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THESIS

A COMPARISON OF SIX REPAIR SCHEDULING
POLICIES FOR THE P-3 AIRCRAFT

by

Peter J. Latta

March 1988

Thesis Advisor: D. P. Gaver

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for the P-3 Aircraft

by

Peter James Latta
Lieutenant, United States Navy
B.S., University of Southern California

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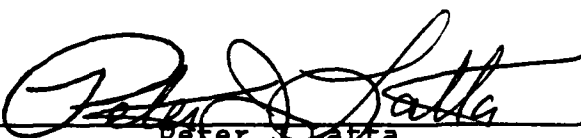requirements for the degree of

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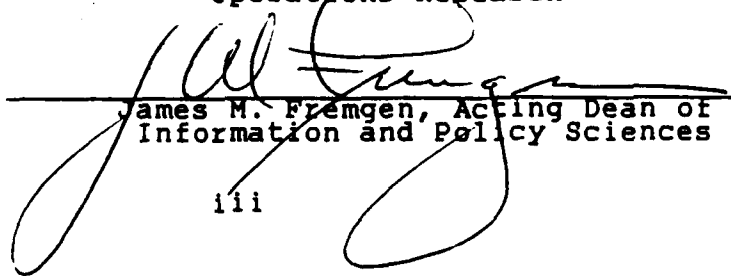Peter J. Latta

Approved by: _____
Donald P. Gaver, Thesis Advisor

_____
Patricia Jacobs, Second Reader

_____
Peter Purdue, Chairman, Department of
Operations Research

_____
James M. Fremgen, Acting Dean of
Information and Policy Sciences

iii

Abstract

There are a finite number of identical aircraft each of
which contain a number of different types of components
which fail at different rates. In order for an aircraft to
be operational, all of its components must be operational.
Each component type has a finite number of spares. Failed
components are repaired at a single server facility.
Simulation is used to study the effect of 6 different repair
scheduling policies. The repair policies are compared on the
basis of average number of operating aircraft at the end of
a mission period of one week. It is found that a repair
policy which first repairs the component of the type with
the fewest operating components is the best. In particular,
it is much better than first-in, first-out, and also may
well improve upon a policy that serves the longest waiting
line first. A simple spares stockage policy is developed and
evaluated when the above scheduling policy is in use.

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I. INTRODUCTION

This project was defined by and is under the direction of Professor Donald P. Gaver of the Department of Operations Research, of the Naval Postgraduate School. The objective is to study the means by which a maintenance policy might be more effective in support of a client. In this study, the client is a detachment of U.S. Navy P-3 aircraft.

This thesis presents a comparison of six different types of repair policies which a server may implement on a queuing line of different components. These components are subsystems of larger, identical systems (eg. radios and aircraft). Each of these components are mission-essential to the aircraft and fail independently of each other. There are n_i spares allocated to each component i, $i = 1,...,I$. The repair facility and the spare provisioning constitute the maintenance effort of the detachment. The repair facility has a single server who must decide on priorities for repairing the different types of failed components (Figure 1).

Simulation is used to study six repair policies for the server. The first priority policy is First-In, First-Out; the second policy serves the most numerous component type in queue first; the third serves first the largest product of the numbers of component types and individual component traffic intensities; the fourth's criteria is to serve the least frequent failure component first (smallest failure rate); the fifth repairs the most frequent failure component first (largest failure rate); and the sixth scans the current operating inventory for each component and repairs the component with the fewest operating. The six policies are compared on the basis of the average number of aircraft that have all I mission critical components up after a

1

miss· n of length T. The results of the simulations are presented in tabular form in Appendix B.

Systems

| Plane 1 | | | | Plane 2 | | |

Subsystems (Parts)

| 1 | 2 | 3 | | 1 | 2 | 3 |

Maintenance Effort

Repair facility

Server

Spare Allocation

Part 1. | 1 | | 2 |

Part 2. | 1 |

Part 3. | 1 | | 2 | | 3 |

Waiting line →

1

3

2

2
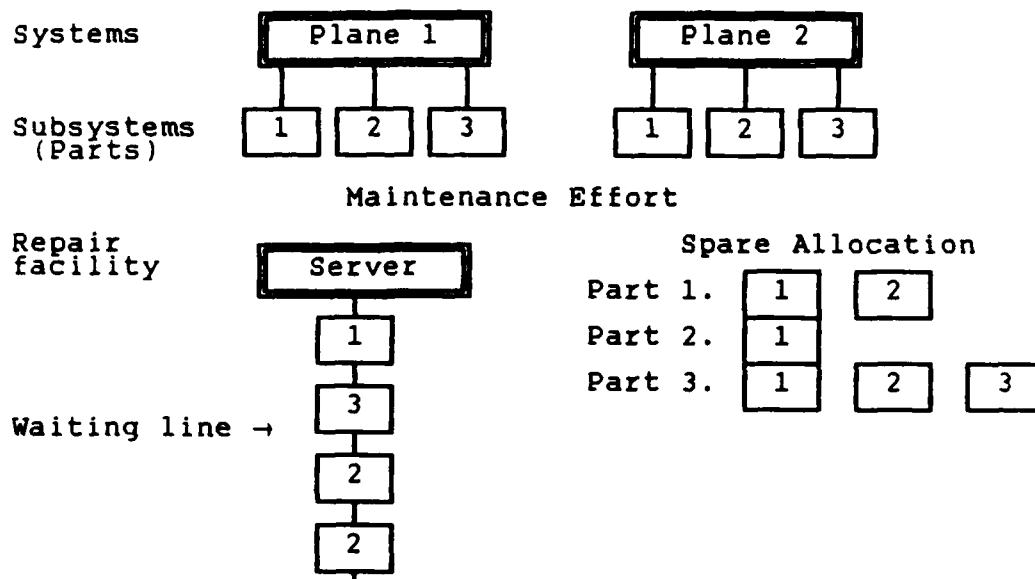
Figure 1.1.   System Diagram with Repair Facility

Maintenance and Material Management data from the Naval Aviation Logistics Data Agency (3-M/NALDA) are used for estimating failure rates and repair rates. In addition, extensive interviews with personnel at the Aviation Intermediate Maintenance Department at Moffett Field, California; and Naval Air Systems Command at Washington D.C., supplemented the data. The interviews indicated a need to look at the small detachment (less than six aircraft) problem as well as the short detachment problem (less than 90 days).

The Aviation Detachment consists of a small number of aircraft, each of which contains large numbers of components, sub-components, sub-sub-components, and so forth. Each of these systems contribute to the availability of a given aircraft's readiness for flight. Each aircraft, in turn, contributes to the detachment's ability to carry out its mission for some duration, which is typically not a long period of time.

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Simplifying assumptions are made in order to reduce the size and complexity of the analysis, aid in model verification, and provide understandable results. The only equipment considered for this study were pieces of electronics gear which were designated as mission-critical and failure-prone. The length of a mission is measured in flight hours and approximates one week's worth of flying. Resupply of the detachment occurs at that time; all parts are replenished.

The simulation models were implemented using FORTRAN 77 programs that are listed in Appendix A. The user inputs failure rates of specified parts, total mission time before resupply, total components, and total initial spares per component. The output displays the average number of "up aircraft" at the time of mission completion, as well as distributional information. A detailed discussion is provided in Chapter III.

II. **NATURE OF THE PROBLEM**

The detachment of small numbers of P-3 Orion aircraft by the U.S. Navy to remote sites around the world is a current method of operation by Fleet Commanders. These detachments are of relatively short duration, about six to eight weeks. They are required to be self-sustained or sustainable through air resupply. Small and measured amounts of replacement components arrive by P-3 or C-130 aircraft. The ability of these detachments to perform their mission is heavily dependent on (a) spare parts flown in initially and then at specified intervals, and (b) maintenance repair policy and capability.

In the case of the first, (a), considerable effort has been expended to address the spare part requirements for P-3 detachments to remote areas. However, the bulk of these consider larger detachments than three aircraft [Ref 1], and longer duration than six weeks. The case of provisioning smaller, shorter duration groups is most frequently achieved by senior maintenance personnel using corporate knowledge and experience to derive the requirements. In the case of the second (b), little information is available on the study of the effects of different repair policies. General experience by the author indicates that repair policy is a function of the current maintenance administration (policy as it relates to which part to fix when).

The overall goal of the Chief of Naval Operations is to achieve at least seventy-two percent of fully mission capable aircraft in a squadron. In whole numbers of aircraft, this translates to two of three in a small detachment. But this goal belies the fact that for a small group of planes to accomplish its mission, clearly all the aircraft must be available most of the time.

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The equipment selected for the present analysis was avionic gear which had, (a) mean time between failures short enough to ensure a reasonable chance of failure during a period of detachment, (b) was determined to be mission essential by proper authorities, and (c) was repairable or replaceable by the detached personnel. Each piece of gear was considered to fail independently of the others. The overall mission availability of an aircraft is modelled as a series system. If all the components are up, then the aircraft is up.

Availability

Figure 1.2. Minimum Path Representation of N Component System

The failure interarrival times at the queue of all components are assumed to be exponentially distributed. The service times are also assumed to be exponential. For the first series of simulation runs, the failure and service rates were the same for all parts. For the latter simulation runs, individual failure and repair rates for components are used.

III. MODEL DESCRIPTIONS

A. FAILURE MODELS

There are a variety of approaches to the modelling of component supply in a multi-component system with spares allocation. Generally speaking, as components fail and spares are utilized for replacements, spare part inventories can be entirely depleted. Any additional failures which occur beyond that inventory can result in systems as a whole being unavailable as they await maintenance. The rate at which parts arrive at the service center is a constant until that point is reached because the number of parts in use at any given moment, based on the operating aircraft, is constant. When the number of operating systems (aircraft) starts to drop, so do the corresponding arrival rates. A model incorporating this effect is referred to as the decreasing arrival rate model. This is a simple situation to simulate, and to obtain results for. However, it is not easy to derive analytical results for it. A more analytically tractable model is to assume arrivals of a part type to the service center form a Poisson process. This will be hereafter referred to as the constant arrival rate model. This latter approach is rationalized as follows; the remaining systems are required to increase their work load (flying hours) to compensate for the loss of a system(s), ergo more strain on the remaining systems. In addition to this, though, a higher (constant) arrival rate would represent a conservative approach to calculating spare requirements. A higher arrival rate would yield greater spares allocation in provisioning (most provisioning models use failure rates as the prime method of specifying spare requirements).

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Initially, two simulation models were written to compare the two models for numbers of failures: constant, and alternatively decreasing, arrival rates. Ideally, if the constant rate simulation results did not depart excessively from the actual decreasing rate simulation, then it would be desirable to use the constant rate model because it could be studied analytically.

Monte Carlo simulations were written in Fortran 77 and utilized a proven random number generator (LLRANDOM II). The simulations modeled aircraft components failing and being replaced by available spares; failed components were not serviced by a repair facility. The simulations used event stepping from failure to failure with exponential times between failures. To facilitate the analytical analysis, the number of aircraft was set at three, the total number of types of components per plane at two, and the number of spares for each type of component at one. The failure rate of component 1 is 0.02 failures per hour; the failure rate of component 2 is 0.0143 failures per hour. Each aircraft requires both component types to be in operation so that it, in turn, may operate. The generated output was the average number of up aircraft at the end of a specified time. The constant arrival model was verified through calculation (Appendix A). This simulation was then modified slightly to cause the failure rate to decrease when whole systems dropped off line to create the second model. Both simulations had five hundred replications. The results are listed below in Table III-1.

TABLE III-1. RESULTS OF MONTE CARLO SIMULATIONS OF DECREASING, CONSTANT, AND ANALYTICAL FAILURE RATE MODELS

Model	Initial Aircraft	Initial Spares	Time in Hours	Expected Up Aircraft
Decreasing	3	1	120	1.022
Constant	3	1	120	0.022
Analytical (Constant)	3	1	120	0.0201

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The conclusion drawn from the simulations is that the constant failure model does not describe well the situation of the failure rate for the components decreasing as whole systems drop off line. However, when whole systems or aircraft drop off line for maintenance, the remaining aircraft must fly the same work load. This results in subjecting the components on the remaining planes to more hours in operation. Therefore, the assumption that demand rates for spares decrease as whole systems drop off line is not entirely correct either. This situation of increased hours of operation on remaining aircraft is not easily quantifiable and might be consequential. The disparity between the models may be less dramatic for this reason. For this reason, the constant model is more commonly used in application (e.g., in various METRIC models at the RAND Corporation) [Ref. 2]. Reality is probably a middle ground between the two. However, the constant arrival rate model will be used in this with the caveat that it produces a conservative approach to provisioning.

B. QUEUING MODELS

The repair scheduling policy that a maintenance facility uses directly affects the available inventory of spares. How dramatically a given policy may influence systems as a whole is of concern to any maintenance supervisor. Six repair simulation models were written in Fortran 77 to study the effects of different repair policies on keeping whole units or systems operating. Model algorithms are listed in Appendix C. Example Fortran code is listed in Appendix D.

1. Simulation Background

The baseline simulation models an aircraft detachment located at a remote site. The detachment consists of several aircraft, the collection of which are serviced by a single maintenance facility. This facility has a single server who can work on a single part at a time. The server draws his parts from a single queue. As soon as he completes

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a repair, he immediately commences work on the next part if a backlog exists. Each aircraft contains several component types, each of which has a spare allocation (although the allocation may be zero). Each aircraft requires one of each component to operate. The detachment is expected to conduct operations for a period of time, and to be self-sufficient. A resupply occurs at the end of this period and all spares are replenished. The primary measure of effectiveness is average number of operating aircraft at the time of resupply; variance of the number of operating aircraft is also tabulated; the empirical distribution could be tabulated if desired. For this study, resupply occurs at the end of one week or approximately one hundred and twenty flight hours.

The assumptions which were incorporated in the simulation are as follows: the interarrival times of component failures are described by an exponential distribution; each component has a unique failure rate and fails independently of other components; failed components are instantaneously removed from the aircraft, replaced with available spares, and placed in either the repair queue or directly with the repair server; the arrival of failed components to the repair facility is described by a Poisson process with a rate equal to the sum of all component failure rates times the number of detached aircraft; cannibalization or the interchange of components to maximize working whole aircraft will occur; an aircraft needs all of its components to operate and anything less constitutes a down aircraft. Consequently, arrivals of failed components to the repair facility form a Poisson process with constant rate which does not change if the number of whole systems change. However, if no aircraft are operating, then the arrival rate is 0.

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A component which arrives for repair is of type i with probability:

$$\lambda_i \; / \; (\lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_i)$$

Component i's service time is described by an exponential distribution with parameter μ_i (mu); no balking occurs at the queue; the queue has potential length equal to the total number of components in the system; and the repair facility is capable of repairing all components.

2. Simulation Structure

All simulations evolve from a basic "failure-repair" model with a First-In, First-Out service policy. These repair models simulate continuous time systems by using "event stepping" of a simulation clock time from failure to repair, failure to failure, repair to failure, repair to repair events.

All simulations are structured with a main program to read input files, generate failures, control simulation clock and run parameters, and print statistics; a queue subroutine for repairs and policy decision criteria; a statistical subroutine to assimilate run data and generate output statistics; a random number subroutine to call the IMSL library and the LLRANDOM II package to generate arrays of pseudorandom uniform variates; and, in all but the baseline simulation (First-In, First-Out policy), a priority subroutine to assign a component priority based on decision criteria.

Input parameters are total mission duration (in-flight hours), total number of components per aircraft (parts), total number of spares allocated per component, and total number of replications of the simulation. The input file contains specific failure and repair rates for each component.

The output from a simulation run contains the arrival rate (lambda) at the queue; service rate and traffic intensity in those cases where service rates for all parts

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were set equal; expected numbers of operating aircraft at mission termination, variance and standard deviation; a tally of the number of Up Aircraft at the end of each run, for all runs; average maximum queue size; and average wait, in hours, by a part in the queue.

