Proceedings of the 1988 Winter Simulation Conference
M. Abrams, P. Haigh, and J. Comfort (eds.)

Simulation: The correct approach to complex availability problem

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ABSTRACT

Recently, system owners and operators have increasingly emphasized the actual amount of time equipment is capable of performing its intended function.

For military systems, added complexity, longer service life requirements, reduced periodic maintenance, and less frequent checkouts have increased system availability requirements. However, these factors compound the difficulty in estimating the system's true availability.

With dormant or semi-dormant systems, the amount of time a system "appears" available may differ from the "real" availability. The difference in "real" and "apparent" availability is often the result of a transition from an operational but dormant state to an inoperational but dormant state.

The major contributions of this research are:

(1) the development of the concept of "complex" availability that applies to systems which combine two or more elements of instantaneous, mission system, or steady-state availability, and

(2) the development of a modeling technique to estimate the "real" availability for a system which involves "complex" availability.

INTRODUCTION

In recent years, system owners and operators have placed increased emphasis on the actual amount of time equipment is capable of performing its intended function. This emphasis can be attributed to increased consolidation of tasks to single equipment, increased criticality of information, escalating information rates, and increased cost of ownership (Hasslinger, 1978). Because of these factors, system requirements usually specify availability goals. System availability goals are usually set with regard to the requirements of a system's primary mission (Fabbro, 1979).

Since failure in operation and the consequent bad reputation can be very costly, it is important to evaluate the availability of a product in so far as possible at the design and pre-production stage. This approach minimizes the risk of waiting until the product is in the customer's hands before discovering availability shortfalls and risking the company's reputation (Galetto, 1977). Consequently, the importance of system availability has increased in both the private and public sector.

Reliability, Maintainability, and Availability Relationship

While reliability is concerned with the system capability of survival, maintainability is related to the system capability of repair. By combining these two factors, a family of parameters is created which reflect system effectiveness as a whole, or system "availability" (Thomason,1969). Tillman et. al. (1982) distinguish between reliability and availability as reliability being the probability of failure free operation whereas availability is the readiness of the system.

Military Systems Availability

For military systems, increasing complexity, longer service life requirements, and reduced periodic maintenance and checkouts have increased system availability requirements. However, these factors compound the difficulty in estimating the system's true availability.

With stored equipment, the primary concern is that it works properly when required. Masterson and Miller (1976) indicate this is the primary problem for many classes of systems, such as stored spacecraft, weapon systems, electronic components stored prior to assembly, TV sets stored in a warehouse or showroom, or even used cars on the corner lot. Hasslinger (1978) states: " It is axiomatic that such emphasis would manifest itself in the form of proof upon purchase that an equipment will perform to minimum availability requirements."

After long periods of dormancy (nonuse), the "availability" for military systems has been a major concern throughout history. A system taken out of storage is expected to accomplish its mission without a performance degrading malfunction. For example, in early military history spoilage of items such as food and gun powder was a major concern. When aircraft availability exceeded flying hour requirements a few years ago, care was taken to periodically move parked aircraft to mitigate the effects of nonuse (e.g., flat tires, fluid drain, etc.) (Trapp et. al., 1981). As military systems have continued to become more complex, expensive, and sophisticated, coupled with shorter response times, the requirement for higher availability rates has increased.

"Real" Vs. "Apparent" Availability

With a continuously operating system, availability can be determined at any desired time. The penalty for operating continuously is the downtime caused by system failures with attendant loss of availability during checkout and repair. A dormant system, theoretically should have fewer failures; however, it is unfortunate that there is not a positive indication of system status when dormant by which to judge the system's

availability. With dormant or semi-dormant systems, the amount of time a system "appears" available may differ from the "real" availability. The difference in "real" and "apparent" availability is often the result of a transition from an operational but dormant state to an inoperational but dormant state.

This research focused upon developing methodology to estimate the "real" availability for the Small ICBM weapon system, a key system in President Reagan's Strategic Modernization Program.

