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Analysis of the Impact of Reliability, Availability and Maintainability on Ship Survivability

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ABSTRACT

The JJMA Ship Vulnerability Model is a tool for assessing the survivability of a ship against enemy weapons. We are currently expanding this tool into a risk assessment tool for ferry operations: We can, for example, statistically run the ship aground, and determine the probability of disabling the ship's propulsion system. This investigation should also take into account the inherent less-than-100% reliability of each system. Thus, in the case of a ship running aground, this should be coupled (statistically) with the probability of the bilge pumping system choosing that moment to be broken.

Running the model in a Monte Carlo simulation allows us to predict the probability that a given accident scenario will lead to a specific consequence, such as ship evacuation. By then increasing the reliability of certain systems we can decrease the probability of an evacuation (or other consequence.) The result is that we can help the ship owner decide where to focus his efforts, in terms of engineering the total survivability of the ship.

The JJMA Ship Survivability Model (JJMA-SVM) provides estimates of ship systems' vulnerability at various levels of availability including 100%. The JJMA-SVM is a 3D, stochastic, physics-based model that takes into account damage mechanisms, ship geometry and structure, and system arrangements. Fault tree analysis is used to estimate degradation of ship system performance due to damage, as well as components' non-reliability.'

The process has been developed to analyze military threats (weapon effects.) It is a comprehensive process, however, which is easily extended to evaluate ship vulnerability from non-combat causes such as weather, collisions or grounding.

This methodology serves as a tool to guide ship designers during all phases of ship design in order to achieve a balanced, reliable and survivable ship design that meets the specified requirements and remains within the budgetary constraints.

Calculations of ship vulnerability have in the past generally included an assumption that the ship's systems are 100% available at the time of the incident. Actually, availability of ship systems can be much lower. Availability requirements for ship systems are most often set at 85% to 95% levels. If systems availability is neglected in the analyses, the ship may appear less vulnerable to damage than it is in reality.

This paper describes a process for combining RAM (Reliability, Availability and Maintainability) and ship vulnerability analyses and for determining the impact of RAM factors on ship vulnerability.

An example is provided showing the results of RAM and vulnerability analyses of a small gas turbine-driven ship propulsion system.

1. INTRODUCTION

Most specifications today state ship systems availability requirements both before and after an enemy attack. This paper describes an assessment process for ensuring that these requirements are met in a balanced and affordable manner.

Ship system components can become deactivated from either non-reliability causes (equipment's age, lack of maintenance, faulty parts, etc.) or from damage, due either to enemy action or to non-combat causes such as weather, ship grounding, or collision.

For our analysis we use the JJMA Ship Vulnerability Model (JJMA-SVM). This is a computerized process for determining which ship system components will suffer damage due to an incident and how much of the ship's functional capability will remain after an incident.

The JJMA SVM was originally developed to assess weapon effects on warships. Only recently have we expanded this tool for use on commercial ships. In fact, the tool can be used to assess the effects caused by virtually any damage source: All that is required is a statistical description of the source. In the balance of this paper we will use a simple military damage source – a weapon hit. The reader should understand that this is only one of the myriad incident types that could be selected.

We have conducted RAM analyses to determine the availability of the selected system components and used these values in determining system performance degradation due to warhead damage.

In development of our approach we relied on existing software such as "Quest", "Fault Tree+". For calculating the effects of weapons on ship structure and magazines we relied on Microsoft "Excel" and "HECSALV" computer software. For the assessment of weapon effects on a ship system, we relied on a "first principles" approach and available empirical information.

Our assessment methodology is a tool to be used in all phases of ship design and is flexible enough to accommodate improvements in weapon effects algorithms and algorithms on equipment tolerance to these effects.

2. OVERALL APPROACH

Figure 1 outlines our overall approach to ship vulnerability assessments. The initial phase of the process is to assemble data on damage incident characteristics, hit distribution, hit location and damage mechanisms. For a weapon this includes fuse setting, warhead striking velocity, mass and casing material, and ship structure thickness and material strength. For a grounding incident this would include bottom characteristics (rocks or mud?) and ship speed. Other input information includes ship system and hull structure arrangements, components fragility levels, and equipment component availability data. Note that component fragility levels depend upon the nature of the “threat.” A grounding “threat” poses the danger of water damage to components, which may or may not be susceptible to damage from this source. A weapon hit, on the other hand, poses a different type of threat to the component, and the component will have a different fragility level in the face of this threat. Thus the component fragility levels depend upon the nature of the considered threat.

