based on the current Poisson approach is used, or whether the model proposed in Chapter III is adopted. Consequently, Qe shall be assumed to be zero, and will not be discussed further.

TABLE II

Existing vs. RIMAIR Model Allowance Levels

RIMSTOP (1) Level	Model Variable	Quantity computed Existing	Quantity computed RIMAIR
Repair cycle	PR'	1.62	1.62
Order and shipping time	PB'	0.0	1.52
Total pipeline	P'	1.62	3.14
Safety	QP - P'	2.38	1.86
Operating	CL	1.00	1.00
Replenishment	(2)	(2)	(2)
Endurance (1)	NB'	3.00	-
Mobilization (1)	QM	-	QM (3)
Total	QT	8 units	6+QM units

NOTES:

(1) Mobilization / endurance levels are addressed in DODI 4140.47 vice the RIMSTOP instructions.

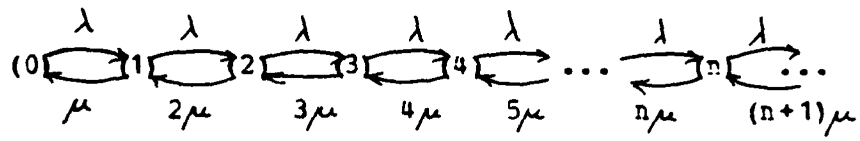
(2) NAVSUP has successfully defended the "one-for-one" principle as the rule for replenishing repairables from the wholesale system. This establishes the replenishment quantity as one less than the allowance in all cases.

(3) Although documentation for the computation of the mobilization quantity is not available, it is understood that the final RIMAIR allowance will not be any less than the current allowance, and will be higher in many cases.

C. THEORETICAL BASIS FOR THE EXISTING MODELS

1. A Queueing System Model

No justification for use of the Poisson distribution is provided in the literature available on the current system. However, a model presented in elementary queueing theory provides exactly the structure that is used in the existing model, and this will be presented here as a basis for comparison to the proposed model. This model is for the $M/M/\infty$ queue.



Parameter	Name	Assumptions
λ	Arrival rate	Independent arrivals Constant rate Exponential interarrival times
μ	Service rate (repair rate)	Exponential service times, identical for each server Each service is independent
ρ	Traffic rate	$\rho = \lambda/\mu$
P	Mean number in system (pipeline)	$P = \rho$
T	Mean time in system	$T = P/\lambda = 1/\mu$
W	Mean waiting time	$W = 0$ (By specification, there are enough servers to serve each unit as it enters.)
$\pi(n)$	Probability of being in state n	$\pi(n) = \dfrac{e^{-\rho}\rho^n}{n!}$

Figure 2.2 $M/M/\infty$ Queue Characteristics.

The M/M/∞ queueing model assumes that the number of demands in an interval is Poisson, repair times are exponential, and that there are "infinitely many" servers. In practical terms, the specification for infinitely many servers may be assumed to be the same as saying that the expected waiting time for any item entering the system is zero. Consequently, the physical queue may display characteristics similar to that of an M/M/∞ system even if there is only one server when the probability of having two units in the system at the same time is effectively zero.

The state diagram at the top of Figure 2.2 provides the basic characteristics that will be used to compare the M/M/∞ model with a model to be proposed in Chapter III. (The current model and the RIMAIR pipeline model both use the Poisson distribution in computing allowances, so the discussion of the assumptions that its use implies apply to both.) Given the state diagram, it is easy to determine the probability of being in any given state, n, as follows:

$$\lambda \pi(0) = \mu \pi(1),$$

so

$$\pi(1) = \lambda/\mu \, \pi(0),$$

$$\pi(1) = \rho \, \pi(0);$$

$$(\lambda+\mu)\pi(1) = \lambda \pi(0) + 2\mu \pi(2),$$

so

$$\pi(2) = \frac{\lambda}{2\mu} \pi(1),$$

$$\pi(2) = \frac{1}{2} \rho \, \pi(1),$$

$$\pi(2) = \frac{1}{2} \rho^2 \pi(0);$$

and in general,

$$(\lambda + n\mu)\, \pi(n) = \lambda\, \pi(n-1) + (n+1)\mu\, \pi(n+1),$$

so

$$\pi(n+1) = \frac{1}{n+1}\, \rho \cdot \pi(n),$$

$$\pi(n+1) = \frac{1}{(n+1)!}\, \rho^{n+1}\, \pi(0).$$

With the requirement that all state probabilities must sum to one,

$$\sum_{i=0}^{\infty} \pi(i) = 1;$$

the state probabilities are than determined to be:

$$\pi(0) = e^{-\rho};$$

and for n>0,

$$\pi(n) = e^{-\rho}\, \frac{\rho^n}{n!}. \qquad (2.5)$$

The mean number in the system, average queue length, expected time in system and other system parameters can be derived this result and from Little's formula ($P = \lambda T$). Any book that includes elementary queueing models, such as Kleinrock [Ref. 7], Ross [Ref. 8], or Turban and Meredith [Ref. 9], provide these relationships, and they are listed in Figure 2.2 .

An inventory model that has the characteristics listed in Figure 2.2 would use Equation 2.4 in solving for QP. In application, as indicated before, the existing system computes the quantity QP that provides protection closest to the desired level, then adds one for operating level.

2. Implications of Adequately-many Servers

The Poisson model has a number of very nice features that make it attractive, given that the assumption of adequately many servers is acceptable. First of all, there is only one parameter to the distribution, which makes maintenance of a data base simple. This parameter is the forecast of the expected number of items in the repair pipeline at any given time. This is easily done with the 3-M data base because both the number of items repaired during any given period and their average turnaround time are readily available. Additionally, expanding the size of the pipeline to include the wholesale resupply pipeline is accomplished simply by adding the two pipeline quantities.

Another nice feature is that saturation of the queue can never occur; by assuming that there are always adequately many servers, demand can never cause backups or waiting times. Forecasts for increased demand periods (wartime mobilization) are done simply by multiplying the expected number in the system by an appropriate constant. Because saturation never occurs, there is always a finite steady-state solution available. This is not the case with a limited-server queueing model.

III. A PROPOSED MODEL

A. PRELIMINARY RESEARCH

The preliminary work for the proposed model was accomplished at the Naval Postgraduate School, Monterey, California as a class project for a course on Stochastic Models given by Prof. Paul Milch. The results provided in that study, [Ref. 10], are presented here because they provided a major step in the development of the proposed model.

The study was done from July to September 1982 using a data base obtained from NAMSO (Navy Maintenance Support Office, Mechanicsburg, PA) of data collected throughout the Navy from January through March 1982. Due to the nature of the data base, it had already been processed using the TAT constraints listed in Figure 2.1. Because the entire data base included over 300,000 records, the study was done on selected classes of repair actions and equipments in order to keep it to a manageable size. The equipments chosen were radar navigation units repaired ashore (2055 records), radar navigation units repaired afloat (587), and helo rotor systems repaired ashore (187). Despite the wide disparity in these three classes, the results were extremely similar.

One of the major findings of the study was that times reported for the repair and awaiting parts processes were not independent. It was noted that longer repair (RPR) times tended to be associated with significant awaiting parts (AWP) time, and the maintenance actions with short RPR time generally had no AWP time. This was expected because experience at Navy repair facilities had shown that repairs are not homogeneous; some types of in-depth repair tend to take more time for fault isolation, require more parts, and take longer for checkout than others in which an adjustment or the replacement of a gasket is all that is required.

A second key finding was that times associated with the TAT elements were not all distributed in an exponential manner. The distribution for the RPR and AWP TAT elements were generally too exaggerated to be exponential; any exponential fit to the low end of the distribution failed to account for the large number of data points in the tail. Conversely, any distribution fit to the tail came far short of including the large number of observations with TATs of zero or one day.

The dependence of the RPR and AWP times lead to the establishment of a new variable for repair cycle time. Its distribution had the same general shape as the RPR and AWP distributions, but on inspection it appeared to decompose into two exponential distributions with different means. This fostered the concept of treating the repair cycle as two parallel repair processes, one in which the repair rate was very fast (on the order of one day), and the other in which the repair process took ten to twenty times longer.

The last key result of the early project was the idea of modelling the repair queue with a capacity constraint. This was not explicitly brought out through analysis of the data, but rather was considered because experience with Navy repair activities has provided many examples of instances in which capacity was limited, forcing inducted material to wait for a technician or test bench. This situation has been addressed more formally in the recently concluded RAND CABAL study, [Ref. 11], which is quoted in part.

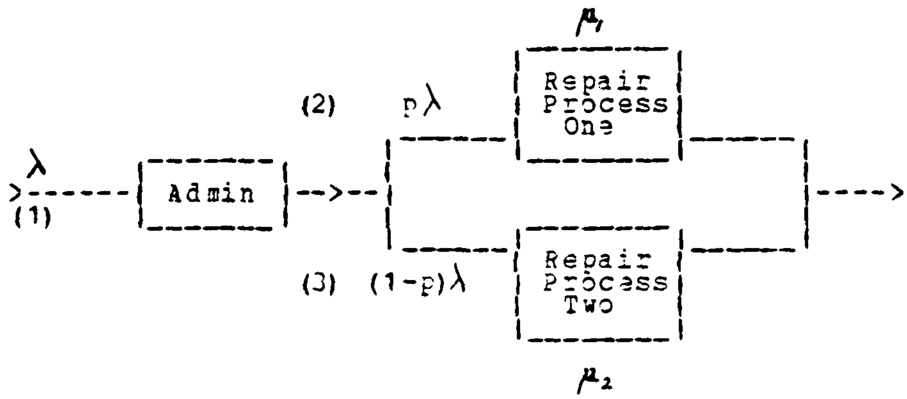
> With the exception of VAST (Versatile Avionics Shop Test), loading on the most highly used piece of equipment in each avionics shop rarely exceeded 60 percent. This means that, given full operational availability, most shops have sufficient wartime capacity. VAST, on the other hand, showed a wartime utilization rate of 160

percent -- the wartime workloads exceeded VAST capacity by 60 percent.

> Under a sustained wartime scenario with all aircraft flying continuously at programmed rates, the backlog for VAST continues to grow. The important issue is what impact this growing backlog will have on aircraft availability. A number of factors tend to partially alleviate the impact over a limited time horizon. The on board stock of spare parts will be consumed as the backlog grows, so backlog does not directly equate to holes in aircraft (or backorders against supply). To the extent that backorders can be consolidated on the fewest number of aircraft through the cannibalization of components, the impact is further reduced. Finally, priority repair management, which controls the induction of components into the VAST shop based on aircraft needs, will also reduce the impact...
>
> In sum, the present VAST capacity is probably sufficient only for those wartime scenarios where carrier aircraft are required to operate at programmed rates for limited periods of time, followed by periods when the carrier is able to stand down and thus has time to work off the VAST backlog. If, however, the carrier is required to operate its aircraft for longer periods of time when the average flying rate is equal to or exceeds the programmed rates, as the VAST backlog grows aircraft capability will begin to degrade. Priority scheduling for VAST provides only a short-term remedy for the capacity shortfall.

While the RAND people only discuss VAST in terms of inadequate capacity, their study was to some extent a "best case" analysis; the projection for capacity constraints for other test benches was based on complete bench availability, full qualified manning, and adequate piece-part support. Given real-world support shortcomings, there is a chance that non-VAST facilities can also become saturated.

The model developed in the earlier study has been expanded upon in this thesis, and is illustrated in Figure 3.1 in its simplest form. The remainder of this chapter describes the new sample data base, provides validation for the underlying assumptions, presents the theoretical basis for the M/M/1 queue, defines the proposed model in operational terms, and provides an example of how it works.



Description:

(1) All demands enter the system, with rate λ, and go thru administrative processing.

(2) A proportion (p) of these demands enter repair process one, and are served with rate μ_1.

(3) The remaining demands enter process two and are served at rate μ_2.

Figure 3.1 The Proposed Model (Simplified).

B. THE RANGER DATA BASE

The data base used for the study was obtained from NAMSO and consisted of maintenance data, supply system identification, and unconstrained turnaround time measurements extracted from the April-October 1982 WESTPAC-Indian Ocean Deployment of the USS RANGER (CV-61). This data base contains 18,278 records for all material inducted into the IMA aboard RANGER during the cruise.

The model proposed in the earlier study assumed limited repair capacity, unlike the model currently in use or the RIMAIR pipeline model. In order to evaluate the impact of that assumption, moderately fast moving items were analyzed; slow movers offer little hope of discriminating between models even if only a single test facility is available. Consequently, only aviation repairable items that had exhibited twenty or more actions during RANGER's six-month cruise were selected for analysis. There were 79 such items. The following summaries present the basic characteristics of the entire data base, and contrast them with the characteristics of the selected sample. (Appendix A provides more complete statistics on the data.)

1. Supply System Identification

Table III provides the breakdown for the entire RANGER data base and the selected sample for three key supply system identifiers: the cognizance code (cog), the material control code (MCC), and the special material identification code (SMIC). Although the national stock number (NSN) is the prime identifier for any given unit or part, it does not carry much information about what an item is and what it may be used for; the three identifiers listed in the table are usually associated with the NSN in order to convey this information.

Complete descriptions of the codes are provided in the appendices of Naval Supply Systems Command (NAVSUP) P-485 [Ref. 12]. Brief descriptions for the codes listed in the table are as follow:

a) The cognizance code (cog) designates the inventory manager who exercises supply management over specified categories of material [Ref. 12: Appendix 18].

   1) '1R' designates ASO-managed consumable material.

TABLE III

RANGER Data Base Supply Data Summary

Category/ Key values	Number of actions (%) Entire RANGER Data base		Selected Sample	
Cog				
1R: ASO consumable	1149	(6.3)	105	(3.6)
2R: ASO depot-level repairable	8171	(44.7)	1859	(64.5)
8R: ASO depot-level repairable	1132	(6.2)	920	(31.9)
Other	881	(4.8)	0	(0.0)
None	6945	(38.0)	0	(0.0)
TOTAL	18278		2884	
MCC				
D: field-level repairable	1235	(6.8)	105	(3.6)
E: CLAMP repairable	5144	(28.1)	1527	(52.9)
H: Non-CLAMP depot-level repairable	4350	(23.8)	1252	(43.4)
Other	328	(1.8)	0	(0.0)
None	7221	(39.5)	0	(0.0)
TOTAL	18278		2884	
SMIC				
CS: S-3A aircraft	1818	(9.9)	247	(8.6)
CY: AWG-9 radar	994	(5.4)	653	(22.6)
FA: A-6 aircraft	760	(4.2)	156	(5.4)
FE: EA-6B aircraft	750	(4.1)	175	(6.1)
FZ: GFE program	606	(3.3)	242	(8.4)
PF: F-14A aircraft	1186	(6.5)	143	(5.0)
SZ: ASN-92 (CAINS) inertial nav system	454	(2.5)	331	(11.5)
Other	4363	(23.9)	937	(32.5)
None	7347	(40.2)	0	(0.0)
TOTAL	18278		2884	

2) '2R' and '8R' designate ASO-managed repairable material.

3) 'Other' represents a number of other cogs with few relatively few demands each.

b) The material control code (MCC) is designated by the inventory manager to segregate items into manageable groupings [Ref. 12: Appendix 9.F].

1) 'D' designates a field-level repairable.

2) 'E' designates an intensified-management depot-level repairable, managed under the Closed-Loop Aeronautical Material Program (CLAMP).

3) 'H' is a depot-level repairable not otherwise designated.

4) 'Other' represents items with any other MCC assigned.

c) The special material control code (SMIC) is assigned to an item to ensure its technical integrity **[Ref. 12: Appendix 9.L]**. ASO generally assigns SMIC codes for material under their cognizance to identify the weapon system to which the item applies, to identify the function if more than one weapon system is involved, or to identify a special program the item is managed under.

1) 'CS' items apply to the S-3A antisubmarine patrol aircraft.

2) 'CY' applies to the AWG-9 radar system on the F-14A.

3) 'FA' applies to the A-6 attack aircraft.

4) 'FE' applies to the EA-6B electronic warfare aircraft.

5) 'FZ' appies to a special project for government furnished equipment.

6) 'PF' applies to the F-14A fighter aircraft.

7) 'SZ' applies to the ASN-92 (CAINS) Carrier Airborne Inertial Navigation System.

8) 'Other' represents more than forty other SMIC's, each having relatively low demand.

Each of the above codes also had many observations listed as 'none' for the entire RANGER data base. The 38% listed as 'none' for the cog codes indicates that 38% of the manufacturer's parts numbers listed on the VIDS/MAF maintenance data forms could not be matched to any NSN (every NSN in the Navy Supply System has a cog, and vice-versa.) The slightly higher quantities listed as 'none' in the MCC and SMIC categories include these 38% plus some other items for which an NSN and cog were available, but for which that code was not assigned. Some maintenance actions listed as 'none' may reflect actions for non-stock-numbered items, but certainly many are the result of poor data entry procedures.

It is obvious that the sample used for this thesis is not a representative sample, nor was it intended to be. The 79 items in the sample experienced about 16% of the total demand for the RANGER deployment, yet the 920 '8R' actions, for example, represent more than 31% of the 8R actions in the data base. Only maintenance actions matched to NSN's are included in the sample, however; it is likely that the RANGER data base includes data for items used in the sample, but which were not credited to the correct stock number because of data input problems. One missed digit in the long part number block will cause a mismatch to occur.

During development of the proposed model, many decisions were made with the idea that the model might actually be applied in real-world situations. Choices available at decision points were considered in accordance with the degree of simplicity and practicality that they offered. Thus, analysis was restricted to 1R D, 2R, and 8R cognizance material because it is for these categories of material that the current model is used, and to which the RIMAIR model should be applied.

2. Data Base TAT Characteristics

Turnaround time analysis is at the heart of the inventory modelling problem, and it is important to recognize the structure within which the TAT elements are reported. As stated briefly in Chapter II, TAT and the elements that make it up (IP, SKD, RPR, AWP) are reported into the data collection system indirectly by use of the VIDS/MAF source document; the values for the various TAT elements are computed by NAMSO based upon the dates that various key events in the maintenance cycle occur, as recorded in Figure 2.1.

There is an important limitation inherent in this system. Quick actions, in which two or more of the events occur on the same date, will be computed to take zero days. It is not possible to have a failed item removed from an aircraft and complete the repair cycle in zero time, yet the sample revealed that 35.2% of all turnaround times were reported as taking 0 days. The inability of the data collection system to measure the bulk of the actions any more accurately than as zero or one day caused a considerable problem when conducting independence tests and in simulating the system. In some applications of their allowance model, ASO uses a minimum TAT of one day when this situation occurs. An important point for future consideration, as the maintenance data system evolves, will be to attempt to provide greater resolution in TAT's.

Table IV presents a comparison of the TAT elements reported in the entire RANGER data base with those in the sample. There are two important observations to be made from this TAT information. First, the average time reported for most of the TAT elements are low because many of the observations reported for the TAT elements were 0; this was the case for 2427 of the 2884 in-process time observations (84.2%), 2202 of the scheduling time observations (76.4%), 1790 of the repair time observations (62.1%), and 1016 of the TAT observations (35.2%). The aforementioned inability to measure times in less than whole day intervals may affect any model that is very sensitive to estimation of the repair rate.

Second, there is a considerable amount of time spent in attempting to repair and obtain parts for units that are later BCM'd. The BCM action portion of the table shows that

TABLE IV

Data Base TAT Summary

A. All successful repair actions.

TAT Element	Entire data base #	Mean (days)	Standard Deviation (days)	Selected Sample #	Mean (days)	Standard Deviation (days)
IP	12524	0.72	13.1	2502	0.55	4.6
SKD	12524	1.29	4.6	2502	0.53	2.1
RPR	12524	1.67	5.6	2502	1.23	4.2
AWP	12524	1.93	7.2	2502	1.31	5.4
AWP*	1763	13.69	14.3	304	10.79	11.7
TAT	12524	5.61	17.0	2502	3.62	9.1

B. All BCM actions.

TAT Element	Entire data base #	Mean (days)	Standard Deviation (days)	Selected Sample #	Mean (days)	Standard Deviation (days)
IP	5754	1.32	13.9	382	1.26	8.0
SKD	5754	1.22	13.8	382	0.74	2.6
RPR	5754	1.86	14.8	382	2.07	7.1
AWP	5754	3.17	10.1	382	5.74	14.4
AWP*	894	20.42	17.3	95	23.08	20.9
TAT	5754	7.57	27.0	382	9.80	19.3

C. All actions.

TAT Element	Entire data base #	Mean (days)	Standard Deviation (days)	Selected Sample #	Mean (days)	Standard Deviation (days)
IP	18278	0.91	13.4	2884	0.65	5.2
SKD	18278	1.27	8.6	2884	0.56	2.2
RPR	18278	1.73	9.5	2884	1.34	4.7
AWP	18278	2.32	8.2	2884	1.90	7.3
AWP*	2657	15.95	15.7	399	13.71	15.3
TAT	18278	6.23	20.7	2884	4.44	11.2

* AWP average for those actions that experienced AWP.