The repair policies of the various simulations differ at the waiting line of the queue. Policies adjust part positions in line for service by current repair decision criteria.

3. Simulation Techniques

Pseudorandom number generation is accomplished by utilizing a proven pseudorandom number package resident in the computer library titled LLRANDOM II; it was developed by Dr. P.A.W. Lewis of the Naval Postgraduate School (to check for the effect of the starting seed) [Ref. 3]. A subroutine calls LLRANDOM II three separate times, with three separate seeds, to generate three distinct arrays to store the uniform random variates. These uniform random variates are used to generate failure interarrival times, repair times, and determine which part has failed.

Failure interarrival times and repair times are exponential and are calculated using an inverse transform method. By incorporating this method into the simulations, any of a variety of distributions could be selected for the repair times (using the memoryless property of the exponential distribution heavily in generating failure times). The algorithm states that given a cumulative distribution function, $F(x) = P(X \leq x)$. $F(X)$ is uniformly distributed over the interval zero to one. By equating a uniform random variate to the CDF, $F(X)$, and solving for the inverse of $F(X)$, random variates with the distribution of $F(X)$ can be generated. [Ref. 4]

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Sample data on the number of up aircraft at mission termination is assimilated in the STATS subroutine. Sample statistics are then calculated where:

X_j = Number of up aircraft at mission's end on run j

n = Total number of runs

Q_i = Maximum queue size during simulation run i

W_i = Total amount of time (hrs) spent waiting for maintenance by the ith arrival at the queue

m = Total number of parts which waited in queue for all runs

$$\bar{X} = E\{number\ of\ up\ aircraft\} = \sum_{j=1}^{n} X_j / n$$

$$Var\{X\} = Variance\ of\ X = \sum_{i=1}^{n} (X_i - \bar{X})^2 / (n - 1)$$

$$S.D. = Standard\ Deviation\ of\ X = (Var\ X)^{.5}$$

$$W_Q = Average\ wait\ in\ the\ queue = \sum_{i=1}^{m} W_i / m$$

$$\bar{Q} = Average\ maximum\ queue\ size = \sum_{i=1}^{n} Q_i / n$$

4. Simulation Walkthrough

A simulation run begins with the initialization of mission parameters such as stock levels of components (components in use plus spares), mission clock, subroutine parameters for the queue, various flags and counters. The initial failure interarrival time is calculated and compared to an initial repair time (initially set high). The lesser of the two times determines the next event and the mission clock is advanced to that exact moment. Stock levels are adjusted when the events occur; repairs increment, failures decrement stocks. In the case of failures, after the appropriate stock is reduced, a component is instantly placed in the repair facility where it may either be served immediately or join a queue (repair policy will determine what position in line the part assumes). After a failed part

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has arrived at the repair facility, all component stock levels are scanned to ensure at least one aircraft remains in operation. If all aircraft are down, failures cease, the mission clock is advanced to the next repair time, and the repair event occurs. If at least one aircraft is up, failure and repair events continue as before. In the case of a repair event, after the appropriate stock is incremented, the next part in line is immediately brought into service and a new repair time is calculated. The component stocks are scanned again to ensure at least one aircraft is up. If the event where previously no aircraft were up but because the correct type of part was fixed one now exists, a failure interarrival time is then calculated and event comparison transpires as before. If the all aircraft are still down after a repair, the clock again advances to the next repair time and that event occurs.

The mission clock is allowed to be advanced from event to event until the scheduled time exceeds the predetermined mission duration. When this value is met or exceeded, the simulation run stops, data is gathered on those left waiting for service in the queue (waiting time) and the number of operating systems is recorded. The run number is compared to the total number of replications value input at the start. If more runs are required, a mission profile is reinitialized and the process repeats itself. Otherwise, statistics described in previous sections are computed and then displayed (at the terminal).

5. First-In, First-Out Model

This model is the basic simulation from which all others were extended. The First-In, First-Out or FIFO is a common form of maintenance scheduling policy. When a part arrives in the queue it is placed at the end of the line. When the server becomes available to work, the part at the head of the line or first to arrive, is served next. There are never any interruptions once service starts.

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6. Dynamic 1 Model

This policy adopts the following criteria: use a First-In-First-Out routine until such time as there are two or more of a given type of part in line, at which time the more numerous part type receives first priority for repair. For example, there are three types of parts in the queue awaiting maintenance, parts A, B, and C. There are two part A's, three part B's, and one part C. Parts B would move to the front of the line and be serviced first as long as they remain the most numerous.

7. Dynamic 2 Model

This service rule tells the repairman to count the number of parts of each type of component and multiply this by the individual traffic intensity of the component, then pick the largest value. The rule in the form of equations is as follows:

$$\rho_i = \lambda_i / \mu_i = \text{Traffic intensity of component } i$$
$$\text{Priority} = \text{Max}\{\rho_i \times N_i(t)\}$$

Where:

$N_i(t)$ = the number of parts of type i in the service line at time t

μ_i = the service rate of component i

λ_i = the failure rate of component i

8. Dynamic 3 Model

This scheduling policy determines service priority based on the current available stock of operating parts for each type component. After the repairman scans the stock levels, he reorders the parts in the service line to favor the one with the lowest operational inventory.

9. Failure Rate Priority-Low

This model assigns priority of service based on the failure rate of the type part. Those with the smallest failure rate, or least frequently failing, are given first service regardless of their arrival time. When the server scans the queue for the next part to fix, he compares the

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individual part lambdas to select the next repair. If multiple parts are of the same type, a FIFO policy is used. The abbreviation FRP-Low is used throughout the text.

10. Failure Rate Priority-High

This model is similar to FRP-Low with the following modification; priority is assigned to the most frequently failing or highest failure rate part. If multiple numbers of the same part are being considered, a FIFO policy is used. The abbreviation FRP-High is used throughout the text.

C. DATA

The primary source for failure and repair rate data in this study is the NALDA (Naval Aviation Logistics Data Agency) data base. The reason this source is used is because it employs extensive error checking algorithms in its database. It is considered the best source of clean data (error reduced) for P-3's by the experts at Naval Air Systems Command and in the fleet. The information it supplied was supplemented by personal interviews by the author with maintenance supervisors at the AIMD, N.A.S. Moffett Field, California.

The interviews cautioned that even though extensive error checking algorithms are employed by the data base, they were not error free. Precise values for the Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR) would require extensive data analysis. Reasonable approximations, however, could be easily extracted. Interviews provided an understanding of the sources of the data entries and the means to extract reasonable approximate values.

The focus of this thesis is repair policy evaluation. The author sought out values for failure and repair rates which would test repair decision criteria with a range of values and be representative of mission essential avionics. The final values are listed in Table III-2. The complexity of the P-3 avionics suite makes it necessary to approximate

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failure and repair rates for components. This is done because a component is composed of subcomponents, which are in turn composed of sub-subcomponents. Data information is gathered on the subcomponent level but requirements are derived on the whole component level. A separate study can be done to determine the component failure and repair rates as a whole. This thesis required only approximate values. Failure rates are derived from the mean number of flight hours between failures (MFHBF). The repair rates are derived from dedicated maintenance man hours (DMMH) at the AIMD, or intermediate maintenance level. It is important to note that the precise numerical values are not important as long as the relative magnitudes are correct and are reasonably representative of actual values.

TABLE III-2. FAILURE AND REPAIR RATES

Component$_i$	Lambda$_i$	MFHBF	Mu$_i$	DMMH
1	0.0200	50.0	1.000	1.0
2	0.0143	70.0	0.417	2.4
3	0.0180	55.5	1.000	1.0
4	0.0026	389.0	0.333	3.0
5	0.0193	51.8	0.666	1.5
6	0.0219	145.8	1.333	0.8
7	0.0010	1000.0	0.200	5.0
8	0.0110	90.9	0.400	2.5
9	0.0300	33.3	2.000	0.5
10	0.0060	166.7	0.444	2.3

IV. SIMULATION RUNS

A. BACKGROUND

The six repair policies were exercised through a series of different case studies in which input parameters were varied identically for all six policies. The Measure of Effectiveness (MOE), average number of aircraft in operation at the termination of the mission for each repair policy, was then compared. Due to the experimental nature of these repair policies, a control environment was needed to provide a benchmark of performance. Case studies 4 and 5 were an attempt to achieve this effect. Their model inputs were set equal across all component types (a more detailed discussion follows). Embellishments of the system operating environment were conducted in Case 6 and evolved further in Cases 1 through 3. These refinements subjected the models to ever more variable and complex system parameters.

The input parameters which were altered were: numbers of aircraft (planes); spares allocation for each component type; and individual component failure and repair rates. The total number of component types contained on each aircraft was held constant at 9 for all repair policies and cases. All simulations had five hundred replications.

1. Spares Allocation

Two different schemes for changing spare part stockage levels were devised. The first scheme is referred to as the "Spare to Plane Ratio" method. Initial spare provisions are set equal for all component types (i.e. component A's spares are initialized at 12 parts, as are component B's, as are C's, etc). As the name of the method indicates, the amount which the spare levels are varied is in proportion to the number of aircraft in the detachment. This ratio changes from 2, to 1.5, to 1, to 0.5, to 0.1666

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(1/6). For example, if there are six detachment aircraft (Planes), all components spares are varied from 12 (spare to plane ratio of 2), to 9 (1.5), to 6 (1), to 3 (0.5), to 1 (0.166). These provisioning changes constitute the differences between Cases 4a-4e, 5a-5e, and 6a-6e.

The second scheme is referred to as the "K-Standard Deviation" method. Predictions of the average number of failures a component will experience during a mission period is a measure of the demand for spares. The Poisson process is employed to estimate the mean number of spares each component would require during a mission period. The sensitivity of this estimate of the demand for spares is tested by adding to or subtracting from the mean K standard deviations of spares (from the appropriate Poisson distribution). For example, if the mean number of spares plus two standard deviations were stocked, the demand for parts could be expected to be met 95% of the time (without repair). The provisioning calculations proceed as follows:

Expected Demand for Part i = $[a \times t \times \lambda_i] = E[X_i]$

Standard Deviation of Demand = $(E[X_i])^{.5}$

Spare Policy Component i = $E[X_i] + K \times (E[X_i])^{.5}$

Where:

a = Number of aircraft

t = Total mission length

λ_i = Failure rate of Component i

K = Standard Deviation factor

The result of this policy for components having different failure rates is stock levels which are different for each component type. The most frequently failing component receives the most spares. Variations of the value of K determine the difference in Cases 1a-1h, 2a-2h, and 3a-3h.

2. **Failure and Repair Rates**

Two separate parameter schedules are used in the experimentation process. In the first, failure and repair rates are set equal for all component types (i.e., Component

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A's failure rate is 0.02 failures per hour and its' repair rate is 0.84 units per hour, as are Component B's, etc). This input schedule is used for Cases 4a-4e, and 5a-5e. The second schedule uses individual failure and repair rates listed in Table III-2 (Failure rates = Lambda$_i$, Repair rates = Mu$_i$). This parameter schedule is used for Cases 1a-1h, 2a-2h, 3a-3h, and 6a-6h.

3. Output

The output of each case is given in Appendix B. The listed results include the Mean number of operating aircraft at mission termination (Average Up Planes), the Variance of the number of up aircraft, the Standard Deviation of the number of up aircraft, the Standard Error of the Mean, and the fraction of Up Planes operating at mission termination.

The number of operating aircraft at the end of a given run is determined by analyzing the number of operating parts of component type i, i = 1,...,I. The component with the minimum number of operating parts determines the maximum number of operating planes. The Mean number of operating aircraft is calculated from the numerical average of Up Aircraft at the end of all replications (runs). This is the common sample mean:

$$\text{Mean Up Aircraft} = \sum_{i=1}^{500} X_i / 500 = \overline{X}$$

Where:

X_i = Number of Up Aircraft on run i

The Variance of the run sample and the Standard Deviation are:

$$\text{Variance} = \sum_{i=1}^{500} (X_i - \overline{X})^2 / 499 = \text{Var}[X]$$

$$\text{Standard Deviation} = (\text{Var}[X])^{.5}$$

The Standard Error of the Mean is given by the relation:

$$\text{Standard Error} = S_{\overline{x}} = (\text{Var}[X] / 500)^{.5}$$

The Fraction of Up Planes operating at mission termination is used as a measure of effectiveness for the policies. It

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is calculated after each subcase is completed and is derived by dividing the Mean number of operating Aircraft (E[X]) by the total number of detachment aircraft. [Ref. 5]

4. Random Seeds and Stability

In order to establish that the simulations had reached stability in sampling variance, five of the six models were simulated by varying only the random number seeds used in generating failures and repairs[1]. Four sets of seeds were utilized. Two-way Confidence Intervals for the Means (Expected Number of Up Aircraft) were then computed at a level of 95%. The distribution of the Sample Means was assumed to be Normal in accordance with the Central Limit Theorem. The results are listed in Appendix B. and demonstrate that the sampling variance had stabilized. For any given policy, the Means of any combination of three random number sets fell within the confidence interval of the remaining fourth set. For any given set of random number seeds, the six repair policy Means established a rank order by magnitude. This relative ranking between policies did not change for all four seed sets. As a result, it was determined that reliable output from the simulations could be anticipated with five hundred replications.

B. CASE DESCRIPTIONS

1. Case 4-5

These cases were designed to give a baseline measure of how the models would compare in a environment where interrelational effects between parameters such as failure and service rates, and stock levels, could be minimized. Case 5 differs from Case 4 in the number of total aircraft. Subcases of Case 4 and 5 delineate variations in initial spare provisioning as described by the "Spare to Plane Ratio" method. Inherent to the background of both cases are

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[1]The sixth model, Dynamic 3 was added after this exercise. Stability of variance for it was assumed based of the other models' results.

failure and repair rates, and total numbers of components per plane (9). Failure and repair rates are fixed at equal values (0.02 and 0.84 respectively) for all types of components. These rates represent average values for the listing in Table III-2.

2. **Cases 1-3**

In these cases, the failure and service rate for the components differ. These cases were designed to analyze how sensitive the various models were to a dynamic environment where several of the parameters are varied (and may have potential interrelated effects). For example, high failure rates and high service rates in conjunction with large quantities of spares may result in the server dedicating a significant portion of his effort towards a single type part. As before, Cases 1, 2, and 3 differ in numbers of detached aircraft. Case 1 contains three; Case 2 contains six; Case 3 contains twelve. Subcases delineated spare provisioning as described by the "K-Standard Deviation" method. Cases 1, 2, and 3 differ in their selection of values of K. The range of K is +1 to -4. Negative values of K are selected to explore the effects of decreasing spare levels. The actual spare allocations as a function of case number are listed in Table B-3 of Appendix B. An excerpt from that Table is given below as an example.

TABLE IV-1   MODEL PARAMETERS: SPARE ALLOCATION OF
                COMPONENTS FOR SIMULATION CASES

	Case 1a	Case 1b	Case 1c	Case 1d
K-Factor	+1	0.0	-0.5	-1.0
PART 1	10	7	6	5
PART 2	7	5	4	3
PART 3	9	6	5	4
PART 4	2	1	0	0
PART 5	10	7	6	4
PART 6	11	8	6	4
PART 7	1	0	0	0
PART 8	6	4	3	2
PART 9	14	11	9	8

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Unique component failure and service rate are input from Table III-2. Total components per aircraft are nine.

3. **Case 6**

This was an intermediate step from Cases 4-5 and Cases 1-3 for parameter selection. Spare stockage levels employed the "Spare to Plane Ratio" method as per Cases 4 and 5. This determined the variation in the subcases (6a-6e). Unique failure and repair rates are initialized at the values listed in Table III-2, and as per Cases 1-3. The number of component types per aircraft is unchanged at nine.