Uncertainty in the "real" availability for any system could be introduced through a variety of sources such as:

(1) failures which occur during dormancy,
(2) failure which are undetected when the system is tested (this could be thought of as the test equipment's probability of detection capability),
(3) the reliability and availability of test and maintenance resources, and
(4) components in the system which are not capable of non-destructive test (most notable are propellants).

With these uncertainties, it may be possible that a steady state condition will be reached where a number of the missiles believed "apparently" available for launch would not be available if called upon to launch (hence not "really" available).

Dormancy is a particular concern because the missile systems are designed to spend the majority of their life in a non-operating environment. Systems with limited operational status testing capability can cause substantial uncertainty in the "real" availability. Therefore the research question is stated as:

H_0: "Real" Availability = "Apparent" Availability

H_1: "Real" Availability < "Apparent" Availability

However, an examination of the formulated hypothesis reveals that the condition where "real" availability > "apparent" availability is not being tested. It is physically impossible for "real" availability to exceed "apparent" availability. The reason is that the downtime is the same for for "apparent" and "real" availability except for the condition of inoperational but dormant state for "real" availability. Therefore, the only condition where "real" availability would equal "apparent" availability is when the total time the system is inoperative but dormant during field deployment, equals zero. It is not possible for that time to be less than 0.

In order to test this hypothesis, a methodology was developed to estimate the "real" availability of the Small ICBM. The objectives in the development of this methodology were:

(1) estimate "real" availability and
(2) provide a capability to perform sensitivity analysis.

MODEL DEVELOPMENT

In surveying previous research, six different modeling approaches were identified which could be used to estimate the simple availability of a system. Those techniques were:

(1) Markov models,
(2) renewal theory,
(3) queueing theory,
(4) integral approach,
(5) dynamic modeling,
(6) and simulation.

Types of Availability

The first step in evaluating the models identified in the survey of previous research was to determine which type of availability was best addressed by each of the different model types. Tillman et al (1982) advocated "steady-state availability may be a satisfactory measure of systems which are operated continuously. Average uptime availability (also referred to as mission or equipment availability) may be a satisfactory measure for systems whose usage is defined by a duty cycle. For systems which are required to perform a function at any random time, instantaneous availability may be the most satisfactory measure." These types of availability (steady-state, mission, and instantaneous) can be thought of as "simple" forms of availability. The Small ICBM availability problem crosses the lines of the three traditional availability definitions and required special treatment to estimate the "real" availability of the system. To redress this deficiency, a new class of availability referred to as "complex" availability was developed. "Complex" availability conditions exist when two or more forms of "simple" availability exist in the system under consideration.

Additionally, both Ross (1970) and MIL-STD-721B reinforce the concept that availability for a semi-dormant or dormant system, such as the Small ICBM, is instantaneous availability. However, the selection of availability type for this research was more complex because the Small ICBM system has some portions of the system which function continuously. Therefore it is not totally dormant or semi-dormant. The security system and wake-up processor are examples of continuously operated subsystems on the Small ICBM. Additionally, some portions of the system, such as a rocket motor, are required to function for a specified period of time thus are in the mission availability category. Consequently, the methodology selected needed to be capable of addressing instantaneous, mission, and steady-state availability. Table 1 identifies the methodologies and authors which were identified in the survey of previous research.

Methodology to Address "Complex" Availability

A review of the various modeling methodologies reflected in Table 1 identify several approaches to the steady-state availability model and one model which addressed instantaneous availability. However, only the following three models address "complex" availability (a combination of two or more types of simple availability):

(1) Tillman et.al (1982), a renewal theory approach coupled with numerical analyses which addresses instantaneous and mission availability,

(2) Ingerman's (1978) simulation based methodology which addresses mission and steady-state availability,

(3) and the Boozer-Frantz (1981) simulation based methodology which addresses mission and steady-state availability.