5754 of the 18278 maintenance actions documented resulted in BCM action, and that these actions had an average TAT of 7.57 days. If these actions were spread out evenly over the course of the 178 day deployment, it would mean that, on average, there were 244.7 non-RFI units on board ship in the repair cycle on any given day that would later be BCM'd. The

RIMAIR model will not take these items into account when developing allowances to support the repair cycle.

Although the RIMAIR model ignores the time that units declared BCM spend in the repair cycle (the BCM TAT), the BCM TAT could be included in either the repair pipeline (by assuming that all inductions are attempted repairs) or as part of the order and shipping time. Ignoring the BCM maintenance cycle time, especially for units held in anticipation of obtaining parts, can seriously hamper support for these items.

3. Maintenance Data Characterization

The factors used to classify maintenance actions into one repair process or another should exist within the maintenance data base, which is described in great detail in the Naval Aviation Maintenance Program (NAMP) manual, OPNAVINST 4790.2B [Ref. 13]. The aviation maintenance data collection system is used for manhour accounting, documenting aircraft utilization, failure data reporting, and many other purposes. Some of the data elements directly concern repair of failed components removed from aircraft, and these data elements have been analyzed to determine if they provide the capability to distinguish between the type one repair process, which is conceptualized as a quick test-and-check type of repair, and the type two repair, which is thought to be a more in-depth repair that generally takes longer and requires more part support. The following data elements are the ones that have been analyzed. An example of the type of information provided by each code is listed for each category; complete explanations for each of the various codes are too long for inclusion in this thesis. The interested reader is referred to the descriptions that are provided in the NAMP appendix indicated.

a) The action taker (AT) code classifies repair actions as to their result, and what maintenance action brought about the result [Ref. 13: Appendix H]. For example, AT code 'C', for repair, is listed as "Repair includes cleaning, disassembly, inspection, reassembly, lubrication, and replacement of integral parts; ..", etc.; its use indicates that the repair was successful.

b) The malfunction (MAL) code specifies the type of defect found by the maintenance person attempting repair [Ref. 13: Appendix M]. '290' for example, is listed as "fails diagnostic/automatic tests"; guidance from higher authority and experience will dictate to a maintenance technician when use of this entry is more appropriate than any other.

c) The type maintenance (TM) code specifies the maintenance action or inspection that took place in removing the defective item from its installation [Ref. 13: Appendix K]. TM code 'B' is listed as "Unscheduled maintenance. Used... for all maintenance actions except the following:". Four detailed exceptions are then listed: two types of inspections, calibration for a specific category of equipment , and maintenance of transient aircraft.

d) The when discovered (WD) code specifies the operation or maintenance action that led to the discovery of the defective item. [Ref. 13: Appendix V]. WD code 'W' is described as "used when a need for maintenance is discovered during in-shop repair and/or disassembly for maintenance."

The category 'Other' is used for these codes to reflect actions where the number of observations was too few to warrant inclusion in the table. For example, there were 89 different MAL codes used for actions related to items in the sample; a number of these were used only once.

Table V provides a summary of the data available in the RANGER data base for these four maintenance codes and contrasts this with data used in the sample. This data is presented for two reasons. First, it helps to illustrate the variety and richness that is available in the aviation 3-M data base for characterizing maintenance actions. Although there are relatively few codes listed here, there are hundreds of malfunction (MAL) codes and many more in the other categories.

The second reason for presenting this data is that these maintenance data codes should provide a means of differentiating repairs into the theorized process one and process two of the model. This will be shown in the following section.

C. ANALYSIS OF THE TAT ELEMENTS

As was noted earlier, the establishment of the repair system as two parallel processes is an important element of this model. The following procedure was used to develop this concept. First, the lack of independence of the current TAT elements is shown. Based upon this result, a new variable structure is developed. It is then shown that the TAT data for the repair processing time are not distributed in an exponential manner. The repair process is analyzed with the result that there are actually multiple repair processes occurring simultaneously. A simple model is then hypothesized which classifies all repair actions into two subsets, depending solely on the existence or absence of AWP time. These two underlying processes are shown to be independent of each other and to have exponential distributions. Finally, revised TAT limits for use with the new variables are presented.

TABLE V

RANGER Data Base Maintenance Characteristics

Category/ Key Values	Entire RANGER Data base	(%)	Selected Sample	(%)
Action Taken (AT)				
A: No repair required	2410	(13.2)	503	(17.4)
C: Repair	8488	(46.4)	1980	(68.7)
J: Calibrated	1207	(6.6)	0	(0.0)
Other repairs	398	(2.2)	19	(0.6)
REPAIR TOTAL	12503	(68.4)	2502	(86.7)
1: BCM-repair not authorized	2435	(13.3)	134	(4.6)
4: BCM-lack of parts	822	(4.5)	87	(3.0)
5: BCM-fails check&test	650	(3.6)	47	(1.6)
7: BCM-beyond authorized depth	1212	(6.6)	106	(3.7)
Other BCMs	635	(3.5)	8	(0.3)
BCM TOTAL	5754	(31.5)	382	(13.2)
Other actions	18	(0.1)	0	(0.0)
TOTAL	18278		2884	
Malfunction Code (MAL)				
070: Broken physically	842	(4.6)	105	(3.6)
127: Improper adjustment	1691	(9.3)	555	(19.2)
169: Incorrect voltage	571	(3.1)	225	(7.8)
242: Fails to operate	2031	(11.1)	127	(4.4)
255: No output	731	(4.0)	149	(5.2)
290: ATE test failure	4001	(21.9)	351	(12.2)
374: Internal failure	811	(4.4)	118	(4.1)
799: No defect	1803	(9.9)	372	(12.9)
804: No defect, scheduled maintenance	1575	(8.6)	126	(4.4)
Other	4222	(23.1)	756	(26.2)
TOTAL	18278		2884	
Type Maintenance Performed (TM)				
B: Unscheduled	15791	(86.4)	2737	(94.9)
D: Daily Inspection	452	(2.5)	130	(4.5)
P: Calendar Inspection	579	(3.2)	1	(0.0)
S: Conditional Inspection	1272	(7.0)	2	(0.1)
Other	184	(0.9)	14	(0.5)
TOTAL	18278		2884	
When Discovered (WD)				
D: Inflight, no abort	4076	(22.3)	1187	(41.2)
H: Between flights, by ground crew	4083	(22.3)	891	(30.9)
W: In shop	4320	(23.6)	181	(6.3)
Other	5799	(31.8)	625	(21.6)
TOTAL	18278		2884	

1. Independence of the TAT Elements

Chapter II provided the current procedure for limiting TAT element observations. The 1977 ASO study that developed the current limits, [Ref. 4], assumed the TAT elements to be independent. This is not a valid assumption. Chi-square tests of independence with α-levels of 0.01 lead to the following conclusions:

a) In-process time (IP) is independent of the other three elements. This was expected because IP measures the time required for administration and transportation functions performed by the operational level (squadron) maintenance personnel and the local supply activity, and is not related to the repair process itself.

b) Scheduling time (SKD), repair time (RPR), and awaiting parts time (AWP) are not independent variables. These three variables measure the functions most closely related to the actual repair, and their relationship to each other is not surprising.

Table VI provides the results of the independence tests which tested each of the four TAT elements for independence from each of the others. Part A provides a brief definition for each of the elements; part B summarizes the results of the chi-square independence tests; and independence tests using Pearson's correlation coefficient (r) are presented in part C of the table. Both sets of tests indicate that the hypothesis that IP is independent of SKD, RPR, and AWP cannot be rejected. The significance levels of the tests range from 0.207 to 0.340. The tests for independence between the SKD, RPR, and AWP elements are all rejected at the 0.01 level.

A derived variable, called repair-cycle time (RCT), is now formally defined as the sum of the scheduling, repair, and awaiting parts times for a given maintenance action.

TABLE VI

TAT Element Independence Test Results

A. Definitions

TAT element	Time period measured From	Until
IP :In process	removal	receipt at IMA
SKD:Scheduling	receipt at IMA	work starts
RPR:Repair Less AWP time	work starts	completion
AWP:Awaiting parts	work stoppage	work resumes

B. Chi-square tests for independence were performed on the data elements using SPSS. Data for the elements were grouped into categories so that no cell would have less than 3 for an expected observation. Test results are listed as follows:

Chi-square: VAR1 × VAR2 — test value (d.f.) sig level

	SKD	RPR	AWP
IP	2.6 (2) p=.266	5.9 (4) p=.209	3.4 (3) p=.335
SKD		26.7 (8) p=.0008	24.3 (6) p=.0005
RPR			372.8 (12) p=.0000

C. Correlations using Pearson's r.

	SKD	RPR	AWP
IP	-0.0077 (2884) p=.340	-0.0116 (2884) p=.266	-0.0111 (2884) p=.275
SKD		0.0853 (2884) p=.000	0.0477 (2884) p=.005
RPR			0.2311 (2884) p=.000

$$RCT = SKD + RPR + AWP \tag{3.1}$$

A test of independence between RCT and IP yielded a chi-square value of 3.5 with 5 degrees of freedom and a significance level of 0.628, leading to a conclusion of independence between RCT and IP.

The use of RCT as a key variable in a simple model is dependent upon the assertion that it is exponential. A statistical test of this assertion results in rejection of the exponential distribution. The mean of RCT is 3.793; an exponential distribution with this same mean would have approximately 32.7% of its observations for 0-1 days, and 8.2% for 10 or more days. The empirical distribution for RCT has more weight in both these categories: 71.0% (2048 of 2884 observations) for 0-1 days, and 10.4% (299 of 2884) for 10 days or more. A formal test for the exponential distribution was performed with the Lilliefors test for exponential distributions. The resulting value was 0.383 with 30 degrees of freedom, which leads to the rejection of the hypothesis that the distribution is exponential at the 0.01 level of significance.

Similar conclusions were reached in the earlier study **[Ref. 10]**. In that study the data were split into two parts each roughly approximated by an exponential distribution. The empirical distribution of the RANGER RCT lends itself to a similar conclusion; if two separate exponential processes with different mean times were occurring simultaneously, their joint distribution could exhibit the characteristics that the RCT distribution does. The factor or factors that facilitate classifying items into one or the other of the underlying processes must now be identified.

2. Decomposition of RCT

Table VII presents a summary of RCT time observations broken down by the maintenance data elements previously listed in Table V . The table provides the number of cases listed in each category for each code, the average value for RCT for that category, and the standard deviation. All times are listed in days. The results of separating the data in this manner are to indicate that there are differences in RCT for different values of the codes. For the AT code, AT 'A' (no repair required) had an average RCT value of 0.79 days; AT 'C' (successfully repaired) had a mean of 3.52 days; and AT '4' (BCM for lack of parts) had a mean time of 26.77 days. The breakdown by MAL code was equally enlightening: MAL '799' (no defect) had mean RCT of 0.78 days, but MAL '290' (fails dignostic/automatic tests) and MAL '255' (no output) had mean values of RCT of 9.07 and 11.09 days, respectively. The TM and WD codes also showed differences between their values, but not to the same extent.

The existence or absence of AWP time was also used as a Bernoulli variable for the purpose of differentiating the repair processes. This was done on the belief that certain types of repair action are more likely to result in AWP time, and therefore the existence of AWP may be a key to differentiating the processes.

ANOVA tests were run on the variables using RCT values as the dependent variable in an attempt to differentiate the processes. Using the existence of AWP to differentiate between the processes is biased because RCT includes AWP time within it. Therefore, additional tests were run on RCT without AWP time included. Table VIII provides the results of these tests. Part A of the table provides the results of separate tests for significance in

TABLE VII

RCT Values for Selected Data Elements

Category/ Key Values	N	Mean (days)	Standard Deviation (days)
Action Taken (AT)			
A: No repair required	503	0.79	2.10
C: Repair	1980	3.52	9.34
Other repair actions	19	16.05	-
REPAIR TOTAL	2502	3.07	7.92
1: BCM-repair not authorized	134	0.26	1.60
4: BCM-lack of parts	37	26.77	23.70
5: BCM-fails check&test	47	0.98	2.11
7: BCM-beyond authorized depth	106	7.53	17.70
Other BCMs	8	6.88	-
BCM TOTAL	382	8.54	17.97
TOTAL	2884	3.79	8.94
Malfunction Code (MAL)			
070: Broken physically	105	2.59	5.58
127: Improper adjustment	555	1.11	4.21
169: Incorrect voltage	225	5.15	11.18
242: Fails to operate	127	1.43	10.11
255: No output	149	11.09	16.76
290: ATE test failure	351	9.07	15.62
374: Internal failure	118	5.09	8.72
799: No defect	372	0.78	2.33
804: No defect, scheduled maintenance	126	1.47	1.50
Other	756	3.70	-
TOTAL	2884	3.79	9.56
Type Maintenance Performed (TM)			
B: Unscheduled	2737	3.88	10.20
D: Daily Inspection	130	1.95	5.60
P: Calendar Inspection	1	0.00	----
S: Conditional Inspection	2	1.50	0.71
Other	14	3.71	-
TOTAL	2884	3.79	10.02
When Discovered (WD)			
D: Inflight, no abort	1187	4.27	11.04
H: Between flights, by ground crew	891	3.29	9.25
W: In shop	181	2.09	5.46
Other	625	4.10	-
TOTAL	2884	3.79	9.98

explaining the variability of RCT when using the four maintenance codes (AT, MAL, TM, and WD) and the presence of AWP separately to try to explain the variance. The test revealed that all of the codes except TM were significant in explaining the variability. The sum of squares explained by WD, even though significant, was small compared to the sum of squares explained for the other three variables. Consequently, when testing for the significance of the variables when used together in the ANOVA test, only AT, MAL, and AWP were used. The result of this test is provided in the bottom of part A, and indicates that AWP is the best single indicator for explaining the variability of RCT.

Part B of the table shows the results of performing the same tests, but using the sum SKD+RPR as the variable to be explained; the reason for doing this is to minimize the bias inherent in using the presence of AWP to indicate the variability in a variable that includes AWP time. The results are similar: MAL, WD, and AWP are the best indicators when tested separately, but this time MAL turns out to be a slightly better indicator when the three variables are tested jointly.

To summarize, the ANOVA tests revealed that the best variables for use as factors to differentiate the repair processes were the MAL code, the AT code, and the existence/absence of AWP. These were all significant at the 0.001 level whether AWP time was included in RCT or not. The AWP code provided the greatest ability to explain variations in RCT, which includes AWP time, and the MAL code provided the greatest ability to explain variations in the RPR+SKD times (i.e., RCT without including AWP time.)

Use of the MAL code for differentiating repair processes is probably the most logical choice, but there is an inherent problem. It is easy to accept that the type of repair action necessary for a unit depends upon the exact

TABLE VIII

RCT ANOVA Results

A. Results of separate ANOVA tests on the variables, using RCT with AWP included.

Variable	Sum of Squares	D.F	Mean Square	F	Significance Level
MAL	36122.8	88	410.5	4.52	.0000
TM	1133.4	7	161.9	1.61	.1270
AT	60529.4	10	6052.9	75.80	.0000
WD	4860.4	19	255.8	2.57	.0002
AWP(Y/N)	99460.5	1	99460.5	504.90	.0000
TOTAL	289869.8	2883			

Using the best indicators from the above tests, with reduced number of categories due to size constraints, a three-way ANOVA was run on MAL (9 specific codes, plus other), AT (repair/BCM), and AWP (Y/N).

Main Effects	Sum of Squares	D.F	Mean Square	F	Sig Level
All	109192.1	11	9926.6	157.79	.0000
MAL	6041.8	9	671.3	10.67	.0000
BCM/rep	5256.0	1	5256.0	83.52	.0000
AWP(Y/N)	69947.3	1	69947.3	1111.86	.0000
Residual	180677.8	2872	62.9		
TOTAL	289869.8	2883			
TOTAL	81380.2	2883	28.3		

B. Recognizing the AWP bias, the same tests were run using the value SKD+RPR.

Variable	Sum of Squares	D.F	Mean Square	F	Significance Level
MAL	5888.8	88	66.9	2.48	.0000
TM	302.4	7	43.2	1.53	.1515
AT	3513.7	10	351.4	12.96	.0000
WD	595.2	19	31.3	1.10	.3323
AWP(Y/N)	3731.5	1	3731.5	138.50	.0000
TOTAL	81380.2	2883			

Main Effects	Sum of Squares	D.F	Mean Square	F	Significance Level
All	6321.9	11	574.7	21.99	.0000
MAL	2459.1	9	273.2	10.46	.0000
BCM/rep	332.5	1	332.5	12.72	.0000
AWP(Y/N)	1640.9	1	1640.9	62.79	.0000
Residual	75058.3	2872	26.1		
TOTAL	81380.2	2883	28.3		

malfunction it has. There are, however, 89 different malfunction codes used for various items in the sample. It is not practical to define a simple model for each MAL code, and grouping codes became too complex a task within the time available. Consequently, the existence or absence of AWP, which is the second-best discriminator, was used to define the two repair processes shown in Figure 3.1 .

The following definitions will be used for the two repair processes, modifying Equation 3.1 :

a) for actions without AWP time:

$$RC1 = SKD + RPR;$$

$$RCT = RC1.$$

b) for actions with AWP time:

$$RC2 = SKD + RPR;$$

$$RCT = RC2 + AWP. \tag{3.2}$$

It is desirable to maintain a distinction between the AWP time itself and RC2, even though it is the existence of AWP that is used to differentiate RC2 from RC1.

The proposed model will assume capacity constraints on the repair process, which would normally affect only the scheduling and repair functions. AWP time is actually time out of the process, and there is no physical reason to expect a capacity constraint on the AWP process. Statistics for RC1 and RC2 are listed in Table IX . Part A shows the number of cases, average SKD+RPR value, and standard deviation of the SKD+RPR value for the two groups of maintenance actions defined by the existence or absence of AWP. Testing the hypothesis that the groups are from the same population results in rejecting this hypothesis at the 0.001 level.

TABLE IX

Repair Cycle Values for the Two Processes

A. Analysis of the existence or absence of AWP time provides the following values for (SKD+RPR):

Category	N	Mean (days)	Standard Deviation (days)
RC1: No AWP time	2485	1.44	4.21
RC2: AWP occurred	399	4.73	9.19
TOTAL	2884	1.90	5.19

An approximate t-test using separate variance estimates yielded a value of 7.04 with 425.2 d.f, p=0.00 .

B. Analysis of the existence or absence of AWP time provides the following values for RCT:

Category	N	Mean	Standard Deviation
RCT (=RC1, no AWP)	2485	1.44	4.21
RCT (=RC2+AWP)	399	18.45	19.13
TOTAL	2884	3.79	10.03

An approximate t-test using separate variance estimates yielded a value of 17.64 with 404.2 d.f, p=0.00 .

C. Correlations of RC1 and RC2 with IP and AWP.

	IP	AWP
RC1	-.0130 (2485) p=.259	no AWP
RC2	.0189 (399) p=.353	.1733 (399) p=.000

Part B of the table provides the same basic information as part A, but includes the AWP time in with the SKD+RPR observations. The result is that the mean and standard deviation for the observations that include AWP is considerably higher. Testing the hypothesis that both groups are from the same population is again rejected. Part C provides the Pearson correlation coefficient (R) test for independence of RC1 and RC2 from IP and AWP. RC1 and RC2 are accepted as being independent from IP, but testing RC2 results in rejecting the independence hypothesis, as expected.

The following figures illustrate the breakdown of RCT into the decomposed cycles. Figure 3.2 provides the distribution of repair cycle days (SKD+RPR) for all actions in the selected sample. These same observations are plotted as two separate distributions, based on AWP, in Figure 3.3 . The plot of RC1 is seen to have a very small tail, as expected. RC2 has a long tail, and includes most of the longer actions. The reduction in the mean and standard deviation of process one times over the aggregate times is the result of removing most of the slow moving maintenance actions. The fact that the standard deviation is still too high for the distribution to be a true exponential is partially due to a few very large numbers, which are censored when data limits are applied.[3]

Results of formally testing the distributions of RC1 and RC2 with the Lilliefors goodness-of-fit test for the null hypothesis that each is an exponential distribution are as follows: variable RC1 has a test value of 0.078 with 30 degrees of freedom, which results in the conclusion that the null hypothesis cannot be rejected; variable RC2 has a test value of 0.088 with 30 d.f., which also results in the conclusion that the null hypothesis cannot be rejected.

----

[3]Although the data base contains observations for RC1 or RC2 that are large compared to the mean (e.g. 10-30 days), there are also 6 observations in excess of 50 days. These data observations are not considered to be representative of the actual underlying repair process. Observations like these, which may have resulted from poor data entry procedures, force the use of upper limits (constraints) on the data used to compute allowances.