Initially in the ship design process much of this data is not fully defined. At that stage, we rely on approximate data based on preliminary design and previous ship experience. The analysis continues until the final stages of the design thus providing the ship designer with useful guidance on effective ship survivability features.

The JJMA SVM process is as follows: We use the component MTTF (Mean Time To Failure) and MTTR (Mean Time To Repair) data to determine components’ availability probability. We run a Monte Carlo random numbers trial for each component at each trial to determine which components were disabled on each trial due to non-reliability cases. Next, we perform a vulnerability analysis to determine which additional components were deactivated due to the incident. We use “Fault Tree” computer code[13.1] to determine the system’s availability at each trial. We perform approximately 10,000 trials and determine degradation percentages in systems’ availability due to components’ deactivation from both weapon effects and from non-reliability causes.

Ship systems are designed to meet availability requirements stated in ship specifications. To achieve that level of performance the system’s component availability is determined from manufacturer-supplied information or from U.S. Navy data banks. Sufficient component redundancy is provided for a system to meet or exceed the specified systems requirement. Given such a system, a vulnerability analysis is conducted to determine ship systems availability at some system operational capability level, e.g., at 50% propulsion system capability.

In this paper, for purposes of showing the impact of a system’s reliability on its total vulnerability, we have conducted a sensitivity analysis of a propulsion system for six different overall system availability values. Component availability was adjusted to meet each of the overall system availability values. Each of the six systems was then analyzed for vulnerability and the results plotted to show the impact of availability on system vulnerability. More information is presented in section 5.4 of this paper.