Table 1: Availability Models

AUTHOR(s)	METHODOLOGY	AVAILABILITY TYPE(s)	DISTINGUISHING FEATURES	APPLICATIONS
Regulinski (1980)	Markov Process	Steady-state	Network overloads and Interference	Communicating Computer Networks
Gates and Martin (1980)	Markov Process	Steady-state	(1) Non-Homogeneous Repair Times (2) Series-Parallel Subsystems Relationship	Power Generation Plants, Communications, and Radar Systems
Tillman, Kuo, Nassar, Hwang (1982)	Renewal Theory	(1)Instantaneous (2)System	System Cycles	System Effectiveness in General
Ascher (1978)	Nonhomogenous Poisson Process	Steady-State	(1) Small Percentage of Parts are Replaced at a Time (2) Reliability Growth may be taking place (3) Additional Failures May Occur During Repair	None Identified in the Literature Reviewed
Ross (1970)	Alternating Renewal Process	Steady-State	Independent of System State at Time = 0	None Identified in the Literature Reviewed
Barlow and Proschan (1981)	Renewal Theory	Steady-State	Exponentially Distributed Mean Time Between Failures and Mean Time to Repair	None Identified in the Literature Reviewed
Pell, Hall, Schneider (1978)	Renewal Theory	Steady-State	Gamma Distributed Probability Density functions for Time to Fail and Time to Renew	None Identified in the Literature Reviewed
Hasslinger (1978)	Queuing Theory	Steady-State	Independent of when failures occur	Producer's Risk
Galetto (1977)	Integral Theory	Steady-State	(1) Non-Markovian Processes can be addressed (2) Non-exponential Probability Density Functions for Failure and Repair Times	None Identified in the Literature Reviewed
Vaurio (1982)	Integral Theory	Steady-State	General Development for Steady-State Availability	Heat Removal Systems of Nuclear Power Plants
Masterson and Miller (1976)	Dynamic	Instantaneous	(1) Long Term Stored Systems Can be Modeled (2) Unscheduled System Activations are Addressed	Stored Spacecraft
Ingerman (1978)	Simulation	(1) Mission (2) Steady-State	(1) Flexibility (2) Event Based	Through the System Life Cycle of the E-2, P-3, AV-8a aircraft and DDG Class Destroyers
Boozer and Frantz (1981)	Simulation	(1) Mission (2) Steady-State	(1) Flexibility (2) Event Based	High Utilization Situations (Surge Usage of Aircraft and Vehicles

The development of an approach to address instantaneous, mission, and steady-state availability for the Small ICBM system was a unique modeling effort. The renewal theory approach with a numerical analyses solution did not appear applicable to the Small ICBM problem. In the development of the renewal theory approach, Tillman et al. (1982) assume "the system is regarded as a complete unit and should not be split into subsystems." With the Small ICBM in the early development phase, frequent changes to subsystem reliability should be expected. Any change in the estimated subsystem reliability would require a recomputation of system reliability. However, even more significant is the loss of information about the probability density functions for the estimated subsystem reliabilities and renewal periods. One other complication in using the renewal theory approach is the lack of flexibility and information for making system policy and cost tradeoff decisions.

The simulation approach to availability modeling offered flexibility in addressing the Small ICBM availability issue. Simulation often provides more information about the system's operating performance than can be obtained from analytic means (Moore and Clayton; 1976). Naylor et al. (1966) identify simulation as an appropriate analysis tool because:

(1) simulation makes it possible to study and experiment with the complex interactions of a given system,

(2) through simulation, the effects of certain information, organizational, and environmental changes on the operation of a system can be quantified by making alterations in the model of the system and observing the effect of these alterations on the system's behavior,

(3) simulation of complex systems can yield valuable insight into which variables are more important than others in the system and how these variables interact,

(4) simulation can be used to experiment with new situations about which little or no information exist so as to prepare for what may happen,

(5) simulation can serve as a "preservice test" to try out new policies and decision rules for operating a system, before running the risk of experimenting on the real system, and

(6) simulation makes it possible to study dynamic systems in real or compressed time.