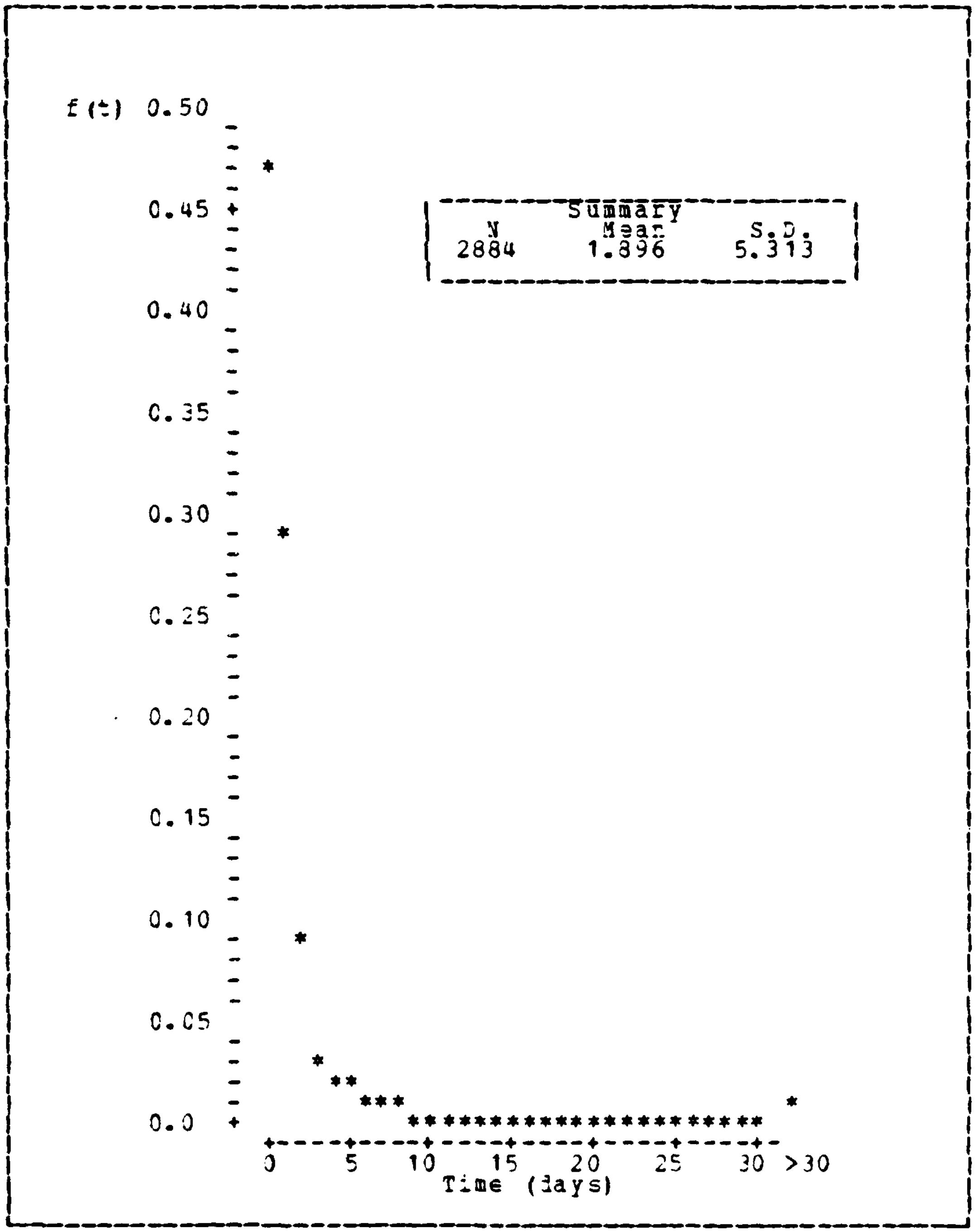


Figure 3.2 SKD+RPR Empirical Mass Function (all actions).

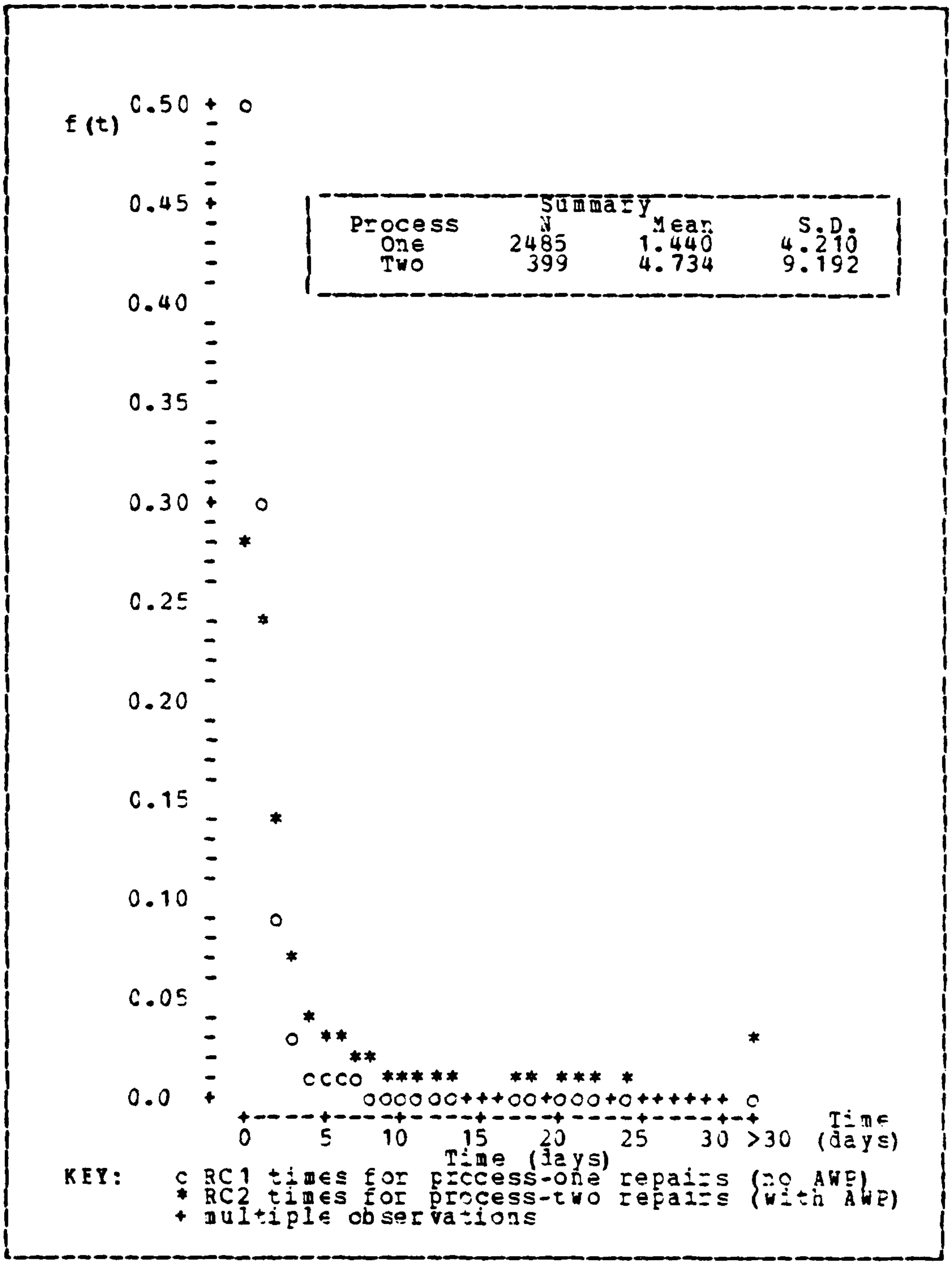


Figure 3.3 Empirical Mass Functions for RC1 and RC2.

3. Revised TAT Limits

Chapter II discussed some problems of using TAT limits but recognized the need for some limit to be applied. Analysis of the sample data revealed that applying the existing limits had a very serious effect on the statistics generated by the data, particularly for in-process time. The existing one day limit reduced the mean value for IP from 0.646 days to 0.158 days, a reduction of more than 75%. SKD, limited at 3 days, has its mean value reduced from 0.557 days to 0.339 days, a 39% reduction. RPR and AWP are similarly reduced, and the final reduction on TAT is from 4.44 days down to 2.74 days, a 38.3% reduction. By using these values to compute allowances, it is in fact implying that the next deployment will have 38.3% fewer items in the repair process on any given day than the deployment being used as a data base had.

Because these reductions seem quite severe, modified limits were developed using approximately the 98th percentile of the empirical distributions for the various TAT elements. Table X presents the results of this analysis. Part A of the the table shows each TAT element, the existing limit, the raw (unlimited) and limited average times, the number of observations in the sample that were limited, and the percentage of observations limited. Part B provides the same information, but with revised TAT limits developed through analysis of the sample data. The result of using these revised TAT limits is to reduce TAT from 4.44 days to 3.80 days, or a reduction of 14.4%, which is much less severe. These modified limits will be used when developing allowances with the proposed model, and their effects on both the existing and proposed models will be shown in the simulation results. Their use is not meant to imply that they are correct values for the aviation 3-M system as a

TABLE X

Revised TAT Limits

A. Effect of existing limits on sample data.

TAT Element	Existing Limit	Average Raw (days)	Average Limited (days)	Cases affected #	Cases affected (%)
IP	1 day	.646	.158	125	(4.33)
SKD	3 day	.557	.339	91	(3.16)
RPR	8 day	1.34	.886	98	(3.40)
AWP	20 day	1.90	1.36	93	(3.22)
AWP*	20 day	13.7	9.85	93	(23.31)
TAT	----	4.44	2.74	359	(12.45)

*AWP average for the 399 actions that had AWP

B. Effect of new limits on sample data.

TAT Element	New Limit	Average Raw (days)	Average Limited (days)	Cases affected #	Cases affected (%)
IP	6 days	.646	.309	53	(1.84)
RC1 (units without AWP)	12 days	1.44	1.18	53 of 2485	(2.13)
RC2 (units with AWP)	35 days	4.73	4.45	8 of 399	(2.01)
AWP* (units with AWP)	60 days	13.7	13.5	7 of 399	(1.75)
TAT	-	4.44	3.80	120	(4.16)

whole to use, but rather that some relaxation of the current limits is warranted.

4. TAT Analysis Summary

It has been shown that the TAT elements are not independent, that repair cycle time is not exponential, and two independent subprocesses can be defined based upon the existence or absence of AWP time that are acceptably exponential in distribution.

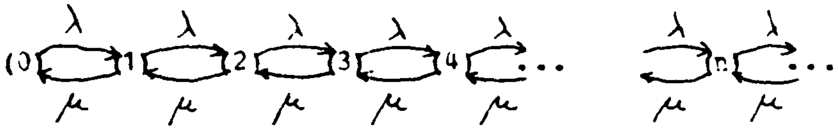
The existence or absence of AWP time is itself a condition dependent upon a number of factors. The complexity of a malfunction, the inability of test equipment or technicians to isolate the fault, or the nonavailability of the correct repair parts may cause an item to go AWP. No simple inventory model can take all of these into account; the SPECTRUM large scale simulation system developed at the Naval Air Development Center, Warminster, PA, is probably the only system that encompasses such a level of complexity. However, any allowance development model of the magnitude of SPECTRUM is too large for day-to-day use. Consequently, the simple approach of recognizing the inherent differences between repair actions that cause AWP and those that do not is the chosen method for defining the two separate repair processes.

D. THEORETICAL BASIS FOR THE PROPOSED MODEL

1. M/M/1 Queue Characteristics

The M/M/1 queue is the simplest elementary queueing model which provides the capability to examine a queueing system as it approaches saturation. It assumes interarrival times are exponential, repair times are exponential, and there is only one server. In practical terms, an IMA may have a number of test benches or technicians capable of repairing an item, but other jobs, down benches, shift work, etc. may reduce the effective number of servers to one. Consequently, the physical queue may display characteristics similar to that of an M/M/1 system.

The state diagram (Figure 3.4) provides the basic characteristics that will be used to compare the M/M/1 model with the existing model. The state probabilities are easily determined from the state transition diagram as follows:



Parameter	Name	Assumptions
λ	Arrival rate	Independent arrivals Constant rate Exponential interarrival times
μ	Service rate (repair rate)	Exponential service times, unaffected by queue length Each service is independent
ρ	Traffic intensity	$\rho = \lambda/\mu$
P	Mean # in system (pipeline), infinite population	$0<\rho<1$ $P = \rho/(1-\rho)$ $\rho = 1$ P undefined $\rho > 1$ $P \rightarrow \infty$
	Mean # in system (pipeline), population of size K	$\rho \ll 1$ $P = \rho + \rho^2$ $\rho \rightarrow 1$ $P = K/2 + K(K+2)(\rho-1)/12$ $\rho \gg 1$ $P \rightarrow K - \frac{1}{\rho}$
T	Mean time in system	$T = P/\lambda$ $= 1/(\mu-\lambda)$
W	Mean waiting time	$W = T - 1/\mu$ $= \rho/(\mu-\lambda)$
$\pi(n)$	Probability of being in state n, infinite pop	$\rho<1$ $\pi(n) = (1-\rho)\rho^n$ $\rho \geq 1$ $\pi(n) = 0$ (transient)
	Probability of being in state n, finite pop K	$\rho \neq 1$ $\pi(n) = (1-\rho)\rho^n/(1-\rho^{K+1})$ $\rho = 1$ $\pi(n) = \frac{1}{K+1}$

Figure 3.4 M/M/1 Queue Characteristics.

$$\lambda \pi(0) = \mu \pi(1),$$

so

$$\pi(1) = \lambda/\mu \, \pi(0),$$

$$\pi(1) = \rho \, \pi(0);$$

$$(\lambda+\mu)\pi(1) = \lambda \pi(0) + \mu \pi(2),$$

so

$$\pi(2) = \frac{\lambda}{\mu} \pi(1),$$

$$\pi(2) = \rho \, \pi(1),$$

$$\pi(2) = \rho^2 \pi(0);$$

and in general,

$$(\lambda+\mu)\pi(n) = \lambda \pi(n-1) + \mu \pi(n+1),$$

so

$$\pi(n+1) = \rho \, \pi(n),$$

$$\pi(n+1) = \rho^{n+1} \pi(0).$$

With the specification that all state probabilities must sum to one,

$$\sum_{i=0}^{\infty} \pi(i) = 1,$$

the probabilities are determined to be:

$$\pi(0) = 1-\rho, \qquad 0<\rho<1;$$

and for $n > 0$,

$$\pi(n) = (1-\rho)\rho^n, \qquad 0<\rho<1.$$

Since the desired quantity is the quantity Q such that the probability that there are Q or less in the system equals the safety level parameter (SL), Q is found as follows:

$$SL = \sum_{i=0}^{Q} \pi(i),$$

$$= (1-\rho) \sum_{i=0}^{Q} \rho^i, \qquad 0<\rho<1;$$

so

$$SL = 1-\rho^{Q+1}, \qquad 0<\rho<1,$$

and Q solves as

$$Q = \frac{\ln(1-SL)}{\ln \rho} - 1 \qquad (3.3)$$

An inventory model that satisfies the assumptions listed in Figure 3.4 is restricted in that it is possible to quickly saturate the system when the service rate is less than the arrival rate ($\rho > 1$); at that point both the number in the system and the waiting time of an item entering the system grow without bound. There is no steady-state solution in this case, and it is necessary either to redesign the system for greater repair capacity or to specify an endurance period during which saturation will be allowed to occur, causing the number of units awaiting service to build up. The endurance period must then be followed by a period having a demand rate lower than the repair rate, thereby allowing an activity to work through the backlog.

2. Saturation Considerations

The specification that the ratio of the arrival rate to the service rate of a single server (ρ) be less than one was not necessary for solution of the $M/M/\infty$ queue model because there were always enough servers available to provide service to arriving units. This is not the case in the M/M/1 queueing model, where the assumption that there is but a single server leads to the possibility that the system will become saturated when the arrival rate equals or exceeds the service rate. A queueing model with a capacity constraint was chosen specifically to model this situation.

When the M/M/1 queueing model is applied to a situation where the number of units that may require service is infinite, the expected number in the system, $P = \rho/1-\rho$, increases without bound as the value of ρ approaches unity. For $\rho \geq 1$, there is no steady state solution for the number of units in the system.

In the actual situations to be modelled, however, the population is finite, though generally large with respect to the number in an unsaturated queue. This situation is more formally referred to as a M/M/1//K system, indicating that the arrival rate, service rate, and single server assumptions of the M/M/1 queueing model hold, but with the additional specification that there are only K units that may fail and enter the system for repair. This system has been analyzed separately from the M/M/1 model in available literature, and the formulae for the expected number in the system as approaches or exceeds unity are quite different. The formulae provided in Figure 3.4 were obtained from Morse [Ref. 15: p. 18], and are as follows:

let P = number in the repair system, and
K = number in the population.

Then

$$P = \begin{cases} \rho + \rho^2 & \rho \ll 1 \\ K/2 + K(K+2)(\rho - 1)/12 & \rho \to 1 \\ K - \frac{1}{\rho} & \rho \gg 1 \end{cases} \tag{3.4}$$

The formula for $\rho \ll 1$, $\rho + \rho^2$, is a second order approximation for the steady state formula used in the infinite approximation case. The formulae for approaching or exceeding one are significantly different. The number of items that can fail in the infinite population case is assumed to be infinite regardless of the number of items that have already failed, and the arrival rate is constant. With a finite population, however, the number of items that can fail decreases as the number in the repair system grows and the number in the system can never exceed the population size K. Consequently, the steady state formula for $\rho = 1$ solves as P=K/2, and the limit as $\rho \rightarrow \infty$ is P=K. The nature of the system to which the model is being applied, primarily air stations and aircraft carriers, makes the finite population model considerably more appropriate than the infinite population model.

One additional comment about applying this model to Naval Aviation activities is appropriate at this point. It has been assumed that the service rate is constant; in practice it will vary somewhat with the number of units awaiting service. Some units experience improved repair rates as the number of backlogged units increase because of priority repair. Some items requiring piece-parts observe shorter AWP times when cross-cannibalization with items already AWP occurs. There is in fact a degree of extra repair capacity that becomes apparent during high demand periods, keeping the system below saturation unless it is physically not possible to improve service times (as seems to be the case with VASI). Regardless, the point made earlier in the CABAL study, [Ref. 11: p.38], that either time must be provided to work off the backlog or readiness degradation will result must be taken to heart by those who design the system, and by those in command.

The RANGER data base obtained for analysis did not include the populations of the items that failed. From experience, it is known that the populations may range from as few as four, for an E-2C specific item, to more than a hundred in the case where there are multiple installations on different aircraft types. Consequently, attempting to estimate K for the different items being studied was not considered feasible. Additionally, the exact numbers and configurations for some weapons systems are classified information. In order to perform the simulation desired to test the model, therefore, it was necessary to use two other approximations for the number of units in the system. The first approximation estimates the number of items that will buildup in a saturated ($\rho>1$) queueing system over time.

The second approximation was adapted from the first (buildup) approximation to allow application when $\rho \leq 1$. These are presented here, and were programmed into the simulation allowance computation routines to allow for the computation of "reasonable" allowance quantities when K was not known and ρ was in the region $(1-\delta,\infty)$ (δ small).

The buildup rate approximation was presented in Newell [Ref. 14], and obtains a solution for a transient state by estimating the rate of buildup of the queue in an infinite population. His formula was adapted as follows:

let

μ = service rate;

λ = demand rate, with $\lambda > \mu$ ($\rho > 1$);

T = expected time in system;

Po = expected number in the queue at time 0, prior to saturation,
= λ T;

B(t') = Expected backlog increase during (0,t')
= $(\lambda-\mu) \times t'$;

QB(t') = the number for which the value of the CDF of a Poisson distribution with mean B(t') is closest to the required safety (SL); and

Q(t') = number in the queue at time t'.

Then

$$Q(t') = P_o + QB(t') \tag{3.5}$$

This expression for the buildup rate is only a first-order approximation in the case of a finite population because the observed demand rate from such a population will decrease as the number of items from the population waiting in the queue grows. The failure rate per unit may remain constant, but the number of RFI units will steadily decrease, thus lowering the observed demand rate.

The second approximation was adapted from the buildup approximation to allow for computation of allowances in the region $(1-\delta, 1]$, (δ small). In this region the buildup approximation is not applicable because there is no buildup expected: $\lambda \leq \mu$. The finite population approximation of the number in the repair system for small ρ, $P = \rho + \rho^2$, grows steadily worse as ρ approaches one because third order and higher terms become significant. As previously stated, the expected number in a system with an infinite population increases without bound as ρ approaches unity. The finite population approximations for ρ close to one would provide values close to K/2, but the value of K is not available. There is a need during simulation, however, to establish allowances for a few items which have ρ just less than one. Consequently, the following simple approximation for the number in the system was developed.

