Translating Aircraft Reliability and Maintainability into Measures of Operational Effectiveness

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This paper describes a numerical model for translating aircraft subsystem reliability and maintainability characteristics into measures of aircraft operational effectiveness. The model incorporates the impact of constraints on the availability of manpower resources required to accomplish subsystem repairs.

Introduction

SENIOR leadership of the U.S. Air Force has mandated that the reliability and maintainability (R&M) of new weapon systems be given primary consideration from the very earliest stages of system development.[1] One problem of interest in early design stages is the allocation of R&M goals to various major subsystems such that operational effectiveness of the overall system is maximized. The impact of R&M allocations on system operational effectiveness has traditionally been predicted through the use of Monte Carlo simulation models such as the Logistics Composite Model (LCOM).[2] Such models are generally designed for batch mode operation using detailed input data. The simulations require multiple computer runs to place confidence bounds on the computed results, and run times are usually substantial.

This paper describes a simple numerical model that could be employed in place of Monte Carlo simulation to translate subsystem R&M characteristics into operational effectiveness measures for a military aircraft. These measures include aircraft availability (average portion of time an aircraft is mission capable) and sortie generation rate (number of sorties launched per aircraft per day). The numerical model permits rapid prediction of effectiveness resulting from alternative R&M allocation strategies.

Scope and Assumptions

The model assumes that critical failure of any subsystem has no effect on the probability of critical failure of any other subsystem; thus, application below the major subsystem is limited. Scheduled maintenance and battle damage repair are not addressed, although the model could be expanded to include these considerations. The effects of constraints on the availability of spare parts and specialized maintenance equipment are not addressed, but the model does consider the impact of restrictions on the availability of manpower resources needed to accomplish repairs.

The first operation performed by the model is aggregation of the subsystem characteristics into combined probability distributions of repair time for each group of subsystems requiring a particular type of maintenance specialist for repair. In performing this aggregation, the model assumes that the amounts of time between failures of each subsystem are exponentially distributed. This is an appropriate assumption for major subsystems when many design details are unknown and subsystem reliability is sufficiently high.[3] High reliability also permits the assumption of only one major subsystem failure during an aircraft sortie.[4] All sorties are assumed to be of a constant duration.

In translating the aggregate repair time distributions into measures of operational effectiveness, all subsystems are assumed to require only one type of maintenance specialist for repair. Thus, the aggregate distributions are independent and are each associated with a unique type of maintenance specialist.

Formation of Aggregate Repair Time Distributions

Time to failure for an aircraft or subsystem can be expressed in terms of a number of time-limited operational sequences (sorties) until failure. The exponentiality of subsystem failure time distributions for highly reliable aircraft thus permits calculation of subsystem sortie reliabilities which remain constant for each sortie flown. Subsystem sortie reliabilities can be calculated as

$$r_i = P(s_i > 1) = 1 - \int_0^1 \left(\frac{s_i}{m_i}\right) \exp\left(-\frac{s_i}{m_i}\right) ds_i$$
$$= 1 - \left[-\exp\left(-\frac{1}{m_i}\right) + 1\right] = \exp\left(-\frac{1}{m_i}\right) \quad (1)$$

where r_i is the sortie reliability of subsystem i, s_i the number of sorties to failure, and m_i a postulated mean number of sorties between failures. Since the exponential distribution has the "memoryless" property, the subsystem reliabilities can be applied to each sortie independent of the failure history of previous sorties. For an aircraft with a total of N major subsystems, overall aircraft reliability R can then be calculated as

$$R = 1 - \prod_{i=1}^{N} (1 - r_i) \quad (2)$$

By assuming that a failed aircraft will arrive with only one failed subsystem, conditional probabilities p_i can be computed to represent the probability that any subsystem has failed given the aircraft has failed. The conditional probability of failure for any subsystem i (given aircraft failure) can be expressed as

$$p_i = (1 - r_i) \Big/ \sum_{i=1}^{N} (1 - r_i) \quad (3)$$

To determine the probability P_k that a particular manpower resource k is required to repair a failed aircraft, the p_i for all subsystems requiring resource k must be summed. The probability that a subsystem i has failed given manpower resource k is required for repair can then be calculated as p_i/P_k.

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For each manpower resource, a cumulative distribution function (CDF) for aircraft repair time can now be developed. Since subsystem failures are independent and multiple subsystem failures are discounted, the repair time CDF $F_k(t)$ for manpower resource k can be defined by the probabilistic mixture

$$F_k(t) = \sum_{i=1}^{K} p_i F_i(t) \tag{4}$$

where K is the total number of subsystems requiring resource k, and $F_i(t)$ is the known or postulated repair time CDF for subsystem i. The repair time CDF for resource k defines the proportion of failed aircraft that will be repaired within time t.

