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

Hye Lyeong Kim, Sang Yeong Choi

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).

\[
Ai = \frac{MTBF}{MTBF + MTTR}
\]

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.

\[
Aa = \frac{MTBM}{MTBM + MTM}
\]

where
MTBM: Mean time between maintenance
MTM: 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,
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].

\[
A_o = \frac{T_{UT}}{T_{UT}+T_{DT}} = \frac{T_{UT} + T_{CM} + T_{PM} + T_{ALDT}}{TT}
\]

(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.

\[
A_o = \frac{TT - T_{DT}}{TT} = \frac{TT - (T_{CM} + T_{PM} + T_{ALDT})}{TT}
\]

(4)

Where

TT: Total Time, T= 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]: the 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 complexity. Therefore, equation 3 can be substituted by equation 4.

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.

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.

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 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.

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.

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operational task.

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

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

[Fig. 2 Mission-Task-Function-System QFD]

[Fig. 3 Depth-first backward inference route]
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.

### 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:

- **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.

#### 2) Simulation input data

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

- **System RBDs**: A system RBD is described with system connection rules for each task. Each task has its operating functions.

- **System failure and repair time parameters**:
  - All end components or subsystems which construct a system have their probability distribution function and repair time probability distribution function are known.

- **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.

#### 3) Simulation output data

- **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.

- **Providing mission reliability**:
  - The number of missions. Each mission has operational tasks, time length and functions.
  - 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>
<thead>
<tr>
<th>Order</th>
<th>Operational Task</th>
<th>Task ID</th>
<th>Operating Function ID</th>
<th>Time Length(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cruising</td>
<td>T1</td>
<td>F1</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Reconnaissance</td>
<td>T2</td>
<td>F2</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>Detection</td>
<td>T3</td>
<td>F2, F3</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Threat Evaluation &amp; Weapon Assignment</td>
<td>T4</td>
<td>F4</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Tracking Targets</td>
<td>T5</td>
<td>F2, F5</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>Engagement</td>
<td>T6</td>
<td>F2, F4, F5, F6</td>
<td>48</td>
</tr>
<tr>
<td>7</td>
<td>Damage Assessment</td>
<td>T7</td>
<td>F2, F4</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>Cruising</td>
<td>T1</td>
<td>F1</td>
<td>24</td>
</tr>
</tbody>
</table>

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.

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

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.

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. The equation for mission reliability is bellow.

$$R_{MD} = \frac{MTBF}{MTBF+MTTR}$$

(8)

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

<table>
<thead>
<tr>
<th>Replication</th>
<th>Availability</th>
<th>Mission Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9965</td>
<td>0.8390</td>
</tr>
<tr>
<td>2</td>
<td>0.9972</td>
<td>0.8480</td>
</tr>
<tr>
<td>3</td>
<td>0.9958</td>
<td>0.8200</td>
</tr>
<tr>
<td>4</td>
<td>0.9963</td>
<td>0.8340</td>
</tr>
<tr>
<td>5</td>
<td>0.9976</td>
<td>0.8620</td>
</tr>
<tr>
<td>6</td>
<td>0.9962</td>
<td>0.8180</td>
</tr>
<tr>
<td>7</td>
<td>0.9964</td>
<td>0.8250</td>
</tr>
<tr>
<td>8</td>
<td>0.9962</td>
<td>0.8320</td>
</tr>
<tr>
<td>9</td>
<td>0.9968</td>
<td>0.8430</td>
</tr>
<tr>
<td>10</td>
<td>0.9969</td>
<td>0.8540</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Test value = 0.9963</th>
</tr>
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<tbody>
<tr>
<td>t</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Availability</td>
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</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Test value = 0.8272</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Reliability</td>
</tr>
</tbody>
</table>

### 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.

### References