In theory, an inventory model attempts to provide an allowance quantity by estimating the distribution of the number of units in the repair system, then finding a quantity such that the value of the CDF at that quantity is equal to the safety level. The approximation chosen for ρ in the interval $(1-\delta, 1]$ (δ small) was to assume the number of demands during a transient interval were Poisson with rate λ, but that repairs were deterministic with rate μ. The following formula was actually applied:

let

T	= mean experienced process time;
t'	= length of endurance period;
Po	= the expected number in the system at time 0, = λ x T;
SL	= desired safety level;
λ x t'	= expected number of demands in (0,t');

QL(t') = the number for which the value of the CDF of a Poisson distribution with rate $\lambda \times t'$ is closest to SL;

ER(t') = expected number of repairs in (0,t'), = $\mu \times t'$; and

Q(t') = desired allowance.

Then

$$Q(t') = P_0 + QL(t') - ER(t'). \tag{3.6}$$

Equation 3.6 will be referred to as the deterministic repair approximation, and the quantity Q(t') will be used as the allowance when the following conditions are met:

a) $\rho < 1$,

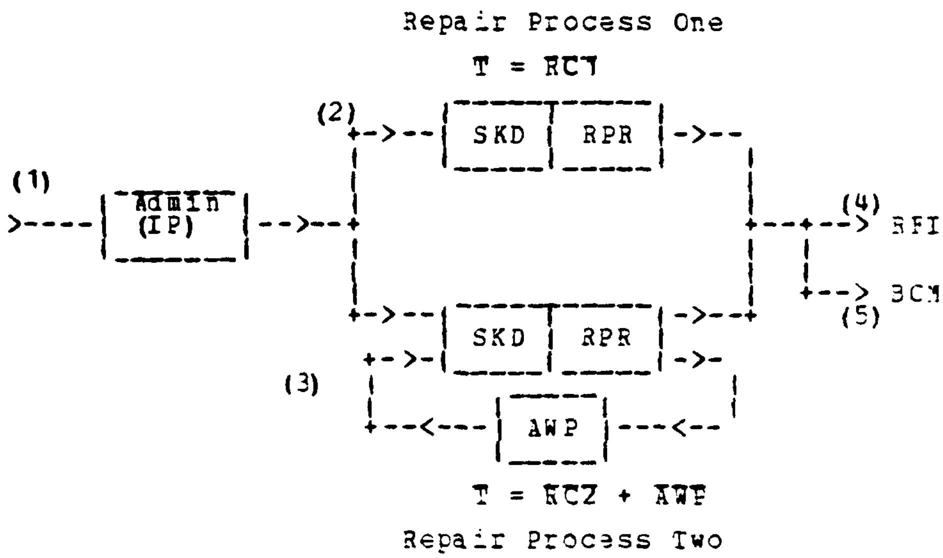
b) QL(t') > ER(t'), and

c) Q(t') < $\rho/(1-\rho)$.

The use of $\lambda \times T$ as the expected number in the system at time 0 is straightforward; it is the number expected to be in the system at any given time. Arrivals are a Poisson process, so the number of arrivals in the period (0,t') is distributed as a Poisson random variable. Assuming repairs to be deterministic allows the expected number of repairs in (0,t') to be computed simply as $\mu \times t'$, with the understanding that there is always something in the system to be repaired. When ρ is greater than one, the buildup approximation is used.

E. A CAPACITATED MODEL

The inventory model proposed for use with naval aviation repairable items is provided in Figure 3.5 . The following provides a detailed look at how an allowance can be computed with it.



Description:

(1) All units enter the system, and go thru administrative processing, measured by IP.

(2) A number (NR1 + NB1) of these units enter repair process one, and are served with the average RC1 time.

(3) The remaining units (NR2 + NB2) enter process two, are served in the repair facility with average time RC1, and spend an average time AWP awaiting parts.

(4) Upon completion of the appropriate maintenance actions, most of the units leave the repair cycle ready-for-issue (RFI), and are returned to inventory (NR1 + NR2).

(5) A percentage of the items that leave the repair process (NB1 + NB2) are declared beyond the capability of the local IMA facility to repair (BCM), and are returned to the wholesale system. An RFI unit is sent to the activity from the wholesale system, and put in inventory.

Figure 3.5 The Proposed Model (Operational).

1. Application of the M/M/1 Model

Application of the M/M/1 queue model to the available data necessitates making some assumptions and manipulating the equations listed in Figure 3.4 . Available data provide the information needed to compute the process rates as follows:

a) Demand rate (λ):

let

NR1 = number of repairs without AWP;

NB1 = number of BCM's without AWP;

NR2 = number of repairs with AWP;

NB2 = number of BCM's with AWP; and

t = length of data collection period.

Then

process one demands = λ_1 = (NB1 + NR1)/t;

process two demands = λ_2 = (NB2 + NR2)/t;

total demand = λ = $\lambda_1 + \lambda_2$.

b) Service rate (μ): average time in the system is known from the TAT data base, allowing the service rate to be computed. The subscripted variables (μ_i, λ_i, Ti) stand for the appropriate variable in either process one or two:

$$Ti = 1/(\mu_i - \lambda_i);$$

so

$$\mu_i = \lambda_i + 1/Ti.$$

c) Traffic intensity (ρ) is obtained directly from:

$$\rho_i = \lambda_i / \mu_i.$$

Once the forecast for the demand and service rate has been determined, the allowance for the repair process is computed as follows:

a) Compute the quantities QLi(t') (the SL percentile of the number of demands to be received in (0,t'), where t' is the endurance period), and ERi(t') (the expected number of repairs in (0,t'), μ_i t').

b) Compute the allowance from one of the following three cases.

1) If $\rho i < 1$, and $QLi(t') < ERi(t')$, use the infinite population formula (Equation 3.3):

$$Q_i = \frac{\ln(1 - SL_i)}{\ln \rho_i} - 1 \tag{3.7}$$

2) If $\rho i < 1$, $QLi(t') > ERi(t')$, use the deterministic repair approximation (Equation 3.6):

$$Q_i(t') = (\lambda_i \cdot T_i) + QL_i(t') - ER_i(t') \tag{3.8}$$

3) If $\rho i > 1$, use the buildup approximation (Equation 3.5):

let

$Bi(t')$ = expected queue buildup in $(0,t')$
= $(\lambda i - \mu i) \times t'$;

$QBi(t')$ = the number for which the value of the CDF of a Poisson distribution with rate $Bi(t')$ is closest to SL; and

$$Q_i(t') = \lambda_i T_i + QB_i(t') \tag{3.9}$$

These equations allow the proposed model to be used in the simulation despite the lack of population size information for the sample items.

2. Allowance Computation Procedure

Data needed to compute an allowance with this model is essentially the same as the data needed for the Poisson model, but must be analyzed differently. The steps are as follows:

a) Gather information from the 3-M data base; apply IAT element limits where appropriate.

b) Compute the following quantities:

   1) NR1 - number of repairs without AWP;
   2) NB1 - number of BCM's without AWP;
   3) NR2 - number of repairs with AWP;
   4) NB2 - number of BCM's with AWP;
   5) E(IP) - expected value of admin (in-process) time;
   6) E(RC1) - expected value of SKD + RPR time for all actions which had no AWP (NR1 + NB1);
   7) E(RC2) - expected value of SKD + RPR time for all actions that had AWP time (NR2 + NB2);
   8) E(AWP) - expected value of AWP for those items that had AWP (NR2 + NB2);
   9) E(OST) - expected value of off-station order and shipping time for items BCM'd (NB1 + NB2);
   10) t - time period over which the data was gathered;
   11) FH - flying hours for the data period t; and
   12) FH' - flying hour forecast.

c) Compute the flying hour forecast factor (F),

$$F = (FH'/t') / (FH/t).$$

d) Compute the demand rates:

$$\lambda_1 = (NB1 + NR1) / t;$$

$$\lambda_2 = (NB2 + NR2) / t; \text{ and}$$

$$\lambda = \lambda_1 + \lambda_2.$$

e) Compute the uncapacitated pipeline quantity.

   1) Administrative pipeline forecast (PA'):

$$PA' = F \times \lambda \times E(IP)/t.$$

   2) Awaiting parts pipeline forecast (PP'):

$$PP' = F \times \lambda_2 \times E(AWP)/t.$$

   3) Wholesale resupply pipeline forecast (PW'):

$$PW' = F \times (NB1 + NB2) \times E(OST)/t.$$

   4) Total uncapacitated pipeline forecast (PT'):

$$PT' = PA' + PP' + PW'$$

f) Provide Poisson protection to PT', at the specified safety level, as was done in Equation 2.4 The resulting quantity is QP.

g) Compute the quantity expected to be in repair process one.

1) Compute repair rate (μ_1):

$$\mu_1 = \lambda_1 + 1/E(RC1).$$

2) Project future traffic intensity (ρ_1') as:

$$\rho_1' = F \times \lambda_1 / \mu_1.$$

3) Project the protected number of demands in (0,t') and the expected number of repairs:

QL1(t') = the SLth percentile of the CDF of a Poisson distribution with rate $F \times \lambda_1 \times t'$; and

$ER1(t') = \mu_1 \times t'$.

4) If $\rho_1' < 1$, and $QL1(t') < ER1(t')$, solve for the number in repair process one (Q1) to the desired safety level (SL1) by using Equation 3.7:

$$Q1 = \ln(1-SL1)/\ln(\rho_1') - 1,$$

with the requirement that $Q1 > 0$.

5) If $\rho_1' \leq 1$, and $ER1(t') < QL1(t')$, use the deterministic repair approximation provided in Equation 3.8:

$$Q1(t') = Po + QL1(t') - ER1(t').$$

6) If $\rho' > 1$, use the approximation provided in Equation 3.9:

$B1(t') = (\lambda_1 - \mu_1) \times t'$;

QB1(t') = the number for which the value of the CDF of a Poisson distribution with rate B1(t') is closest to SL1; and

$Po = F \times \lambda_1 \times T$;

then

$$Q1(t') = Po + QB1(t').$$

h) Repeat step g above using the appropriate variables for process two to compute the repair process two allowance (Q2).

i) The final allowance is the sum of the individual allowances (Q), plus the allowed operating level (OL) of one.

   1) If neither the buildup approximation nor the deterministic repair approximation had to be used in computing the allowances for processes one and two, the final allowance (QT) is a steady state allowance, and is computed as follows:

      let

      $$QS = Q1 + Q2 + QP;$$

      then

      $$QT = QS + OL.$$

   2) If either of the repair processes used one of the approximations, then the steady state allowance is not available. The allowance for the endurance period is:

      let

      $$QS(t') = \{Q1(t') \text{ or } Q1\} + \{Q2(t') \text{ or } Q2\} + QS;$$

      then

      $$QT(t') = QS(t') + OL.$$

3. Computing the Safety Level

The proposed model requires that safety level parameters be established for the uncapacitated (admin, AWP, and wholesale resupply) pipeline, repair process one, and repair process two. There are numerous ways to combine the three safety level settings to provide an overall safety level equal to the specified safety level. The simplest method would be to let all three equal the specified level, but flexibility in varying the safety level settings for the two repair processes is extremely desirable. Consequently, the safety level parameter for the admin, AWP, and wholesale resupply pipeline is set at the specified safety level, and the safety levels for the two repair processes are combined to meet the specified safety level based on the total number of days that items had actually been in each process during the data collection period. The number in the repair process is the product of the demand rate and the average time in the process. Therefore,

let

SL = specified safety level;

SL1 = process one safety level;

SL2 = process two safety level;

P1 = average number in process one
$= \lambda_1 \times E(RC1)$; and

P2 = average number in process two
$= \lambda_2 \times E(RC2)$.

Then the following relationship must be satisfied:

$$SL \cdot (P1 + P2) = SL1 \cdot P1 + SL2 \cdot P2. \qquad (3.10)$$

SL is set by higher authority and P1 and P2 are obtained from the data base; to specify SL1 or SL2 before the final allowances may be computed. For computation purposes, SL will be fixed at 0.90.

It was found in tests of sample items that setting SL1 at about 0.97 or 0.98 generally gave the best results in terms of overall protection. It was necessary to modify this in cases where the linear relationship established in Equation 3.10 could not hold. There were a few items for which no maintenance action resulted in AWP time; the safety level was set to 0.90 in these cases.

4. An Example of the Proposed Model

The following example should help to demonstrate how the model works in computing an allowance. The same basic data used in the Chapter II example is utilized to facilitate comparison.

a) Gather TAT data.

TAT element data (days)

BCMs:	IP	RC1	RC2	AWP	TAT	
BCM 1	0	2	-	-	2	
BCM 2	0	1	-	-	1	NB1 = 2 units.
BCM 3	1	-	8	10	19	NB2 = 1 unit.
Repair data (reordered):						
Repair 1	0	1	-	-	1	
Repair 3	0	5	-	-	5	
Repair 4	0	0	-	-	0	
Repair 5	1	2	-	-	3	
Repair 6	1	3	-	-	4	
Repair 8	0	5	-	-	5	
Repair 9	1	1	-	-	2	NR1 = 7 units.
Repair 2	1	-	7	31	39	
Repair 7	4	-	9	24	37	
Repair 10	0	-	5	3	8	NR2 = 3 units.

b) Compute the following from the data (revised TAT limits used):

Action	Var	Total (days)	Mean
Administrative	IP	9	.692
Process one	RC1	20	2.22
Process two	RC2	29	7.25
Awaiting parts	AWP	68	17.00
Order and ship	OST	--	26.00
Data period	t	90	
Forecast period	t'	60	
Flying hours	FH	1453 hours	
Forecast flying hours	FH'	1700 hours	

c) Compute the forecast factor (F):

$$F = (FH'/t')/(FH/t),$$
$$F = (1700/60)/(1453/90),$$
$$F = 1.755 .$$

d) Compute the demand rates:

$$\lambda_1 = (NB1+NR1)/t,$$
$$\lambda_1 = 9/90 = 0.10 \text{ units/day.}$$

$$\lambda_2 = (NB2+NR2)/t,$$
$$\lambda_2 = 4/90 = 0.0444 \text{ units/day.}$$

$$\lambda = \lambda_1 + \lambda_2,$$
$$\lambda = 0.1444 \text{ units/day.}$$

e) Compute the uncapacitated pipeline allowance.

1) Admin pipeline forecast (PA'):

$$PA' = F \times \lambda \times E(IP)/t,$$
$$= 1.755 \times .1444 \times .692,$$
$$= 0.175 \text{ units.}$$

2) Awaiting parts pipeline forecast (PP'):

$$PP' = F \times \lambda_2 \times E(AWP),$$
$$= 1.755 \times .0444 \times 17.0,$$
$$= 1.325 \text{ units.}$$

3) Wholesale resupply pipeline forecast (PW'):

$$PW' = F \times ((NB1+NB2)/t) \times E(OST),$$
$$= 1.755 \times (3/90) \times 26,$$
$$= 1.521 \text{ units.}$$

4) Provide Poisson protection for this pipeline:

$$PT' = PA' + PP' + PW',$$
$$= .175 + 1.325 + 1.521,$$
$$= 3.021 \text{ units.}$$

Poisson probabilities for a mean of 3.021 are:

n	f (n)	F (n)
0	0.0488	0.0489
1	0.1473	0.1960
2	0.2225	0.4185
3	0.2240	0.6425
4	0.1692	0.8117
5	0.1022	0.9140*
6	0.0515	0.9654
7	0.0222	0.9876
8	0.0084	0.9960

*n = 5 provides protection closest to 0.90,

so

$$QF = 5 \text{ units.}$$

f) Compute the quantity expected to be in repair process one.

1) Compute repair rate (μ_1):

$$\mu_1 = \lambda_1 + 1/E(RCT),$$
$$= .10 + (1/2.22),$$
$$= 0.55 \text{ units/day.}$$

2) Compute the expected number of repairs in $(0,t')$:

$ER1(t') = \mu_1 \times t'$,

so

$$ER1(90) = .55 \times 90, = 49.50 \text{ units.}$$

3) Compute the protected number of demands in $(0,t')$:

let

$SL1 = 0.98$;

then

$QL1(t')$ = 98th percentile of the CDF of a Poisson $(F \times \lambda_1 \times t')$ distribution;

$$F \cdot \lambda_1 \cdot t' = 1.755 \times .10 \times 90, = 15.795 \text{ units;}$$

therefore

$$QL1(90) = 24 \text{ units.}$$

4) Project future traffic intensity (ρ_1') as:

$$\rho_1' = F \times \lambda_1 / \mu_1,$$
$$= 1.755 \times .10 / .55, = 0.319 .$$

5) Solve for the protected number in repair process one.

$\rho_1 < 1$, and $ER1(90) > QL1(90)$, therefore compute Q1 as:

$$Q1 = (\ln(1 - SL1)/\ln(\rho_1)) - 1,$$
$$= (\ln(.02)/\ln(.319)) - 1, = 2.42 \text{ units.}$$

g) Solve for SL2:

$$P1 = \lambda_1 \times E(RC1), = 0.222 \text{ units;}$$

$$P2 = \lambda_2 \times E(RC2), = 0.322 \text{ units; and}$$

$$SL \times (P1+P2) = SL1 \times P1 + SL2 \times P2,$$

$$.90 \times .544 = .98 \times .222 + SL2 \times .322,$$

and

$$SL2 = 0.845 .$$

h) Repeat the above using the appropriate variables for process two:

$$\mu_2 = \lambda_2 + 1/E(RC2),$$
$$= .0444 + 1/7.25,$$
$$= 0.182 \text{ units/day.}$$

$ER2(t') = \mu_2 t'$,

so

$$ER2(90) = .182 \times 90,$$
$$= 16.38 \text{ units;}$$

$B2(t') = F \cdot \lambda_2 \cdot t'$;

so

$$B2(90) = 1.755 \times .0444 \times 90,$$
$$= 7.013 \text{ units;}$$

$$QI(90) = 84.5\text{th percentile of the CDF of Poisson}(7.013),$$
$$= 9 \text{ units;}$$

$$\rho_2' = F \times \lambda_2 / \mu_2,$$
$$= 1.755 \times .0444/.182,$$
$$= 0.428; \text{ and}$$

$\rho_2' < 1$, and $ER2(90) > QL2(90)$, so find Q2 as:

$$Q2 = (\ln(1 - SL2)/\ln(\rho_2')) - 1,$$
$$= (\ln(1 - .845)/\ln(.428)) - 1,$$
$$= 1.20 \text{ units.}$$

i) Compute the final allowance (QT) as:

$$QS = Q1 + Q2 + QP,$$
$$= 5 + 2.42 + 1.20,$$
$$= 8.62 \Rightarrow 9 \text{ units; and}$$

$$QT = QS + OL,$$
$$= 9 + 1,$$
$$= 10 \text{ units.}$$

Table XI provides a summary of the values computed by this model versus the RIMSTOP levels. Comparisons between the RIMAIR model and the proposed model will be provided in Chapter IV.

TABLE XI

RIMSTOP - Proposed Model Allowances

RIMSTOP Level	Model Expression	Example Quantity	
Repair cycle		2.72	
Administrative	PA'		0.18
Process one	P1'		0.47
Process two	P2'		0.75
Awaiting parts	PP'		1.33
Order and shipping time	PW'	1.52	

Total pipeline forecast	P'	4.24	
		======	
Protected allowances	Q1	2.42	
	Q2	1.20	
	QP	5	

Total protected quantity (rounded)	QS	9	
		======	
Safety Level	QS-P'	4.76	
Operating Level	OL	1.00	
Final allowance	QT	10	

IV. COMPARING THE MODELS

A. QUEUE CHARACTERISTICS

1. Theoretical Differences

The M/M/∞ queueing model, which is the theoretical basis for the RIMAIR allowance computation model, and the M/M/1 queueing model, which underlies the repair process allowance computation in the proposed model, were presented separately in Chapters II and III, respectively. Figure 4.1 summarizes their characteristics. The M/M/1 queueing model is distinguished from the M/M/∞ model by the limit that exists on its service capacity. The assumption of a single server introduces the possibility that a unit entering the system will find the server busy, and therefore must wait for service. Use of the M/M/∞ model presumes that there will always be an empty server, implying that waiting time will be zero.

The difference becomes most apparent when the demand rate approaches or exceeds the service rate. Even under these conditions, there is still no waiting time experienced in the M/M/∞ system; whereas the number of units awaiting service in the M/M/1 system grows significantly. When the demand rate exceeds the service rate, the M/M/1 system becomes saturated and the only bound that exists on the number awaiting service in the system is the number in the population itself.

This basic difference brings about every other difference between the systems. For the same traffic intensity ρ, the number expected to be in the M/M/1 system is higher because of the presence of units waiting for service. For the same reason, the total time that a unit is expected to be in the M/M/1 system is higher.