Determination of Operational Effectiveness

Approach

The operational effectiveness realized by an aircraft with a particular set of aggregate repair time distributions is dependent on the aircraft concept of operations. An operational unit consisting of a fixed number of aircraft launches sorties according to a daily schedule. The schedule can be constrained by many factors, such as scheduled maintenance and mission planning restrictions. Furthermore, whenever an aircraft returns from a sortie, it must undergo routine "turnaround" operations, such as refueling and reloading of munitions, before it can begin another sortie. Another consideration applicable to some types of aircraft is the concept of a "sortie launch window," which limits aircraft launches to certain hours of each day, such as daylight hours. The impact of the window concept is significant because it permits use of nonwindow time to correct aircraft malfunctions without affecting the sortie generation rate.

A unique modeling approach that can incorporate all of the necessary operational concepts without resorting to Monte Carlo techniques is a "deterministic simulation," which models the movement of aircraft from one status to another (e.g., flying a sortie to being repaired) as a continuous flow. At discrete points in time, the quantities of aircraft in each status can be counted. These quantities can, in turn, be used to determine the aircraft availability and sortie generation rate at each discrete point in time. If the interval between the points of time is sufficiently small, the average values for these discrete availabilities and sortie generation rates will approximate the theoretical values for the entire time period examined.

Methodology

At any point in time, an aircraft will be in one of four states. It will either be flying a sortie, undergoing turnaround operations, undergoing repairs, or waiting for launch in a ready condition. In any time interval examined, aircraft may change from one state to another in accordance with the

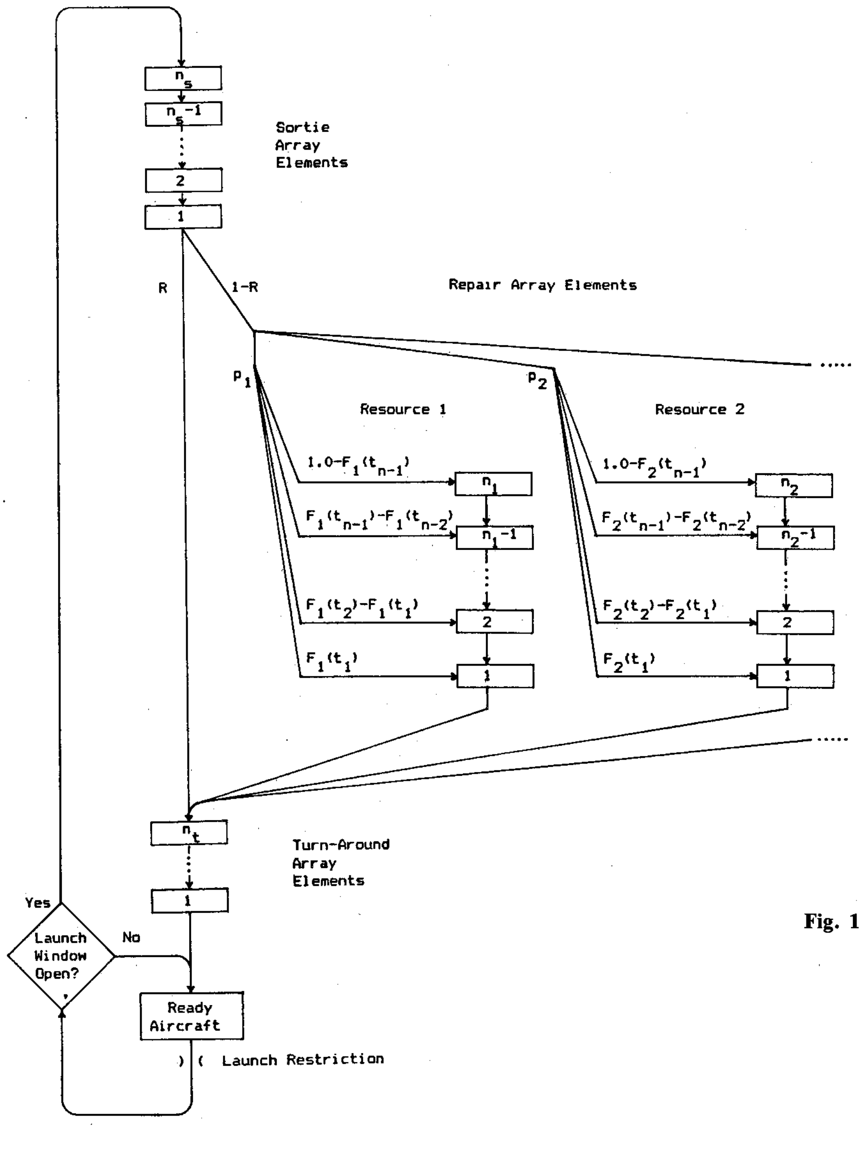

Fig. 1 Aircraft movement between states.