Morganthaler (1961) additionally cites simulation as a valuable tool because:

(1) it affords a convenient way of breaking down a complicated system into subsystem, and

(2) when new components are introduced into a system, simulation can be used to help predict bottlenecks and other problems that may arise in the operation of a system.

A discrete or event based simulation model of the Small ICBM system was selected as the best approach for estimating its "real" availability. The reasons for selecting this approach include those cited above by Naylor et al. (1966) and Morganthaler (1961). Additionally, Hillier and Lieberman (1974) state: "the technique of simulation has long been an important tool of the designer.... With the advent of high-speed digital computer with which to conduct simulated experiments, this technique has become increasingly important to the operations researcher. Thus, simulation has become an experimental arm of operation research."

Further, Rubinstein (1981) notes that many real world problems are too complex to be solved by analytical methods and that the most practical approach to their study is through simulation. He specifically addresses simulation of stochastic systems such as regenerative systems with various types of queues.

For all the reasons cited above and since the Small ICBM "real" availability estimate must be made considering a complex system with various subsystem reliabilities, repair time, and queues based on maintenance resources and policies, simulation was selected as the preferred approach.

Simulation Model

The language selected for the simulation was the General Purpose Simulation System (GPSS). GPSS is a process-oriented simulation language particularly well suited for queuing systems (Law and Kelton, 1982).

Within the model, each missile deployed was treated as a transaction. Each transaction had sufficient parameters to account for the thirteen major subsystems. Each parameter contained an appropriately selected failure time for that subsystem. The failure times were randomly selected from probability distributions which describe the nature of failures for that subsystem. To properly account for downtime, distributions of the time required for transportation, test, and maintenance were developed.

Figure 1 presents a simplified overview of the physical system. Although Figure 1 represents the flow of the missiles through the system, other details which need to be considered include:

(1) the rate of the initial deployment to the field,
(2) the repair and testing cycles within the subassembly portion of the system,
(3) the capability of test equipment to find failures,
(4) the probability of inducing failures in equipment during test procedures,
(5) the transition from "real" availability to "real" unavailability, and
(6) the resources available for transportation, testing, and maintenance.