Parameter Symbol	Parameter Name	Assumptions M/M/∞		M/M/1
λ	Arrival rate	Independent arrivals Constant rate Exponential interarrival times		Same Same Same
μ	Service rate	Exponential service times, identical for each server Each service is independent		Exponential service times, single server Same
ρ	Traffic intensity	$\rho = \lambda/\mu$		$\rho = \lambda/\mu$
P	Mean # in system (pipeline quantity), infinite population	$P = \rho$	$0<\rho<1$	$P = \rho/(1-\rho)$
			$\rho = 1$	P undefined
			$\rho > 1$	$P \rightarrow \infty$
	finite population K		$\rho \ll 1$	$P = \rho + \rho^2$
			$\rho \rightarrow 1$	$P = K/2 + K(K+2)(\rho-1)/12$
			$\rho \gg 1$	$P \rightarrow K - 1/\rho$
T	Mean time in system	$T = P/\lambda = 1/\mu$		$T = 1/(\mu-\lambda)$
W	Mean wait time	$W = 0$		$W = T - 1/\mu$
$\pi(n)$	Prob of being in state n, infinite pop	$\pi(n) = \frac{e^{-\rho}\rho^n}{n!}$	$\rho < 1$	$\pi(n) = (1-\rho) \times \rho^n$
			$\rho \geq 1$	$\pi(n) = 0$ (transient)
	Prob of being in state n, finite pop K		$\rho \neq 1$	$\pi(n) = (1-\rho)\rho^n/(1-\rho^{K+1})$
			$\rho = 1$	$\pi(n) = \frac{1}{K+1}$

Figure 4.1 Queue Characteristics, M/M/∞ vs M/M/1.

2. Differences in Application

Application of the data base to both models starts with the same information: demands per unit time and average service time. The major difference in the models shows up in the computation of the service rate, μ. In the M/M/∞ model, the service rate is the reciprocal of the average service time ($P = 1/T$), which is also the mean time in the system. In the M/M/1 model, however, the mean time in the system is the reciprocal of the <u>difference</u> between the service rate and the arrival rate, ($P = 1/(\mu-\lambda)$). This expression is valid only when the service rate exceeds the demand rate. In order to compute allowances, therefore, it is necessary to assume that on the average the system is not saturated over t (the data collection period). This allows the service rate to be computed as $\mu=\lambda+1/T$, and the actual service rate used in the M/M/1 model will be higher than that in the M/M/∞ model given the same values for demand rate (λ) and average time in the system (T). Consequently, the traffic intensity ρ is lower in the M/M/1 formulation, and the assumption that the system is not saturated during the demand period leads to a traffic intensity value (ρ) that is less than one. By contrast, the ρ value in the M/M/∞ queue can assume any value because the queue cannot become saturated.

The fact that both models assume that average past experience did not result in saturation is a key point. If a model is developed without knowing any more about the service facility than the fact that it had never been saturated, a modeller would be hard pressed to decide on the appropriate model; both of the queueing models detailed here could be used. The key difference between the two models lies in the ability to forecast the effects of future demand increases. Use of the M/M/∞ model in forecasting implies a belief that the system will never become saturated, no matter how much demand increases; use of the M/M/1 model allows for the possibility that the system can become saturated if demand increases sufficiently. It was belief in this latter condition, limited repair capacity, that led to the development of the proposed model.

3. Theoretical Allowance Comparison

The allowances that would be calculated by each theoretical model, given the appropriate traffic intensity (or pipeline quantity) and protection level are provided in Tables XII and XIII . (Table XII was computed by listing the allowance quantity that is closest to the specified SL.) The differences generated in an infinite population queueing situation by the underlying theoretical models are worth noting.

The situation in which there is no forecast demand increase is considered first. In this situation, both models use the same pipeline quantity computed as $P = \lambda T$, as explained in the previous section. Table XII indicates that the M/M/1 model will generate an allowance of 4 units if the pipeline quantity is 1.5 units (traffic intensity 0.60) and the protection level is 0.90. By comparison, Table XIII shows that the M/M/∞ model will generate an allowance of only 3 units when the same pipeline quantity and protection level is used.

If the forecast factor (F) is used to anticipate increased demand, then the difference between the allowances computed by the models becomes larger. If F=1.33, the allowance computed by the M/M/1 model given the input data from the previous example would be 9 units: the forecast traffic intensity would be 0.80 (1.33 x 0.60), which leads to an average pipeline quantity of 4 units, and a protected quantity of 9. The M/M/∞ model allowance would not increase

TABLE XII

M/M/1 Model Allowances, Infinite Population

Traffic Intensity ρ	Average Pipeline Quantity P	Protection Level (SL)						
		0.5	0.75	0.85	0.9	0.95	0.98	0.99
0.05	0.053	0	0	0	0	0	1	1
0.1	0.111	0	0	0	0	1	1	1
0.2	0.25	0	0	0	1	1	2	2
0.3	0.429	0	0	1	1	2	2	3
0.4	0.667	0	1	1	2	2	3	4
0.5	1.00	0	1	2	2	3	5	6
0.6	1.50	0	2	3	4	5	7	8
0.7	2.333	1	3	4	6	7	10	12
0.8	4.0	2	5	8	9	12	17	20
0.9	9.0	6	12	17	21	27	36	43
0.95	19.0	13	26	36	44	57	75	89
0.98	49.0	33	68	93	113	148	194	228
0.99	99.0	68	137	188	228	297	388	457

TABLE XIII

M/M/∞ Model Allowances

Average Pipeline Quantity ρ = P	Protection Level (SL)						
	0.5	0.75	0.85	0.9	0.95	0.98	0.99
0.1	0	0	0	0	1	1	1
0.2	0	0	0	0	1	1	1
0.3	0	0	0	1	1	2	2
0.4	0	0	1	1	1	2	2
0.5	0	0	1	1	2	2	2
0.6	0	1	1	1	2	2	3
0.7	0	1	1	1	2	3	3
0.8	0	1	1	2	2	3	3
0.9	0	1	1	2	2	3	3
1.0	0	1	2	2	3	3	4
1.5	1	2	2	3	3	4	5
2.0	1	2	3	3	4	5	6
3.0	2	4	4	5	6	7	8
5.0	4	6	7	8	8	10	10

at all: the 0.90 protection level allowance for a traffic intensity of 2.00 (1.33 x 1.5) is still 3 units. The effect of having adequately many servers is quite substantial; assuming that units will not have to wait for service will cause allowances to be significantly lower than if only a single server is available.

4. Applied Allowance Differences

The RIMAIR and the proposed model allowance computation procedures can be directly compared if the following conditions are met:

a. all actions are repairs without AWP,

b. none of the TAT observations is limited,

c. the average IP value is 0.0,

d. the demand rate (λ) is specified, and

e. the M/M/1 system is not saturated.

In other words, direct comparison can be made only if the data provide the same SKD+RPR times after the differing TAT element limits are applied, and all other TAT element observations are zero. In this restricted case, both models use the same values for demand rate (λ) and process time (T). Consequently, both processes have the same expected pipeline (P), $P = \lambda T$. The service rates will be higher for the M/M/1 queue, as explained previously. The M/M/∞ model has service rate (ρ) equal to P, while for the M/M/1 queue, ρ can be expressed in terms of P as follows:

$$P = \rho \;/\; (1-\rho)$$

so

$$\rho = P \;/\; (P+1)$$

Using this relationship, it is straightforward to compare the process rates and allowances generated by the two models for any specified level of demand. Table XIV provides two examples.

The top example (A) compares allowances computed by each model when the forecast demand rate is the same as the experienced demand rate. There is no difference in the allowances generated when the average pipeline quantity is 1.0 unit or less. As P increases, however, the proposed model computes allowances that are greater than those computed by the RIMAIR model. At P=5.0, the difference in allowance is 4 units: 8 is the allowance computed by the RIMAIR model, and 12 is computed by the proposed model. For larger values of P, the deterministic service approximation (for the three month endurance period) provides allowances at least as large as those computed by the RIMAIR model, but less than would have been computed by the infinite population formula for the expected number in the system. If that formula had been used, the allowances would have been much higher: 23 for P = 10 units and 35 for P = 15.

The bottom table shows the results of using the proposed model and forecasting a 25% increase in demand, but with no increase in the repair rate. For all values of P' equal to or greater than 1.25, the proposed model computes a higher allowance, even when the approximations for the three month endurance period are used.

The endurance period approximations provide a capability to project requirements that are more "reasonable" than the unbounded solutions in the infinite population case, but they are still not bounded as they would be if the number in the population were known and the finite population model used. The allowances provided by the two endurance period approximations can grow without bound because there is no limit on t', and it is important to note that they do not provide steady state solutions.

TABLE XIV

Model Allowance Comparison

A. Comparison with no forecast demand increase.

Safety Level: SL = 0.90
Demand rate: λ = 0.50/ day
Endurance period: t' = 3 months
Experienced TAT: T as listed
Forecast factor: F = 1.00

T days	P	RIMAIR model ρ	RIMAIR model Allowance	Proposed model ρ	Proposed model Allowance	Increase (%)
0.2	0.1	0.1	0	0.091	0	0
0.4	0.2	0.2	0	0.167	0	0
0.6	0.3	0.3	1	0.231	1	0
1.	0.5	0.5	1	0.333	1	0
2.	1.0	1.0	2	0.500	2	0
3.	1.5	1.5	3	0.600	4	33
4.	2.0	2.0	3	0.667	5	60
6.	3.0	3.0	5	0.750	7	43
10.	5.0	5.0	8	0.833	12	50
20.	10.0	10.0	14	0.909	14*	0
30.	15.0	15.0	20	0.938	20*	0

* indicates cases where the deterministic service approximation for the endurance period was used.

B. Comparison using the above input data to predict process rates and forecasting increased demand.

SL, L, t, and T as above.
Forecast factor: F = 1.25
Forecast demand: λ' = 0.625/day
Forecast for ρ: ρ' = F x ρ
Forecast for P: P' = λ' x T

T days	P'	RIMAIR model ρ'	RIMAIR model Allowance	Proposed model ρ'	Proposed model Allowance	Increase (%)
0.2	.125	0.125	0	0.114	0	0
0.4	.250	0.250	1	0.208	1	0
0.6	.375	0.375	1	0.288	1	0
1.	.625	0.625	1	0.375	1	0
2.	1.25	1.25	2	0.625	4	100
3.	1.88	1.88	3	0.750	7	133
4.	2.50	2.50	4	0.833	12	200
6.	3.75	3.75	6	0.938	9*	50
10.	6.25	6.25	9	1.042	10**	11
20.	12.50	12.50	17	1.136	23**	35
30.	18.75	18.75	24	1.172	31**	29

* indicates cases where the deterministic service approximation for the endurance period was used.

**indicates cases where the endurance period buildup rate approximation was used.

The steady state solution for the M/M/∞ model is provided by the Poisson distribution, and time to reach steady state is never at issue. Allowing the M/M/1 system to become saturated, however, requires that an endurance period be specified in order to compute allowances for the transient states. Even if the system is not saturated, the steady state approximation using $SL=1-(\rho^{P+1})$ provides the same allowance whether $\lambda=0.01$/day or $\lambda=10$/day, as long as the ratio λ/μ is constant. The time to reach this steady state is considerably longer in the case $\lambda=0.01$/day, however, and the allowance necessary to support a 90 day operational period is lower.

B. SENSITIVITY TO INPUT DATA

1. Data Base Problems

The data base used as input to either model has numerous problems, particularly in the identification of manufacturer's parts numbers to national stock numbers. Because of these problems, ASO personnel are required to manually massage the received data prior to the computation of allowances. As a minimum, they compare at least two sets of data covering similar usage periods at similar sites before accepting any single set of inputs for allowance computation. Large differences in TAT, percentage of demands repaired, and demand rates are common. The current model is reasonably stable in that it requires fairly substantial changes in one of these factors before an increased or decreased allowance is computed; the RIMAIR model should be just as stable.

The high price of most components; the usual tight funding constraints on transportation, repair, and procurement budgets; and the long lead times necessary for both budgeting and procurement all create a strong influence for

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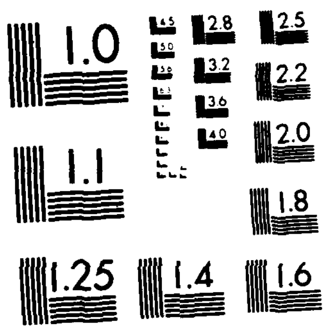

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

establishing an item's allowances once only when the item first enters the supply system. Frequently identical allowances are established for a group of sites, such as all aircraft carriers, and are considered fixed unless extraordinary conditions arise. Allowances are changed, of course, primarily as unanticipated demand forces increases. Poor initial provisioning, lower than expected reliability or maintainability, lack of repair parts, and numerous other situations cause these increases. The environment remains, however, to minimize change as much as possible.

Proposing the use of a new model requires that an estimate of its effect on the established system be made. In the case of the model proposed in this thesis, the effect could be significant. The use of relaxed TAT limits causes higher allowances to be generated for many items. The inclusion of BCM TAT in the pipeline also increases allowances. The use of the capacity-constrained model would cause allowance increases for items with P values above about 1 unit. None of these effects is necessarily bad; in fact, establishing the validity of the proposed model might create a vehicle that would help justify additional funds for needed support. Certainly the existence of very real capacity constraints on the VAST system is well documented. Establishing a legitimate cost for the allowances needed to support this system at a mobilization tempo could provide planners with information for making a better cost-effectiveness tradeoff on system support. It remains to be shown, however, whether the model is useful on a cruise-to-cruise or site-to-site basis, or whether it is too sensitive to small changes in input data.

2. Selected Examples

The relative sensitivity of the RIMAIR model compared to the proposed model can be demonstrated using the sample input data used previously. In order to compare allowances on a fair basis it is necessary to use the same input data in each model. Consequently, the RIMAIR model will be modified to include BCM TAT and to use the relaxed TAT limits developed in Chapter III. The result of doing this is shown in Table XV . Part A of the table provides the input data, which is applicable to all examples in this section. Part B shows the allowance computation with both the original and revised inputs to the RIMAIR model, and the allowance computation for the proposed model.

Inclusion of the BCM TAT and use of the relaxed TAT constraints increases the pipeline quantity used in the RIMAIR model from 3.14 to 3.98 units. The pipeline is somewhat higher in the proposed model because of the forecast factor. If the forecast factor were 1.00, both models would have the same total pipeline; with a forecast factor greater than one, the number in the repair processes of the proposed model grow faster than the forecast factor because of the increased number of units awaiting service. The major difference between the allowances computed by the two models, however, is the increased safety level quantity computed by the proposed model.

The following examples are provided to illustrate the effect that different input data would have on the allowances generated by the RIMAIR model and the proposed model. In each case, the results of the allowances computed will be compared to the allowances shown in Table XV Allowances computed for the RIMAIR model include the BCM TAT and use the relaxed TAT limits. The example cases are:

TABLE XV

RIMAIR - Proposed Model Allowance Comparison

A. Input data

	TAT element data (days)				
	IP	RC1	RC2	AWP	TAT
BCM 1	0	2	-	-	2
BCM 2	0	1	-	-	1
BCM 3	1	-	8	10	19
Repair 1	0	1	-	-	1
Repair 2	1	-	7	31	39
Repair 3	0	5	-	-	5
Repair 4	0	0	-	-	0
Repair 5	1	2	-	-	3
Repair 6	1	3	-	-	4
Repair 7	4	-	9	24	37
Repair 8	0	5	-	-	5
Repair 9	1	1	-	-	2
Repair 10	0	-	5	3	8

Action	Var	Total (days)	Mean
Administrative	IP	9	.692
Process one	RC1	20	2.22
Process two	RC2	29	7.25
Awaiting parts	AWP	68	17.00
Order and ship	OST	--	26.00
Data period	t	90	
Forecast period	t'	60	
Flying hours	FH	1453 hours	
Forecast flying hours	FH'	1700 hours	
Flying hour factor	F	1.755	

B. Allowance Computation

RIMSTOP Level	RIMAIR Model Var	Orig # units	Rev # units	Proposed Model Var	# units
Repair cycle	PR'	1.62	2.03	PA'+P1'+P2'+PP'	2.72
OST	PB'	1.52	1.95*	PW'	1.52
Total pipeline	P'	3.14	3.98	P'	4.24
Safety	QP-P'	1.86	2.02	QS-P'	4.76
Operating	OL	1.00	1.00	OL	1.00
Total	QT	6	7	QT	10

*OST figure for revised RIMAIR model includes BCM TAT.

a) The percentage of successful repairs is increased to 100% (same TAT observed).

b) The percentage of successful repairs in decreased to 46% .

c) The flying hour factor (F) is 1.00.

d) The flying hour factor (F) is 1.25.

e) No AWP time is experienced.

These are the type of differences generally observed when sites with similar aviation support missions are compared. These cases are "what if" cases, using the TAT data from the 13 maintenance actions listed in Table XV to compute allowances as if the number of successful repairs were different in cases a) and b) , as if the future demand forecast were different in cases c) and d), and as if the piece-part support were improved in case e).

The case (a) assumption, that all 13 inductions resulted in successful repair, has the same effect on the allowances computed by both models. Table XVI A presents the results in the following format. The RIMAIR model and the proposed model are shown on the left and right side of the table, respectively. Two sets of output are presented for each model. For the RIMAIR model, the output from the Table XV example (in the column labeled "Rev") and the output that results from the change being illustrated by the current case (column labeled "Now") are provided. The columns labeled "Orig" and "Now" for the proposed model represent the Table XV example and the current case, respectively. Within each set of output, the data are grouped to help illustrate the pipelines that are computed by the models, and the allowances that are generated by the pipelines.

Table XVI A shows that the allowance that would result if all of the 13 units inducted had been successfully repaired would be 5 units using the RIMAIR model, and 8

TABLE XVI

Model Comparison: Varying Repair Percentage

A. 100% of items inducted are repaired.

RIMAIR Model			Proposed Model				
Variable	Rev	Now	Var	Orig		New	
			PA'	.18		.18	
			PP'	1.33		1.33	
			PW'	1.52		0.0	
PB'	1.95	0.0	PT' ->QP	3.02	5	1.50	3
			P1' ->Q1	.47	2.42	.47	2.42
PR'	2.03	2.46	P2' ->Q2	.75	1.20	.75	1.20
P'	3.98	2.46	P'	4.24		2.72	
SL	2.02	1.54	SL	4.76		4.28	
QP	6	4	QS		9		7
OL	1	1	OL		1		1
Total	7	5			10		8

B. Only 46% of items inducted are repaired.

RIMAIR Model			Proposed Model				
Variable	Orig	Now	Var	Orig		Now	
			PA'	.18		.18	
			PP'	1.33		1.33	
			PW'	1.52		3.55	
PB'	1.95	4.87*	PT' ->QP	3.02	5	5.05	8
			P1' ->Q1	.47	2.42	.47	2.42
PR'	2.03	1.13*	P2' ->Q2	.75	1.20	.75	1.20
P'	3.98	6.01	P'	4.24		6.27	
SL	2.02	2.99	SL	4.76		5.73	
QP	6	9	QS		9		12
OL	1	1	OL		1		1
Total	7	10			10		13

units if the proposed model were used. These allowances are both two units less than the comparable allowances generated in Table XV This is the result of eliminating the wholesale resupply pipeline.

The case (b) results are shown in Table XVI B. The number of successful repairs to is reduced to 6 of the 13 units inducted (46%). The starred (*) quantities for the RIMAIR model actually depend on which maintenance actions (high TAT, low TAT, or whatever) resulted in BCMs; the total RIMAIR pipeline will be the same in either case. The allowance computed by the RIMAIR model increases 3 units to a total of 10 units when the number of BCMs increase. The allowance computed by the proposed model also increases 3 units, to a total of 13. In both models, the increase is due to the larger wholesale resupply pipeline that results when fewer units are repaired locally.

If BCM TAT had not been included in the RIMAIR pipeline, the allowances that would have resulted would have been lower. In the case of 100% repair, the allowance would decrease from the original 6 to 5 units. In the case of fewer repairs, however, the final allowance depends on knowing specifically which of the maintenance actions listed in Table XV A resulted in units being declared BCM. If the units with the highest TAT had been declared BCM, the resulting allowance would be only 6 units; there would be no increase from the original allowance because the increased resupply pipeline is offset by a reduced repair pipeline. If the 6 units with the highest TAT had been repaired, however, the increased repair pipeline causes the resulting allowance to increase to 8 units.

This helps to illustrate the need for including the BCM TAT in the pipeline. The expected number of units in the total pipeline does not change in these two cases, but the allowance computed varies by two units because in the first case (where the allowance remains 6), the BCM'd items had substantial TAT that was ignored; in the second case (allowance 8), they had relatively little TAT, so the deficiency was minimal.

Cases (c) and (d) illustrate the effect demand forecasting has on the allowances. In the first of these, presented in Table XVII A, the allowance is computed directly from the input data, without any forecasted demand increase; the pipeline quantities for each model are the same. In case (d), a forecast factor of 1.25 is used.

The allowances computed by the proposed model are still greater than the allowances computed by the RIMAIR model in cases (c) and (d), but the amount that it is greater has decreased. In case (c) (F=1.00), the proposed allowance quantity is reduced two in the uncapacitated pipeline and two more in the repair cycle because the traffic intensities have been significantly reduced. The resulting allowance of 6 units is now only one unit higher than the allowance of 5 computed by the RIMAIR model. The reduction in allowance in the proposed model that results from lower traffic intensity can be used as an argument that increased repair capacity for some items would result in lower allowance quantities. In reverse, it shows the allowance increase necessary when forecasting higher demand rates without an increase in repair capacity.