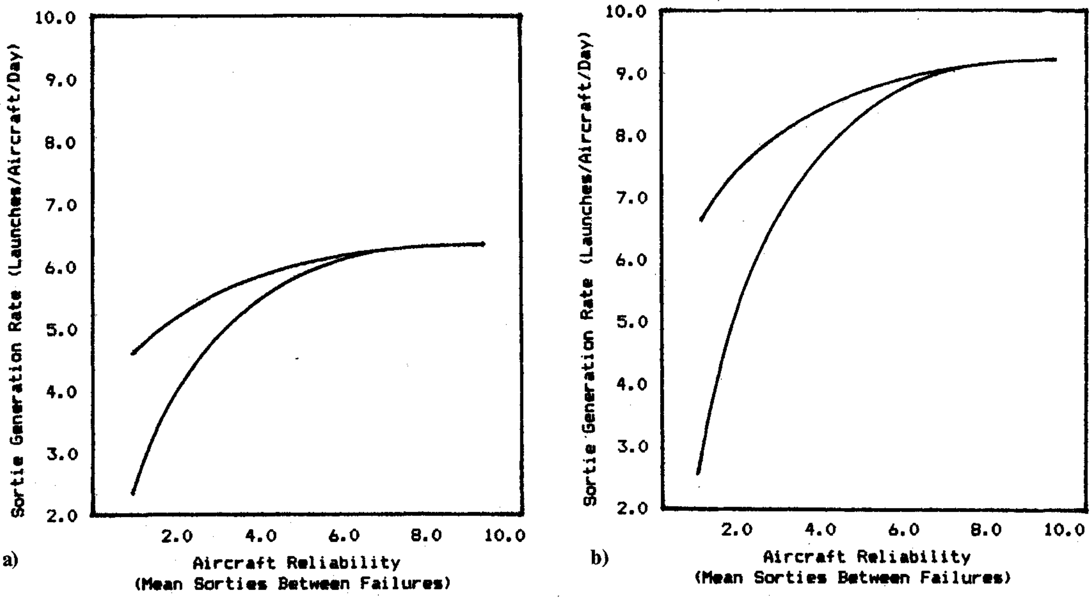

Fig. 2 Numerical model results: a) restricted scenario, b) unrestricted scenario.

relationships illustrated in Fig. 1. Since we are interested in calculating average values over time, the movement between states need not be restricted to whole numbers of aircraft. Portions of aircraft can be moved from one state to another in accordance with the probability associated with that movement. For example, if an aircraft design produces an overall aircraft reliability R, a portion R of a single aircraft recovering from a sortie will immediately enter the turnaround state and a portion $1-R$ will enter the repair state. The aircraft quantity entering the repair state will similarly be portioned into quantities to be repaired by each manpower resource according to the various P_k.

An important operation performed by the model is separation of aircraft quantities undergoing repair into portions requiring different repair times. Values of the analytical repair time CDF's produced by aggregation can be calculated for various points of time separated by a constant interval. If this interval width coincides with the interval width between time points examined, aircraft quantities can be portioned into aircraft quantities that will leave the repair state at different times. The probability that an aircraft will leave the repair state between repair time t_1 and repair time t_2 is simply the difference in cumulative probabilities associated with the two times $[F_k(t_2)-F_k(t_1)]$. To implement the repair time interval probabilities in the computer model, the probabilities can be stored in an array whose elements represent each repair time interval. The number of elements in the array can be established by determining the number of time intervals necessary to reach a total cumulative probability very near to 1.0.

In order to track the quantity of aircraft in any state at any point in time, state arrays must be established for the sortie state, turnaround state, and repair states for each manpower resource. The number of elements in each repair state array (n_k) will be equal to the number of elements in each repair time probability array, maintaining a one-to-one correspondence. Assuming sortie and turnaround times are constant, the number of elements in the sortie state array (n_s) and turnaround state array (n_t) will be equal to the state duration divided by the time interval width. Figure 1 illustrates the configuration of the various state arrays; the rectangular symbols in the figure represent array elements.

In running the operational effectiveness model, time must be advanced in the specified time increment up to a specified maximum time. At each time increment, aircraft quantities will move through the state arrays or from one state to another. The use of separate repair arrays for each manpower resource permits modeling of queuing delays. Resource availability can be expressed in terms of a maximum number of aircraft that can be simultaneously repaired by each resource. If the total quantity of aircraft in a repair array exceeds the resource availability, then only portions of the aircraft quantities are allowed to advance through the repair array. For example, if there are only enough maintenance specialists of type 1 to simultaneously repair 2.0 aircraft, but 2.5 aircraft are in the repair array at a particular time, only 80% (2.0/2.5) of all aircraft in the array are allowed to advance. The other 20% will remain in their current array element for another time increment, reflecting queuing delay.