V. RESULTS OF CASE STUDIES

The purpose of the case studies is to compare different repair policies using as the primary MOE average number of aircraft up at the end of a mission of finite length. A repair policy substantially more responsive to shortages then a simple First-In, First-Out routine should stand out. The Dynamic 3 policy consistently achieved this result. Conversely, the Failure rate priorities are consistently poor performers (relative to the FIFO benchmark). The other two Dynamic policies are sensitive to the spare provisioning policy. Recall the fact that both Dynamic 1 and Dynamic 2 set priority for service based on total numbers of component types awaiting maintenance. High-failure rate parts, which are also provisioned more heavily, will tend to consume the available server's capacity. Those parts which are stocked at lower levels (based on lower failure rates) are relegated to the "back of the line". It is the effect of all the lower rate failure items being placed at the end of the line which causes the Dynamic 1 and 2 to drop in performance (when there are unequal numbers of spares for each component). There is a cross-over point for these two models relative to the FIFO policy, that point being when the spare provisions are depleted to the point where stock levels begin to equalize (K factor $\leq$ -2.25). More detailed case by case discussions are provided in this chapter.

Case study results are listed in Table B-1, Appendix B. The graphical summaries contained in this chapter provide a visual means to summarize the effectiveness of each of the repair policies relative to each other. Since Cases 4-5 provide a baseline measure for the models, they will be discussed first, followed by Case 6, and then Cases 1-3.

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A. CASES 4-5: EQUAL FAILURE AND REPAIR RATES

The equality of failure rates for each component and repair rates for each component should demonstrate the relative capability of each repair policy to replenish spare stock levels and keep airplanes operating. A significant difference between policies can be determined by comparing the Mean and the Standard Error for each data point from Appendix B and calculating Normal confidence intervals for the mean (also by recalling that for Normal distributions, 95% of a population distribution should lie roughly within 2 standard deviations of the mean). By analyzing the data and graphs (Figures 5-1, 5-2), for Cases 4-5, the Dynamic policies (1, 2, 3) are consistently more able to keep aircraft operating (stocks replenished).
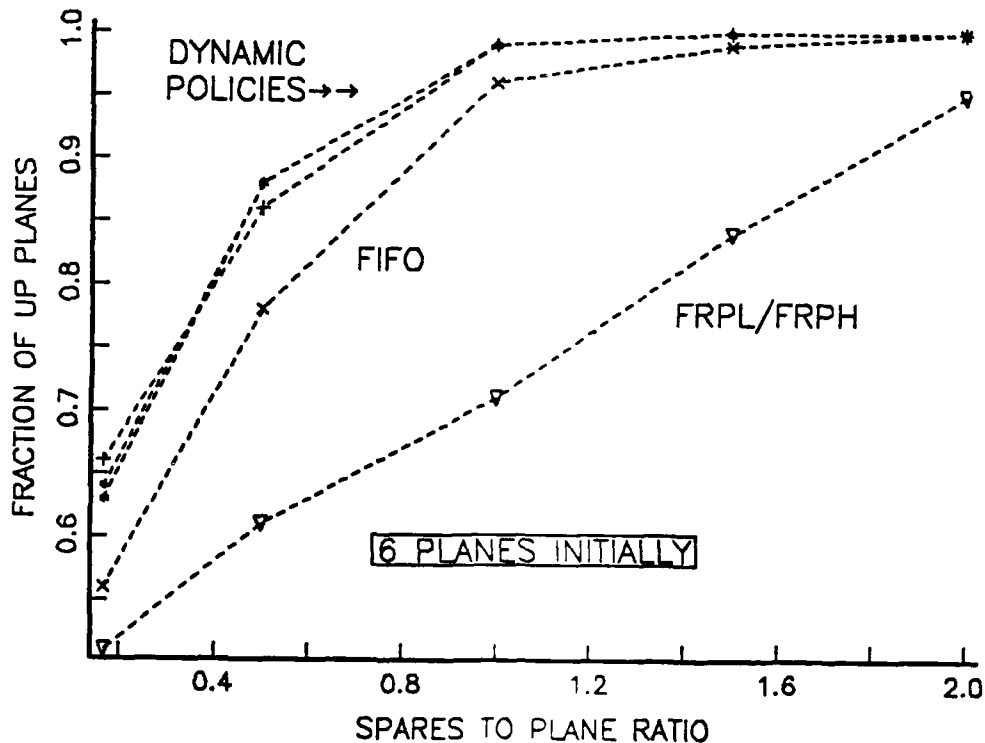
Figure 5.1.   Fraction of Operating Planes as a Function of Spares to Planes Ratio (Case 4).

The difference between them and the FIFO routine is significant at the point where the spare to plane ratio is equal to 1.5. Since failure and service rates are equal for

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all components, Dynamic and Dynamic 2 are in essence following the same policy as Dynamic 3; that being, repair the lowest stock level first (or conversely the most numerous in the queue).
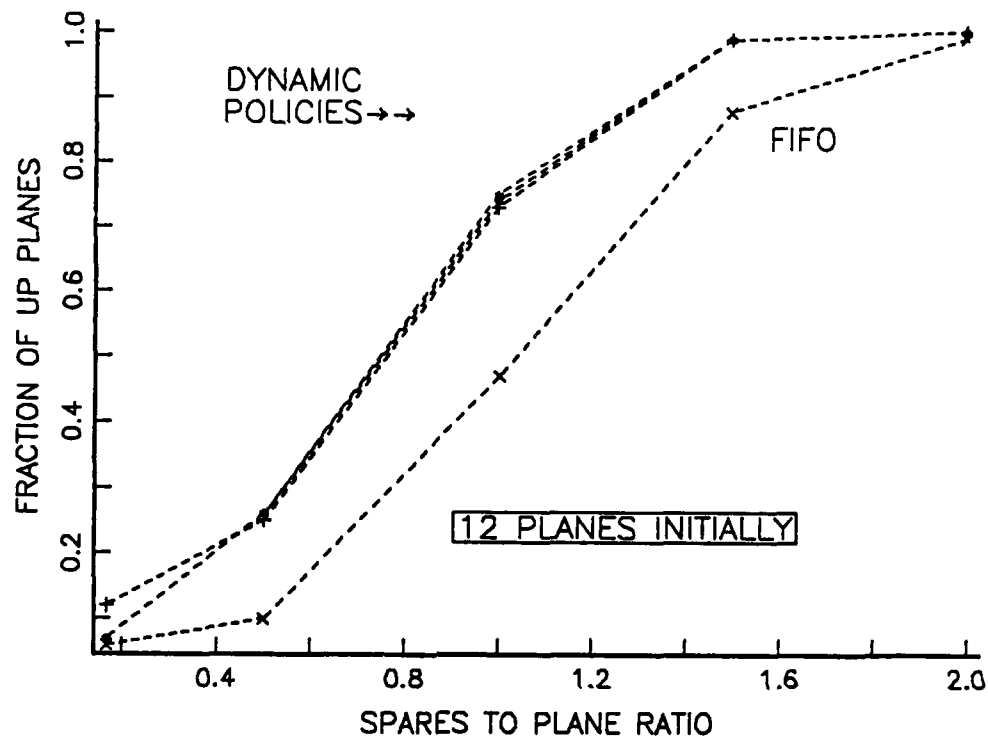
Figure 5.2. Fraction of Operating Planes as a Function of Spares to Planes Ratio (Case 5).

The actual differences in the policies are attributed to variation within the simulation. The means for the Dynamic policies were within 1.96 standard deviations of each other (95 % Confidence Interval). The Failure rate priority policies were not considered in Case 5 due to their poor performance in Case 4. In Case 4, they demonstrated performance which was as much as twenty five percent less effective than FIFO. The difference between the Failure rate priority routine and FIFO is because FRP-L and FRP-H assign priorities one through nine to each of the parts. Since all the rates were identical, the priority assigned was one for component one, two for component two, etc. Also, since the

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rates were identical, there is no difference in component priorities in FRP-L and FRP-H.

B. CASE 6: DIFFERENT FAILURE AND REPAIR RATES; IDENTICAL SPARES STOCKING

These simulations address the issue of how the policies respond to variable failure and service rates with a constant part stockage. Individual component failure and repair rates are given by Table III-2. Again, since the numbers of spares is the same for all parts, Dynamic and Dynamic 2 still reflect the Dynamic 3 policy (numbers in the queue relate to the stock levels which relates to Up Planes). The Dynamic policies are still consistently better than either FIFO or the Failure Rate policies (Figure 5-3).
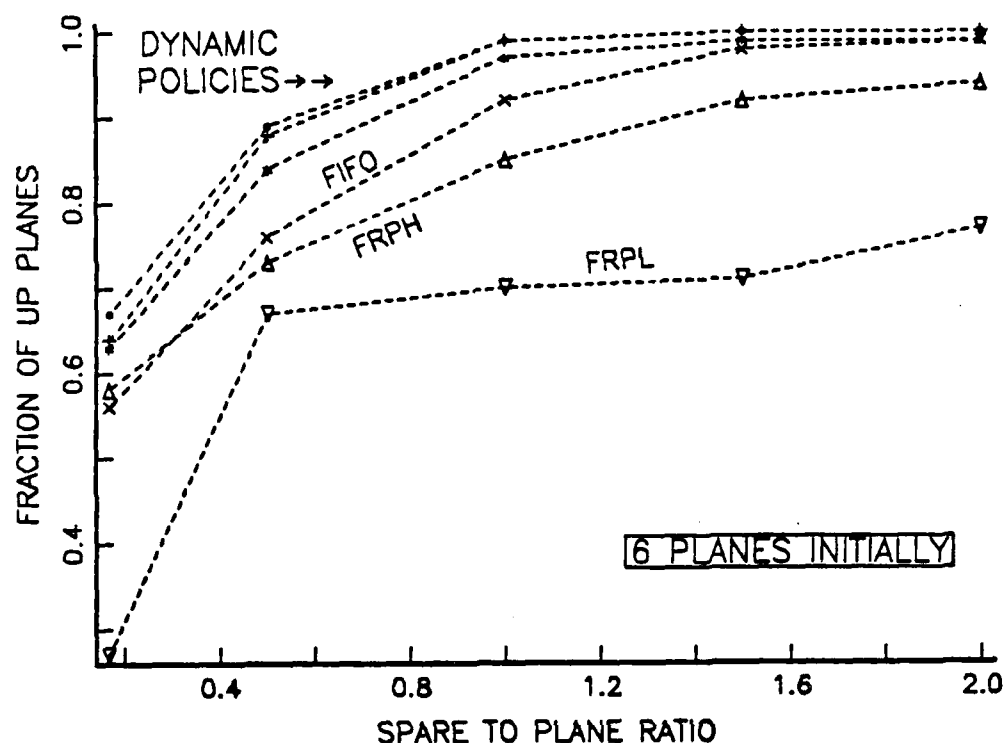
Figure 5.3.   Fraction of Operating Planes as a Function of Spares to Planes Ratio (Case 6).

Again, the point of significant departure for the Dynamic policies and FIFO occurred at a plane to spare ratio of 1.5. The Dynamic policies' means fell outside of a 95% confidence interval for the FIFO policy. The differences between the

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Dynamic policies is attributed to variation in the Mean (within a 95% confidence interval). The Failure rate policies showed improvement. These two policies are now dissimilar because failure and repair rates are different. Between the two, FRP-H performs significantly better than FRP-L (based on a 95% confidence interval about the means).

C. CASE 1-3: DIFFERENT RATES, DIFFERENT STOCKS

In these cases, we see a change occur in the abilities of Dynamic 1 and Dynamic 2 to replenish stock levels. Initial stock levels are no longer equal for all parts. They vary for each component based on failure rates. High failure rate components are supplied the most spares; low failure rate components the least. Since Dynamic 1 and Dynamic 2 repair the component having the most numerous failed parts first, the issue of replacing the most needed operating stock is skirted. High-failure items can fill the queue and still maintain sufficient operating units on all aircraft. Other units may fail; however, if they fail in insufficient numbers, they may never be served. For example, in a case in which the expected demand (failures) is stocked for Component 1 and 8 (K = 0 for 6 planes), their respective spares are 14 and 8. Component 1's failure rate is approximately twice eight's (0.02 vice 0.011). Therefore, Component 1's arrive at the repair facility twice as often. If there are 14 Component 1s waiting for repair and 13 Component 8s waiting for repair, then the Dynamic 1 and 2 policies would choose Component 1 to repair next even though there are still 6 Component 1s operating and only 1 Component 8 operating. This policy would result in only 1 plane operating. A comparison of Case 6 with Case 2 will demonstrate what happens when the spare provisioning policy is changed from equal spares for all components (Spare to Plane Ratio method) to a failure-based system (K-Standard Deviation method). The Dynamic 3 policy is concerned only with those components which are in most demand (lowest

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operating stock level), regardless of the number awaiting service. It doesn't waste time on repairing those failed parts that have sufficient spare stock levels at a given moment. Dynamic 3 was consistently the best of all policies (Figure 5-4,5-5,5-6).
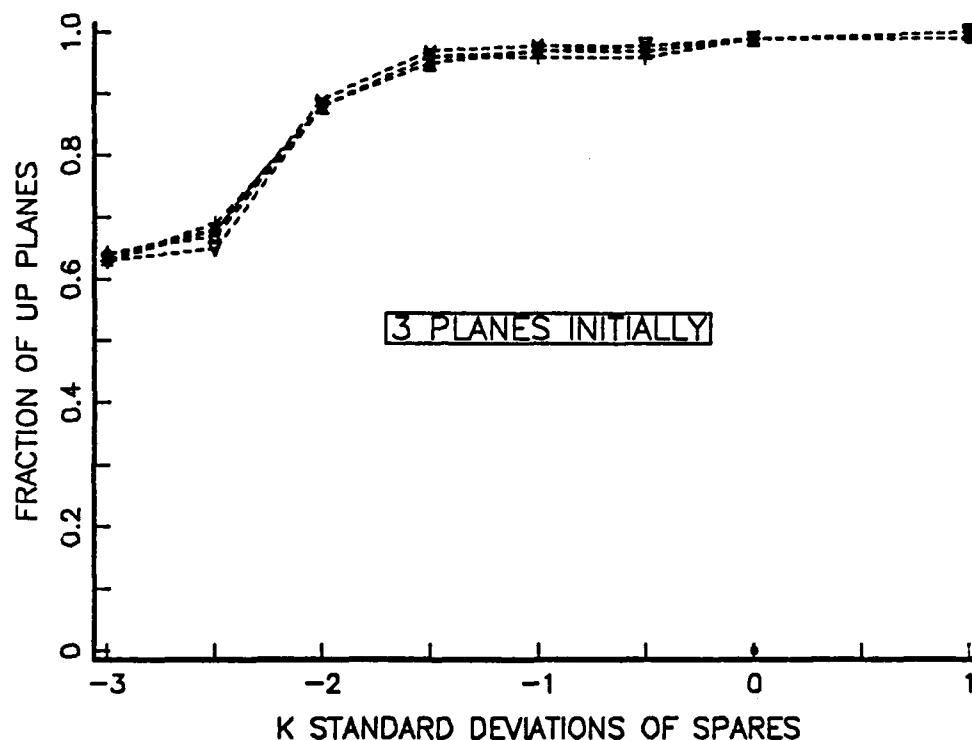
Figure 5.4.   Fraction of Operating Planes as a Function
            of K Standard Deviations of Parts (Case 1).