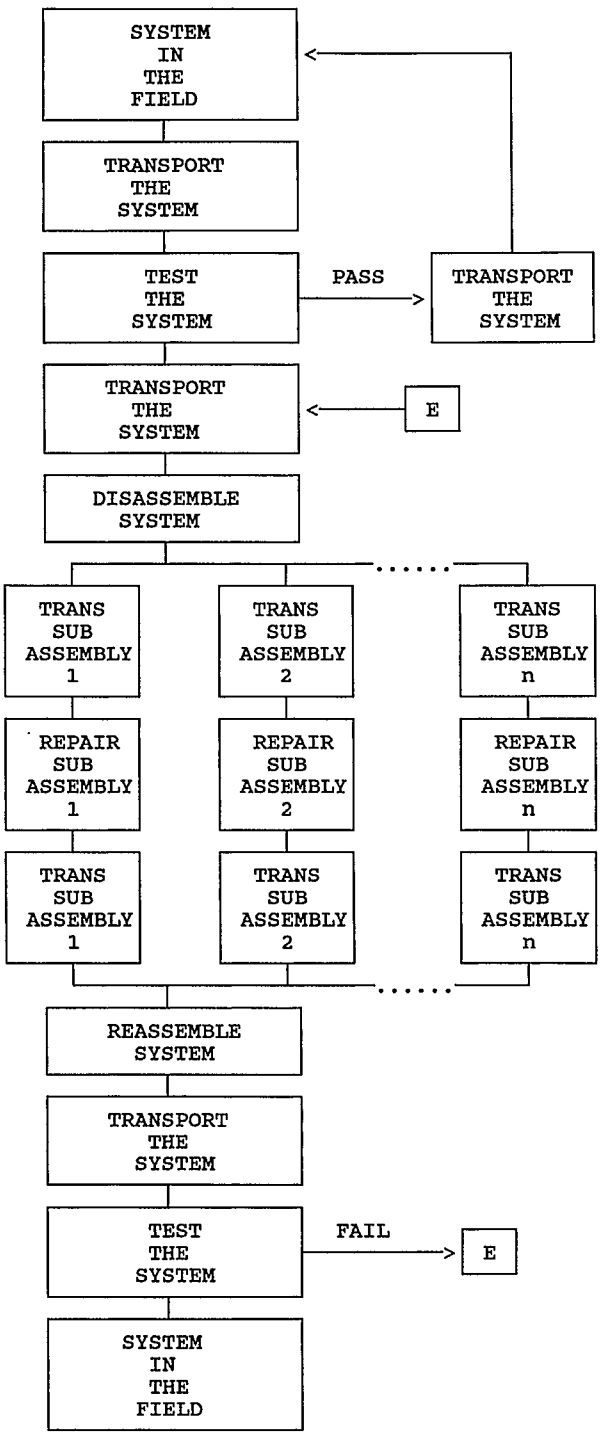

Figure 1: Physical System Overview

Other information required to complete the statement of the problem included:

(1) the best time estimates and distributions for each of the activities performed in the model,
(2) the best estimates of the failure times and the associated probability distributions for each of the major subsystems,
(3) the magnitude of the resources available for each of the "servers" in the system,
(4) the capability of test equipment to detect failures,
(5) the probability that tests induce failures for each of the subsystems,
(6) the time period of interest for the analysis, and
(7) the policy identifying the time when the systems are scheduled to cycle through maintenance.

Model Verification and Validation

The next step in the analysis was to identify the procedures which were used to verify and validate the model as the problem statement outlined above was translated into a simulation model. Selecting from the possible procedures, emphasis was placed upon model verification and validation during the development process. Law and Kelton (1982) define model verification as determining whether a simulation model performs as intended, i.e. debugging the computer program. Validation is determining whether a simulation model is an accurate representation of the real-world system under study. The verification that the model was performing as intended was accomplished by:

(1) developing each portion of the model as a segment or module. The basic model started with just one transaction representing a missile system. The transaction passed only through the logic of gathering the basic information required to perform the statistical analysis. Rather than using the random number process for generating failures, only two subsystems with constants were supplied to the model during verification. This allowed the modeler to examine the logic as the transaction (representing a missile) flowed through the model. Other parameters such as the test outcomes were set to constants to verify that the model behaved properly. This incremental approach was extended throughout the development process to increase confidence that the simulation was following the logic of the real system.

(2) performing a structured walk-through of the model with other analysts to ensure that both the underlying physical process was a reasonable representation of the Small ICBM deployment and that the coding of the model into GPSS constructs was properly accomplished.

(3) operating the model with simplified assumptions as discussed in (1) above. This approach of using fewer systems assisted the modeler in verifying the results particularly as the model became more complex. In some cases, simplified distributions were used to facilitate calculations so that the accuracy of the model results could be verified. For example, the use of known parameters provided verification that the model behaved properly. Two examples of this technique were (1) setting the field cycle time and MTBFs equal and (2) setting the cycle time to two thirds the MTBF. In the first case the "real" availability and the "apparent" availability should nearly be equal. In fact they were equal when the failure detection capability was perfect or the two parameters were nearly equal when failure detection capability was near one. In the second case, half of every other cycle was spent in the inoperative but dormant state which would affect only "real" availability. Therefore, the "real" availability estimate was approximately three fourths of the "apparent" availability.

(4) debugging of the model by running the system in an interactive mode. The use of the interactive mode allowed the modeler to trace the movement of the "missile" through the system providing confidence in the model logic and activities.

