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A Study on a Discrete Event Simulation Model for Availability Analysis of Weapon Systems

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***Abstract*—**This paper discusses a discrete event simulation model for the availability analysis of weapon systems. This model incorporates missions, operational tasks and system reliability structures to analyze the availability of a weapon system. The proposed simulation model consists of 5 modules: Simulation Engine, Maintenance Organizations, System, its Mission Profile and RBD which are based on missions and operational tasks. Simulation Engine executes three kinds of discrete events in chronological order. The events are mission events generated by Mission Profile, failure events generated by System, and maintenance events executed by Maintenance Organization. Finally, this paper shows the case study of a system's availability analysis and mission reliability using the simulation model.

***Keywords*—**MTBF (Mean Time Between Failure), MTTR (Mean Time To Repair), Availability, Reliability, RBD (Reliability Block Diagram)

I. INTRODUCTION

IN order to acquire reliable systems which are high quality, readily available, and able to satisfy user needs in a timely manner and reasonable price, availability factors facilitate achieving this objective. Availability is the measure of the degree to which a system is in an operable state and can be committed at a planed mission when the mission is called for at an unknown point in time [1]. When the requirements of a newly acquired weapon system are developed, finding out the appropriate availability goals to complete given missions is important.

Most large systems, including weapon systems, perform complex missions which can be divided into consecutive time phase [2, 3]. In order to perform a given mission, each component of a weapon system provides its capability which is characterized by functions during each time phase. Consequent functions are called the duty cycle. Most weapon systems have their duty cycle which is described in their mission profile.

In each phase, a weapon system needs to accomplish a specific operational task. And, operating functions, its logical structure, time length, and the failure rates of components often vary from phase to phase. For these reasons, it is difficult to compute availability in analytical ways, and a simulation method is needed. This paper intends to propose a discrete event simulation model for the availability analysis of weapon systems. Then it shows the case study of the availability analysis of a weapon system using the proposed simulation model. The simulation model can be also appropriate for other complex systems.

The structure of this paper is as follows. In the second section, the availability factors and the previous works on the availability analysis methods are reviewed. In the third section, the overview of the simulation model and the concept of system reliability block diagram (RBD) are described, and input and output data for the simulation model are addressed. In the fourth section, a case study is presented using the proposed simulation model. The simulation model is applied to establishing the availability goal of a fictional warship. Then, it is concluded in the fifth section.

II. LITERATURE REVIEW

A. Availability Factors

The term availability is used in a variety of contexts. It is used as a measure of system readiness. Availability falls into three according to considerations: Inherent Availability (Ai), Achievement Availability (Aa) and Operational Availability (Ao).

Inherent Availability is the probability that a system, when used under stated conditions in an ideal support environment with readily available tools, spares, maintenance personnel, etc, will operate satisfactorily at any point in time as required [4]. It excludes scheduled maintenance actions, administrative delay time, logistics delay time, and is expressed as (1).

$$A_i = \frac{MTBF}{MTBF+MTTR} \qquad (1)$$

where
MTBF: Mean time between failure
MTTR: Mean time to repair (mean corrective maintenance time)

Achievement Availability is similar to the definition for Ai except that scheduled maintenance is considered.

$$A_a = \frac{MTBM}{MTBM+\bar{M}} \qquad (2)$$

where
MTBM: Mean time between maintenance
$\bar{M}$: Mean active maintenance time (mean corrective maintenance time and mean scheduled maintenance time)

Operational Availability is similar to the definition of Ai, but it considers scheduled maintenance, administrative delay time,

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logistics delay time. Ao is the probability that a system, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon [4].

$$A_o = \frac{TUT}{TUT+TDT} = \frac{TUT}{TUT+TCM+TPM+TALDT} \quad (3)$$

Where

TUT: Total Up Time, Time that a system is available to perform a designated mission

TDT: Total Down Time, Time that a system is non-available for tasking [1]

TUT is equal to TT minus TDT, and TDT is divided into TPM (Total Preventive Maintenance time), TCM (Total Corrective Maintenance time) and TALDT (Total Administrative and Logistics Downtime). Therefore, equation 3 can be substituted by equation 4.

$$A_o = \frac{TT-TDT}{TT} = \frac{TT-(TCM+TPM+TALDT)}{TT} \quad (4)$$

Where

TT: Total Time, TT= TUT + TDT

If one imposes an availability metric as a design requirement for a given system supplier, and the supplier has no control over the operational environment in which that system is to function, then Ai or Aa may be appropriate metric against which the supplier's system can be properly assessed. Conversely, if one is to assess a system in a realistic operational environment, then Ao is a preferred metric to employ for assessment purposes [4]. Further, the term availability may be applied at any time in the overall mission profile representing a point estimate or may be more appropriately related to a specific mission phase in which the requirements can be different from other phases.

