Operational Availability Modeling and Simulation Evaluation

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SUMMARY & CONCLUSIONS

In this paper, we first investigate the concept and measuring models of system operational availability, and their limitations. To overcome the limitations of the existing models, we present an instantaneous operational availability model and an average operational availability model, as well as a simulation-based method for evaluating those two models. The distinction between the two models is illustrated by simulation examples. The sensitivity analysis of impacting factors shows that the inherent reliability of a system is the key factor affecting the operational availability, thus improving system inherent reliability is the most effective way to improve the operational availability. The second most important factor is the number of initial spare parts. Analysis results also show that the operational availability has not increased significantly by increasing the number of maintenance personnel or cutting down the mean maintenance time.

1 INTRODUCTION

Operational availability is one of the key system performance parameters, which reflects the system's reliability, maintainability, and supportability characteristics. It is the probability that the system is in the operable/working state at an instant of time [1]. As the top level metric, operational availability is typically decomposed into lower level parameters. In additional, operational availability is one of the most important parameters used by the military units for measuring the operational readiness of an operational unit. Therefore, evaluation of operational availability plays an important role in the whole life cycle of a system.

Since the concept of operational availability was brought forward, many different availability models have been built and applied in the analysis of different systems in different application areas. However, the assumptions made in those models were often neglected when they were used, which results in the inaccurate or incorrect evaluation of operational availability, thus cannot reflect the real level of the system performance or supportability. Therefore, it is essential to review how these models that are in common use today were derived, to analyze the related assumptions of these models, and to establish new proper models and methods to evaluate the system operational availability. In this work, we will also investigate factors that have influence on the system operational availability.

2 CONCEPT OF OPERATIONAL AVAILABILITY

The concept of operational availability was applied to evaluate the availability of a single system or equipment in past time. Nowadays, it has been commonly applied to evaluate the availability of an operational unit that consists of multiple identical systems or equipments [2].

The probability that a single equipment or system is up at time t is given by [1]

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\exp\left[-(\lambda+\mu)t\right] \tag{1}$$

Where λ is the failure rate and μ is the repair rate. Note that the reciprocal of λ gives the mean time to failure (MTTF) or mean time between failures (MTBF) and the reciprocal of μ is mean time to repair (MTTR) [3]. The assumptions made by equation (1) are:

1. The failure times are independent and exponential distribution, i.e., the failure rate λ is constant, it does not change with usage or age.
2. The repair times are independent and identically distributed exponential random variables with parameter μ.
3. Repair will begin immediately upon the occurrence of a failure. Time for waiting for parts, maintainers, or other maintenance resources is neglected.

Based on (1), the average or mission availability is evaluated as [4].

$$A_{avg}(t_1, t_2) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} A(t)dt \tag{2}$$

Where t_1 is the mission start time, and t_2 is the mission end time.

Equation (1) contains a steady-state term and a transient term. As t goes to infinity the transient term goes to zero, equation (1) gives the steady-state availability as shown in (3):

$$A_{ss} = A(t)\big|_{t\to\infty} = \frac{\mu}{\lambda+\mu} \tag{3}$$

For most real systems, the failure rate change with time

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during the life cycle, and it typically follows the well-known bathtub curve. So policies such as maintenance and/or rebuilt should be needed for assumption 1 to hold.

Since the MTBF is the reciprocal of λ and the MTTR is the reciprocal of μ, Equation (3) can also be written as:

$$A_{ss} = \frac{\mu}{\lambda + \mu} = \frac{MTBF}{MTBF + MTTR} \tag{4}$$

Equation (4) can also be used to evaluate unit containing multiple identical systems/equipments, for example, an operating unit containing multiple identical vehicle s, provided the following additional assumptions hold:

4. The failure event of each copy of the system is independent and the failure times of all the copies have the same exponential distribution with parameter λ. In other words, each copy of the system has the same unchanging failure rate as the other copies and they are independent of each other.
5. The repair event of each copy of the system is independent and the repair times have the same exponential distribution with parameter μ. This implies that copies of the system do not compete for the limited maintenance resources.