Similarly, the validation of the simulation model used three techniques.

(1) A re-examination of the formulation of the problem was accomplished to reveal possible flaws. This validation was accomplished in conjunction with verification technique (2) above.

(2) The various mathematical expressions were re-examined to determine that they were dimensionally correct.

(3) The input parameters were varied to check whether or not the output in the model behaved in a plausible manner.

Simulation Model Characteristics

With the problem statement completed and the verification/validation process established, the next step in the model was to interpret the problem statement in context of GPSS formulation. As noted earlier, each transaction in the model represented a missile system. Each of these missile systems have unique characteristics, such as the mean time to failure for the Guidance and Control (G&C) subsystem, which were represented in the GPSS model as parameters associated with each of the transactions. To facilitate capture of the transition from an operational but dormant missile system to an inoperational but dormant missile system special tests were introduced into the model. Since it was theoretically possible that this transition could occur during the transportation cycle, this transitional state also required special model treatment.

Another complicating factor in the modeling process was the concept that testing induces failures, some of which may go undetected. Thus inoperative but dormant systems would be returned to the field without being "really" available.

An additional characteristic uniquely developed in this analysis was the concept that each of the subsystems were not fully restored to a "like new" condition if they do not undergo maintenance. For example, if the G&C had failed and the failure was detected in the system level test, the reentry system would be taken to its maintenance facility for test. However, if a failure was not induced by its subsystem level test, no maintenance would be performed on it and it would be returned to the field with only the remaining portion of its original life.

A feature not normally addressed in availability models which was included in this analysis was the condition of multiple failures. The possibilility of multiple failures occurring coupled with the possibility of the tests failing to discover this condition was addressed in the model.

Analysis Methodology

The number of simulation runs required to provide the estimate for "real" and "apparent" availability was determined

using a sequential process with a specified level of precision. As explained by Law and Kelton (1982), the actual confidence-interval half-length was the absolute precision of the confidence interval. By contrast, the relative precision of the confidence interval was the ratio of the confidence-interval half-length to the magnitude of the point estimator. Although not strictly correct, the relative precision may be thought of as the "proportion" of μ by which the point estimate may differ from μ. The procedure assumed the observations were a sequence of identical independently distributed random variables which need not be normal. The specific objective of the procedure was to construct a 100(1-α) percent confidence interval for μ such that the relative precision was less than or equal to γ, for $0<\gamma<1$.

An appropriate statistical analysis technique was selected based upon the information available a priori. In this situation, no information was assumed about either the population mean, or the population variance. Therefore, the Student's-t distribution was a reasonable choice for constructing and conducting the hypothesis test.

However, as noted earlier it is impossible for "real" availability to exceed "apparent" availability, therefore the distribution is truncated appearing as one half of the usual Student's t distribution. To adapt this truncated distribution to a probability density function, an appropriate "k" was identified as a multiplier. The probability density function must sum to 1 and the area under the curve for this truncated distribution equals .5, therefore "k" must equal 2. The appropriate critical t value is selected using k(α/2). Since "k" equals 2, the appropriate critical t value was selected using α (2[α/2] = α).

According to Dixon and Massey (1957), if sampling was accomplished from two populations, occasionally extraneous factors may cause a significant difference in means, whereas there was no difference in the effects which are attempting to be measured. Ostle (1963) recommended that if two samples of equal size can be obtained and if the the observations in the one sample can be logically paired with the observations in the other sample, a modified procedure for the comparison of the two data sets may be used. Snedecor and Cochran (1980) stated the aim of the pairing was to make the comparison more accurate by having members of any pair as alike as possible except in the treatment difference that the investigator deliberately introduced. This is commonly referred to as the "paired t-test".