B. Methods of the Availability Analysis of Systems

Availability and reliability are often confused, partly because the term reliability trends to be used when availability is what was really intended. There are two broad groups of analytical approaches to compute system availability and reliability [5, 6]: one is based on the state-space solution model, and the other is the logic networks solution model.

As the representative solutions of the state-space solution model, Markov models use state transition diagrams to model the time spent in each operational and nonoperational state from which the probability of a system operation and down can be calculated. Petri-nets are an adaptable and versatile, yet simply graphical modeling tool used for representing dynamic systems. Chew [7] and Sadau [8] researched about using Petri-nets to evaluate the availability and reliability of a system. The main drawback of the state-space approach is their elaborate technique, including Markov models solution, Petri-nets and the analysis of failure effects [5, 6]. Furthermore, the system size has to be limited under these solutions.

The network approach is more comprehensible and requires simpler computations than the state space approach. Although the network approach allows a suitable representation of a system, it should be presented a system logic diagram and it may not be an easy task to construct it. A system logic diagram for the availability and reliability analysis of a system is called a system RBD (Reliability Block Diagram). Complicated systems can often be represented as a network in which system components are connected in series, parallel or combinations of these. The system RBD addresses a system's reliability evaluation based on its component reliability and topologies through which the components are connected.

The System RBD can be analyzed in two different ways. The first is an analytical way, in which one analyzes the logical outcome by analyzing the trends in the subsystems behaviors. Then, the system should be represented by analytical methods, which can become very complex in large systems.

The second is a simulation way, in which system RBDs are applied to the Monte Carlo simulation. The Monte Carlo simulation works in a probabilistic way. It needs an event driven simulation engine that generates random numbers that correlate with a certain state of a system. It has been used in many simulation models to generate typical events in each simulation. The Monte Carlo simulation makes possible to calculate time-dependent reliability and availability [5, 6, 9].

In this paper, the Monte Carlo simulation based on system RBDs is applied to develop the simulation model for the availability analysis of weapon systems. System RBDs are derived from the mission analysis of a system. A system RBD is constructed with the components related to a functioning mode and it changes with mission phases. And, the system RBD is used to infer whether a system is available or not according to the state of its operating components. Dealing with weapon systems, and taking into account the complexity of operational mode and their structures, a simulation model is the most appropriate technique to handle.

III. The Discrete Event Simulation Model For Availability Analysis

A. Overview of the Simulation Model

The proposed simulation model consists of 5 modules: Simulation Engine, Maintenance Organization, System, Mission Profile and System RBD, and those are presented in Figure 1. In this simulation model three types of events are considered: mission events, system events and maintenance events.

A mission event is generated time orderly based on the Mission Profile which is initialized with summarized mission scenarios. The mission event is the beginning of a mission or an operational task. A system event is randomly generated by the System, and it is exactly a component failure. System consists of subsystems, components and so on. A system failure is proved by referring to the System RBD which is initialized with availability rules of a system. Availability rules of a system change depending on the Mission Profile. If a component failure event takes effect on a system operation, it changes to a maintenance event. The maintenance event is the act of repairing the system failure caused by the component failure, and it is repaired at a maintenance shop of the Maintenance Organization. It takes time to restore the system to required level of performance. Repair time is randomly determined by the Simulation Engine based on the failed component's repair time of probability distribution function, which is normal distribution, exponential distribution, log-normal distribution, etc.