Once again, the Failure policies do not to perform well. In Case 1 with 3 planes, there is a tight bunching of all the policies. This is due to the fact that the server is not very busy with 3 planes and as a result, the form of the repair policy is not critical. As the number of planes increase, the policies diverge; the server becomes less able to rejuvenate stocks in the face of higher demands.
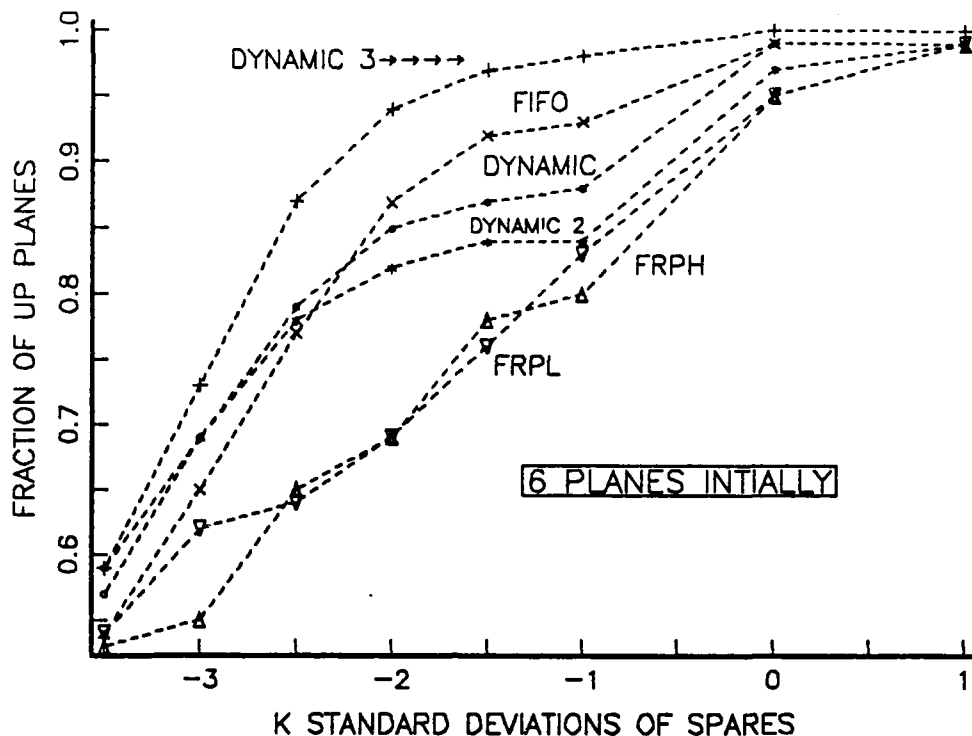
Figure 5.5. Fraction of Operating Planes as a Function of K Standard Deviations of Parts (Case 2).
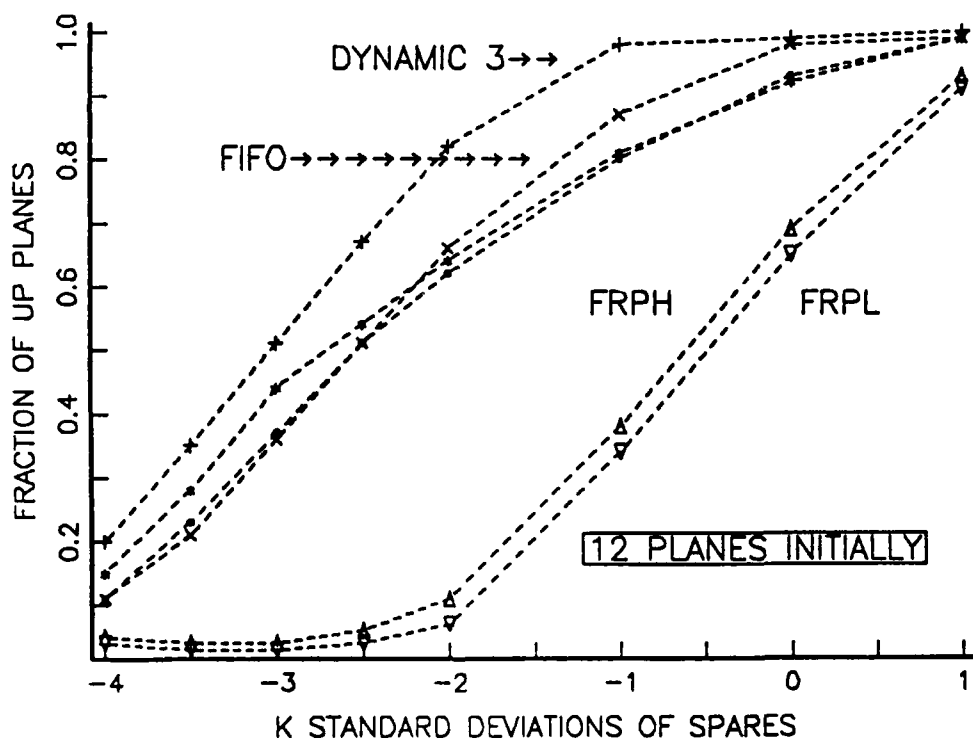
Figure 5.6. Fraction of Operating Planes as a Function of K Standard Deviations of Parts (Case 3).

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VI. RESULTS AND CONCLUSIONS

This thesis has presented a comparison of six repair scheduling policies. The Dynamic 3 repair model, which schedules service in favor of the component with the lowest operating stock, yields a significant improvement of available aircraft at the end of a resupply period when compared to a simple First-In, First-Out policy. A key factor in repair policy scheduling is the current inventory of available operating components. The other models which were studied in this thesis failed to address this issue directly. As a result, when spares were stocked in unequal numbers (the most likely real world situation), the other policies (Dynamic, Dynamic 2, FIFO, FRP-L, FRP-H) did not perform as well as Dynamic 3.

The overall goal of the Chief of Naval Operations is to achieve at least seventy-two percent of fully mission capable aircraft. The maintenance support of a squadron and the supporting airwing are responsible for accomplishing that goal. It is clear from the studies conducted in this thesis that significant differences in aircraft availability can result simply by the manner in which a maintenance effort schedules its repairs. A policy such as Dynamic 3 can assist in achieving the CNO goal better than FIFO. Spare stock levels are maintained more effectively regardless of the provisioning policy or the workload in the repair facility. However, a simple and sensible stocking policy increases effectiveness even more; the K-policy illustrates this fact. F ture study into other repair and stockage policies is recommended to study their effects on system availability. Other repair policies may look into the effects of different distributional assumptions for failure and repair times, as well as repair scheduling. It is also

necessary to consider the effect of breakdowns of the repair facility itself: How can these be best accommodated? Finally, it is desirable to reduce the computational effort needed to evaluate repair and stockage policies either by improving simulation efficiency by Monte Carlo "swindle", or by their replacement by analytic approximations. These steps are under current examination.

APPENDIX A

A. THE PROBABILITY CALCULATIONS OF UP AIRCRAFT

The following calculations are used to verify the constant arrival rate simulation model with no repair facility.

Parameters:

$A_i(t) = $ The number of type i components available and up during the interval $(0,t]$

$F_i(t) = $ The number of type i components which fail during the interval $(0,t]$

$I = $ The total number of types of components

$a = $ The total number of aircraft

$n_i = $ The total number of spares of type i component

$\lambda_i = $ The failure rate for component i

Each aircraft requires one of each type of component to operate. The maximum number of up aircraft at any given moment t is equal to the lowest level of up components for any given type of part. Therefore, the number of up aircraft at any given time t is:

$$A(t) = Min\{A_1(t), A_2(t), \ldots, A_I(t),\ldots,a\} \quad (A.1)$$

If we use the constant failure rate assumption, component i will fail at constant rate equal to a λ_i, even if the number of up aircraft is less than a. We assume an exponential failure distribution and cannibalization of parts. This leads to approximating the failure time of part i by a Poisson arrival process. We are interested in the probability of a minimum number of aircraft being up at time t:

$$P\{Min \,\# \, A/C \, up \geq k\}\ldots\ldots$$

$$P\{A(t) \geq k\} = \prod_{i=1}^{I} P\{ A_i(t) \geq k\} \quad (A.2)$$

$$= P\{ \# \, A/C \, avail. \geq k\}$$

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since different components are assumed to fail independently and based on the number of aircraft hours flown $(0,t]$

The probability that the number of components that fail of type i in the interval $(0,t]$ is less than or equal to some fixed value j is:

$P\{\#$ parts that fail type i in $(0,t] \leq j\} =$

$$P\{F_i(t) \leq j\} = \sum_{k=0}^{j} \frac{e^{-a\lambda_i t}(a\lambda_i t)^k}{k!} \quad,\text{ if } j < a+n_i \quad (A.3)$$

$$P\{F_i(t) \leq j\} = 1 \quad\quad\quad,\text{ if } j \geq a+n_i$$

Now, recall that the number of failed components plus the number of available components equals the total components.

$$F_i(t) + A_i(t) = a + n_i \rightarrow A_i(t) = a + n_i - F_i(t) \quad (A.4)$$

We would like to solve for the probability that the number of available components of type i at time t is greater than or equal to some number k or $P\{A_i(t) \geq k\}$. So substituting A.4. for $A_i(t)$, we solve:

$$P\{a + n_i - F_i(t) \geq k\} \rightarrow P\{F_i(t) \leq a + n_i - k\} =$$
$$P\{A_i(t) \geq k\}.$$

If we let the number $j = a + n_i - k$ and plug into our previous solution (A.3) for the number of components that fail of type i in the interval $(0,t]$: $P\{F_i(t) \leq j\}$ ....

$$P\{F_i(t) \leq a + n_i - k\} = \sum_{L=0}^{a+n_i-k} \frac{e^{-a\lambda_i t}(a\lambda_i t)^L}{L!} \quad (A.5)$$

$$= P\{A_i(t) \geq k\}$$

We now solve for the boundary conditions:

lower: $j < a + n_i$, $j = a + n_i - k \rightarrow k \geq 1$

upper: $k \leq a$, since you can not exceed the total number of aircraft in the system as an upper bound.

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In summary, the probability that the number of up aircraft is greater than some fixed number k is given by...

$$P\{A(t) \geq k\} = \prod_{i=1}^{I} \sum_{L=0}^{a+n_i-k} \frac{e^{-a\lambda_i t} (a\lambda_i t)^L}{L!} \quad \text{if } 1 \leq k \leq a$$

$P\{A(t) \geq 0\} = 1$ ... the entire probability space

$P\{A(t) \geq a+1\} = 0$ ... you cannot exceed the total number of aircraft.

The expected number of up and operating systems at the end of some period t is given by the product of the probability of a given value and that value:

$E\{A(t)\} = 0 \times P\{A(t)=0\} + 1 \times P\{A(t)=1\} + 2 \times P\{A(t)=2\} + \ldots$

The variance of the expected number of up and operating systems at the end of period t is given by:

$E\{A(t)^2\} = 0 \times P\{A(t)=0\} + 1^2 \times P\{A(t)=1\} + 2^2 \times P\{A(t)\} + \ldots$

$Var\{A(t)\} = E\{A(t)^2\} - E\{A(t)\}^2$

where: $P\{A(t)=0\} = P\{A(t) \geq 0\} - P\{A(t) \geq 1\}$

The constant arrival simulation without repair is verified with the parameters:

$I = 2$, $a = 3$, $n_1 = 1$, $t = 120$, $\lambda_1 = 1/50$, $\lambda_2 = 1/70$

The probabilities then follow:

$P\{A(t)=1\} = P\{A_1(t)=1\} \times P\{A_2(t) \geq 1\}$
$\quad\quad + P\{A_1(t) \geq 1\} \times P\{A_2(t)=1\} = 0.01479$

$P\{A(t)=2\} = P\{A_1(t)=2\} \times P\{A_2(t) \geq 2\}$
$\quad\quad + P\{A_1(t) \geq 2\} \times P\{A_2(t)=2\} = 0.00273$

$P\{A(t)=3\} = P\{A_1(t)=3\} \times P\{A_2(t) \geq 3\}$
$\quad\quad + P\{A_1(t) \geq 3\} \times P\{A_2(t)=3\} = 0.00001$

$E\{A(t)\} = 1 \times 0.01479 + 2 \times 0.00273 + 3 \times 0.00001$

$E\{A(t)\} = 0.0201$, $E\{A(t)\}^2 = 0.0004$

$E\{A(t)^2\} = 0.0258$

$Var\{A(t)\} = 0.0254$

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP AIRCRAFT VS SIMULATION CASE NUMBER

	Case 1a	Case 1b	Case 1c	Case 1d
Planes	3	3	3	3
K-Factor[2]	1	0	-0.5	-1
Parts/Plane	9	9	9	9
Lambda/Mu	----Individual Failure, Service rates used-----			
Dynamic 1				
Mean	3.00	2.99	2.93	2.92
Variance	0.00	0.01	0.07	0.07
S.Dev.	0.00	0.10	0.27	0.27
$S_{\bar{x}}$[3]	0.00	0.00	0.01	0.01
% Up A/C	1.00	0.99	0.98	0.97
Dynamic 2				
Mean	3.00	2.98	2.89	2.89
Variance	0.00	0.02	0.09	0.09
S.Dev.	0.00	0.14	0.32	0.32
$S_{\bar{x}}$	0.00	0.01	0.01	0.01
% Up A/C	1.00	0.99	0.96	0.96
Dynamic 3				
Mean	3.00	2.97	2.93	2.93
Variance	0.00	0.03	0.06	0.07
S.Dev.	0.00	0.17	0.25	0.26
$S_{\bar{x}}$	0.00	0.01	0.01	0.01
% Up A/C	1.00	0.99	0.98	0.98
FIFO				
Mean	3.00	2.97	2.93	2.92
Variance	0.00	0.03	0.07	0.07
S.Dev.	0.00	0.17	0.27	0.27
$S_{\bar{x}}$	0.00	0.01	0.01	0.01
% Up A/C	1.00	0.99	0.98	0.97
FRP-Low				
Mean	3.00	2.96	2.91	2.91
Variance	0.00	0.04	0.08	0.08
S.Dev.	0.00	0.19	0.29	0.29
$S_{\bar{x}}$	0.00	0.01	0.01	0.01
% Up A/C	1.00	0.99	0.97	0.97
FRP-High				
Mean	2.99	2.96	2.92	2.92
Variance	0.01	0.04	0.09	0.08
S.Dev.	0.10	0.20	0.29	0.29
$S_{\bar{x}}$	0.00	0.01	0.01	0.01
% Up A/C	0.99	0.99	0.97	0.97

[2]K-Standard Deviation method used, see Chapter IV

[3]$S_{\bar{x}} = \{(Variance/500)\}^{.5} = $ Standard Error

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP AIRCRAFT VS SIMULATION CASE NUMBER[4]

	Case 1e	Case 1f	Case 1g	Case 1h
Planes	3	3	3	3
K-Factor	-1.5	-2.0	-2.5	-3.0
Parts/Plane	9	9	9	9
Lambda	--------Individual Failure rates used--------			
Mu	--------Individual Service rates used--------			
Dynamic 1				
Mean	2.89	2.65	2.03	1.93
Variance	0.12	0.32	0.38	0.39
S.Dev.	0.34	0.57	0.61	0.63
$s_{\bar{x}}$	0.02	0.03	0.03	0.03
% Up A/C	0.96	0.88	0.68	0.64
Dynamic 2				
Mean	2.87	2.63	2.09	1.89
Variance	0.12	0.33	0.39	0.31
S.Dev.	0.34	0.56	0.62	0.63
$S_{\bar{x}}$	0.03	0.03	0.03	0.02
% Up A/C	0.96	0.88	0.69	0.63
Dynamic 3				
Mean	2.91	2.68	2.04	1.91
Variance	0.09	0.29	0.42	0.36
S.Dev.	0.31	0.55	0.64	0.59
$S_{\bar{x}}$	0.01	0.02	0.03	0.02
% Up A/C	0.97	0.89	0.68	0.63
FIFO				
Mean	2.89	2.64	1.96	1.92
Variance	0.11	0.34	0.38	0.36
S.Dev.	0.33	0.59	0.62	0.60
$S_{\bar{x}}$	0.02	0.03	0.03	0.03
% Up A/C	0.96	0.88	0.65	0.63
FRP-Low				
Mean	2.86	2.65	2.02	1.93
Variance	0.17	0.37	0.39	0.33
S.Dev.	0.41	0.61	0.63	0.57
$S_{\bar{x}}$	0.02	0.03	0.03	0.03
% Up A/C	0.95	0.88	0.67	0.64
FRP-High				
Mean	2.86	2.65	2.05	1.93
Variance	0.16	0.35	0.38	0.34
S.Dev.	0.39	0.59	0.62	0.59
$S_{\bar{x}}$	0.02	0.03	0.03	0.03
% Up A/C	0.95	0.88	0.68	0.64

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[4]Note: None of the policies differ much, either practically or statistically.