Since the "apparent" availability and "real" availability estimates were obtained from the same simulation model on the same simulation run started with the same random number seed, the sample estimates can be paired logically. When this relationship exists, the appropriate procedure is to calculate the differences between each pair and then estimate the true mean difference. According to Dixon and Massey (1957), this method's advantage is the lack of an assumption that the two variances are equal or the values of "apparent" availability and "real" availability are independent. This approach to pairing results in a loss of information because there was a slight increase in the probability of accepting the null hypothesis when false. Dixon and Massey (1957) indicate; (1) the increase is slight when sample sizes are moderately large, i.e., greater than 10, and (2) that the level of significance is not affected.

With only N - 1 degrees of freedom in the estimate of the variance for the "paired t test", larger differences are accepted than when there are 2N - 2 degrees of freedom. However, this slight increased probability of accepting larger differences is offset by the smaller estimate of the variance should the availability estimates be correlated.

Sensitivity analysis was used to (1) identify the relative sensitivity of parameters (i.e., those that cannot be changed much without changing the solution) and (2) evaluate solutions over the likely range of values for those sentitive parameters.

The methodology used to identify parameters which could affect the estimate for "real" availability was determined in a two step process. The first step was to conduct an F test on the variances to determine whether the assumption of equal but unknown variances was valid. If there was insufficient evidence to reject the hypothesis that the unknown variances were equal, the second step in the analysis was to determine whether the "real" availability was sensitive to a change in a parameter. Another hypothesis test was performed to determine whether the mean of the baseline "real" availability differed from the mean of the "real" availability with one of the parameters changed.

The natural pairing of the data which was observed for the original hypothesis test no longer existed for the sensitivity analysis. In the sensitivity analysis, the simulations were accomplished as if they were separate experiments. Therefore, a different approach to testing whether the means of the two populations were equal was required.

The normal distribution for the differences where the mean of the differences equals zero is represented in Figure 2.

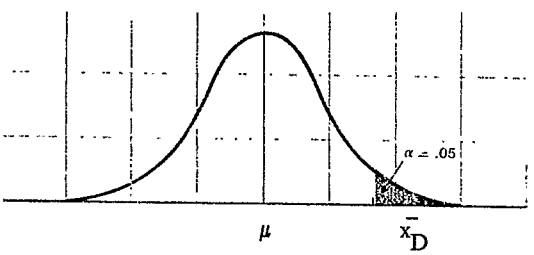

Figure 2: Distribution of Differences

The shaded region represents the α error, i.e., the probability of rejecting the hypothesis that the means were the same when in fact they were the same. In Figure 2, the shaded region represents an α = .05 for the one tail hypothesis test. Using a standard mathematical statistics approach, the null hypothesis would be rejected at the α = .05 level because the sample mean does not fall in the acceptance region.

Rather than arbitrarily select an α level to conduct the hypothesis test, an alternative approach is to estimate the α level at which the null hypothesis would be rejected. In Figure 2, an extremely small α would have had to be selected before the null hypothesis would not be rejected. In general as the estimated α approaches zero, it supports the alternate hypothesis.

Pursuant to this concept, Abramowitz and Stegun (1972) provided an approximation for calculating α for large ν (ν=degrees of freedom>5).

$$\alpha = 1 - A(t|\nu) \approx 2P(x) - 1$$

where

$$x = \frac{t\,(1 - (1/4\nu))}{(1 + (t^2/2\nu))^{1/2}}$$

where t is the calculated Student's t statistic.

P(x) can be calculated using the following approximation:

$$P(x) = 1 - Z(x)(a_1 t' + a_2 t'^2 + a_3 t'^3)$$

where $Z(x) = (1/(2\pi)^{1/2})\, e^{-x/2}$

$t' = 1/(1+px)$

$p = .33267$

$a_1 = .4361836$

$a_2 = -.1201676$

$a_3 = .9372980$

The approximations from Abramowitz and Stegun (1972) were used to estimate the α level. Since the strong correlation between the samples no longer exists, the standard t test is preferred to the paired t test for the differences between the means. Therefore the number of samples used in the two estimates, baseline and adjusted parameter, was predicted from the estimate for "real" availability and $\gamma = .01$.