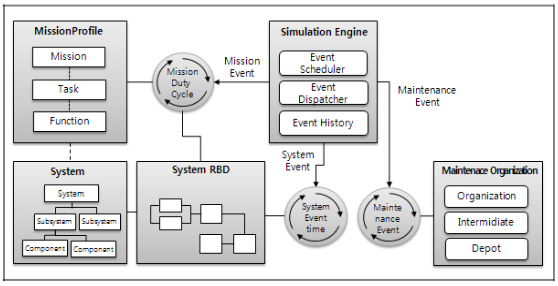
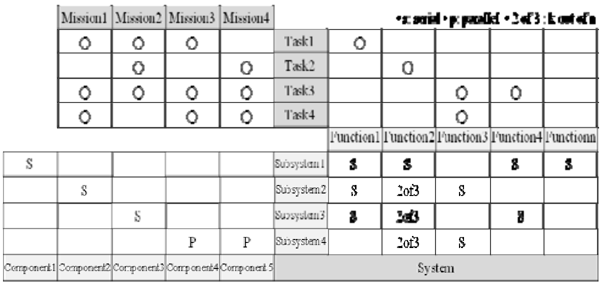


Fig. 1 Overview of the discrete event simulation for analysis of systems availability

With regard to Simulation Engine for analysis of the availability of systems, the main benefit of the discrete event simulation model is that it models the studied system in a stochastic way by randomly drawing time for probability distribution functions for failure and repair time.

B. *System Availability Rules*

The availability of a system is related to its given missions and operational tasks under different environmental conditions over time. Its availability depends on each operational task, and the system reliability structure may change drastically with the task type. During each operational task phase, operating components construct a system RBD. The system RBD presents the logical structure of a system, sub-system and components, so it can be often called the availability and reliability structure of a system. The system RBD is a composition of components for a specific function, and it can be used as availability rules for the system. Availability rules are used to diagnose whether the system is available or not at a certain phase. The relation between functions and components of a system represents in a system QFD (Quality Function Diagram) which is shown in Figure 2. The system QFD is derived from the mission analysis of a system in its concept development phase. In order to achieve given missions, each operational task is executed by operating the functions of a system. A function is operated by a system, subsystems or components. From this analysis, the system structure is roughly identified. Therefore, to evaluate the availability of a system, it is needed to set up relations between missions, operational tasks, functions and components beforehand.



•s: serial •p: parallel •2of3 : k out of n

	Mission1	Mission2	Mission3	Mission4						
	○	○	○		Task1	○				
		○		○	Task2		○			
	○	○	○	○	Task3			○	○	
	○		○	○	Task4			○		
						Function1	Function2	Function3	Function4	Functionn
S					Subsystem1	S	S		S	S
	S				Subsystem2	S	2of3	S		
		S			Subsystem3	S	2of3		S	
			P	P	Subsystem4		2of3	S		
Component1	Component2	Component3	Component4	Component 5	System					

Fig. 2 Mission-Task-Function-System QFD

To detect a component failure, the backward inference method is applied and an inference process goes on from the top level of node, i.e., a conclusion, to the bottom of all nodes and finds out the state of all nodes, and then the conclusion is proved. The example of inference routes, which is based on the system QFD shown in Figure 2, is described in Figure 3.

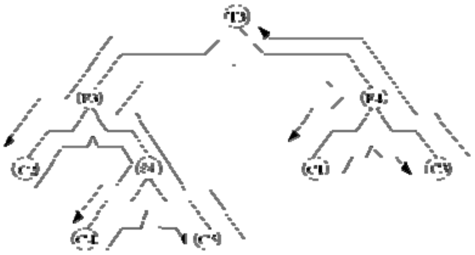


Fig. 3 Depth-first backward inference route

In Figure 3, from rule T3 to rule C3, the simulation engine checks all rules with depth-first strategy and it can search following the arrow line courses. That inference process will be repeated until the last node is proved whether it is available or not. The first node is often an operational task which is equivalent to the top level of a system executing the operational task. The lower nodes are functions which are decomposed into subsystems and components. Therefore, this search route can be equivalent to a system RBD which depends on an operational task.