TABLE B-1 MODEL STATISTICS: EXPECTED NUMBER OF UP AIRCRAFT VS SIMULATION CASE NUMBER

	Case 2a	Case 2b	Case 2c	Case 2d
Planes	6	6	6	6
K-Factor	1	0	-1	-1.5
Parts/Plane	9	9	9	9
Lambda	--------Individual Failure rates used--------			
Mu	--------Individual Service rates used--------			
Dynamic 1				
Mean	5.99	5.93	5.27	5.23
Variance	0.01	0.09	0.71	0.72
S.Dev.	0.10	0.32	0.84	0.85
$S_{\bar{x}}$	0.00	0.01	0.04	0.04
% Up A/C	0.99	0.99	0.88	0.87
Dynamic 2				
Mean	5.96	5.83	5.03	5.03
Variance	0.01	0.25	1.09	1.09
S.Dev.	0.11	0.49	1.05	1.05
$S_{\bar{x}}$	0.00	0.02	0.05	0.05
% Up A/C	0.99	0.97	0.84	0.84
Dynamic 3[a]				
Mean	6.00	6.00	5.88	5.83
Variance	0.00	0.00	0.11	0.19
S.Dev.	0.00	0.00	0.34	0.43
$S_{\bar{x}}$	0.00	0.00	0.01	0.02
% Up A/C	1.00	1.00	0.98	0.97
FIFO				
Mean	5.99	5.99	5.61	5.53
Variance	0.01	0.02	0.42	0.65
S.Dev.	0.10	0.15	0.65	0.80
$S_{\bar{x}}$	0.00	0.01	0.03	0.04
% Up A/C	0.99	0.99	0.93	0.92
FRP-Low				
Mean	5.94	5.69	4.97	4.58
Variance	0.22	1.11	2.95	4.09
S.Dev.	0.46	1.05	1.72	2.02
$S_{\bar{x}}$	0.02	0.05	0.08	0.09
% Up A/C	0.99	0.95	0.83	0.76
FRP-High				
Mean	5.96	5.71	4.78	4.69
Variance	0.07	0.66	2.03	2.54
S.Dev.	0.26	0.81	1.42	1.59
$S_{\bar{x}}$	0.01	0.04	0.06	0.07
% Up A/C	0.99	0.95	0.80	0.78

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[a]Note: Dynamic 3 looks very good in Cases 2c and 2d.

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TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP AIRCRAFT VS SIMULATION CASE NUMBER

	Case 2e	Case 2f	Case 2g	Case 2h
Planes	6	6	6	6
K-Factor	-2	-2.5	-3.0	-3.5
Parts/Plane	9	9	9	9
Lambda	--------Individual Failure rates used--------			
Mu	--------Individual Service rates used--------			
Dynamic 1				
Mean	5.11	4.73	4.16	3.44
Variance	0.94	1.49	1.91	2.00
S.Dev.	0.97	1.22	1.38	1.41
$S_{\bar{x}}$	0.04	0.05	0.06	0.06
% Up A/C	0.85	0.79	0.69	0.57
Dynamic 2				
Mean	4.94	4.69	4.07	3.51
Variance	1.18	1.38	1.88	1.99
S.Dev.	1.09	1.18	1.37	1.43
$S_{\bar{x}}$	0.05	0.05	0.06	0.06
% Up A/C	0.82	0.78	0.68	0.59
Dynamic 3				
Mean	5.64	5.19	4.40	3.52
Variance	0.64	1.33	2.16	1.95
S.Dev.	0.80	1.15	1.47	1.39
$S_{\bar{x}}$	0.04	0.05	0.07	0.06
% Up A/C	0.94	0.87	0.73	0.59
FIFO				
Mean	5.21	4.65	3.89	3.24
Variance	1.18	2.16	2.86	2.66
S.Dev.	1.09	1.47	1.69	1.63
$S_{\bar{x}}$	0.05	0.07	0.08	0.07
% Up A/C	0.87	0.77	0.65	0.54
FRP-Low				
Mean	4.16	3.85	3.69	3.25
Variance	4.67	5.12	4.28	3.86
S.Dev.	2.16	2.26	2.07	1.97
$S_{\bar{x}}$	0.09	0.10	0.09	0.09
% Up A/C	0.69	0.64	0.62	0.54
FRP-High				
Mean	4.15	3.88	3.31	3.18
Variance	3.42	3.63	3.53	2.93
S.Dev.	1.85	1.91	1.53	1.71
$S_{\bar{x}}$	0.08	0.09	0.09	0.08
% Up A/C	0.69	0.65	0.55	0.53

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP
                 AIRCRAFT VS SIMULATION CASE NUMBER

	Case 3a	Case 3b	Case 3c	Case 3d
Planes	12	12	12	12
K-Factor	1	0	-1	-2
Parts/Plane	9	9	9	9
Lambda	--------Individual Failure rates used--------			
Mu	--------Individual Service rates used--------			

Dynamic 1
Mean	11.89	11.12	9.66	7.42
Variance	0.15	1.09	1.97	3.52
S.Dev.	0.38	1.05	1.40	1.88
$S_{\bar{x}}$	0.02	0.05	0.06	0.08
% Up A/C	0.99	0.93	0.80	0.62

Dynamic 2
Mean	11.87	11.06	9.69	7.68
Variance	0.21	1.21	1.99	3.47
S.Dev.	0.46	1.10	1.41	1.86
$S_{\bar{x}}$	0.02	0.05	0.06	0.08
% Up A/C	0.99	0.92	0.81	0.64

Dynamic 3
Mean	12.00	11.96	11.73	9.84
Variance	0.00	0.14	0.64	4.43
S.Dev.	0.00	0.38	0.80	2.10
$S_{\bar{x}}$	0.00	0.02	0.04	0.09
% Up A/C	1.00	0.99	0.98	0.82

FIFO
Mean	11.99	11.71	10.49	7.88
Variance	0.01	0.43	2.17	5.99
S.Dev.	0.10	0.66	1.47	2.45
$S_{\bar{x}}$	0.00	0.03	0.07	0.11
% Up A/C	0.99	0.98	0.87	0.66

FRP-Low
Mean	10.97	7.83	4.04	0.84
Variance	4.81	12.27	11.30	2.94
S.Dev.	2.19	3.50	3.36	1.68
$S_{\bar{x}}$	0.09	0.16	0.15	0.08
% Up A/C	0.91	0.65	0.34	0.07

FRP-High
Mean	11.12	8.27	4.53	1.32
Variance	3.95	9.89	11.43	4.16
S.Dev.	1.99	3.15	3.38	2.04
$S_{\bar{x}}$	0.09	0.14	0.15	0.09
% Up A/C	0.93	0.69	0.38	0.11

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP AIRCRAFT VS SIMULATION CASE NUMBER

	Case 3e	Case 3f	Case 3g	Case 3h
Planes	12	12	12	12
K-Factor	-2.5	-3.0	-3.5	-4.0
Parts/Plane	9	9	9	9
Lambda	--------Individual Failure rates used--------			
Mu	--------Individual Service rates used--------			
Dynamic 1				
Mean	6.15	4.46	2.75	1.36
Variance	5.03	5.30	4.58	2.37
S.Dev.	2.24	2.30	2.14	1.54
$S_{\bar{x}}$	0.07	0.07	0.09	0.07
% Up A/C	0.51	0.37	0.23	0.11
Dynamic 2				
Mean	6.56	5.23	3.31	1.84
Variance	4.81	5.72	5.24	3.12
S.Dev.	2.19	2.39	2.29	1.77
$S_{\bar{x}}$	0.06	0.07	0.10	0.08
% Up A/C	0.54	0.44	0.28	0.15
Dynamic 3				
Mean	8.07	6.16	4.20	2.45
Variance	6.74	6.49	5.82	3.73
S.Dev.	2.59	2.55	2.41	1.93
$S_{\bar{x}}$	0.12	0.11	0.11	0.09
% Up A/C	0.67	0.51	0.35	0.20
FIFO				
Mean	6.16	4.36	2.53	1.26
Variance	8.55	8.13	5.01	2.38
S.Dev.	2.92	2.85	2.24	1.54
$S_{\bar{x}}$	0.08	0.08	0.10	0.07
% Up A/C	0.51	0.36	0.21	0.11
FRP-Low				
Mean	0.43	0.38	0.38	0.51
Variance	1.43	1.03	1.46	1.33
S.Dev.	1.19	1.01	1.21	1.15
$S_{\bar{x}}$	0.05	0.05	0.05	0.05
% Up A/C	0.04	0.03	0.03	0.04
FRP-High				
Mean	0.78	0.46	0.51	0.61
Variance	2.13	1.24	1.25	1.27
S.Dev.	1.46	1.11	1.12	1.13
$S_{\bar{x}}$	0.05	0.05	0.05	0.05
% Up A/C	0.06	0.04	0.04	0.05

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP
              AIRCRAFT VS SIMULATION CASE NUMBER

	Case 4a	Case 4b	Case 4c	Case 4d	Case 4e
Planes	6	6	6	6	6
Spares*	12	9	6	3	1
Parts/Plane	9	9	9	9	9
Lambda	-----Failure rate all components = 0.02-----				
Mu	-----Service rate all components = 0.84-----				
Dynamic 1					
Mean	6.00	6.00	5.98	5.28	3.82
Variance	0.00	0.00	0.03	1.09	1.96
S.Dev.	0.00	0.00	0.18	1.04	1.40
$S_{\bar{x}}$	0.00	0.00	0.01	0.05	0.06
% Up A/C	1.00	1.00	0.99	0.88	0.64
Dynamic 2					
Mean	6.00	6.00	5.97	5.27	3.77
Variance	0.00	0.00	0.05	1.16	2.13
S.Dev.	0.00	0.00	0.22	1.08	1.46
$S_{\bar{x}}$	0.00	0.00	0.01	0.05	0.07
% Up A/C	1.00	1.00	0.99	0.88	0.63
Dynamic 3					
Mean	6.00	6.00	5.96	5.18	3.63
Variance	0.00	0.00	0.06	1.26	2.19
S.Dev.	0.00	0.00	0.24	1.12	1.48
$S_{\bar{x}}$	0.00	0.00	0.01	0.05	0.07
% Up A/C	1.00	1.00	0.99	0.86	0.61
FIFO					
Mean	6.00	5.97	5.78	4.70	3.33
Variance	0.00	0.06	0.58	2.32	2.86
S.Dev.	0.00	0.23	0.76	1.52	1.69
$S_{\bar{x}}$	0.00	0.01	0.03	0.07	0.08
% Up A/C	1.00	0.99	0.96	0.78	0.56
FRP-Low					
Mean	5.68	5.09	4.28	3.65	3.03
Variance	1.04	2.78	4.47	4.49	3.89
S.Dev.	1.02	1.67	2.11	2.12	1.97
$S_{\bar{x}}$	0.05	0.07	0.09	0.09	0.09
% Up A/C	0.95	0.84	0.71	0.61	0.51
FRP-High					
Mean	5.68	5.09	4.28	3.65	3.03
Variance	1.04	2.78	4.47	4.49	3.89
S.Dev.	1.02	1.67	2.11	2.12	1.97
$S_{\bar{x}}$	0.05	0.07	0.09	0.09	0.09
% Up A/C	0.95	0.84	0.71	0.61	0.51

---

*Spares to Plane Ratio method used to calculate spares

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP
             AIRCRAFT VS SIMULATION CASE NUMBER

	Case 5a	Case 5b	Case 5c	Case 5d	Case 5e
Planes	12	12	12	12	12
Spares[7]	24	18	12	6	2
Parts/Plane	9	9	9	9	9
Lambda	-----Failure rate all components = 0.02-----				
Mu	-----Service rate all components = 0.84-----				

Dynamic 1

	Case 5a	Case 5b	Case 5c	Case 5d	Case 5e
Mean	12.00	11.92	8.88	3.15	0.82
Variance	0.00	0.16	3.86	3.62	0.89
S.Dev.	0.00	0.39	1.97	1.90	0.95
$S_{\overline{x}}$	0.00	0.01	0.09	0.09	0.04
% Up A/C	1.00	0.99	0.74	0.26	0.07

Dynamic 2

	Case 5a	Case 5b	Case 5c	Case 5d	Case 5e
Mean	12.00	11.94	8.95	3.15	0.81
Variance	0.00	0.09	4.07	3.75	0.93
S.Dev.	0.00	0.29	2.02	1.94	0.96
$S_{\overline{x}}$	0.00	0.01	0.09	0.09	0.04
% Up A/C	1.00	0.99	0.75	0.26	0.07

Dynamic 3

	Case 5a	Case 5b	Case 5c	Case 5d	Case 5e
Mean	12.00	11.91	8.75	2.94	0.74
Variance	0.00	0.19	4.01	3.32	0.72
S.Dev.	0.00	0.44	2.00	1.82	0.85
$S_{\overline{x}}$	0.00	0.02	0.09	0.08	0.04
% Up A/C	1.00	0.99	0.73	0.25	0.12

FIFO

	Case 5a	Case 5b	Case 5c	Case 5d	Case 5e
Mean	11.92	10.51	5.61	1.25	0.66
Variance	0.25	4.57	8.03	2.07	0.83
S.Dev.	0.50	2.14	2.83	1.44	0.91
$S_{\overline{x}}$	0.02	0.10	0.13	0.06	0 04
% Up A/C	0.99	0.88	0.47	0.10	0.06

---

[7]Spare to Plane Ratio method used for computing spares

TABLE B-1   MODEL STATISTICS: EXPECTED NUMBER OF UP
             AIRCRAFT VS SIMULATION CASE NUMBER

	Case 6a	Case 6b	Case 6c	Case 6d	Case 6e
Planes	6	6	6	6	6
Spares*	12	9	6	3	1
Parts/Plane	9	9	9	9	9
Lambda	----Individual	component	Failure	rates	used---
Mu	----Individual	component	Service	rates	used---
Dynamic 1					
Mean	6.00	6.00	5.95	5.31	3.99
Variance	0.00	0.00	0.09	1.27	2.05
S.Dev.	0.00	0.00	0.29	1.13	1.43
$S_{\bar{x}}$	0.00	0.00	0.01	0.05	0.06
% Up A/C	1.00	1.00	0.99	0.89	0.67
Dynamic 2					
Mean	5.99	5.98	5.81	5.01	3.78
Variance	0.00	0.07	0.54	1.87	2.64
S.Dev.	0.04	0.26	0.74	1.37	1.63
$S_{\bar{x}}$	0.00	0.01	0.03	0.06	0.07
% Up A/C	0.99	0.99	0.97	0.84	0.63
Dynamic 3					
Mean	6.00	6.00	5.95	5.25	3.84
Variance	0.00	0.00	0.07	1.36	2.35
S.Dev.	0.00	0.00	0.26	1.17	1.53
$S_{\bar{x}}$	0.00	0.00	0.01	0.05	0.07
% Up A/C	1.00	1.00	0.99	0.88	0.64
FIFO					
Mean	5.97	5.90	5.50	4.54	3.37
Variance	0.07	0.29	1.36	3.15	3.49
S.Dev.	0.26	0.55	1.16	1.78	1.87
$S_{\bar{x}}$	0.01	0.02	0.05	0.08	0.08
% Up A/C	0.99	0.98	0.92	0.76	0.56
FRP-Low					
Mean	4.61	4.28	4.22	4.04	3.26
Variance	4.94	5.45	5.55	5.09	4.77
S.Dev.	2.22	2.34	2.36	2.26	2.18
$S_{\bar{x}}$	0.10	0.10	0.11	0.10	0.10
% Up A/C	0.77	0.71	0.70	0.67	0.27
FRP-High					
Mean	5.63	5.53	5.10	4.39	3.50
Variance	1.45	1.72	2.81	3.83	3.75
S.Dev.	1.21	1.31	1.68	1.96	1.94
$S_{\bar{x}}$	0.05	0.06	0.07	0.06	0.09
% Up A/C	0.94	0.92	0.85	0.73	0.58