With the inherent flexibility of simulation, the analytic tool developed was used to perform resource allocation and policy evaluations, thereby identifying to management the relative value of resources or policies for improving "real" availability.

RESULTS

The results using the baseline data to estimate "real" and "apparent" availability were unexpected. Even though the dormant MTBF values were quite high, the two different availability estimates were quite different. At $\alpha = .05$, there was sufficient evidence to reject the null hypothesis that the estimates were the same.

Although the test of hypothesis was one of the central themes of the research, the sensitivity anlysis gained additional importance since the null hypothesis ("real" availability = "apparent availability) was rejected. The estimates of "real" and "apparent" availability only reflect the relative relationship of those values. The essential value gained from the hypothesis test was there is a statistically significant difference with some baseline estimates of system parameters. However, the purpose of the sensitivity analysis was to identify those parameters which could affect the estimate for "real" availability?

The sensitivity analysis addressed the effects of:

(1) field deployment time,
(2) maintenance cycle times,
(3) maintenance and test activity times,
(4) subsystem's reliability,
(5) test equipment probability of detecting failures, and
(6) test equipment probability of inducing failures,

For each of these parameters, best "best" estimates and "worst" best estimates were identified from a variety of sources. The sensitivity analysis incorporated the extremes in "best" estimates to identify those parameters which had the most impact on the estimate of "real" availability.

The parameters associated with the resource levels available for maintenance, test, and transportation activities were also planned as part of the sensitivity analysis. However, rather than arbitrarily select test limits, the parameters were varied based upon the behavior of the model. For example, if long queues were observed while the missile was waiting to capture a transportation server, the number of servers would be increased until the queue length became reasonable.

A planned objective of the sensitivity analysis was to vary the parameters within the allowable ranges to maximize the real availability. This insight allows decision makers the opportunity to adjust resources and focus attention on the subsystems which have the largest impact on the system's "real" availability.

The sensitivity analysis discussed previously revealed that the "real" availability could be increased by:

(1) policy decisions on maintenance cycle time,
(2) policy decision on deployment cycle time,
(3) certain subsystem reliabilities,
(4) test equipment probability of detecting failures, and
(5) test equipment probaility of inducing failures.

CONCLUSIONS

The major contributions of this research were:

(1) the development of the concept of "complex" availability which applies to systems which combine two or more elements of instantaneous, mission or system, or steady-state availability, and

(2) the development of a modeling technique to estimate the "real" availability for a system which falls into the category of "complex" availability.

Primarily the Small ICBM remains in a dormant state throughout the life cycle with only periodic system tests and maintenance. However, some subsystems are in continuous operation throughout the life cycle. The use of simulation allowed the following unique features to be included in the formulation of the estimate for "real" availability:

(1) capturing the non-available time due to transition from the operational but dormant state to an operative but dormant state during deployment and transportation phases of the system cycle,

(2) test equipment which was not 100 percent reliable in detecting failures, either at the system or subsystem level,

(3) the possibility that test equipment actually may induce failures which may or may not be detected prior to redeployment,

(4) the condition that not all subsystems are restored to a "like new" condition through the maintenance and testing cycle, and

(5) the occurrence of multiple failures coupled with the possibility that the tests could fail to discover this condition.

Complex availability is the proper description for an emerging set of availability problems for both private and military systems. Examples can be found in a broad range of manufacturing situations and military systems.

Estimating "real" availability for a complex system is one of the difficult challenges facing the reliability, availibility, and maintainability community today. Simulation provides the flexibility to meet this challenge.

The results indicated that there was sufficient evidence to reject the contention that "real" availability was equal to "apparent" availability. Sensitivity analysis revealed that, with correct emphasis, "real" availability estimates for the Small ICBM system could be improved.

The concept of complex availability, the concern of "real" versus "apparent" availability, and the methodology to estimate "real" availability can be extended to other areas within the private and public sector.

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