Each node represents an availability rule, and a connection line represents the connectivity of each rule. The state of the top level node (T3 in Figure 3) is determined by the states of the lower nodes such as functions (F3, F4), a subsystem (S4) and components (C1, C2, C3, C4, C5). The top level is the system operating the specific task represented T3 in Figure 3. The system is decomposed into its major subsystems. These subsystems operate functions represented F3 and F4 in Figure 3. Each subsystem is decomposed into components, and so on. ~~.4~~ The availability state of each node is computed in the following way.

$$\text{State of series connection node : } S_s = \begin{cases} 1, & \sum_{i \in E_m}^{n} s_i \geq n \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

$$\text{State of a parallel connection node : } S_p = \begin{cases} 1, & \sum_{i \in E_m}^{n} s_i \geq 1 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$\text{State of a k out of n connection node : } S_k = \begin{cases} 1, & \sum_{i \in E_m}^{n} s_i \geq k \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Where
Em: Element of a structure
n: Number of elements constructing a structure
k: Least number of available elements for a structure availability

C. *Simulation process of the availability analysis of a system*

Logical simulation flow for a system's availability analysis is abstracted in Figure 4. As shown the overview of the flow diagram, the Simulation Engine schedules 3 types of events and searches for the earliest event then executes it in chronological order. It also advances simulation clock and saves simulation histories while the simulation clock is less than the simulation period.

The Simulation Engine advances the simulation clock to the earliest event time. If the earliest event is a mission event or a system event, the System checks the state of all related components. In case of that there is a failed component and it makes an effect on the system operation (as the state of top level system is 0), the system failure event turns into a maintenance event and the system changes its state into down. And, Simulation Engine finds the next earliest event, and advances the simulation clock to the next event time.

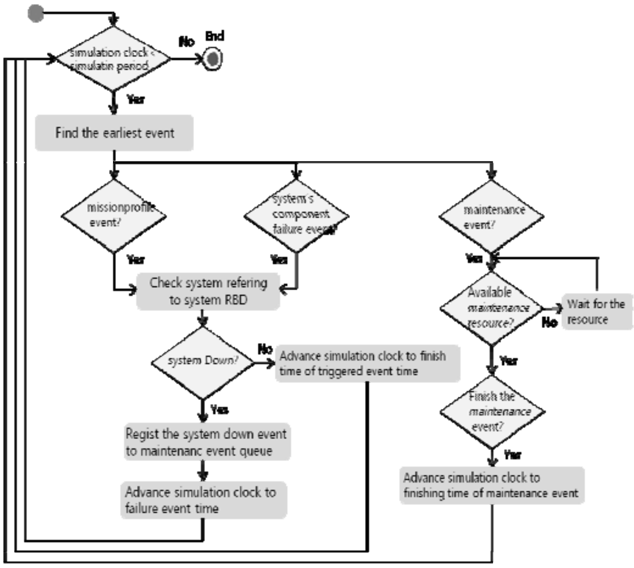


Fig. 4 Logical flow diagram for the descret event simulation

If the earliest event is a maintenance event, it would be transferred to the maintenance queue of the Maintenance Organization. The maintenance event is in a stand-by state until its needed maintenance resources (maintenance personnel and spare parts etc) are available. The Maintenance Organization consists of maintenance resources of each echelon. In general, maintenance echelon falls into three, depot maintenance level, intermediate maintenance level and organization maintenance level. Maintenance personnel and spare parts are allocated to each maintenance shop of three maintenance echelons. When maintenance resources are available, the maintenance event readily goes under the repair process and it takes times to repair which is randomly generated based on the failed component's repair time ~~of~~ probability distribution function.

D. Assumptions and Input & Output Data of the Simulation Model

1) *Simulation Assumptions*

In order to implement the proposed simulation model, basic assumptions are made as bellow:

a) Mission: Missions given to achieve are executed in time order. Each mission consists of sequential operational tasks. In order to perform a mission, one or more operational tasks should be executed.

b) Operational Task: An operational task is executed by one or more operating functions which are operated at the same time. The operational task is either success or failed, and it determines the system availability and mission reliability.

c) Function: A function is either success or failed. One or more functions can be operated at the same time during a specific time length. The function determines an operational task completion.

d) System RBD: System RBDs are reliability structures of a system according to the system's functions. Each function has its own system RBD. It is assumed based on the system QFD which shows relations of operational tasks, functions, a system, subsystems and components.

e) System check: A system state is diagnosed whenever an operational task changes. The state of a system is determined by the availability states of subsystems and components related to operating functions.

f) System and Components: The states of the components are statistically independent. Each component's failure probability distribution function and repair time probability distribution function are known.

g) Component recovery policy: All Components are repaired-same-as-new. The repair begins as a component fails and its needed maintenance resources are available. As components are replaced, the time involved in this activity, except for the time to acquire spare parts and maintenance personnel, will be denoted by repair time. When operational availability is computed, repair time is considered as down time. And, the time to cost acquiring maintenance personnel, spare parts and other administrative delay time are considered as down time, too.