At any point in time examined, all aircraft leaving the repair array immediately enter the last element of the turnaround array. All aircraft leaving the turnaround array are added to an existing quantity of ready aircraft, some of which may immediately enter the last element of the sortie array in accordance with launch constraints. If the current time is not in the sortie launch window, no aircraft enter the sortie array. If the quantity of aircraft in the ready state is less than the maximum quantity of permitted launches per interval, all aircraft in the ready state enter the last element of the sortie array, and the quantity of ready aircraft is reduced to zero. If the quantity of aircraft in the ready state is greater than the maximum permitted launch quantity, the maximum permitted launch quantity enters the last element of the sortie array, and the quantity of ready aircraft is reduced accordingly.

For any point in time, an aircraft availability can be calculated as the sum of the quantities of aircraft in the sortie and ready states divided by the total number of aircraft in the operational unit. This computation requires a determination of the total quantities of aircraft in each array at each time increment. To determine the average availability for the entire period considered by the model, the availabilities at each time increment can be summed and then divided by the total number of time intervals examined. To determine the average daily sortie generation rate, the quantities of aircraft entering the sortie state during each time interval can be summed and then divided by the number of days in the period considered by the model.

Another result of interest is the average queuing delay for each type of maintenance specialist. The total quantity of aircraft that are not advanced through each repair array due to resource availability can be summed as the model is run. Average queuing delay for a resource can then be determined by multiplying this quantity by the model time increment and dividing by the total time period modeled. The queuing delay information is useful because it could be used to determine resource requirements or develop a more efficient assignment of resources to subsystems.

Model Implementation and Results

The model described has been implemented on a Digital Research MicroVAX computer and a Zenith Z-100 microcomputer. Both implementations employ a network of menus to enhance user interaction in evaluating alternative strategies for R&M allocation and manpower assignment. The user must specify subsystem repair time distribution forms (exponential or log normal) and parameters. The user must also specify a maintenance manpower requirement and reliability for each subsystem. Other inputs include aircraft force size, sortie time, turnaround time, launch constraints, and manpower resources available. Any data set generated by the user can be saved for later use.

Figure 2 illustrates the application of the model to demonstrate the relationship between overall aircraft reliability and sortie generation. In this example, repair time data representative of the F-16 fighter are used, and subsystem reliabilities are varied over a wide range. The operational concept includes a force size of 24 aircraft with sortie times of 2.0 h and turnaround times of 0.4 h. Plot A displays results for a restricted scenario in which the sortie launch window is open 16.0 h per day and no more than 10.0 launches are permitted every hour. Plot B presents results for an unrestricted scenario in which all aircraft are launched whenever they are available. The upper lines in each plot present model results when resource availability is set to permit simultaneous repair of all aircraft. The lower lines illustrate the effect of constraints on the availability of manpower resources. For these runs, subsystems are assigned to one of five types of maintenance specialists, and only one team of each type specialist is available at any time. The plots demonstrate that substantial queuing delay occurs for aircraft at low reliability levels, significantly reducing the sortie generation rate.

The model runs used to produce the plots shown in Fig. 2 examine a 30-day period in increments of 0.2 h. Each run expended approximately 30 s of core processing time on the MicroVAX. The values for effectiveness measures produced by the model were highly compatible with those produced by a Monte Carlo simulation. The simulation, however, consumed up to 18 min of core processing time on a VAX 11/780 computer for some runs. The numerical model thus offers an attractive alternative to Monte Carlo simulation for assessing R&M tradeoffs early in the weapon system acquisition process.

References

[1]Department of the Air Force, "Memorandum for All Major Commands—Separate Operating Agencies/CC, Washington, Sept. 1984.

[2]Conlon, J.C. et al., *Test and Evaluation of System Reliability, Availability and Maintainability, DOD Handbook 3235,* Government Printing Office, Washington, D.C., March 1982, pp. 4–8.

[3]Dietz, D.C., "An Analytical Methodology for Predicting Repair Time Distributions of Advanced Technology Aircraft," M.S. Thesis, GOR/OS 85-3, Air Force Institute of Technology, Dec. 1985, p. 3–3.

[4]Dietz, D.C., "An Analytical Methodology for Predicting Repair Time Distributions of Advanced Technology Aircraft," M.S. Thesis, GOR/OS 85-3, Air Force Institute of Technology, Dec. 1985, p. 8–4.