Increasing the forecast from 1.00 to 1.25 raises all of the rates by 25%, as shown in Table XVII B. The expected number in the repair pipeline of the proposed model increases slightly more than this. Both models exhibit lower allowances than in the original case where F=1.755, but each increased the allowance one unit over the case where F=1.00.

TABLE XVII

Model Comparison: Varying Forecast Factors

A. Demand forecast factor (F) is 1.00.

RIMAIR Model Variable	Rev	Now	Proposed Model Var	Orig		Now	
			PA'	.18		.10	
			PP'	1.33		.75	
			PW'	1.52		0.87	
PE'	1.95	1.11	PT' ->QP	3.02	5	1.72	3
			P1' ->Q1	.47	2.42	.22	1.30
PR'	2.03	1.16	P2' ->Q2	.75	1.20	.32	.32
P'	3.98	2.27	P'	4.24		2.27	
SL	2.02	1.73	SL	4.76		2.73	
QP	6	4	QS		9		5
OL	1	1	OL		1		1
Total	7	5			10		6

B. Demand forecast factor (F) equals 1.25 .

RIMAIR Model Var	Rev	Now	Proposed Model Var	Orig		Now	
			PA'	.18		.12	
			PP'	1.33		.94	
			PW'	1.52		1.08	
PE'	1.95	1.39	PT' ->QP	3.02	5	2.15	4
			P1' ->Q1	.47	2.42	.29	1.65
PR'	2.03	1.45	P2' ->Q2	.75	1.20	.44	.57
P'	3.98	2.83	P'	4.24		2.88	
SL	2.02	2.17	SL	4.76		3.12	
QP	6	5	QS		9		6
OL	1	1	OL		1		1
Total	7	6			10		7

In cases (a) and (b), both the RIMAIR model (with BCM TAT included and using revised TAT constraints) and the proposed model showed the same relative change between allowances; in cases (c) and (d), the proposed model exhibited larger decreases in allowance because the traffic intensities were lower. The last case, case (e), shows the effect when no AWP time is experienced. Table XVIII provides

TABLE XVIII

Model Comparison: AWP Eliminated

RIMAIR Model Var	Rev	Now	Proposed Model Var	Orig		New	
			PA'	.18		.18	
			PP'	1.33		0.0	
			PW'	1.52		1.52	
PB'	1.95	1.11	PT'	3.02		1.70	
			->QP		5		3
			P1'	.47		1.63	
			->Q1		2.42		3.79
			P2'	.75		0.0	
PR'	2.03	1.16	->Q2		1.20		0.0
P'	3.98	2.27	P'	4.24		3.33	
SI	2.02	1.73	SL	4.76		3.67	
QP	6	4	QS		9		7
OL	1	1	OL		1		1
Total	7	5			10		8

the results. The proposed model again exhibits the same decrease in allowance (two units) that the RIMAIR model does. With no AWP time experienced, all of the units are assumed to go through the same repair process in the proposed model, and the expected number in the system (at

F=1.755) is higher than it was when there were two separate repair processes occurring in parallel. This is a flaw in the proposed model; the expected number in the system should not rise this much.

The proposed model did not exhibit any more variability in cases a), b), and e) than the RIMAIR model with revised input data did. In cases c) and d), which examined the effect of forecasting, the changes in the proposed model were larger, which is exactly what it was designed for. In the case of F=1.00, the proposed model computed an allowance that was only 1 unit higher than the RIMAIR allowance. At F=1.25, the proposed model allowance was still one unit higher. In the original case, however, with F=1.755, the proposed model computed an allowance that was three units higher, because the traffic intensities in the repair processes were increased significantly, without any expected increase in the repair rate.

These few examples help to illustrate the changes brought about in a single item when input factors are changed. In Chapter V, the complete sample of 79 items is examined to show the effects some of these same factors have when the models are applied across part of the inventory.

V. MODEL SIMULATION

A. USS RANGER DATA BASE

The data base provided by NAMSO was used in a simulation to test the hypotheses that evolved during the modelling process. The processing dates for each action (i.e. removal, induction, etc.) were used to simulate the performance of the allowance levels developed by both the RIMAIR model and the proposed model.

Simulating with real-world data has both advantages and serious drawbacks. The key advantage is that the assumptions that were developed about the distribution of the TAT element times did not have to be used in generating random numbers, as would have to be done in developing a Monte-Carlo simulation. The only statistics that were drawn from the data were the average TAT element times and the number of transactions of each type that occurred; all repair cycle actions were assumed to happen on the date indicated in the data base.*

There are two disadvantages to using real-world data in simulating the performance of the models. First, it does not allow for multiple tests of any given hypothesis. No confidence interval for the results can be obtained, whereas repeated trials of a Monte-Carlo simulation with different

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*Wholesale resupply time was not included in the data base. This time interval was set deterministically as 26 days, which was computed as the expected value of wholesale resupply time when 85% of required items are supplied in 15 days, and the remaining 15% are delayed an additional 74 days. These times are the NAVSUP goals for wholesale resupply of aviation activities. Lack of actual resupply times is not considered a serious deficiency because the proposed model was built to model the repair process and comparisons between the two models are not significantly affected.

random numbers would allow the construction of confidence intervals. Consequently, results from the various simulations may be accepted as an indication of how one model performs against the other, but are in no way conclusive.

Another disadvantage of using real-world data is that it is biased. The actual TAT's experienced by the RANGER reflect not only their own repair capabilities, but also the number of RFI units in inventory. There are three repair priorities used on most ships: low for normal stock replenishment, medium for high-demand repairables when they fall to 25% RFI on hand, and high for units needed immediately for installation. These latter units are known as EXREP's (expeditious repair units), and all efforts are made to complete EXREP's quickly. Cross-cannibalization of parts is common in this situation if there are any AWP units from which to obtain parts, and off-ship parts expediting is used to the maximum degree possible. The important point, therefore, is that RANGER TAT data reflects repair actions required by both demand and inventory position. The data base provides the demand history, but tracking inventory position over time is considerably more difficult.

It was noted in chapter II that the model used for past AVCAL's was not the RIMAIR model but an older model that provided Poisson protection to the repair pipeline and also added an attrition portion equal to the 90 day BCM forecast. Although these quantities can be obtained, the number of units actually on board at any given time would not be known because actual inventory levels may not have agreed with the allowances, i.e., part of the inventory was off the ship supporting detachment operations and/or dates for material received from the wholesale system are not available. The bottom line is that the ship has to manage with a given number of units and the TAT observations must reflect this. Consequently, the simulation cannot forecast how the RANGER might have done with different allowances; it can only compare the performance of the allowances computed by the RIMAIR and proposed models when applied to the RANGER's data.

B. MEASURE OF EFFECTIVENESS

The desired inventory goal is to provide a specified minimum aircraft availability for the least inventory investment possible. This is not possible in this simulation because there is no simple method for relating the availability of components to aircraft availability. Additionally, the unit prices for the items were not included in the sample data specifically to avoid the possibility of a few extremely high-priced items influencing the results. In application, unit price considerations can be taken into account by varying safety levels (or by some other method) and would probably have similar effects on either the RIMAIR or proposed model allowances.

An inventory effectiveness goal can always be reached if enough items are added to inventory. Budgets for inventory procurement and rework are limited, however, so inventory models must also be reasonably efficient in terms of the number of units they stock to reach the goal. The measure of effectiveness (MOE) for this simulation, therefore, should reward an allowance model that comes close to meeting the stockage goal (assumed to be 90% in accordance with the safety level setting) and penalizes a model that computes too high an allowance in doing this. The difficulty in applying such an MOE is in deciding an appropriate balance between the reward and the penalty. In order to rate the results of the simulation, then, both the achieved effectiveness figures for each model under a given set of conditions, and the total number of units computed by the model for allowances will be provided.

C. SIMULATION RESULTS

The simulation results show the relative values for a number of policies that have been recommended. First, the RIMAIR and proposed models are compared in the form in which they are presented in Chapters II and III, respectively. Comparison is made between the protected pipeline and repair cycle quantities that each model computes, without adding any operating level or mobilization additives. The RIMAIR model is then made comparable to the proposed model by applying the revised TAT limits (Table X) to the input data, and by including the BCM TAT in the pipeline. Both models are then enhanced by stipulating a minimum one day TAT for any action to help compensate for the lack of time discrimination in the data base. Next, the results of adding the operating level of one each is shown. Examples of line items where each model seems to perform better are then presented and analyzed in an attempt to distinguish characteristics that make one model or the other perform better.

The last two simulations explore two different aspects of the models. In the first of these, different safety level settings for the proposed model are compared. The proposed model presents more flexibility for safety level development because of the tradeoff between safety levels set for repair process one and two, and the effect of different settings is shown. Finally, both models are used to predict allowances with flying hour factors in the range 1.00 to 2.00. The use of increased flying hours is supported by analysis of the RANGER's deployed operations.

1. Baseline Simulation

The baseline simulation results presented in table XIX provide the results of the RIMAIR and the proposed models as they would perform without considering operating levels in either model, without setting TAT to a minimum of one day, and without including the BCM TAT in the RIMAIR pipeline model. Additionally, each model uses its own TAT constraints. This comparison is presented as a "worst case" analysis.

Each simulation table provides the parameters used in that simulation and the results of the simulation, which are the summaries of the model performance for the 79 sample items. Information provided includes the number of simulated issues made off-the-shelf, the number of EXREPs that had to be processed to satisfy the remaining demands, off-the-shelf effectiveness, and the sum of the allowances for all items. The 'Delta' column in Table XIX indicates the number of additional off-the-shelf issues provided by the proposed model over those provided by the RIMAIR model, and the additional number of units in allowance required to make those issues.

The baseline results are biased against the RIMAIR model because it is hampered by the current conservative TAT limits and by the exclusion of TAT for items declared BCM in the pipeline. This is, however, the basic model that will soon be applied to AVCAL's and other aviation outfitting. It is surprising to note that it would have provided less than half of the effectiveness goal of 0.90 protection. The points made in Chapter II are repeated: the current TAT limits are too restrictive, failure to use BCM TAT in the pipeline is a serious deficiency, and the underlying assumption of unlimited repair capacity is not valid.

The proposed model also falls short of the desired performance of 0.90, but to a lesser degree. The model is very sensitive to repair rates, and the inability to measure repair times in hours may affect these results. Similarly, the model assumes that demand and repair times are constant; significant changes in the rates over the course of the deployment are likely to diminish the model's performance.

TABLE XIX

Simulation: Baseline Comparison

Purpose: To provide baseline figures on the RIMAIR model as it is presented in Chapter II, and on the proposed model as presented in Chapter III.

Parameters:
Flying hour factor (F) = 1.00 .

TAT limits: (days)	IP	SKD	RPR	RC1	RC2	AWP
RIMAIR	1	3	8	-	-	20
Proposed	6	-	-	12	35	60

Minimum TAT: 0 days for both models.

Safety levels:	Uncapacitated pipeline	Repair process One	Repair process Two
RIMAIR	0.90		
Proposed	0.90	max 0.97	max 0.90

Operating levels: not included in allowances.

Results:

	Model RIMAIR	Model Proposed	Delta
Total demands	2884	2884	
Total issues	1257	1970	+ 713
Total EXREPs	1627	914	
Overall effectiveness	43.6%	68.3%	
Total allowance (units)	161	236	+ 75

Further comparison of the RIMAIR model with the proposed model on the basis presented above is not very enlightening. To achieve a more meaningful comparison, the input data for the RIMAIR model is made comparable with the proposed model, and the results are shown in Table XX . The results of four separate simulations are presented in that table. First are the baseline RIMAIR model results shown in Table XIX . Next are the results of adding the BCM TAT to the pipeline before computing the RIMAIR allowances. The

TABLE XX

Simulation: RIMAIR Baseline Improvement

Purpose: To provide baseline figures on the RIMAIR model that will be comparable to those of the proposed model.

Parameters:
Flying hour factor (F) = 1.00 .

TAT limits: (days)	IP	SKD	RPR	RC1	RC2	AWP
Original	1	3	8	-	-	20
Revised	6	-	-	12	35	60

Minimum TAT: 0 days.

Safety levels: 0.90

Operating levels: not included.

Results:

	Original baseline	RIMAIR Model W/BCM TAT included	W/revised TAT cons.	With both
Demands	2884	2884	2884	2884
Issues	1257	1459	1482	1673
EXREP's	1627	1425	1402	1211
Effectiveness	43.6%	50.4%	51.4%	58.0%
Allowance	161	184	183	206

Delta from original RIMAIR model:

Issues	-	+202	+225	+416
Allowances	-	+ 23	+ 22	+ 45

Conclusion: Including BCM TAT and using the TAT constraints developed in chapter III improve the RIMAIR model results and are used in further comparisons.

third gives the results of using the revised TAT limits. The fourth gives the results of combining both of these enhancements. Below the listings for the latter three simulations are the differences between the results using the revised inputs and the original RIMAIR baseline results.

The effect of changing the TAT constraints and including the BCM TAT in the pipeline is quite substantial. The 33% improvement in effectiveness is the benefit achieved by using as much information as possible about the underlying process in developing allowances. Both of these changes should be implemented when the RIMAIR model is applied to the AVCAL process. All further simulations in this chapter include these enhancements to the original RIMAIR model.

The next table presents the effects of using a minimum 1 day TAT with both the RIMAIR model and the proposed model (Table XXI A), and provides the results of including operating levels of one unit to each allowance generated by the models (Table XXI B). Again, for each of these cases, the difference that the change makes in each model is provided as the delta quantity.

Use of a minimum one day TAT helps both models and will be used for both in the following simulations. Inclusion of the operating level, however, raises the effectiveness of both models past the 0.90 goal, and the additional units added to inventory exhibit "diminished returns" in terms of improved effectiveness. The operating level will not be included in the allowances computed in the following simulations.

The operating level result is very significant for two reasons. It supports the contention that inclusion of the operating level unit helps to mask the ability of the underlying model to provide an appropriate allowance in support of the repair process. Using a good underlying model, with safety levels adjusted to provide the desired overall effectiveness, seems to be a more rational approach than using a poor model and adding 1 unit to each allowance.

TABLE XXI

Simulation: Minimum TAT and Operating Level

A. Purpose: To show the effect of setting a minimum TAT of one day.

Parameters:
Flying hour factor (F) = 1.00 .

Minimum TAT as shown for both models.

Safety levels:	Uncapacitated pipeline	Repair process One	Two
RIMAIR	0.90		
Proposed	0.90	max 0.97	max 0.90

Operating level quantities are not included.

Results:

	RIMAIR Model Minimum TAT 0 days	1 day	Delta	Proposed Model Minimum TAT 0 days	1 day	Delta
Demands	2884	2884		2884	2884	
Issues	1673	1790	+117	1970	2169	+199
EXREPs	1211	1094		914	715	
Effect.	58.0%	62.1%		68.3%	75.2%	
Allowances	206	213	+ 7	236	256	+ 20

Conclusion: Including a minimum of one day TAT helps both models considerably, with relatively little extra investment in inventory.

B. Purpose: To show the effect of adding the OL of one each to the allowances.

Results:

	RIMAIR Model No OL	W/OL		Proposed Model No OL	W/OL	
Demands	2884	2884		2884	2884	
Issues	1790	2679	+889	2169	2784	+615
EXREPs	1094	205		715	100	
Effect.	62.1%	92.9%		75.2%	95.3%	
Allowances	213	292	+79	256	335	+ 79

Conclusion: Including the operating level helps both models achieve better than 90% simulated effectiveness.

It is appropriate to mention that many repairable items carried in AVCAL have the operating level automatically added to their allowance. This will definitely increase overall effectiveness, but it is not likely to provide cost effective results when applied to the inventory as a whole. The benefit of adding the unit operating level to allowances for high-demand items is significant, but there may be many low-demand items for which the addition of a unit operating level may not improve effectiveness at all. Further analysis should be done to determine both the benefits and the costs of automatically adding the operating level, especially when it is applied to the medium- and low-demand items in the inventory.

Examples of specific items for which each model performed best are presented in Tables XXII and XXIII . The statistics reflect the inclusion of BCM TAT in the RIMAIR model, use of the revised TAT limits, and the use of a one day operating level. In the example provided in Table XXII, the proposed model computes an allowance of 2.40 for process one, which includes almost two units for safety level. The administrative, AWP, and resupply pipeline allowance includes almost another unit of safety level. The extra unit safety level obtained by computing the allowance in this manner instead of with the RIMAIR model enabled an additional 18 demands to be filled off-the-shelf; this is a 28.6% improvement over the results obtained by the enhanced RIMAIR model. This item has characteristics that are exactly what the proposed model was designed for, as most units go through a quick repair and then return to the shelf. This example is but one of many items in which setting the safety level for repair process one to 0.97 provided an extra unit or two in safety level, and the extra unit made a significant difference in the ability to meet the demand.

TABLE XXII

Simulation Allowance Comparison #1

Comparison of simulation results for NIIN* 00-140-1775

Item data:	94 actions	avg. IP = 0.06 days
	1 BCM (w/AWP)	avg. TAT= 8.00 days
	93 repairs	avg. TAT= 3.89 days
	71 actions w/o AWP	avg. RC1= 1.39 days
	23 actions w/AWP	avg. RC2= 2.65 days
		avg. AWP= 8.87 days

RIMSTOP Level	RIMAIR Model Quantity	Proposed Model Quantity		Proposed Model SL
Repair cycle	2.032	2.075		
Administrative			.032	
Process one			.555	.970
Process two			.342	.786
Awaiting Parts			1.146	
Order and shipping time	0.191+	0.146		
Total pipeline	2.223	2.221		
Safety	1.728	2.779		
Total	4	5		
EXREPs (%)	31 (33.0%)	13 (13.8%)		

*NIIN is the National Item Identification Number that uniquely identifies each item carried in any portion of the federal supply catalog.

+OST figure for RIMAIR model includes BCM TAT.

Of the 79 items in the sample, in only one case did the proposed model yield a lower allowance than the RIMAIR model; this item is presented in Table XXIII . The proposed model computed an allowance of 0.44 for process one, and 0 for process two. Adding five for the remaining pipeline and rounding yields the final allowance of 5. The RIMAIR model adds the entire pipeline together, and this results in 6 as

TABLE XXIII

Simulation Allowance Comparison #2

Comparison of simulation results for NIIN 00-933-4790

Item data: 23 actions avg. IP = 0.09 days

23 BCMs (0 w/AWP) avg. TAT= 2.04 days

23 actions w/o AWP avg. RC1= 1.95 days

RIMSTOP Level	RIMAIR Model Quantity	Proposed Model Quantity		SL
Repair cycle	0.0	0.265		
Administrative			.012	
Process one			.253	0.900
Process two			0.0	
Awaiting Parts			0.0	
Order and shipping time	3.623*	3.360		
Total pipeline	3.623	3.625		
Safety	2.377	1.375		
Total	6	5		
EXREPs (%)	6 (26.1%)	9 (39.1%)		

*OST figure for RIMAIR model includes BCM TAT.

the allowance quantity. This is the example for showing the possible deficiency in treating the repair processes as separate from the administrative, AWP, and wholesale pipelines. Lack of the extra unit of safety level caused 3 additional EXREPs when the proposed model was used, 17.6% worse than the RIMAIR model.

The differences caused by applying the proposed model to each item in the entire inventory are shown in Table XXIV . The effect on the entire sample is described in terms of the number of additional units of allowance computed by the proposed model, the number of items in the category, the number of EXREPs avoided by having the additional units, and the average number of EXREPs avoided per

TABLE XXIV

Simulation Allowance Comparison Summary

Delta (units)	# items	# EXREP's avoided	Average # EXREP's avoided per unit
-1	1	- 3	- 3
0	41	0	0
+1	32	285	8.9
+2	3	48	8.0
+3	2	49	8.2
Total +43 units		379	8.8

NOTES:

1) "Delta" represents the proposed model allowance minus the RIMAIR allowance.

2) "# items" represents the number of the 79 line items in the sample that have the delta quantity as the difference between the proposed and RIMAIR allowances.

3) The negative sign in the "EXREPs avoided" and "Average EXREPs" columns indicates that the proposed model allowance allowed more EXREPs than the RIMAIR model allowance did.

unit of increase. These summary results indicate that more than half of the items were provided the same allowance by the proposed model as by the RIMAIR model, and all but 5 of the 79 items had allowances within one unit. Considering the fact that the 79 items analyzed in the sample represent 16% of the total demand experienced on the RANGER cruise, by increasing the allowances the few additional units recommended by the proposed model seems a small "cost" for the resulting performance improvement.

2. Simulating Proposed Model Safety Levels

The flexibility provided by the proposed model for setting safety level combinations can also be a liability. It is not intuitive what settings will provide the best overall support. The search for process one safety level settings was made simple by constraining the uncapacitated pipeline and overall repair process levels to 0.90 to compare most closely with the RIMAIR models. There is additional research that can be done in this area, however, in attempting to find the optimal parameter settings for a given application.