2) Simulation input data

a) Mission Profile: The Mission Profile is described with the number of missions. Each mission has operational tasks, time length and functions.

b) System RBDs: A system RBD is described with system connection rules for each task. Each task has its operating functions and components.

c) System failure and repair time parameters:

All end components or subsystems which construct a system have their probability distribution functions of failure and repair time, which should be initialized.

d) Maintenance Organization: The number of maintenance shops is assigned to each maintenance echelon. And, each maintenance shop includes its stocked spare parts and maintenance personnel.

3) Simulation output data

a) Providing availability: Down time is summed up the overall unavailable time of a system including repair time, administrative delay time and logistics delay time. Up time excludes down time from total simulation time, and then the up time is divided by total simulation time.

b) Providing mission reliability: The total number of succeeded missions without system failures is computed, then, the total number of succeeded missions is divided by all number of simulated missions. The mission reliability is system reliability. It is the probability that a system will perform in a satisfactory manner for a given period of time, or in the accomplishment of a mission, when used under specified operating conditions [4].

IV. A CASE STUDY OF A SYSTEM AVAILABILITY ANALYSIS USING THE SIMULATION MODEL

As the example of availability analysis using the proposed simulation model, a fictional system named XYZ warship is considered in this section. For analyzing XYZ warship's availability, a simplified anti-warship warfare scenario is presented. For reasons of brevity, the data of failures and repairs of the system is limited to the first or second indenture of the design. In a real design scenario, each sub-system or component would be broken out into its own reliability block diagram in iterative fashion until all removable assemblies or components are included. And, scheduled maintenance downtime is not addressed in this example scenario.

A. *Simulation Input data*

1) *Mission Profile*

The brevity scenario of an anti-warship warfare is described in Table 1. For illustrative purpose, the real time lengths of operational tasks for the anti-warship warfare have been modified to enforce failures of components.

TABLE I
BREVITY SCENARIO OF THE ANTI-WARSHIP WARFARE

Order	Operational Task	Task ID	Operating Function ID	Time Length(hr)
1	Cruising	T1	F1	24
2	Reconnaissance	T2	F2	48
3	Detection	T3	F2, F3	24
4	Threat Evaluation & Weapon Assignment	T4	F4	24
5	Tracking Targets	T5	F2, F5	24
6	Engagement	T6	F2,F4,F5,F6	48
7	Damage Assessment	T7	F2, F4	24
8	Cruising	T1	F1	24

2) *System RBDs*

From the mission analysis of a XYZ warship, the system QFD is defined, and sub-systems and components are identified. The system QFD is shown in Figure 5. The system connection rules for the anti-warship warfare (M2) are assumed in the below sectors of Figure 5.

The XYZ warship consists of 6 major subsystems. 3 major sub-systems and 9 components are operated to complete the anti-warship warfare according to the system QFD. In case of cruising phase (T1) in Figure 5, a diesel engine (C1) with a redundancy (C2) and a navigation system (SS3) operate to execute movement (F1) for a certain time length t~t+24hour and t+216~t+240hour.

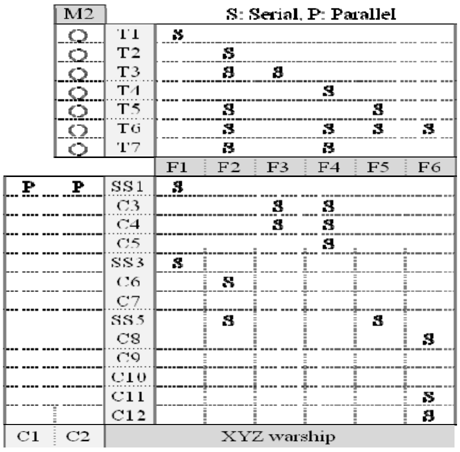


Fig. 5 The mission-task-system QFD of XYZ warship for the anti-warship warfare

As examples of system RBDs for the XYZ warship, the system RBDs for T1 and T6 are shown in Figure 6.