Current R&M literature reveals that operational availability is a function of active maintenance time, and administrative delay and logistics delay time. So to be more specific, the MTTR term can be replaced with MTTR + ALDT (or MDT) for computing steady-state availability [5]:

$$A_o = \frac{MTBF}{MTBF + MTTR + ALDT} \tag{5}$$

Where *ALDT* is the mean administrative and logistics delay time, and MDT is mean down time. Equation (5) is the typical form of operational availability. But additional assumptions that equation (5) must make are:

6. The distribution of MTTR + ALDT follows the exponential distribution and the rate does not change with time.
7. The copies of the system do not compete for spare parts or maintenance resources.

There are other models of operational availability. One of these [6] defines operational availability as "The percentage of time that a weapon system is available to sustain operations." This memorandum provides the following formula.

$$A_0 = \frac{MTBM}{MTBM + MDT} \tag{6}$$

Where MTBM is mean time between maintenance, which is defined as "the mean time between maintenance actions (both preventive and corrective)" and it is a measure of the reliability taking into account maintenance policy. MDT is mean down time, which is defined as "the average time a system is unavailable for use due to either corrective or preventive maintenance". Time includes actual repair time and all delay time(s).

The assumptions by equation (6) are similar to those required by Equation (5) with one modification. In this case one must assume that the aggregated rate of failure and scheduled/preventive maintenance time is exponentially distributed.

3 PROBLEM STATEMENT

Inspection of the existing models of operational availability reviewed in Section 2 reveals that many assumptions must be made by these equations. However, those assumptions are not valid in many real systems. Specifically,

1. Due to the effects of aging, the failure rate would increase or decrease; assumption 1 is not valid in many practical systems.
2. Active repair times typically follow lognormal distribution; assumption 2 is not reasonable.
3. For typical operational unit, active maintenance will delay due to waiting for parts, maintenance personnel, or other maintenance resources. So assumption 3 is also a poor assumption.
4. Copies of the system in an operational unit will often compete for maintenance resources, so assumption 5 and assumption 7 are not valid.
5. Administrative delay time is controlled by a combination of the policies and procedures of the performing organization and the efficiency of their execution. Logistics delay time is a function of the design attributes of support services set-up to supply the resources required for conducting maintenance. It is also relayed to the "supply chain" for the resources under consideration. Therefore, the distribution of MTTR + ALDT does not necessarily follow the exponential distribution as assumed in assumption 6.

For above reasons, it will lose the purpose of operational availability when the existing models are applied without consideration of these assumptions. Because operational availability is determined by active maintenance time and maintenance delay time, and the maintenance delay time includes all aspects of administrative and logistics delay time, it is difficult to compute operational availability by common analytical methods. In this case, simulation methods are helpful to evaluate operational availability. In the next section, we present the availability models used in this work and the simulation method to evaluate the operational availability of a particular operational unit using those models.

4 OPERATIONAL AVAILABILITY MODELS & EVALUATION

For small portions of the life cycle, or large portions of the life cycle with maintenance and/or retirement policies adopted, failure rate can be viewed as an unchangeable term. When doing simulation experiments, random numbers that follow lognormal distribution can be used to simulate the maintenance time. Both supply chain systems and maintenance systems are service systems with many random factors, queuing theory can be applied to solve the problem of sharing of spare parts and maintenance resources.

4.1 Failure Sampling

For small portions of the life cycle, failure rate can be viewed as an unchangeable term. For multiple copies of the same system, we can assume that failure time of each copy of the system has independent exponential distribution with parameter λ. For example, an assumption of exponential distribution with parameter of mean kilometer between failures (MKmBF) was made for vehicle s named M1A1, M2A2, and M2A3 by RAND Corporation when availability and reliability were simulated [7]. So the failure rate can be viewed as a constant and in any time t the probability of occurrence of failure $P_{Failure}$ is

$$P_{Failure} = 1 - \exp\left(-\frac{t}{MTBF}\right) \tag{7}$$

In the beginning of simulation, a uniform simulation clock is defined for the whole operational unit. Time between failures is sampled when the mission starts. At each advancement of the simulation time, judging whether failure time is reached. Mean time between failures can be achieved through statics of simulation results.