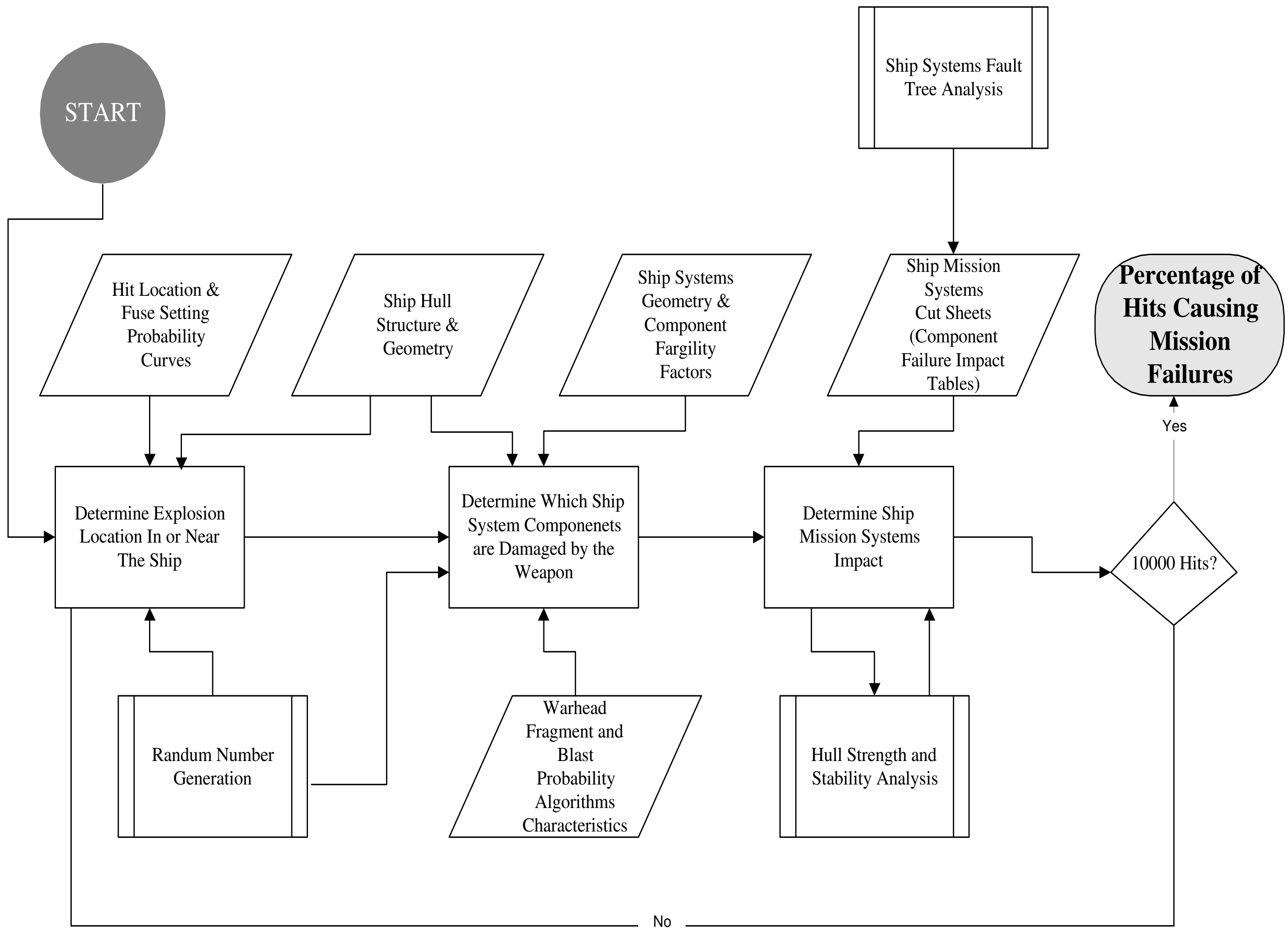


Figure 1 - JJMA Ship Vulnerability Simulation Model

3. JJMA SHIP VULNERABILITY MODEL (JJMA-SVM)

3.1. General.

The JJMA-SVM is a 3D, stochastic, physics-based computerized process, which considers threat characteristics, and ship's structure and materials, system arrangements and threat incident location.

We have adapted an existing "QUEST" computer code to perform the vulnerability analysis. "QUEST" is equipped with excellent computer graphics capability, which is very useful for visualization of various weapon effects on ship structure and equipment. The computer code contains a number of statistical subroutines, which we have adapted for statistical analysis of ship vulnerability.

We use the same fault tree diagrams and "Fault Tree+" computer software that we used to determine systems' availability degradation due to non-reliability causes. If systems' reliability considerations are disregarded, we treat all the components as 100% available during the incident. This gives us classical ship vulnerability assessment values.

We start by building a ship SVM model using a simplified representation of ship geometry, its structure and equipment arrangement. The amount of detail and complexity of the model depends on the number of threats to be analyzed, their effects, characteristics and the availability of ship design information. For a warhead threat the model must include ship configuration, structure, systems, arrangements, hull material properties and plating thickness. For a weather threat the model must include ship motion characteristics. Other inputs describe the design threat characteristics, threat damage algorithms, threat distribution curves and levels of fragility of equipment to specified threat damage mechanisms (e.g., tolerance to shock or fragment damage).

We use a Monte Carlo process to simulate random incidents within a specified incident distribution curve. We compute incident effects for each trial. To determine ship system deactivation probabilities, we divide the number of the incidents that caused system failures by the number of trials (about 10,000). We then compare this number with the specified ship mission availability requirements. If the computed values indicate equal or lower mission loss probabilities, the assessment process is completed and ship design is satisfactory. If mission loss probabilities exceed the specified requirements, system design must be modified and the assessment process repeated.

3.2. Threat Characteristics

In today's world, multitudes of weapons threaten a warship. Selection of design threats requires knowledge of the likelihood of the ship encountering a particular threat and a consequence of being hit by that threat. The process by which warhead threats are established is outside the scope of this paper, and will not be discussed.

As mentioned earlier the JJMA SVM was created as a warship assessment tool. We are only recently "translating" this tool for use in commercial ship analyses. At present we are modelling commercial ship threats as a subclass of warship threats. In other words we model, for example, a rock (grounding) as similar to an underwater mine.

We are in the process of increasing our library of non-military threats.

3.5. Statistical Considerations.

One of the inputs to our SVM is the statistical incident distribution curve. For a military threat the curve shape depends on the type of threat seekers, ship signatures and effect of self-defense measures such as chaff and flares. In this paper we assumed that the hit distribution is Gaussian, with a mean at the centroid of the profile of the ship. In general, this is where radar seekers will guide an attacking missile. Other incident distribution curves will be used for groundings or other types of non-military threats.