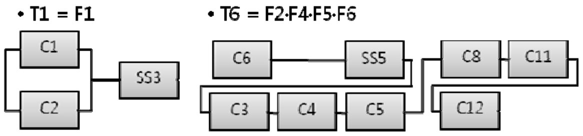


Fig. 6 System RBD examples of XYZ warship for task T1 & T6

3) *System Failure and Repair time Parameters*

Constant failure rates are assumed to mean time between failure (MTBF) and their probability distribution functions should be specified. Failure and maintenance parameters of all subsystems and components of the XYZ warship, which are modified with a similar system's parameters, are tabulated in Table 2. The failure and repair time are assumed to be exponentially distributed. Mean time to repair is assumed 4hour for all components.

System reliability must be sufficient to support the war-fighting capability needed in its expected operating environment. The system reliability may be expressed initially as a desired failure-free interval that can be converted to a failure frequency for use as a requirement. Given that the desired capability is for minimum of 80 percent of XYZ warships to be operating at the end of the 10 days in this scenario. In other words, the mission reliability of XYZ warship is needed to be 80 percent in the accomplishment of the anti-warship warfare.

In table 2, the MTBF of top level system is 1075.54hour which is computed value at exponential distribution of 240hour failure-free interval, and the reliability of top level system is 80 percent at that time. And, the reliability of each sub-system is allocated uniformly. The end components are also uniformly allocated from their upper component, which is a sub-system in this example.

MTTR 4hour is given to each maintenance activity under the state of required maintenance personnel and needed spare parts are readily available. All failed subsystems and components are replaced by designated maintenance man power with spares at each maintenance shop during the repair time.

TABLE II
TEST CASE SYSTEM'S CHARACTERISTICS

Name		Num. of component	Distribution	MTBF(hr)	Num. of Maintenance man power
XYZ		1	**Exponential**	**1075.54**	32
SS1		1	Exponential	6453.24	8
	C1	1	Exponential	1131.85	4
	C2	1	Exponential	1131.85	4
SS2		1	Exponential	6453.24	6
	C3	1	Exponential	19359.73	2
	C4	1	Exponential	19359.73	2
	C5	1	Exponential	19359.73	2
SS3		1	Exponential	6453.24	2
SS4		1	Exponential	6453.24	4
	C6	1	Exponential	12906.49	2
	C7	1	Exponential	12906.49	2
SS5		1	Exponential	6453.24	2
SS6		1	Exponential	6453.24	10
	C8	1	Exponential	32266.22	2
	C9	1	Exponential	32266.22	2
	C10	1	Exponential	32266.22	2
	C11	1	Exponential	32266.22	2
	C12	1	Exponential	32266.22	2

4) Maintenance Organization

The maintenance personnel with 32 man power for a XYZ warship is deployed at an organization/intermediate level maintenance shop. The maintenance personnel with the designated man-power for repair are enough to support readily. And, there is no limitation of spare parts. Therefore, administrative and logistics delay time are not considered in this case study.

B. Simulation Output Data and Analysis

1) System Availability

The simulation model produces the availability of 0.9965(99.65%) for 100 iterations of the 240 hour anti-warship warfare scenario for a XYZ warship. In this case study, maintenance man power and spare parts are enough to support readily, therefore, the simulation results are inherent availability (Ai). The analytical value of Ai is 0.9963(99.63%), which is MTBF/(MTBF+MTTR) = 1075.54/(1075.54+4), and there is 0.02% errors between the simulation result and the analytical value.