4.2 Maintenance Time Sampling

Maintenance action includes scheduled preventive maintenance and unscheduled repair maintenance. For a short time mission, all kinds of preventive maintenance cannot be considered. According to statistics, maintenance time of some machine, electronic, and mechanism follows lognormal distribution. So maintenance time can be got by random sample of lognormal distribution, and the corresponding distribution parameter can be estimated by experience and statistic [8]. Sample of repair time is [8]

$$T_H = \exp\left[\theta + \sigma\sqrt{-2\ln\eta_1} \times \cos\left(2\pi \times \eta_2\right)\right] \tag{8}$$

Where θ and σ are log mean value and log standard deviation by statistic respectively, and η_1 and η_2 are random numbers.

4.3 Administrative and Logistics Delay Time

Maintenance delay time includes all aspects of delay time involved for waiting for the actual maintenance to occur. Maintenance delay time is the main factor of causing the down state of the system. It mainly includes administrative delay time and logistics delay time, among which spare parts delay is the main reason of maintenance delay. For a mission with a longer time, spare parts delay can be achieved by simulation of practical reality, and for a mission with shorter time, because of long turnover time of spare parts, spare parts delay is usually be considered; and the field maintenance is related only with the initial spare parts supply.

For the problem of multiple copies of the system competing for maintenance resources in an operational unit, according to the queue theory, we can repair the system that has failed first based on the principle of first come first serve.

4.4 Availability Computing Models

Based on the above analysis, this section presents simulation computing models for both instantaneous operational availability and mean operational availability during the mission. Data used for the two models comes from the simulation of the reality, so the evaluation of operational availability is much more practical.

For a particular mission, the instantaneous operational availability $A_o(t)$ in the given mission time t can be given as the ratio between the number of items that can be used and the total number of items that are put into use at the start of the mission. It can be expressed by formula as,

$$A_o\left(t\right) = \frac{N_{Total} - N_{Failure}}{N_{Total}} \tag{9}$$

Where $N_{Failure}$ is the number of items that cannot be used or have failed, and N_{Total} is the total number of items used to implement mission.

For the mean operational probability during the entire mission, it can be evaluated as

$$\overline{A}_o = \frac{1}{T}\int_s^{s+T} A_o(u)du \tag{10}$$

Where s is the mission start time, and T is mission ending time.

5 EXAMPLE ANALYSES

5.1 Simulation of Operational Availability

This section presents the simulation of an armor unit performing a simple march mission. Mission profile is: 30 vehicle s in some armor army unit performing a march, and all the items in good condition at the beginning of the mission, then the unit conducts a road march from the assembly area to the combat zone, and maintenance unit takes a certain amount of spares to prepare to support. Some vehicle s will break down on the road march, and maintenance unit will perform field maintenance at once, and repaired vehicle s go on carrying out the mission. Parameters used in the simulation are: mission time is 100 hours, number of vehicle s is 30, mean time between failure of each vehicle is 150 hours, field maintenance time of vehicle follows lognormal distribution with log mean value 1.6 hours and log standard deviation 0.4, the initial number of spare parts taken by maintenance unit is 8 kits, the number of maintenance personnel is 3, and system recoverability when spare parts are available is 90%.

The paper adopts Anylogic 6.5, an internationally-known simulation tool [9], to evaluate the operational availability. Figure 1 shows the change of instantaneous operational.

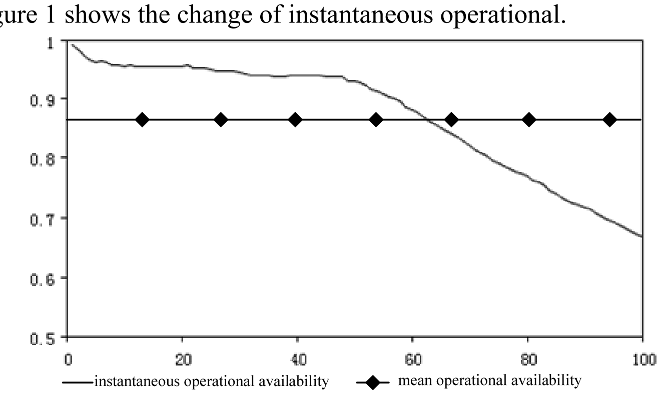

Figure 1- Change of instantaneous operational availability and mean operational availability

availability and mean operational availability during the whole mission time

We can see from the simulation results, in the first half of the mission, due to the availability of enough spare parts, vehicle s can be repaired timely and instantaneous operational availability stays at the level of above 90%. In the second half of the mission, with the consuming of the spare parts, vehicle s cannot be repaired timely due to the shortage of spare parts in the case of failure, the instantaneous operational availability reduces sharply. It becomes 65.7% at the end of mission time. Vehicle s' mean operational availability during the whole process of the mission is 87.3%.