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*Spare to Plane Ratio method used to calculate spares

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TABLE B-2   RANDOM SEED EFFECTS: EXPECTED NUMBER OF UP AIRCRAFT AT MISSION TERMINATION[9]

	Case A	Case B	Case C	Case D
Planes	12	12	12	12
Spares[10]	3	3	3	3
Parts/Plane	9	9	9	9
Random Seeds	16989	15989	14989	14704
	14997	14999	14731	13331
	13997	13999	16789	15652
Dynamic 1				
Mean	1.95	1.87	2.02	1.87
Variance	2.87	3.19	3.40	2.72
S.Dev.	1.69	1.78	1.84	1.65
$S_{\bar{x}}$[11]	0.08	0.08	0.08	0.07
95% CI[12]	2.11,1.80	2.04,1.72	2.19,1.86	2.02,1.73
Dynamic 2				
Mean	0.90	0.83	0.85	0.95
Variance	1.68	1.80	1.76	1.88
S.Dev.	1.29	1.34	1.32	1.37
$S_{\bar{x}}$	0.06	0.06	0.06	0.06
95% CI	1.02,0.79	0.95,0.72	0.97,0.73	1.07,0.83
FIFO				
Mean	0.76	0.82	0.75	0.83
Variance	1.48	1.52	1.13	1.40
S.Dev.	1.21	1.23	1.06	1.18
$S_{\bar{x}}$	0.05	0.06	0.05	0.05
95% CI	0.87,0.66	0.94,0.72	0.85,0.66	0.94,0.73
FRP-Low				
Mean	1.61	1.82	1.84	1.76
Variance	6.68	7.26	7.72	7.60
S.Dev.	2.58	2.69	2.77	2.75
$S_{\bar{x}}$	0.12	0.12	0.12	0.12
95% CI	1.84,1.38	2.06,1.59	2.09,1.60	2.01,1.53
FRP-High				
Mean	1.57	1.65	1.69	1.68
Variance	4.91	4.55	4.61	4.79
S.Dev.	2.21	2.13	2.14	2.18
$S_{\bar{x}}$	0.10	0.10	0.10	0.09
95% CI	1.76,1.38	1.84,1.47	1.88,1.51	1.88,1.49

---

[9]500 replications

[10]Equal numbers of spares for all type components.

[11]$S_{\bar{x}} = \{(Variance/500)\}^{.5}$ = Standard Error

[12]95% CI = Mean $\pm$ $S_{\bar{x}}$ x 1.96 , table values are endpoints

TABLE B-3   SPARE ALLOCATION OF COMPONENTS BY CASE NUMBER: K-STANDARD DEVIATION METHOD

K Factor	Case 1a +1.0	Case 1b 0.0	Case 1c -0.5	Case 1d -1.0
PART 1	10	7	6	5
PART 2	7	5	4	3
PART 3	9	6	5	4
PART 4	2	1	0	0
PART 5	10	7	6	4
PART 6	11	8	6	4
PART 7	1	0	0	0
PART 8	6	4	3	2
PART 9	14	11	9	8

K Factor	Case 1e -1.5	Case 1f -2.0	Case 1g -2.5	Case 1h -3.0
PART 1	3	2	0	0
PART 2	2	1	0	0
PART 3	3	1	0	0
PART 4	0	0	0	0
PART 5	3	1	0	0
PART 6	4	2	1	0
PART 7	0	0	0	0
PART 8	1	0	0	1
PART 9	6	4	3	1

K Factor	Case 2a +1.0	Case 2b 0.0	Case 2c -1.0	Case 2d -1.5
PART 1	18	14	11	9
PART 2	13	10	7	5
PART 3	17	13	9	8
PART 4	3	2	0	0
PART 5	18	14	10	8
PART 6	20	16	12	10
PART 7	2	1	0	0
PART 8	11	8	5	4
PART 9	26	22	17	15

K Factor	Case 2e -2.0	Case 2f -2.5	Case 2g -3.0	Case 2h -3.5
PART 1	7	5	3	1
PART 2	4	2	1	0
PART 3	6	4	2	0
PART 4	0	0	0	0
PART 5	8	5	3	1
PART 6	8	6	4	2
PART 7	0	0	0	0
PART 8	2	1	0	0
PART 9	12	10	8	5

TABLE B-3   MODEL PARAMETERS: SPARE ALLOCATION OF
COMPONENTS VS SIMULATION CASE NUMBER

	Case 3a	Case 3b	Case 3c	Case 3d
K Factor	+1.0	0.0	-1.0	-2.0
PART 1	34	29	23	18
PART 2	25	21	16	12
PART 3	31	26	21	16
PART 4	6	4	2	0
PART 5	33	28	23	17
PART 6	37	31	26	20
PART 7	3	1	0	0
PART 8	20	16	12	8
PART 9	50	43	37	30

	Case 3e	Case 3f	Case 3g	Case 3h
K Factor	-2.5	-3.0	-3.5	-4.0
PART 1	15	13	10	7
PART 2	9	7	5	2
PART 3	13	11	8	6
PART 4	0	0	0	0
PART 5	15	12	9	7
PART 6	17	15	12	9
PART 7	0	0	0	0
PART 8	6	4	2	0
PART 9	27	23	20	17

APPENDIX C

TABLE C-1. FIFO ALGORITHM

Key Variable Description;

Planes: The total number of whole systems operational, in this case aircraft.

TOTSPR: The initial number of spares per type part.

TOTMSN: The total mission length in flight hours (120 Hrs.).

TOTPRT: The total number of types of parts.

TOTRUN: The total number of replications or runs (100).

MSNTIM: The mission time running clock, ranges vary from 0 to 120 hours (TOTMSN).

LOWLVL: An Array which stores the lowest part stock level in the event of a given part failure.

STOCK: An Array which stores the number of up and working components of a given part type (spares + planes).

FAILT: A variable which holds the failure time generated by a uniform random variable and the inverse transform method for an exponential distribution. This is compared to the repair time to determine the scheduling of next event.

COMPLT: A variable which holds the repair time, is generated like the failure time, and when compared to the latter determines the next scheduled event.

SERVTM: A variable which is assigned a exponential value generated by the inverse transform method and is added to the current clock to determine the completion time of the next repair

QPART: An array which stores component types as the wait in the queue.

QSIZE: An array which stores current position a component holds in the queue.

QTIME: An array which stores the time a part enters the queue.

RHO: The traffic intensity equal to arrival rate divided by the service rate in the queue

SUMLAM: The sum of all the part failure rates.

SRATE: the service rate (μ) in the queue.

REPAIR: A counter to track when repairs occur.

FLAG2: A counter to track if stocks are depleted.

RUN: A counter to track run number (0→100)

Input: Failure rate parameters (Lambda(i)) for each component.

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Repair rate parameters (SRATE(i)) for each component.

Output: Mean number of up aircraft at missions end

Variance and standard deviations of above means

Distribution of up aircraft at missions termination (the number of runs with zero aircraft up, the number with two, and so forth).

The average waiting time in the queue

The average queue line

Step 1: Initialize simulation parameters: TOTRUN, TOTMSN, TOTPRT, SRATE, etc.

Step 2: Read in repair rates SRATE(i) and failure rates LAMBDA(i)

Step 3: Call RANDOM; Generate an array to store uniform random numbers, store in A( ),AA( ),AAA( ).

Step 4: Initialize a new mission run: MSNTIM, PLANES, SPARE(I), COMPLT, FLAG2,

STOCK = SPARES + PLANES

SUMLAM = LAMBDA(1) + LAMBDA(2) + ... + LAMBDA(N)

RHO = SUMLAM * PLANES / SRATE[13]

Step 5: Verify at least one aircraft is up (FLAG2 = 1)

Step 6: Generate a failed part:

FAILT = - ln (U) / (SUMLAM x PLANES)

This uses the inverse transform method with a uniform random number (U) from an IMSL routine LLRANDOM II to yield an exponential interarrival time.

Step 7: Scan stock levels (STOCK(i)) and verify at least one aircraft is up (FLAG2 = 1):

If STOCK(i) < 1 (FLAG2 = 0), then check to see if a repair has occurred which will create an up aircraft. If all aircraft are down, advance to next repair time or terminate run.

Step 9: Test to see if a failure or repair is the next event to occur:

Is FAILT < COMPLT ? If so, MSNTIM = FAILT, go to step 11; else MSNTIM = COMPLT,go to step 10. Test both cases to see if mission has terminated: Is MSNTIM greater than TOTMSN ? If so, go to step 18.

Step 10: Call ALTQ; Enter queue, complete repair and increment appropriate stock. Commence service on

----

[13]. Not calculated when using multiple service rates.

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the next part if components remain waiting service, go to step 7.

Step 11:   Determine which part failed; calculate the individual probability a given part i failed:

Probability Part i failed = LAMBDA(i)/SUMLAM

Then, generate a discrete CDF with the probabilities. Pick a uniform random variable to determine the type failure. Decrement the appropriate stock.

Step 12: Call QUEUE: Enter queue with failed part.

STEP 13:   Check to see if server is available and the queue size is less than one:

Is SERVR = 0 and QSIZE = 0 ? If so, enter service, go to step 15, else join queue, go to step 14.

Step 14:   Part joins queue at the end of the service line. Increment QSIZE, store QPART, QTIME, check QMAX versus QSIZE, go to step 7.

Step 15:   Enter service, store waiting time in queue (WAIT(i)), part type (QPART(i)), advance positions in the queue up one position. Calculate service time:

SERVTM = - ln (U) / SRATE(i)

Calculate completion of service time (COMPLT):

COMPLT = MSNTIM + SERVTM

Step 16:   Store the stock levels at the moment of a given failure (JFAIL) at a given time (MSNTIM). Store in LOWLVL the lowest stock level at that time.

Step 17:   If stocks are depleted, cease failures until a repair of the proper type occurs. FLAG2 = 0, Go to step 10.

Step 18:   Call ALTQ1: Talley waiting time, queue size of those parts which remain in the queue at mission termination time MSNTIM

Step 19:   Is this run the last run: RUN ≤ TOTRUN ? If not, go to step 5

Step 20:   Call STATS: compute statistics;

Calculate mean up aircraft: MUPPLN = UPPLANE/RUN

Calculate the variance and standard deviation of MUPPLN

Step 21:   Calculate distribution of up aircraft; talley the number of up aircraft less than one standard deviation from the mean, two standard deviations from the mean, or at the mean, etc (CNTR). Talley the number of runs with zero aircraft up, one aircraft up, and so forth (YCNTR).

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Step 22: Calculate the average wait in line WAITT, average maximum qsize MQBAR, and average number of customers waiting in the queue.

Step 23: Print Statistics

Dynamic 1 Model Modifications[14]:

Step 14A: Count the number of parts of type i in the queue line. Are there equal numbers of parts ? If so, go to step 14c, else go to step 14b.

Step 14b: Sort components by count, reorder position in line in favor of the most numerous component (to the front of the line). Return to step 7.

Step 14c: Sort parts by arrival time in the line (FIFO). Return to step 7.

Dynamic 2 Model Modifications:

Step 14a: Count the number of parts of type i in the queue line (COUNT(i)).

Step 14b: Assign a priority to each type component i:

RHO(i) = LAMBDA(i) / SRATE(i)

LINEUP(i) = RHO(i) x COUNT(i)

Step 14c: Sort components by LINEUP(i), reorder position in line in favor of the largest LINEUP(i). Return to step 7.

Dynamic 3 Model Modifications:

Step 14a: Count the number of operating parts of each component i (STOCK(i)).

Step 14b: Assign a priority to each component type based on the count of current stock in step 14a:

LINEUP(i) < LINEUP(j) iff

STOCK(i) < STOCK(j)

Step 14c: Sort the parts in line by LINEUP(i), reorder positions in favor of the smallest LINEUP(i). Return to step 7.

FRL-L(H) Model Modifications:

Step 2b: Call LINEUP; Read in the values of LAMBDA(i), assign a priority from one to n total type components based on the smallest (largest) LAMBDA(i). Return to step 3

Step 14a: Sort queue line by priority values assigned in step 2b. Reorder position in line to favor the components with the smallest LAMBDA(i). Return to step 7.

---

[14]Modifications apply to FIFO algorithm, steps follow sequentially from there

APPENDIX D

Table D-1.   FIFO Fortran Coding

```
*          INITIALIZATION OF VALUES

   INTEGER RUN,TOTRUN,TOTSPR,FPART,QMAXMN(500),
  1CNT1,CNT2,CNT3,CNT4,YCNT1,YCNT2,YCNT3,YCNT4,YCNT5,YCNT6,YCNT7,
  1YCNT8,YCNT9,YCNT10,YCNT11,YCNT12,YCNT13

   REAL PLANES,LAMBDA(10),SPARE(10),STOCK(10),UPLAN(500),LQ,K,
  1A(100000),LOWLVL(500),TOTAL(10,500),AA(100000),CWAIT(100000),
  1PROB(10),MSNTIM,MQBAR,QT(500,120),FACTOR(10),
  1PPLANE,AAA(60000),MUPLN,SRATE(10)

   COMMON/QUEU/STOCK,MSNTIM,LRUN,QMAXMN,LINEK,CWAIT,CUSTMR,REPARE,
  1SYSARR,TZZ,QT,SRATE,TOTMSN,COMPLT,/STAT/MUPLN,VRPLN,SDPLN,CNT1,
  1CNT2,CNT3,CNT4,YCNT1,YCNT2,YCNT3,YCNT4,YCNT5,YCNT6,YCNT7,
  1YCNT8,YCNT9,YCNT10,YCNT11,YCNT12,YCNT13,
  1MQBAR,WAITT,LQ

   DATA JFAIL/0/,I/0/,II/0/,RUN/1/,TOTRUN/500/,
  1TOTPRT/9/,FLAG2/1/,K/-3.5/
   TOTMSN = 120
   TOTSPR = 01
   PLANES =06.0
*          READ IN FAILURE AND REPAIR RATES
   DO 1 J = 1,TOTPRT
      READ (2,2) LAMBDA(J)
2     FORMAT(F8.5)
1  CONTINUE
   DO 3 J = 1,TOTPRT
      READ (3,8) SRATE(J)
8     FORMAT(F8.5)
3  CONTINUE
   SUMLAM = 0
   DO 7 J = 1,TOTPRT
      SUMLAM = SUMLAM + LAMBDA(J)
7  CONTINUE
    DO 9 I = 1,TOTPRT
       FACTOR(I) = PLANES * LAMBDA(I) * TOTMSN
       SPARE(I) = NINT(FACTOR(I) + K * SQRT(FACTOR(I)))
       IF(SPARE(I) .LT. 0) SPARE(I) = 0
9  CONTINUE

*          CALL LLRAND II, GENERATE RANDOM NUMBER ARRAYS

   CALL RANDOM(A,AA,AAA)

*          INITIALIZE A NEW MISSION

5  MSNTIM = 0.0
   COMPLT = 120
   JFAIL = 0
   PPLANE = PLANES
   XXX = SUMLAM * PLANES
   LRUN = RUN
   FLAG2 = 1
   FLAG3 = 1
   DO 6 J = 1,TOTPRT
      STOCK(J) = SPARE(J) + PLANES
6  CONTINUE
```

```
                REPARE = 0

10      CONTINUE
        IF(FLAG2 .GE. 1) THEN

*               GENERATE ARRIVALS OF FAILED PARTS

        I = I + 1

        Z = I
        U = A(I)
        T = -LOG( U ) / ( SUMLAM * PLANES)
        FAILT = T + MSNTIM
        ENDIF
*               TEST TO SEE IF A FAILURE HAS OCCURED
20      CONTINUE
        IF(REPARE .GE. 1 .AND. FLAG2 .LT.1) THEN
            REPARE = 0
            DO 25 J = 1,TOTPRT
                IF(STOCK(J) .LT. 1) THEN
                        FLAG2 = 0
                        FAILT = TOTMSN
                        GO TO 23
                ELSE
                        FLAG2 = 1
                ENDIF
25          CONTINUE
        GO TO 10
        ENDIF
        REPARE = 0
        DO 26 J = 1,TOTPRT
            IF(STOCK(J) .LT. 1) THEN
                    FLAG2 = 0
                    FAILT = TOTMSN
                    GO TO 23
            ELSE
                    FLAG2 = 1
            ENDIF
26      CONTINUE

*               INCREMENT TIME STEP
*               VERIFY MISSION LENGTH
23      IF(FAILT .LT. COMPLT .AND. FLAG2 .GE. 1)THEN
            MSNTIM =   FAILT
            IF(MSNTIM .GE. TOTMSN) GO TO 22
            GO TO 30
        ELSE
            MSNTIM = COMPLT
            IF(MSNTIM .GE. TOTMSN) GO TO 22
            GO TO 21
        ENDIF

21      CALL ALTQ
29      GO TO 20
*               CALCULATE WHICH COMPONENT FAILED

30      CONTINUE

        DO 31 J = 1,TOTPRT
            PROB(J) = LAMBDA(J) / SUMLAM
31      CONTINUE
*               CALL A RANDOM NUMBER, USE LAMBDA'S TO BUILD CDF,
*                       AND DETERMINE WHICH PART FAILED

        II = II + 1
        ZZ = II
```