Table XXV shows the results of successive simulation runs in which the maximum safety level setting for repair process one was varied. Increasing process-one safety level improves the performance of the model, despite the fact that every increased process-one safety level is balanced with a decrease in process-two safety level in order to meet the overall goal of 0.90 .

The results provided in Table XXV provide additional support for the validity of the proposed model. The overall effectiveness of the inventory increases as the process-one safety level increases. This supports the contention that sufficient support for repair process one is essential for the success of the system as a whole.

The process-one traffic intensities (ρ_1) for the 79 items in the sample are graphed in Figure 5.1 . Only four of the items have ρ_1 above 0.4; the high was 0.533 for NIIN 00-804-5803, based on 96 process-one actions with an average RC1 value of 2.11 days. The median ρ_1 value was only 0.176; the minimum was 0.053 . Consequently, the allowances did not increase much when the safety levels were increased in Table XXV ; some would have increased substantially if the traffic intensities had been in the neighborhood of 0.9 .

TABLE XXV

Simulation: Proposed Model Safety Level

Purpose: To show the results of varying the safety levels for process one in the proposed model.

- -

Parameters:
Flying hour factor (F) = 1.00 .

TAT constraints: (days)	IP	SKD	APR	RC1	RC2	AWP
	6	-	-	12	35	60

Minimum TAT: 1 day.

Safety levels: 0.90 for the admin, AWP, resupply pipeline; 0.90 overall for the repair processes.

- -

Results:

	Maximum safety level for process one				
	0.90	0.95	0.96	0.97	0.98
Demands	2884	2884	2884	2884	2884
Issues	1889	2025	2106	2169	2257
EXREPs	995	859	778	715	627
Effect.	65.5%	70.2%	73.0%	75.2%	78.3%
Allow.	220	237	249	256	272
Delta from next lower case:					
Issues		+136	+81	+63	+84
Allow.		+ 17	+12	+ 7	+16

3. Forecasting Increased Demand

The stated purpose for developing a capacitated model was to to provide more realistic requirements forecasts for periods of increased demand. The simulations presented so far, however, have not shown this. The RANGER data base provides an excellent opportunity to test this. Their deployment included a thirteen week period of operations in the Indian Ocean during which the experienced demand was 25% higher than for the deployment as a whole.

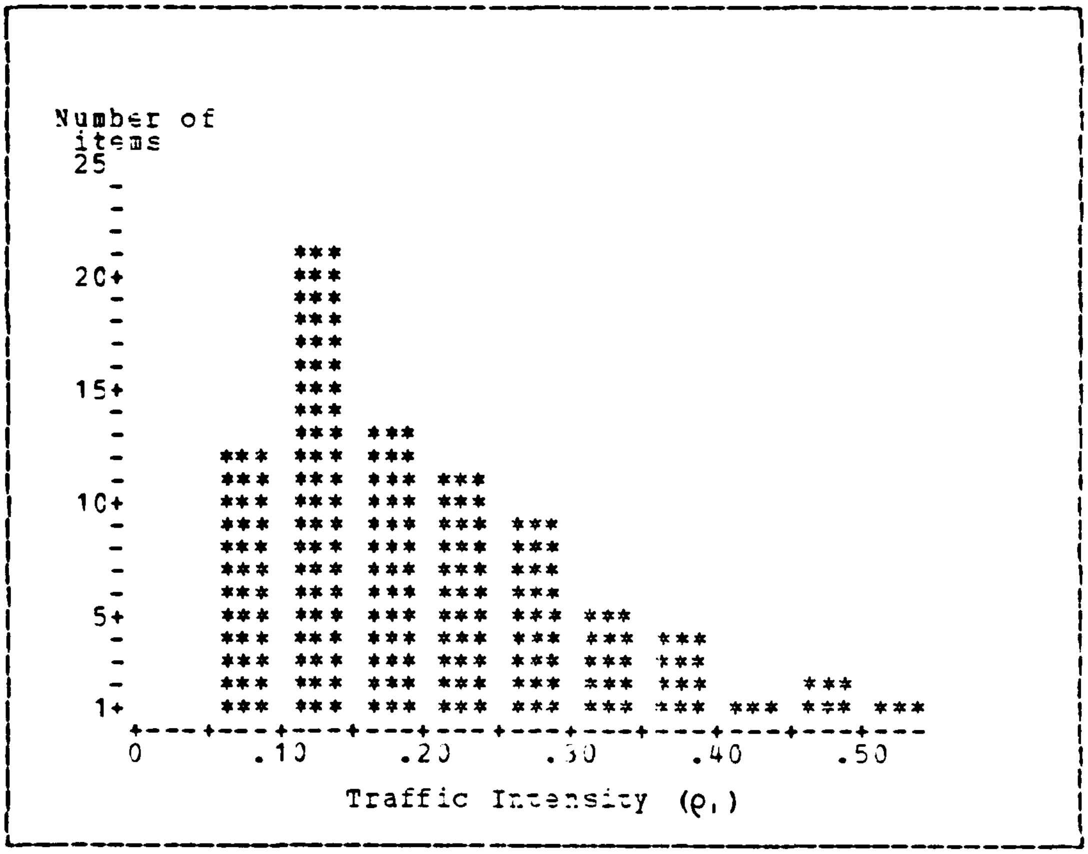

Figure 5.1 Process One Traffic Intensities.

Figure 5.2 provides a graph of the aggregate demand experienced by the 79 sample items during the deployment and highlights the Indian Ocean period. The Indian Ocean portion of the deployment represented approximately 65% of the demand for the entire deployment (1870 of 2884 demands). Because this is such a substantial portion of the deployment, use of a forecast factor (F) of 1.25 may be appropriate when computing allowances with rates based on the entire deployment period.

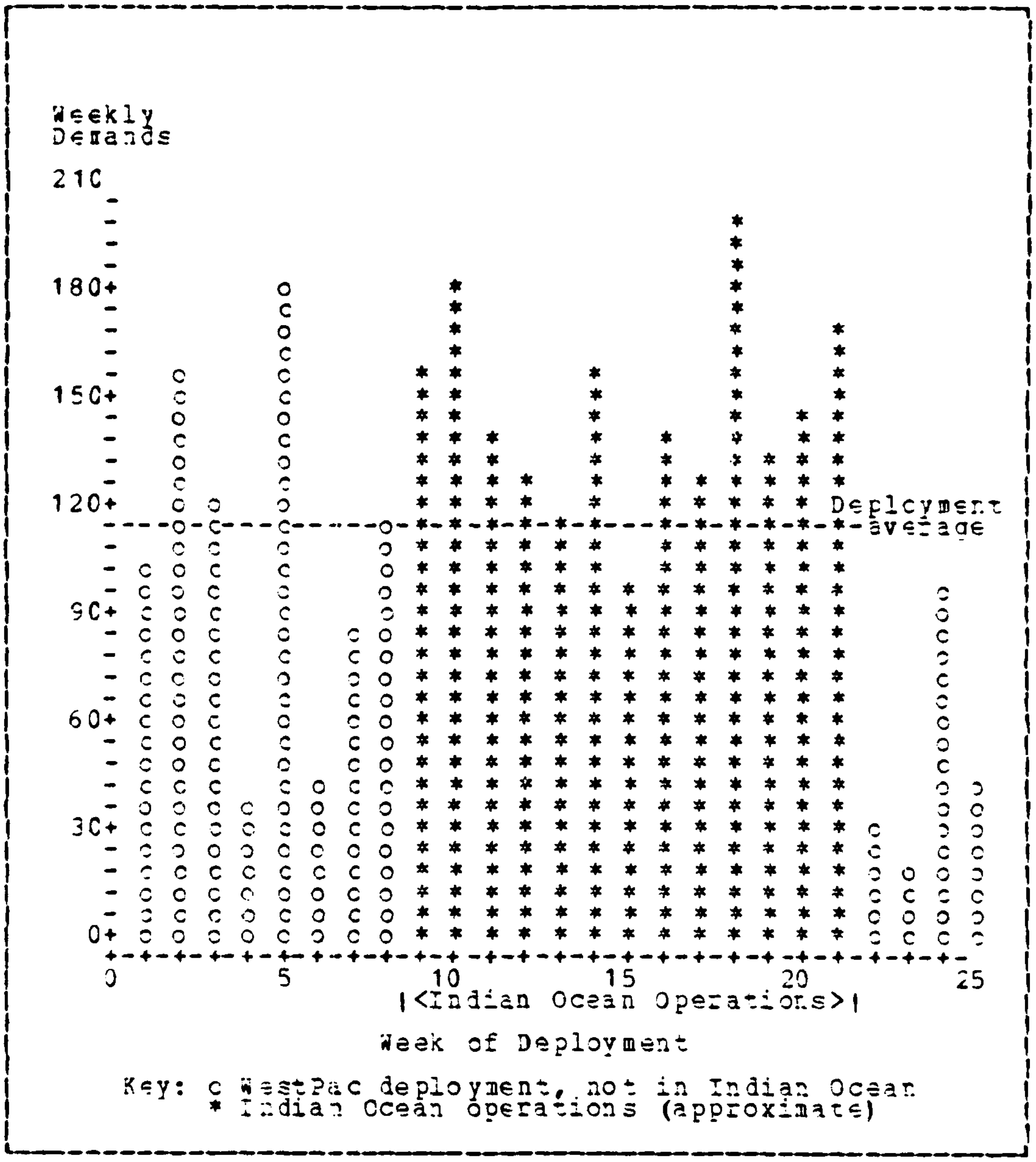

Figure 5.2 Weekly Demand for Sample Items.

In order to support this increased demand period, which is probably a closer approximation to mobilization operations than the average deployment demand figures, the flying hour forecast factor was used. The results of various setting of this factor, for both the RIMAIR and the proposed models, are provided in Table XXVI .

Increasing the flying hour forecast improves the effectiveness achieved by both models, but the effect of "diminishing returns" for increased effectiveness per unit added to inventory can be seen in both models, but is more extreme in the proposed model. It is possible that use of the finite population approximations would improve the results in the proposed model, but this cannot be tested.

The fact that the proposed model was able to achieve 0.857 effectiveness when using a forecast factor of 1.25 (which is the factor for the RANGER's heavy demand period) is very satisfactory considering the model was set for 0.90. Even with the benefit of including the BCM TAT, and using the relaxed IAT limits, the RIMAIR model could provide only 72.9% effectiveness at the same setting. The evidence strongly favors the proposed model as being a better model of the underlying repair process than is the RIMAIR model.

TABLE XXVI

Simulation: Forecasting Increased Demand

Purpose: To show the results of varying the flying hour factors for both models.

Parameters:

TAT limits: (days)	IP	SKD	RPR	RC1	RC2	AWP
Both models	6	-	-	12	35	60

Minimum TAT: 1 day.

Safety levels: 0.90 for the RIMAIR model; 0.90 for the admin, AWP, and resupply pipeline; 0.90 overall for the repair processes; and 0.97 for repair process one in the proposed model.

Results:

RIMAIR Model
Flying hour forecast factor (F)

	1.10	1.25	1.40	1.60	2.00
Demands	2884	2884	2884	2884	2884
Issues	1951	2103	2289	2436	2635
EXREPs	933	781	595	448	249
Effect.	67.6%	72.9%	79.4%	84.5%	91.4%
Allow.	234	259	288	318	386

Proposed Model
Flying hour forecast factor (F)

	1.10	1.25	1.40	1.60	2.00
Demands	2884	2884	2884	2884	2884
Issues	2300	2473	2579	2702	2792
EXREPs	584	411	305	182	92
Effect.	79.8%	85.7%	89.4%	93.7%	96.8%
Allow.	281	329	374	438	589

Delta between models at the same F factor:

Issues	+349	+370	+290	+266	+157
Allow.	+ 47	+ 70	+ 86	+130	+203

VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY OF RESULTS

The support problems experienced by Navy activities during periods of heavy demand for aviation repairables may be partially due to the model being used for computing inventory allowances. The current model and the RIMAIR model that is soon to be implemented share some serious deficiencies. The deficiencies fall in two general categories: the method of using input data, and the model which results from assuming an unlimited-capacity repair process. Analysis of the data from the 1983 deployment of the USS RANGER (CV-61) led to development of an alternate model that corrects some of these deficiencies.

1. Input Data

Both the current and RIMAIR models use the aviation 3-M maintenance data base extensively for computing allowances. This data base has a number of deficiencies that hamper the effectiveness of any model. The two major problem areas addressed in this thesis are the lack of time discrimination in the measurement of repair turnaround time and the upper limits (constraints) that are applied to turnaround time observations before using them for allowance computation.

The lack of TAT discrimination is inherent in the current mechanized data collection system in that the time that actions occur is recorded only with the resolution of 1 day. The result is that 35% of the maintenance actions in the sample were recorded as taking zero days to complete. This obviously understates the actual time needed for processing, resulting in understated allowances. The capability exists to correct this: man-hours and flight-hours are both documented because the need to provide that level of time discrimination was recognized. Repair-processing-hours could likewise be provided. Use of a one-day minimum TAT is a simple way to compensate for the problem; this proved to have a positive effect during simulation. The effectiveness of the RIMAIR model was improved 7% when the one-day minimum TAT was used; the proposed model showed a 10% improvement.

The current model and the RIMAIR model both use TAT limits that are overly conservative and which cause forecast repair times (and the associated repair pipeline quantities) to be significantly less than those that were actually experienced. The current limits are so severe that they inhibit the ability of the inventory model to provide adequate support. The RIMAIR model performance improved more than 17% in the simulation when relaxed limits were applied.

2. Repair Process Assumptions

The current model and the RIMAIR model both use the Poisson distribution to compute allowance quantities, using the repair pipeline quantity or the total pipeline quantity, respectively, as the distribution parameter. The reason for using the Poisson distribution in this fashion is not documented in any available paper, study, or other source. The assumption that the repair process is an $M/M/\infty$ queueing process leads to exactly the same distribution for the number of units in the queue, however, and it is therefore assumed that the $M/M/\infty$ queueing model is the underlying model on which the current and RIMAIR models are based. This model is not appropriate for use with the existing Navy IMA repair facilities because the assumption of unlimited repair capacity is not valid. The limited capacity of the VAST system is well documented; capacity constraints on other systems exist as well.

The current and RIMAIR models also assume that items that are declared BCM and returned to the wholesale system spend no appreciable time in the repair system. This assumption is false: the 382 units in the sample that were declared BCM spent an average of 9.8 days in the repair cycle; the 5754 BCM units in the entire RANGER data base spent an average of 7.57 days in the repair cycle. The exclusion of TAT for units declared BCM in the allowance computation procedure systematically discriminates against activities that attempt to fulfill their mission to repair as many units as possible.

3. A Different Model

Analysis of the sample data provided many insights into the repair process. Among the important results were proof that some of the time elements currently used to compute TAT were not statistically independent and that repair actions were not homogeneous. These two results and the fact that capacity constraints do exist in the repair process led to development of an alternate allowance computation model. The proposed model hypothesized two separate repair processes distinguished by the existence or absence of awaiting parts time and modelled by the M/M/1 queueing model. Simulation results indicated that the proposed model provided better protection than the RIMAIR model for the 79 high-demand inventory items studied.

E. CONCLUSIONS

1. The RIMAIR Model

The RIMAIR model is a better model than the model currently in use in that it provides some measure of protection for attrition items. It is deficient in the exclusion of BCM TAT in the pipeline. The manner in which the Poisson distribution is used to compute allowances also causes allowances to be understated because of the implicit assumption that there are always adequately many servers available, regardless of forecast increases in demand. Last, the current method for truncating recorded turnaround times seriously reduces the estimated average TAT values which are model inputs.

The RIMAIR model was used in the simulation without the one unit operating level so that the ability of the underlying model, which uses the Poisson distribution to provide protection to the pipeline quantity, could be examined. The result was that the RIMAIR model only provided allowances sufficient to fill 43.6% of the 2884 demands in the sample from off-the-shelf RFI material. This poor performance is masked when the one unit operating level is applied. The addition of the one unit operating level to the allowances for the high-demand items was shown to provide effectiveness above 90% for both models. The automatic addition of a unit operating level to allowances for medium- and slow-moving items may not be warranted, however.

2. The Proposed Model

The proposed model attempts to correct the major problems with the RIMAIR model by including BCM TAT in the repair cycle time and by explicitly considering limits on the available repair capacity. While the malfunction code is probably the best discriminator to indicate the complexity of the repair an item undergoes, the existence or absence of AWP time was found to be an acceptable substitute. Two separate repair processes were defined by the existence or absence of AWP time. Allowances computed by the proposed model were generally equal to or greater than the allowances generated by the RIMAIR model. This is the expected result of assuming limited repair capacity.

Allowances generated by the proposed model provided better performance in simulations for forecast demand rates up to 25% higher than the observed demand rate. Degraded performance was obtained when demand increases of 40% or higher were forecast because the demand rates of some items approached or exceeded the capacity of the repair process. This result revealed the necessity for using finite population formulae for calculating queue size when the traffic intensity approaches or exceeds unity. Lack of population size for the sample items significantly hampered this research effort; further studies should include it in the data base.

C. RECOMMENDATIONS

1. Data Base Problems

Considerable work is currently being done on the aviation 3-M data collection system to improve the accuracy and completeness of the data base. Additional work is required to ensure data necessary for proper supply support is collected. The current system records dates appropriate to managing a unit's physical location in the maintenance system, but this is not necessarily the information required for measuring support factors. Data for off-the-shelf time, repair capacity, repair rate, and expected waiting time are all needed if improvements are to be made in the support system. Additionally, it is important to record the changes that occur in these factors as demand increases in order to forecast mobilization requirements. Therefore, three improvements in the data base are recommended based on the lessons learned in researching this thesis. First, the data base used for allowance computation must be expanded to include time off-the-shelf for RFI repairable components and not just the maintenance time associated with NRFI units. Second, the data base must be able to discriminate repair process times in hours instead of days. Third, the data collection system must record information about repair capacities, repair rates, and waiting times.

The existing turnaround limits must be changed if adequate support for the operating forces is to be achieved. There are many ways to detect atypical observations in a data base; the inventory models in use for consumable items have demand filters to test the data observations. Each demand observation can be accepted or rejected as an outlier if the demand observation is significantly different from the item's recent history. There is no reason why a similar filter for retail repairable items, which are more directly associated with readiness, could not be developed.

The idea that TAT limits should serve as management goals is not acceptable if for no other reason than that the current TAT limits are routinely exceeded specifically because of operating policy provided by higher authority. Operators are frequently required to provide off-station support, thereby exceeding the one day in-process time limit. Operators are required to attempt time-consuming fault isolation and repair for extremely difficult malfunctions in order to minimize the number of units returned to wholesale repair depots, and they are also frequently required to hold AWP material thirty days, sixty days, or longer in attempts to obtain piece-parts that may not be available. The operators' reward for performing these tasks, and doing them well in many cases, is to find that someone at ASO disregarded much of the data reflecting what really occurred in order to comply with the mandated limits.

2. Non-homogeneous Repair Processes

The data base showed that there were significant differences in the times necessary to perform various types of repairs, particularly with respect to the type of malfunction that occurred. It may be possible to significantly improve on the results obtained in this thesis if malfunction codes can be subclassified into groups that would facilitate the identification of the theorized type-one and type-two repair processes. Alternately, each inventory item might have only two or three malfunction codes normally applied to it. Identification of these might also provide the capability to identify the two repair processes. In either case, classification by malfunction appears to provide a more acceptable model for use in allowance computation and in logistics support analysis.

The absence or existence of AWP is recognized to be a function of both the malfunction and of the piece-part support that exists at an activity at a given time. Consequently, the percentage of items likely to go AWP will probably vary considerably for the same item from one activity to another. The percentage of malfunctions of any one type generated by similar flight operations should not vary as much. Additionally, the identification of problem malfunctions and the impact they have on inventory support and readiness could aid level of repair analysis and help to identify other maintainability problems.

3. Further Study

Further study of the Navy's intermediate maintenance system and the supply support it requires is both strongly recommended and vitally needed. Intermediate maintenance does not receive much visibility primarily because individual activities are small compared to the depot rework sites. In aggregate, however, they are larger than the depots and are more closely related to day-to-day aviation readiness. Study of the maintenance system, the inventory models, the management interface, and the applications and implications of modern information technology are all open areas. This thesis attempted to examine a small portion of the system, and in doing so raised many more questions than it could answer. The models examined and proposed are all very simple. They can be improved in a number of ways. It is hoped that they will be.

APPENDIX A

USS RANGER SAMPLE DATA

The following tables provide more complete information about the sample data used in the thesis.