2) Mission Reliability

In Figure 7, the mission reliability of analytic calculated value and simulation result are plotted. The solid line shows the simulation result which is the mission reliability of 100 iterations on XYZ warship's anti-warship warfare scenario. At the end of the anti-warship warfare mission, at t + 240hour, the simulation result is 0.8390(83.90%). The dotted line shows the mission reliability of analytic calculated value for the same scenario. The calculated mission reliability is 0.8272(82.72%) at the end of the mission, and there is 1.18% errors between the simulation result and the analytical value. The equation for mission reliability is bellow.

$$R_M = e^{-\frac{MD}{MTBF}} \tag{8}$$

MD = Mission Duration (hour) [1]

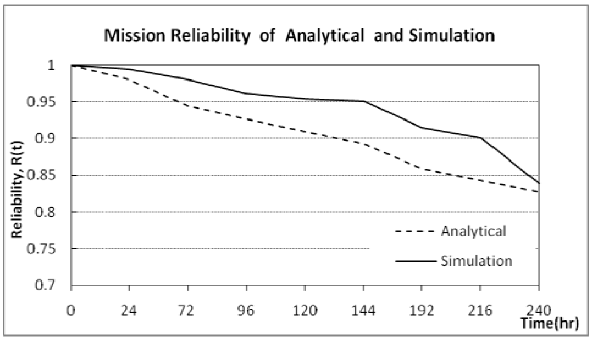


Fig. 7 Mission reliability results of analytical and simulation for the test case

This simulation results are stochastic data, so there are some errors due to randomness. If we continue to experiment and reanalyze using large numbers of iterations, we can get almost same simulation results to analytical value, and increasing the number of iterations increases the accuracy of the results.

The hypothesis that the simulation result is same with the analytical value is tested by using SPSS v16.0 which is a statistical analysis tool. In order to test this hypothesis, one sampled T tests are executed on the availability and the mission reliability of simulation results and analytical values at the same condition.

Simulation results of 10 replications are tabulated in Table 3, and each row consists of the availability and the mission reliability of 100 iterations of the anti-warship warfare scenario for a XYZ warship.

TABLE III
SIMULATION RESULTS FROM 10 REPLICATIONS WITH XYZ WARSHIP'S ANTI-WARSHIP WARFARE SCENARIO

Replication	Availability	Mission Reliability
1	0.9965	0.8390
2	0.9972	0.8480
3	0.9958	0.8200
4	0.9963	0.8340
5	0.9976	0.8620
6	0.9962	0.8180
7	0.9964	0.8250
8	0.9962	0.8320
9	0.9968	0.8430
10	0.9969	0.8540

One-sampled T test parameters for the availability and the mission reliability are tabulated in Table 4 and Table 5, respectively. The one-sampled T test parameters for analytical availability value (Test value in Table 4) and 10 replicated simulation results are derived by analysis with SPSSv16.0. In Table 4, P value (0.123, Significance value) is compared with the significance limit 0.05. The result is P > 0.05, therefore, the null hypothesis (Ho) is accepted. Ho is that the availability value produced from the simulation model can be considered same as the analytical value, which is Test value (0.9963) in Table 4, at 95% confidence interval.

The mission reliability of the simulation model and the analytical mission reliability value (Test value in Table 5) are tested in the same way. One-sampled T test parameters are tabulated in Table 5. P value (0.068) is compared with the significance level 0.05. The result is P > 0.05, therefore, the null hypothesis (Ho) is accepted. Ho is that the mission reliability produced from the simulation model can be considered same as the analytical value, which is Test value (0.8272) in Table 5, at 95% confidence interval.

TABLE IV
ONE-SAMPLE T TEST FOR AVAILABILITY

	Test value = 0.9963					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the difference	
					low	high
Availability	1.702	9	0.123	0.000289	-0.000095	0.00067328

Table . One-sample T test for mission reliability

	Test value = 0.8272					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the difference	
					low	high
Reliability	2.077	9	0.068	0.0096	-0.000858	0.020058

V. CONCLUSION

In this paper, we proposed the discrete event simulation model for the availability analysis of weapon systems and other large systems. Most weapon systems are complex system and perform various missions, so that the system reliability structure changes drastically with its missions and operational tasks. In order to develop the simulation model, the concept of the system RBD based on missions and operational tasks was addressed. The system RBD was used as availability rules of a system. And, the overview of the simulation model with three kinds of discrete events was presented and the simulation model was implemented.

This simulation model is appropriate for both the availability analysis and the mission reliability prediction of complex systems. This simulation model can be easily used to analyze any sustainment requirement such as spare limits, maintenance down time or maintenance man-power allocations.

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