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```
                   X = AA(II)
                   XLWR = 0.0
                   DO 32 J = 1, TOTPRT
                        XUPPR = XLWR + PROB(J)
                        IF(X .GT. XLWR .AND. X .LE. XUPPR) THEN
                             STOCK(J) = STOCK(J) - 1
                             FPART = J
                             GO TO 33
                        ELSE
                             XLWR = XUPPR
                        ENDIF
32            CONTINUE

33            CALL QUEUE(FPART,AAA,*34,*29,*70)

*                   CHECK STOCK LEVELS AND BRANCH

34            CONTINUE
*                   ARE STOCKS LEVELS = 0?
40            CONTINUE
              DO 41 J = 1,TOTPRT
                   IF(STOCK(J) .GE. 1) THEN
                             FLAG2 = 1
                   ELSE
                             FLAG2 = 0
                             FAILT = TOTMSN
                             GO TO 42
                   ENDIF
41            CONTINUE

42            JFAIL = JFAIL + 1

*                   RECORD STOCK LEVELS FOR A GIVEN FAILURE

              DO 51 J = 1,TOTPRT
                   TOTAL(J,JFAIL) = STOCK(J)
51            CONTINUE

              GO TO 10

*                   MISSION TERMINATION
22            CALL ALTQ1
70            CONTINUE
              DO 71 JJ = 1,JFAIL
                   LOWLVL(JJ) = 15
                   DO 72 LL = 1,TOTPRT
                        IF(LOWLVL(JJ).GT.TOTAL(LL,JJ)) LOWLVL(JJ) = TOTAL(LL,JJ)
72            CONTINUE
71            CONTINUE

              IF(LOWLVL(JFAIL) .LE. PLANES ) THEN
                   UPLAN(RUN) = LOWLVL(JFAIL)
              ELSE
                   UPLAN(RUN) = PLANES
              ENDIF


*                   PLOT AND DISPLAY OUTPUT

              IF(RUN .GE. TOTRUN)THEN
                   WRITE(06,*) 'CONTINUOUS TIME, CONSTANT FAILURE RATE, FIFO'
                   WRITE(06,*) 'MISSION TIME =',MSNTIM,'JFAIL',JFAIL
                   WRITE(06,*)'INITIAL PLANES =',PLANES,'INITIAL SPARE FACTOR',K
                   WRITE(06,*) 'RUN NUMBER ',RUN,'CUMULATIVE FAIURES (I)=',ZZ
```

```
*     Z, ZZ , TZZ TRACK ARRAY INPUTS TO VERIFY THEIR DIMENSIONS ARE
*                       NOT EXCEEDED

        WRITE(06,*) 'TOT PARTS=',TOTPRT,'Z=',Z,'ZZZ',TZZ
        WRITE(06,*) 'LAMBDA=',XXX,'SERVICE RATE= VARIABLE'
        WRITE(06,*) 'TRAFFIC INTENSITY RHO= VARIABLE'
      ENDIF
*             TEST RUN NUMBER TO STOP SIMULATION

      IF(RUN .GE. TOTRUN) GO TO 200
        RUN = RUN + 1
        GO TO 5
*           COMPUTE SAMPLE STATISTICS

200   CONTINUE
      CALL STATS(CUSTMR,LRUN,UPLAN,QMAXMN,LINEK,CWAIT,
     1TOTMSN,SYSARR,QT)
*               WRITE OUTPUT OF STATISTICS

      WRITE(06,102) MUPLN,VRPLN,SDPLN
102   FORMAT(1X,'EXPECTED NUMBER OF UP PLANES =',F11.8,
     1/,1X,'VARIANCE OF UP PLANES =',F15.4,


     1/,1X,'STD. DEV. UP PLANES =',F15.4)
      WRITE(06,103) CNT1,
     1CNT2,CNT3,CNT4,RUN,TOTMSN,
     1,YCNT1,YCNT2,YCNT3,YCNT4,YCNT5,YCNT6,YCNT7,
     1YCNT8,YCNT9,YCNT10,YCNT11,YCNT12,YCNT13
103   FORMAT(1X,'NUMBER OF RUNS UP PLANES <= -1 SIGMA =',I4,
     1/,1X,'NUMBER OF RUNS UP PLANES <= MEAN =',I4,
     1/,1X,'NUMBER OF RUNS UP PLANES <= +1 SIGMA =',I4,
     1/,1X,'NUMBER OF RUNS UP PLANES <= +2 SIGMA =',I4,
     1/,1X,'TOTAL RUNS =',I5,'  MISSION TIME=',F5.0,
     1/,1X,'NUMBER OF RUNS W/ 0 PLANES UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 1 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 2 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 3 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 4 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 5 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 6 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 7 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 8 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/ 9 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/10 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/11 PLANE  UP =',I5,
     1/,1X,'NUMBER OF RUNS W/12 PLANE  UP =',I5)


      WRITE(06,104) MQBAR,WAITT,LQ
104   FORMAT(1X,'AVE MAX QUEUE SIZE =',F5.0,
     1/,1X,'AVE WAIT IN THE QUEUE =',F10.4,
     1/,1X,'AVE NUMBER OF CUSTOMERS WAITING IN Q=',F10.4)

      DO 199 I = 1,TOTPRT
      PRINT *,'SPARES TYPE(',I,')=',SPARE(I)
199   CONTINUE
      PRINT *,'K=',K

      STOP
      END
```

```
***********************************************************************

      SUBROUTINE QUEUE(FPT,QA,*,*,*)

      SAVE QSIZE,QPART,LINEUP,SERVR,SERVPT,SERVTM,COMPLT,QMAX,RUN,II,
     1ARRIVE,WAIT,QTIME

      INTEGER QSIZE,SPART,QPART(200),SERVPT,
     1QMAX(500),QRUN,RUN,CNTR,FPT

      REAL QA(60000),QSTOCK(10),QT(500,120),WAIT(100000),QTIME(200),
     1SRATE(10)

      COMMON /QUEU/QSTOCK,QMSNTM,QRUN,QMAX,CNTR,WAIT,QCUST,REPAIR,
     1SYSARR,ZZZ,QT,SRATE,TOTMSN,COMPLT

      DATA SERVR/0/,QSIZE/0/,SERVPT/0/,IJ/0/,RUN/0/,II/0/,
     1FLAG/0/

***********************************************************************
*              PARTS ARRIVE

      IF(QRUN .LT. 2 .AND. FLAG .LT. 1) THEN
          FLAG = 1
          QCUST = 0
          SYSARR = 0
          DEPART = 0
          COMPLT = TOTMSN
      ENDIF

      CLOCK = QMSNTM
      ARRIVE = 1
      SYSARR = SYSARR + 1

*              INITIALIZE QUEUE FOR A NEW RUN
      IF(QRUN .GT. RUN) THEN
          QMAX(QRUN) = 0
          QSIZE = 0
          RUN = QRUN
          SERVR = 0
          COMPLT = TOTMSN
      ENDIF

*              IS THE SERVER BUSY?
      IF(SERVR .LT. 1 .AND. QSIZE .LT. 1) THEN
          QPART(1) = FPT
          GO TO 10
      ENDIF
      GO TO 30

*              CHECK SERVER AVAILABLE,QUEUE, AND SERVICE TIME

      ENTRY ALTQ
      ARRIVE = 0
      CLOCK = QMSNTM

*              INITIALIZE QUEUE FOR A NEW RUN
      IF(QRUN .GT. RUN) THEN
          QMAX(QRUN) = 0
          QSIZE = 0
          RUN = QRUN
          SERVR = 0
          COMPLT = TOTMSN
      ENDIF
1     IF(SERVR .LT. 1 .AND. QSIZE .GE. 1) GO TO 10
      GO TO 100
```

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```
*              THE QUEUES

30      QCUST = QCUST + 1
        IF(QSIZE .LT. 1) GO TO 40
        QSIZE = QSIZE + 1
        QPART(QSIZE) = FPT
        QTIME(QSIZE) = CLOCK
        IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN) = QSIZE
        GO TO 1

40      CONTINUE
        QSIZE = 1
        QPART(1) = FPT
        QTIME(QSIZE) = CLOCK
        IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN)= 1
        GO TO 1

*              THE SERVICE AREA

10      CONTINUE
        SPART = QPART(1)
*              STORE WAITING TIMES FOR QUEUE

        IF(QSIZE .GT. 0) THEN
           II = II + 1
           WAIT(II) = CLOCK - QTIME(1)
*              STORE NUMBER OF PEOPLE IN LINE IN VARIABLE CNTR
        ENDIF
           CNTR = II

        IF(QSIZE .GT. 1) THEN
        PAIRS = QSIZE - 1
        DO 50 I = 1,PAIRS
           QPART(I) = QPART(I+1)
           QTIME(I) = QTIME(I+1)
50      CONTINUE
        QPART(QSIZE) = 0
        QTIME(QSIZE) = 0
        ENDIF

        IF(QSIZE .GT. 0) QSIZE = QSIZE -1


        SERVR = 1
        SERVPT = SERVPT + 1

*              SERVICE IS EXPONENTIAL

        IJ = IJ + 1
        XX = QA(IJ)
        ZZZ = IJ
        SERVTM = -LOG(XX) / SRATE(SPART)
        COMPLT = SERVTM + CLOCK
*              CHECK TO SEE IF SERVICE HAS COMPLETED
*              IF SO INCREMENT PART

100     IF(COMPLT .LE. CLOCK) THEN
           COMPLT = TOTMSN
           REPAIR = 1
           SERVR = 0
           DEPART = DEPART + 1
           QSTOCK(SPART) = QSTOCK(SPART) + 1
        ENDIF
```

```
*            RETURN TO APPROPRIATE SEGMENT OF MAIN PROGRAM
101   IF(REPAIR .EQ. 1 .AND. QSIZE .GT.0) THEN
          REPAIR = 2
          GO TO 1C
      ENDIF

      QT(RUN,CLOCK) = QSIZE
      IF(ARRIVE .GE. 1) RETURN 1
      RETURN 2

*            COUNT RESIDUAL PARTS IN QUEUE AT MISSION'S END
      ENTRY ALTQ1
          IF(QSIZE .GT. 0) THEN
              DO 129 I = 1,QSIZE
                  II = II + 1
                  CNTR = II
                  WAIT(II) = TOTMSN - QTIME(I)
129           CONTINUE
          ENDIF
          RETURN 3

      END

***********************************************************************

      SUBROUTINE STATS(QCUST,RRUN,UPPLAN,QMAX,LINE,SWAIT,
     1TOTMSN,SYSARR,QT)

      COMMON/STAT/MUPPLN,VARPLN,SDPLAN,CNTR1,CNTR2,
     1CNTR3,CNTR4,YCNTR1,YCNTR2,YCNTR3,YCNTR4,YCNTR5,YCNTR6,YCNTR7,
     1YCNTR8,YCNTR9,YCNT10,YCNT11,YCNT12,YCNT13,
     1MXQBAR,WAIT,LQ

      INTEGER RRUN,QMAX(500),
     1CNTR1,CNTR2,CNTR3,CNTR4,YCNTR1,YCNTR2,YCNTR3,YCNTR4,
     1YCNTR5,YCNTR6,YCNTR7,
     1YCNTR8,YCNTR9,YCNT10,YCNT11,YCNT12,YCNT13

      REAL MUPPLN,PSUM(500),UPPLAN(500),MXQBAR,SWAIT(100000),
     1TOTMSN,LQ,QT(500,120)
***********************************************************************
      WAIT = 0
      CNTR1 = 0
      CNTR2 = 0
      CNTR3 = 0
      CNTR4 = 0
      YCNTR1 = 0
      YCNTR2 = 0
      YCNTR3 = 0
      YCNTR4 = 0
      YCNTR5 = 0
      YCNTR6 = 0
      YCNTR7 = 0
      YCNTR8 = 0
      YCNTR9 = 0
      YCNT10= 0
      YCNT11= 0
      YCNT12= 0
      YCNT13= 0
      MUPPLN = 0
      VARPLN = 0
      SDPLAN = 0
      MXQBAR = 0
      LQ = 0
      UPLANE = 0
```

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```
          SSPLAN = 0
          Q = 0

*                MEAN CALCULATIONS

*                SUM UP A/C AT MSN TERMINATION FOR ALL RUNS
*                SUM UP QUEUE MAX'S FOR EACH RUN

          DO 104 J = 1,RRUN
             UPLANE = UPLANE + UPPLAN(J)
             Q = Q + QMAX(J)
104       CONTINUE
          IF(UPLANE .GT. 0) THEN
             MUPPLN = UPLANE/RRUN
          ELSE
             MUPPLN = 0
          ENDIF
          DO 105 J = 1,RRUN
             PSUM(J) = (MUPPLN - UPPLAN(J))**2
             SSPLAN = SSPLAN + PSUM(J)
105       CONTINUE

*                MEAN MAX Q SIZE FOR ALL RUNS

          MXQBAR = Q / RRUN


          PRINT *,'LINE',LINE,'MXQBAR',MXQBAR,'Q',Q

*                CALCULATE THE AVE. WAIT IN QUEUE

          DO 108 IL = 1,LINE
             WAIT = WAIT + SWAIT(IL)
108       CONTINUE
          WAIT = WAIT / SYSARR

*                ASSOCIATED VARIANCE/STD DEV CALC'S

          IF(SSPLAN .GT. 0 .AND. RRUN .GT.1) THEN
             VARPLN = SSPLAN / (RRUN - 1)
             SDPLAN = VARPLN**.5
          ELSE
             VARPLN = 0.0
             SDPLAN = 0.0
          ENDIF
          X1 = MUPPLN - SDPLAN
          X2 = MUPPLN
          X3 = MUPPLN + SDPLAN
          X4 = MUPPLN + (2*SDPLAN)
          DO 106 J = 1,RRUN
             IF(UPPLAN(J) .LE. X1) CNTR1 = CNTR1 + 1
             IF(UPPLAN(J).LE.X2 .AND. UPPLAN(J).GT.X1) CNTR2 = CNTR2 + 1
             IF(UPPLAN(J).LE.X3 .AND. UPPLAN(J).GT.X2) CNTR3 = CNTR3 + 1
             IF(UPPLAN(J).LE.X4 .AND. UPPLAN(J).GT.X3) CNTR4 = CNTR4 + 1