TABLE	Title
XXVII	Sample Item List
XXVIII	Special Material Identification Code
XXIX	When Discovered Code
XXX	Type Maintenance Code
XXXI	Action Taken Code
XXXII	Malfunction Code
XXXIII	In-Process Days
XXXIV	Scheduling Days
XXXV	Repair Days
XXXVI	Awaiting Parts Days
XXXVII	Turnaround Time
XXXVIII	Repair Process One Cycle Time
XXXIX	Repair Process Two Cycle Time
XL	Crosstabulation of BCM and AWP Actions

TABLE XXVII

Sample Item List

COG		NIIN			# of actions
2R		C0	C01	6636	26
2R		C0	004	1259	30
2R		C0	067	7633	64
2R		00	068	1555	28
1R	D	C0	083	3521	38
2R		C0	084	3737	24
2R		00	101	6830	21
2R		00	103	0503	20
2R		00	109	9394	23
8R		00	110	0938	24
8R		00	110	6262	24
8R		00	121	6932	24
8R		C0	121	6946	23
8R		00	121	7299	70
8R		00	122	8112	43
8R		00	123	6781	36
8R		00	123	8886	43
8R		00	123	9369	84
8R		00	123	9376	27
2R		00	127	0189	22
2R		C0	133	9237	25
2R		00	137	6459	43
2R		C0	140	0701	31
2R		00	140	1775	97
8R		00	142	5512	47
8R		00	148	8475	44
2R		00	149	1319	26
2R		00	164	5991	21
2R		C0	168	5105	21
2R		00	168	8388	22
8R		C0	168	8769	38
2R		00	179	8186	39
2R		C0	182	3006	24
2R		00	186	2954	24
2R		00	257	2273	29
2R		00	332	4137	24
2R		C0	400	1202	23
2R		00	413	2990	25
2R		00	431	6234	22
2R		00	567	4548	22
2R		00	567	4549	22
2R		00	612	2637	22
2R		00	630	2328	20
2R		00	717	6101	24
2R		00	729	1371	28
2R		00	738	5993	28
2R		00	782	5308	38
2R		00	804	5803	102
2R		00	810	0136	34
2R		00	810	0140	23
2R		00	900	8081	37
2R		00	930	2659	20
2R		C0	933	8790	23
2R		00	935	0137	41
8R		C1	C04	1603	43
2R		01	004	1614	20
2R		C1	004	7546	24
2R		C1	009	2534	20

cog		NIIN	# of actions
8R		01 009 8855	21
2R		01 011 0736	67
2R		01 011 0855	26
2R		01 011 3797	31
2R		01 011 8480	20
8R		01 013 8638	28
2R		01 014 1878	48
8R		01 017 5299	96
2R		01 021 3503	34
2R		01 025 8311	67
2R		01 027 8706	112
8R		01 029 4982	64
1R	D	01 034 0483	67
2R		01 034 9500	25
2R		01 040 2203	46
2R		01 052 0470	35
8R		01 066 3265	35
2R		01 072 7885	51
8R		01 073 4475	44
8R		01 079 4218	67
2R		01 090 5830	20

TABLE XXVIII

Special Material Identification Code

CATEGORY LABEL	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	CUM FREQ (PCT)
SPC PROJ:AMIS	AZ	107	3.7	3.7
S-3A	CS	247	8.6	12.3
AWG-9 <F-14A>	CY	653	22.6	34.9
PROJECT SHOEHORN	DZ	76	2.6	37.6
E-2C	EE	51	1.8	39.3
COMMON ELECTRONICS	EX	36	1.2	40.6
A-6	FA	156	5.4	46.0
EA-6B <EXCAP>	FE	175	6.1	52.0
COMMON ELECTRONICS	FX	37	1.3	53.3
SPC PROJ-GFE	FZ	242	8.4	61.7
A-7	GA	24	0.8	62.6
SH-2F,3 <LAMPS>	HZ	138	4.8	67.3
ARC-159	JZ	32	1.1	68.4
F-4	MF	23	0.8	69.2
F-14A	PF	143	5.0	74.2
APN-153	PZ	48	1.7	75.9
A-6E	RA	111	3.8	79.7
SPECIAL SUPPORT	SX	36	1.2	81.0
ASN-92 <CAINS>	SZ	331	11.5	92.4
A-7E	TA	66	2.3	94.7
SPC PROJ-TACAN	TZ	61	2.1	96.8
APN-194	WZ	24	0.8	97.7
ALQ-126	ZZ	67	2.3	100.0
	TOTAL	2884	100.0	100.0

TABLE XXIX

When Discovered Code

CATEGORY LABEL	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	CUM FREQ (PCT)
BEF FLIGHT-AC-ABORT	A	7	0.2	0.2
BEF FLIGHT-AC-NO ABORT	B	109	3.7	4.0
INFLIGHT-ABORT	C	40	1.4	5.4
INFLIGHT-NO ABORT	D	1187	41.2	46.5
AFT FL,BETW FL-AC	E	9	0.3	46.9
PILOT-NFO WEEKLY INS	F	2	0.1	46.9
ACC-TRANS INS	G	1	0.0	46.9
BETW FL-GROUND CREW	H	891	30.9	77.8
DAILY INS	J	8	0.3	78.1
PRE FL,PST FL,TA INS	K	5	0.2	78.3
SPECIAL INS	L	95	3.3	81.6
CALENDAR INS	M	1	0.0	81.6
FUNC CHECKFLIGHT	P	19	0.6	82.2
CONDITIONAL INS	Q	59	2.0	84.3
QUALITY ASSURE INS	R	4	0.1	84.4
SCHEDULED CALIB	T	1	0.0	84.4
RELATED MAINT ACT	V	2	0.1	84.5
IN-SHOP RPR OR MAINT	W	181	6.3	90.8
RCPT,WITHD FM SUPPLY	Y	135	4.7	95.5
ADMIN	0	131	4.5	100.0
	TOTAL	2884	100.0	100.0

TABLE XXX

Type Maintenance Code

CATEGORY LABEL	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	CUM FREQ (PCT)
UNSCHED MAINT	B	2737	94.9	94.9
DAILY,PST FL INS	D	130	4.5	99.4
ACC-TRANS INS	E	1	0.0	99.4
PHASED INS	G	3	0.1	99.5
LOCAL MANUFACTURE	L	3	0.1	99.7
CYCLE,EVENT SPEC INS	N	7	0.2	99.9
CALENDAR,MAJOR INS	P	1	0.0	99.9
CONDITIONAL INS	S	2	0.1	100.0
	TOTAL	2884	100.0	100.0

TABLE XXXI

Action Taken Code

CATEGORY LABEL	CODE	ABSOLUTE FREQ	RELATIVE FREQ (PCT)	CUM FREQ (PCT)
NO PER RCD	A	503	17.4	17.4
REPAIR	C	1980	68.7	86.1
WORK STOP	D	11	0.4	86.5
CORROSION TREATMENT	Z	7	0.2	86.7
LOOK INS,CLOSEOUT	0	1	0.0	86.8
BCM-REP NOT AUTH	1	134	4.6	91.4
BCM-LACK EQUIP	2	2	0.1	91.5
BCM-LACK PARTS	4	87	3.0	94.5
BCM-FAILS CHK,TEST	5	47	1.6	96.1
BCM-BEYOND AUTH CAP	7	106	3.7	99.8
BCM-ADMIN	8	6	0.2	100.0
	TOTAL	2884	100.0	100.0

TABLE XXXII

Malfunction Code

CODE	FREQ	ADJ PCT	CUM PCT	CODE	FREQ	ADJ PCT	CUM PCT
000	1	0	0	306	5	0	66
001	1	0	0	308	1	0	66
003	1	0	0	374	118	4	70
C07	8	0	0	381	39	1	72
008	1	0	0	383	21	1	72
C20	8	0	1	394	1	0	72
028	1	0	1	425	1	0	72
C29	1	0	1	429	10	0	73
037	11	0	1	437	2	0	73
070	105	4	5	450	14	0	73
076	1	0	5	479	1	0	73
080	4	0	5	520	1	0	73
086	1	0	5	576	1	0	73
090	1	0	5	601	1	0	73
093	9	0	5	615	21	1	74
101	1	0	5	622	33	1	75
105	8	0	6	649	1	0	75
109	1	0	6	679	1	0	75
121	2	0	6	692	4	0	75
124	2	0	6	704	4	0	76
127	555	19	25	705	29	1	77
135	5	0	25	707	34	1	78
150	1	0	25	725	1	0	78
160	114	4	29	727	1	0	78
161	123	4	33	730	14	0	78
164	1	0	34	766	1	0	78
167	5	0	34	780	4	0	79
169	225	8	42	782	2	0	79
170	24	1	42	786	6	0	79
185	3	0	42	787	14	0	79
190	1	0	42	799	372	13	92
215	3	0	43	804	126	4	97
227	1	0	43	805	4	0	97
232	1	0	43	806	8	0	97
242	127	4	47	811	11	0	97
255	149	5	52	816	1	0	97
257	3	0	52	878	1	0	97
281	2	0	52	900	11	0	98
282	28	1	53	935	1	0	98
283	1	0	53	957	9	0	98
290	351	12	66	958	28	1	99
293	1	0	66	962	16	1	100
294	7	0	66	970	1	0	100
299	1	0	66	988	8	0	100
301	1	0	66				

TABLE XXXIII

In-Process Days

# of days	FREQ	ADJ PCT	CUM PCT	# of days	FREQ	ADJ PCT	CUM PCT
0	2427	84	84	13	3	0	99
1	332	12	96	15	1	0	99
2	32	1	97	18	3	0	99
3	13	0	97	20	3	0	100
4	6	0	97	22	1	0	100
5	11	0	98	27	1	0	100
6	10	0	98	38	1	0	100
7	13	0	99	47	1	0	100
8	5	0	99	49	1	0	100
9	4	0	99	70	1	0	100
10	2	0	99	100	4	0	100
11	5	0	99	101	2	0	100
12	2	0	99				

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A. Statistics: Unconstrained

MEAN	0.646	MEDIAN	0.094
STD DEV	5.200	VARIANCE	27.038
KURTOSIS	296.265	SKEWNESS	16.385
MINIMUM	0 days	MAXIMUM	101 days

B. Statistics: Current Constraint 1 day

MEAN	0.158	MEDIAN	0.094
STD DEV	0.365	VARIANCE	0.133
KURTOSIS	1.504	SKEWNESS	1.872
MINIMUM	0 days	MAXIMUM	1 day

C. Statistics: Proposed Constraint 6 days

MEAN	0.309	MEDIAN	0.094
STD DEV	1.010	VARIANCE	1.020
KURTOSIS	21.578	SKEWNESS	4.548
MINIMUM	0 days	MAXIMUM	6 days

TABLE XXXIV

Scheduling Days

# of days	FREQ	ADJ PCT	CUM PCT
0	2202	76	76
1	502	17	94
2	65	2	96
3	24	1	97
4	18	1	97
5	10	0	98
6	16	1	98
7	6	0	99
8	4	0	99
9	4	0	99
10	5	0	99
11	1	0	99
12	3	0	99
13	3	0	99

# of days	FREQ	ADJ PCT	CUM PCT
14	3	0	99
15	3	0	99
16	1	0	100
17	2	0	100
18	2	0	100
19	1	0	100
20	1	0	100
23	1	0	100
26	2	0	100
27	1	0	100
30	2	0	100
31	1	0	100
32	1	0	100

A. Statistics: Unconstrained

MEAN	0.557	MEDIAN	0.155
STD DEV	2.167	VARIANCE	4.694
KURTOSIS	92.198	SKEWNESS	8.597
MINIMUM	0 days	MAXIMUM	32 days

B. Statistics: Current constraint 3 days

MEAN	0.339	MEDIAN	0.155
STD DEV	0.713	VARIANCE	0.509
KURTOSIS	5.584	SKEWNESS	2.417
MINIMUM	0 days	MAXIMUM	32 days

TABLE XXXV

Repair Days

# of days	FREQ	ADJ PCT	CUM PCT	# of days	FREQ	ADJ PCT	CUM PCT
0	1791	62	62	22	2	0	99
1	660	23	85	23	1	0	99
2	164	6	91	24	1	0	99
3	60	2	93	25	5	0	99
4	37	1	94	26	3	0	99
5	28	1	95	27	1	0	99
6	21	1	96	29	1	0	99
7	13	0	96	30	1	0	99
8	12	0	97	31	1	0	99
9	10	0	97	32	3	0	100
10	6	0	97	36	1	0	100
11	9	0	97	39	1	0	100
12	2	0	98	41	1	0	100
13	4	0	98	42	1	0	100
14	4	0	98	43	1	0	100
15	5	0	98	46	1	0	100
16	4	0	98	48	1	0	100
17	4	0	98	53	1	0	100
18	7	0	99	56	2	0	100
19	3	0	99	60	1	0	100
20	5	0	99	66	1	0	100
21	3	0	99	72	1	0	100

A. Statistics: Unconstrained

MEAN	1.339	MEDIAN	0.305
STD DEV	4.670	VARIANCE	21.811
KURTOSIS	78.221	SKEWNESS	7.790
MINIMUM	0 days	MAXIMUM	72 days

B. Statistics: Current constraint 8 days

MEAN	0.886	MEDIAN	0.305
STD DEV	1.798	VARIANCE	3.234
KURTOSIS	7.915	SKEWNESS	2.867
MINIMUM	0 days	MAXIMUM	8 days

TABLE XXXVI

Awaiting Parts Days

# of days	FREQ	ADJ PCT	CUM PCT	# of days	FREQ	ADJ PCT	CUM PCT
0	2485	--	--	31	2	1	87
1	82	21	21	32	2	1	88
2	25	6	27	33	3	1	89
3	13	3	30	34	2	1	89
4	15	4	34	35	7	2	91
5	12	3	37	36	3	1	92
6	15	4	41	37	2	1	92
7	19	5	45	38	3	1	93
8	17	4	50	39	2	1	93
9	16	4	54	40	1	0	94
10	15	4	57	42	2	1	94
11	11	3	60	43	2	1	95
12	11	3	63	44	1	0	95
13	10	3	65	46	2	1	95
14	7	2	67	47	1	0	96
15	9	2	69	48	2	0	96
16	9	2	72	49	1	0	96
17	6	2	73	50	1	0	97
18	6	2	75	51	1	0	97
19	4	1	76	52	1	0	97
20	4	1	77	53	2	0	98
21	6	2	78	55	1	0	98
22	6	2	80	56	1	0	98
23	4	1	81	60	1	0	98
24	3	1	82	61	1	0	99
25	3	1	82	62	1	0	99
26	3	1	83	67	1	0	99
27	3	1	84	69	1	0	99
28	6	2	85	70	1	0	100
29	4	1	86	95	1	0	100
30	2	1	87	98	1	0	100

Note: Percentages are percentages for actions with AWP.

Total actions 2884
Total actions with AWP 399

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A. Statistics: Unconstrained - actions with AWP

MEAN	13.714	MEDIAN	8.594
STD DEV	15.318	VARIANCE	234.656
KURTOSIS	5.079	SKEWNESS	1.977
MINIMUM	1 day	MAXIMUM	98 days

B. Statistics: Constraint 20 days - actions w/AWP

MEAN	9.850	MEDIAN	8.594
STD DEV	7.386	VARIANCE	54.555
KURTOSIS	-1.499	SKEWNESS	0.221
MINIMUM	1 day	MAXIMUM	20 days

C. Statistics: Constraint 60 days - actions w/AWP

MEAN	13.459	MEDIAN	8.594
STD DEV	14.268	VARIANCE	203.570
KURTOSIS	1.701	SKEWNESS	1.493
MINIMUM	1 day	MAXIMUM	60 days

TABLE XXXVII

Turnaround Time

# of days	FREQ	ADJ PCT	CUM PCT	# of days	FREQ	ADJ PCT	CUM PCT
0	1016	35	35	40	6	0	98
1	884	31	66	41	3	0	98
2	297	10	76	42	3	0	98
3	99	3	80	43	1	0	98
4	57	2	82	44	3	0	98
5	52	2	83	45	1	0	98
6	43	1	85	46	1	0	98
7	35	1	86	47	3	0	98
8	29	1	87	48	1	0	98
9	34	1	88	50	3	0	98
10	27	1	89	51	2	0	98
11	21	1	90	52	1	0	98
12	12	0	90	53	3	0	99
13	13	0	91	54	2	0	99
14	18	1	91	55	3	0	99
15	14	0	92	56	3	0	99
16	13	0	92	57	1	0	99
17	13	0	93	58	2	0	99
18	14	0	93	59	1	0	99
19	16	1	94	61	1	0	99
20	7	0	94	62	5	0	99
21	8	0	94	63	1	0	99
22	12	0	95	64	1	0	99
23	6	0	95	66	2	0	99
24	4	0	95	67	1	0	99
25	8	0	95	68	1	0	99
26	7	0	96	70	2	0	99
27	7	0	96	73	1	0	99
28	9	0	96	75	1	0	100
29	7	0	96	76	1	0	100
30	5	0	97	78	1	0	100
31	2	0	97	82	1	0	100
32	8	0	97	88	1	0	100
33	5	0	97	89	1	0	100
34	1	0	97	94	1	0	100
35	4	0	97	100	3	0	100
36	1	0	97	101	4	0	100
37	1	0	97	105	1	0	100
38	2	0	97				

A. Statistics: Unconstrained

MEAN	4.439	MEDIAN	0.982
STD DEV	11.225	VARIANCE	126.011
KURTOSIS	27.767	SKEWNESS	4.755
MINIMUM	0 days	MAXIMUM	105 days

B. Statistics: Current constraints (TAT=IP+SKD+RPR+AWP)

MEAN	2.743	MEDIAN	0.959
STD DEV	5.363	VARIANCE	28.757
KURTOSIS	9.286	SKEWNESS	3.058
MINIMUM	0 days	MAXIMUM	32 days

C. Statistics: Proposed constraints
TAT = IP + RC1 cr TAT = IP + RC2 + AWP

MEAN	3.804	MEDIAN	0.982
STD DEV	9.059	VARIANCE	82.068
KURTOSIS	24.069	SKEWNESS	4.492
MINIMUM	0 days	MAXIMUM	88 days

TABLE XXXVIII

Repair Process One Cycle Time

# of days	FREQ	ADJ PCT	CUM PCT	# of days	FREQ	ADJ PCT	CUM PCT
0	1246	50	50	18	4	0	99
1	756	30	81	19	5	0	99
2	219	9	89	21	1	0	99
3	66	3	92	22	1	0	99
4	36	1	94	24	1	0	99
5	36	1	95	25	2	0	99
6	19	1	96	26	3	0	100
7	17	1	96	27	1	0	100
8	9	0	97	29	1	0	100
9	12	1	97	30	2	0	100
10	8	0	98	32	2	0	100
11	6	0	98	33	1	0	100
12	2	0	98	51	1	0	100
13	2	0	98	56	2	0	100
14	4	0	98	61	1	0	100
15	8	0	98	62	1	0	100
16	3	0	99	66	1	0	100
17	6	0	99				

Total actions without AWP 2485

- -

A. Statistics: Unconstrained

MEAN	1.440	MEDIAN	0.497
STD DEV	4.210	VARIANCE	17.727
KURTOSIS	95.114	SKEWNESS	8.377
MINIMUM	0 days	MAXIMUM	66 days

B. Statistics: Proposed constraint 12 days

MEAN	1.181	MEDIAN	0.497
STD DEV	2.265	VARIANCE	5.131
KURTOSIS	11.784	SKEWNESS	3.333
MINIMUM	0 days	MAXIMUM	12 days

TABLE XXXIX

Repair Process Two Cycle Time

# of days	FREQ	ADJ PCT	CUM PCT
0	112	28	28
1	94	24	52
2	54	14	65
3	29	7	72
4	17	4	77
5	12	3	80
6	10	3	82
7	7	2	84
8	9	2	86
9	2	1	87
10	3	1	88
11	4	1	89
12	3	1	89
13	2	1	90
14	1	0	90
15	1	0	90
16	1	0	91
17	3	1	91
18	4	1	92
19	1	0	93
20	3	1	93
21	3	1	94
22	3	1	95
23	1	0	95
24	2	1	96
25	1	0	96
26	1	0	96
27	1	0	96
28	1	0	99
29	1	0	99
31	1	0	99
32	3	1	99
33	1	0	99
36	1	0	99
40	1	0	99
41	1	0	100
43	1	0	100
46	1	0	100
48	1	0	100
68	1	0	100
73	1	0	100

A. Statistics: Unconstrained

MEAN	4.734	MEDIAN	1.431
STD DEV	3.786	VARIANCE	14.337
KURTCSIS	128.509	SKEWNESS	9.992
MINIMUM	0 days	MAXIMUM	73 days

B. Statistics, actions w/AWP: Proposed Constraint 35 days

MEAN	4.446	MEDIAN	1.431
STD DEV	7.714	VARIANCE	59.509
KURTCSIS	6.103	SKEWNESS	2.565
MINIMUM	0 days	MAXIMUM	35 days

TABLE XL

Crosstabulation of BCM and AWP Actions

ROW PCT COL PCT TOT PCT	No AWP Time	AWP Time Occurred	ROW TOTAL
Successful Repair	2198 87.8 88.5 76.2	304 12.2 76.2 10.5	2502 86.8
Unit Declared BCM	287 75.1 11.5 10.0	95 24.9 23.8 3.3	382 13.2
COLUMN TOTAL	2485 86.2	399 13.8	2884 100.0

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