We use the Monte Carlo random number process to calculate ship component availability at each roll of the dice and then to compute the probability of component damage due to the incidents which fall within the selected incident distribution curve.

In our analyses we use the "Fault Tree" computer code by Item Corporation 13.2. The vulnerability values are represented by the ratio of successful hits to the total number trial hits. The final output from the assessment is a predicted vulnerability for the ship.

4. SYSTEM AVAILABILITY ASSESSMENT PROCESSES

Average expected ship systems' availability and life cost goals in a given operational environment are fundamental ship design requirements. We use computerized modeling and simulation since they provide the most efficient means for demonstrating that these requirements are met.

4.1. RAM Simulation Models.

We use RAM simulation models based on Monte Carlo methods to determine the expected average ship system and sub-system availability as a function of the reliability of the system's components and their maintenance. The RAM models are also used to determine the expected life cycle repair costs of alternative systems and components, and to assess the effectiveness of system/equipment maintenance and support strategies. Figure 2 shows the process for gathering the input data and conducting the analysis.

We use several software models, i.e., US Navy's Tiger, Deneb Corporation "Quest" and Item Corporation "AVSIM+". This software uses either a fault tree or reliability networks (sometimes referred to as functional flow diagrams), with truth tables to link the dependencies on the systems to their components. Key elements of these analyses are the component reliability, reparability, parts and labor support and a life cycle mission scenario.

4.2. Systems Failure Analysis.

In our analyses we primarily use fault tree diagrams, since they lend themselves to use for complex systems with 20 or more components. The diagrams also allow us to conduct sub-system failure mode analysis. Fault tree analyses start with the failure of a system and through "*or", "and*", and "*majority vote*" gates define all the combinations of systems' components that would cause the system's failure.

The first step in the development of a fault tree diagram is to decide on the level of complexity of the analysis. For example, we must decide whether the diesel is the lowest level of failure in our system, or whether we should go to the next tier (e.g., failure of a diesel fuel pump or component). During the early stages of ship design we may use a relatively coarse model which will become more refined at subsequent stages of ship design. Since weapon effects phenomena are rather imprecise, it is impractical to go to the "nuts and bolts level" and we are forced to remain at the major components' level (e.g., a diesel pump).

For the purpose of demonstration of our approach, we set 100% or 50% propulsion system loss as two top-level events. We then determine all system or component failures (*system events*) which could cause these top events. We work down each branch of the fault tree diagram to determine the causes and likelihood of each event's occurrence and resolve the events into distinct root causes. The bottom of the analysis is a component failure at our targeted level of complexity.

4.3. Component Reliability

Reliability of a ship component is a function of its material, design, and manufacturing quality, age, elapsed time since maintained, and operating environment. The predicted time of component failure is defined in most simulation models as a probability distribution function that includes a Mean Time Between Failures (MTBF) provided by the component manufacturer. Recent models have more sophisticated functions which account for the effects of inspection and failure discovery as well as differences in full-time operation vs. use on demand or standby. JJMA collects and maintains equipment reliability information to assess the effects of engineering and environmental changes and ship vulnerability.

4.4. Component Reparability

Reparability of equipment is a function of its design quality, availability of parts and labor, and ability to repair the equipment within the given mission scenario. Similar to the time of failure, the time to repair, or down time, is defined as a Mean Time to Repair (MTTR) statistical function. MTTR data are available from equipment manufacturers' sources or from the U.S. Navy data banks.