106       CONTINUE
```

```
            DO 107 J = 1,RRUN
              IF(UPPLAN(J) .LE. 0) YCNTR1 = YCNTR1 + 1
              IF(UPPLAN(J).LE.1 .AND. UPPLAN(J).GT.0) YCNTR2 = YCNTR2 + 1
              IF(UPPLAN(J).LE.2 .AND. UPPLAN(J).GT.1) YCNTR3 = YCNTR3 + 1
              IF(UPPLAN(J).LE.3 .AND. UPPLAN(J).GT.2) YCNTR4 = YCNTR4 + 1
              IF(UPPLAN(J).LE.4 .AND. UPPLAN(J).GT.3) YCNTR5 = YCNTR5 + 1
              IF(UPPLAN(J).LE.5 .AND. UPPLAN(J).GT.4) YCNTR6 = YCNTR6 + 1
              IF(UPPLAN(J).LE.6 .AND. UPPLAN(J).GT.5) YCNTR7 = YCNTR7 + 1
              IF(UPPLAN(J).LE.7 .AND. UPPLAN(J).GT.6) YCNTR8 = YCNTR8 + 1
              IF(UPPLAN(J).LE.8 .AND. UPPLAN(J).GT.7) YCNTR9 = YCNTR9 + 1
              IF(UPPLAN(J).LE.9 .AND. UPPLAN(J).GT.8) YCNT10= YCNT10+ 1
              IF(UPPLAN(J).LE.10.AND. UPPLAN(J).GT.9) YCNT11= YCNT11+ 1
              IF(UPPLAN(J).LE.11.AND. UPPLAN(J).GT.10) YCNT12= YCNT12+ 1
              IF(UPPLAN(J).LE.12.AND. UPPLAN(J).GT.11) YCNT13= YCNT13+ 1
107       CONTINUE

          TEMP = 0
          DO 208 I = 1,RRUN
              DO 209 J =1,TOTMSN
                  TEMP = TEMP + QT(I,J)
209           CONTINUE
208       CONTINUE

          LQ = TEMP / (RRUN * TOTMSN)
          RETURN
          END


      *********************************************************************
          SUBROUTINE RANDOM(RA,RAA,RAAA)
          REAL RA(100000),RAA(100000),RAAA(60000)

          N = 100000
          NN = 60000
          IX = 15989
          IIX = 14999
          IIIX = 13999
          CALL LRND(IX,RA,N,1,0)
          CALL LRND(IIX,RAA,N,1,0)
          CALL LRND(IIIX,RAAA,NN,1,0)
          RETURN
          END
```

A.   Dynamic Modifications

```
*              THE QUEUES
30      QCUST = QCUST + 1
        IF(QSIZE .LT. 1) GO TO 40
*              STORE DATA ON NEWLY ARRIVED PART
        QSIZE = QSIZE + 1
        QPART(QSIZE) = FPT
        QTIME(QSIZE) = CLOCK
        IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN) = QSIZE

*              ASSIGN Q PRIORITY BASED ON NUMBERS IN THE Q

*              INITIALIZE AND COUNT NUMBERS OF PARTS IN Q
        DO 31 I = 1,TOTPRT
           QCNTR(I) = 0
31      CONTINUE

        DO 32 I = 1,TOTPRT
           DO 321 J = 1,QSIZE
              IF(I .EQ. QPART(J)) THEN
                 QCNTR(I) = QCNTR(I) + 1
              ENDIF
321        CONTINUE
32      CONTINUE

        DO 341 I = 1,TOTPRT-1
           IF(QCNTR(I) .EQ. QCNTR(I+1)) THEN
              FFLAG = 0
           ELSE
              FFLAG = 1
              GO TO 37
           ENDIF
341     CONTINUE

*              SORT AND ASSIGN PRIORTIES OF SERVICE
37      IF(FFLAG .GE. 1) THEN
           DO 331 I = 1,TOTPRT
              DO 332 J = 1,QSIZE
                 IF(QPART(J) .EQ. I) THEN
                    LINEUP(J) = QCNTR(I)
                 ENDIF
332           CONTINUE
331        CONTINUE

*              ASSIGN PRIORITY TO THE LINEUP WAITING IN THE Q

*              SORT AND ASSIGN ACTUAL POSITIONS IN Q BASED ON PRIORITY

        PAIRS = QSIZE - 1
        DONE = 1
35      IF(DONE .EQ. 1) THEN
              DONE = 0
              DO 351 I = 1,PAIRS
                 IF(LINEUP(I) .LT. LINEUP(I+1)) THEN
                    TEMPL1 = LINEUP(I)
                    TEMPL2 = QPART(I)
                    TEMPL3 = QTIME(I)
                    LINEUP(I) = LINEUP(I+1)
                    QPART(I) = QPART(I+1)
                    QTIME(I) = QTIME(I+1)
                    LINEUP(I+1) = TEMPL1
                    QPART(I+1) = TEMPL2
                    QTIME(I+1) = TEMPL3
                    DONE = 1
                 ENDIF
```

```
351          CONTINUE
             PAIRS = PAIRS - 1
             GO TO 35
        ENDIF
     ENDIF

     IF(FFLAG .LE. 0) THEN
        PPAIRS = QSIZE - 1
        PDONE = 1
36      IF(PDONE .EQ. 1) THEN
           PDONE = 0
           DO 361 I = 1,PPAIRS
                IF(QTIME(I) .GT. QTIME(I+1)) THEN
                      PTEMP2 = QPART(I)
                      PTEMP3 = QTIME(I)
                      QPART(I) = QPART(I+1)
                      QTIME(I) = QTIME(I+1)
                      QPART(I+1) = PTEMP2
                      QTIME(I+1) = PTEMP3
                      PDONE = 1
                ENDIF
361        CONTINUE
           PPAIRS = PPAIRS - 1
           GO TO 36
        ENDIF
     ENDIF

     GO TO 1

40   CONTINUE
     QSIZE = 1
     QPART(1) = FPT
     QTIME(QSIZE) = CLOCK
     IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN)= 1
     GO TO 1


B.   Dynamic 2 Modifications


*            THE QUEUES

30   QCUST = QCUST + 1
     IF(QSIZE .LT. 1) GO TO 40
*            STORE DATA ON NEWLY ARRIVED PART
     QSIZE = QSIZE + 1
     QPART(QSIZE) = FPT
     QTIME(QSIZE) = CLOCK
     IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN) = QSIZE

*            ASSIGN Q PRIORITY BASED ON NUMBERS IN THE Q

*            INITIALIZE AND COUNT NUMBERS OF PARTS IN Q
     DO 31 I = 1,TOTPRT
        QCNTR(I) = 0
31   CONTINUE

     DO 32 I = 1,TOTPRT
        DO 321 J = 1,QSIZE
           IF(I .EQ. QPART(J)) THEN
                QCNTR(I) = QCNTR(I) + 1
           ENDIF
321     CONTINUE
32   CONTINUE
```

61

```
*                 SORT AND ASSIGN PRIORTIES OF SERVICE

              DO 331 I = 1,TOTPRT
                  DO 332 J = 1,QSIZE
                      IF(QPART(J) .EQ. I) THEN
                          LINEUP(J) = QCNTR(I)*RHO(I)
                      ENDIF
332               CONTINUE

331       CONTINUE

*             ASSIGN PRIORITY TO THE LINEUP WAITING IN THE Q

*             SORT AND ASSIGN ACTUAL POSITIONS IN Q BASED ON PRIORITY

          PAIRS = QSIZE - 1
          DONE = 1
35        IF(DONE .EQ. 1) THEN
              DONE = 0
              DO 351 I = 1,PAIRS
                  IF(LINEUP(I) .LT. LINEUP(I+1)) THEN
                      TEMPL1 = LINEUP(I)
                      TEMPL2 = QPART(I)
                      TEMPL3 = QTIME(I)
                      LINEUP(I) = LINEUP(I+1)
                      QPART(I) = QPART(I+1)
                      QTIME(I) = QTIME(I+1)
                      LINEUP(I+1) = TEMPL1
                      QPART(I+1) = TEMPL2
                      QTIME(I+1) = TEMPL3
                      DONE = 1
                  ENDIF
351           CONTINUE
              PAIRS = PAIRS - 1
              GO TO 35
          ENDIF
      GO TO 1

40    CONTINUE
      QSIZE = 1
      QPART(1) = FPT
      QTIME(QSIZE) = CLOCK
      IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN)= 1
      GO TO 1


C.  Dynamic 3 Modifications


*             THE QUEUES

30    QCUST = QCUST + 1
      IF(QSIZE .LT. 1) GO TO 40
*             STORE DATA ON NEWLY ARRIVED PART
      QSIZE = QSIZE + 1
      QPART(QSIZE) = FPT
      QTIME(QSIZE) = CLOCK
      IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN) = QSIZE
```

```
*              COUNT NUMBERS OF OPERATING PARTS IN STOCK

       DO 341 I = 1,TOTPRT-1
           IF(QSTOCK(I) .EQ. QSTOCK(I+1)) THEN
               FFLAG = 0
           ELSE
               FFLAG = 1
               GO TO 37
           ENDIF
341    CONTINUE

*              SORT AND ASSIGN PRIORTIES OF SERVICE
37     IF(FFLAG .GE. 1) THEN

       DO 331 I = 1,TOTPRT
           DO 332 J = 1,QSIZE
               IF(QPART(J) .EQ. I) THEN
                   LINEUP(J) = QSTOCK(I)
               ENDIF
332        CONTINUE
331    CONTINUE

*              ASSIGN PRIORITY TO THE LINEUP WAITING IN THE Q

*              SORT AND ASSIGN ACTUAL POSITIONS IN Q BASED ON PRIORITY

       PAIRS = QSIZE - 1
       DONE = 1
35     IF(DONE .EQ. 1) THEN
           DONE = 0
           DO 351 I = 1,PAIRS
               IF(LINEUP(I) .GT. LINEUP(I+1)) THEN
                   TEMPL1 = LINEUP(I)
                   TEMPL2 = QPART(I)
                   TEMPL3 = QTIME(I)
                   LINEUP(I) = LINEUP(I+1)
                   QPART(I) = QPART(I+1)
                   QTIME(I) = QTIME(I+1)
                   LINEUP(I+1) = TEMPL1
                   QPART(I+1) = TEMPL2
                   QTIME(I+1) = TEMPL3
                   DONE = 1
               ENDIF
351        CONTINUE
           PAIRS = PAIRS - 1
           GO TO 35
       ENDIF
       ENDIF

       IF(FFLAG .LE. 0) THEN
           PPAIRS = QSIZE - 1
           PDONE = 1
36     IF(PDONE .EQ. 1) THEN
           PDONE = 0
           DO 361 I = 1,PPAIRS
               IF(QTIME(I) .GT. QTIME(I+1)) THEN
                   PTEMP2 = QPART(I)
                   PTEMP3 = QTIME(I)
                   QPART(I) = QPART(I+1)
                   QTIME(I) = QTIME(I+1)
                   QPART(I+1) = PTEMP2
                   QTIME(I+1) = PTEMP3
                   PDONE = 1
               ENDIF
361        CONTINUE
```

```
                    PPAIRS = PPAIRS - 1
                    GO TO 36
                ENDIF
            ENDIF
        GO TO 1

40      CONTINUE
        QSIZE = 1
        QPART(1) = FPT
        QTIME(QSIZE) = CLOCK
        IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN)= 1
        GO TO 1


C.  FRP-L(H) Modifications

*               READ IN FAILURE RATES
        DO 1 J = 1,TOTPRT
            READ (2,2) LAMBDA(J)
*           LAMBDA(J) = 0.0167
2           FORMAT(F8.5)
1       CONTINUE
        DO 3 J = 1,TOTPRT
            READ (3,8) SRATE(J)
*           SRATE(J) = 0.84
8           FORMAT(F8.5)
3       CONTINUE
        SUMLAM = 0
        DO 7 J = 1,TOTPRT
            SUMLAM = SUMLAM + LAMBDA(J)
7       CONTINUE
        DO 9 I=1,TOTPRT
            FACTOR(I) = PLANES * LAMBDA(I) * TOTMSN
            SPARE(I)  = NINT(FACTOR(I) + K * SQRT(FACTOR(I)))
            IF(SPARE(I) .LT. 0) SPARE(I) = 0
9       CONTINUE


*               ASSIGN PRIORITY TO PARTS VIA SUBR. QPRIOR

        CALL LINEUP(LAMBDA,TOTPRT)

*               CALL LLRAND II, GENERATE RANDOM NUMBER ARRAYS

        CALL RANDOM(A,AA,AAA)

*               INITIALIZE A NEW MISSION


****************************************************************************
*               THE QUEUES

30      QCUST = QCUST + 1
        IF(QSIZE .LT. 1) GO TO 40
        QSIZE = QSIZE + 1
        QPART(QSIZE) = FPT
        QTIME(QSIZE) = CLOCK
        IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN) = QSIZE

        DO 304 J = 1,TOTPRT
            DO 305 I = 1,QSIZE
                IF(QPART(I) .EQ. J) THEN
                    LINEUP(I) = PRIOR(J)
                ENDIF
305         CONTINUE
304     CONTINUE
```

```
          PAIRS = QSIZE - 1
          DONE = 1

301   IF(DONE .EQ. 1) THEN
          DONE = 0
          DO 302 I = 1,PAIRS
          IF(LINEUP(I) .GT. LINEUP(I+1)) THEN
              TEMP = QTIME(I)
              TEMPQ = QPART(I)
              TEMPQ1 = LINEUP(I)
              QTIME(I) = QTIME(I+1)
              QPART(I) = QPART(I+1)
              LINEUP(I) = LINEUP(I+1)
              QTIME(I+1) = TEMP
              QPART(I+1) = TEMPQ
              LINEUP(I+1) = TEMPQ1
              DONE = 1
          ENDIF
302       CONTINUE
          PAIRS = PAIRS - 1
          GO TO 301
      ENDIF
      DO 303 I = 1,QSIZE
303   CONTINUE
      GO TO 1

40    CONTINUE
      QSIZE = 1
      QPART(1) = FPT
      QTIME(QSIZE) = CLOCK
      IF(QMAX(QRUN) .LT. QSIZE) QMAX(QRUN)= 1
      GO TO 1



XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


      SUBROUTINE LINEUP(QLAMBD,QTOTPT)
      INTEGER QPRIOR(100)
      REAL QLAMBD(10),QTOTPT
      SAVE QPRIOR
      COMMON/RULE/QPRIOR

      DO 1 J=1,QTOTPT
        QPRIOR(J) = J
1     CONTINUE

      PAIRS = QTOTPT - 1
      DONE = 1
2     IF(DONE .GE. 1)THEN
          DONE = 0
          DO 3 J=1,PAIRS
              IF(QLAMBD(J) .GT. QLAMBD(J+1)) THEN
                  TEMP = QPRIOR(J)
                  QPRIOR(J) = QPRIOR(J+1)
                  QPRIOR(J+1) = TEMP
                  DONE = 1
              ENDIF
3         CONTINUE

      PAIRS = PAIRS - 1
      GO TO 2
      ENDIF
      RETURN
      END
```

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