5.2 Analysis of Influential Factors

As the top level metric of armor system, operational availability is affected by many factors like reliability, maintainability, initial number of spare parts and maintaining tactics. We can evaluate sensitivity of factors affecting operational availability by changing these input parameters and re-running the simulations. In particular, we re-perform the simulations by doubling MTBF, the number of initial spare parts as well as the number of maintenance personnel, or cutting down a half of the mean maintenance time. Figure 2and Figure 3 show the change of instantaneous operational availability and mean operational availability for each case.

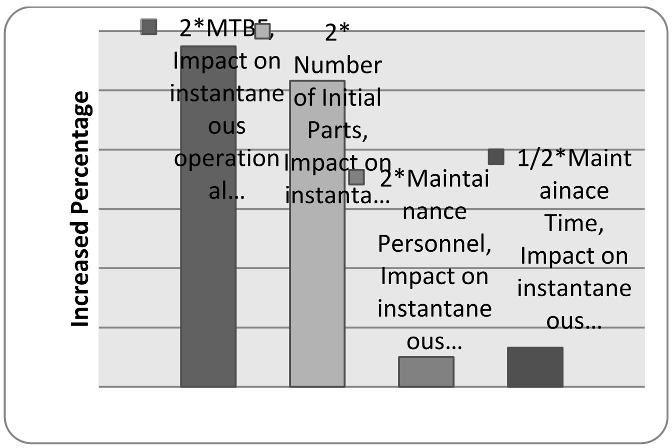

Figure 2 - Sensitivity of instantaneous operational availability to MTBF, number of initial parts, maintenance personnel and maintenance time

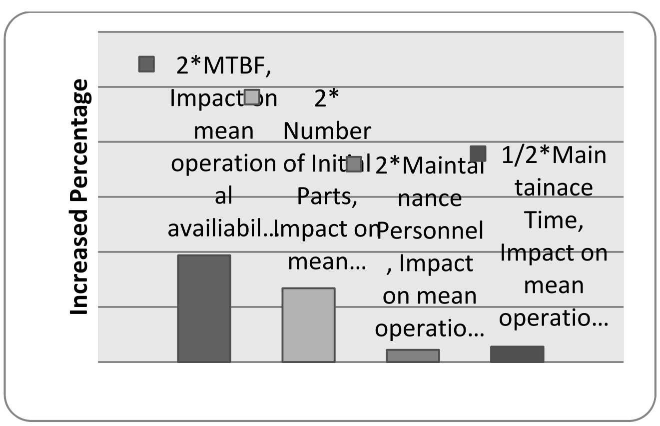

Figure 3 - Sensitivity of mean operational availability to MTBF, number of initial parts, maintenance personnel and maintenance time

From Figure2 and Figure3, we can see that the most important factor affecting operational availability is system's inherent reliability, which is reflected by MTBF. Instantaneous operational availability and mean operational availability increase significantly by increasing MTBF. The second most important factor is the number of initial spare parts. Operational availability has not increased clearly by increasing the number of maintenance personnel and cutting down the mean maintenance time. Therefore, one of the most effective way to increase system's operational availability is to enhance its inherent reliability.

6 CONCLUSIONS

This paper discussed the concept of operational availability, analyzed the limitation of some existing availability models, and presented a more practical way of simulation for evaluating instantaneous operational availability and mean operational availability. The results of simulations show the changing rules of instantaneous operational availability and mean operational availability in the whole mission process. Mean operational availability is different from instantaneous operational availability, and should be strictly differentiated when we compute operational availability. The main factors to affect operational availability are system's inherent reliability and the initial number of spare parts. The number of maintenance personnel and mean maintenance time has little influence on operational availability.

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