At JJMA we identify the standard repairs for the components. Often this consists of a replacement of major parts or the entire unit. We track and account for parts identification time, cost, site storage cost, site storage quantity, site logistics delay, depot stowage quantity and cost of stowage, and manufacturing time. In simplifying the calculation of availability the MTTR values may include logistics delay times and therefore represent the average down time for given equipment

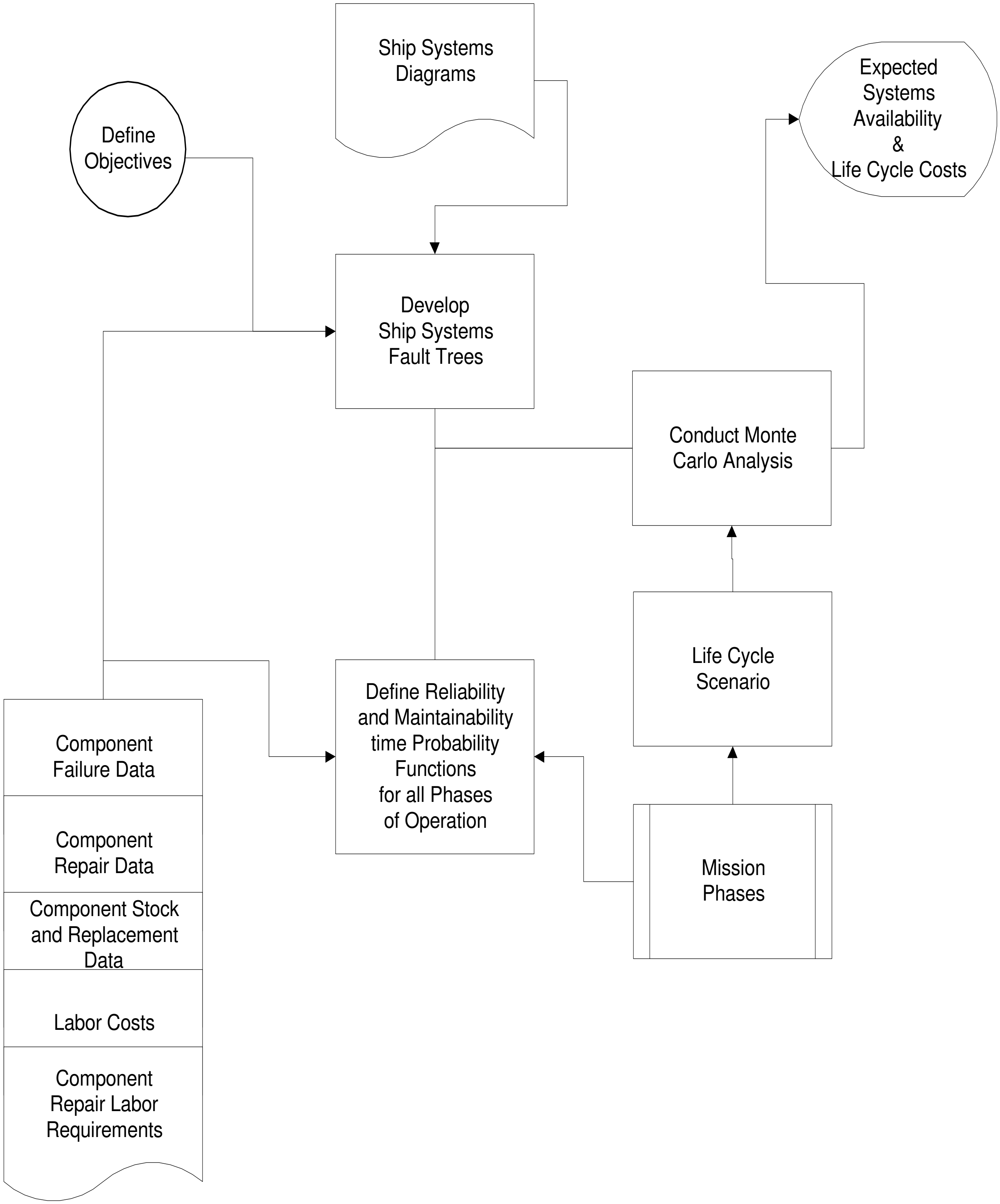


Figure 2 - The Process for Development of the Ship Systems Availability and Life Cycle Cost Analytic Model

4.5. Component Availability, $A_{R\&M}$

To determine availability sensitivity of a top-level design to reliability and maintenance of components, we use a simplified approach. We assume that the average down time is the MTTR and the average up time is the MTTF. Then the component average availability based on reliability and maintainability, $A_{R\&M}$, may be expressed as:

$$A_{R\&M} = 1-(MTTR/(MTTF + MTTR))$$

Or

$$A_{R\&M} = 1-(MTTR/(MTBF))$$

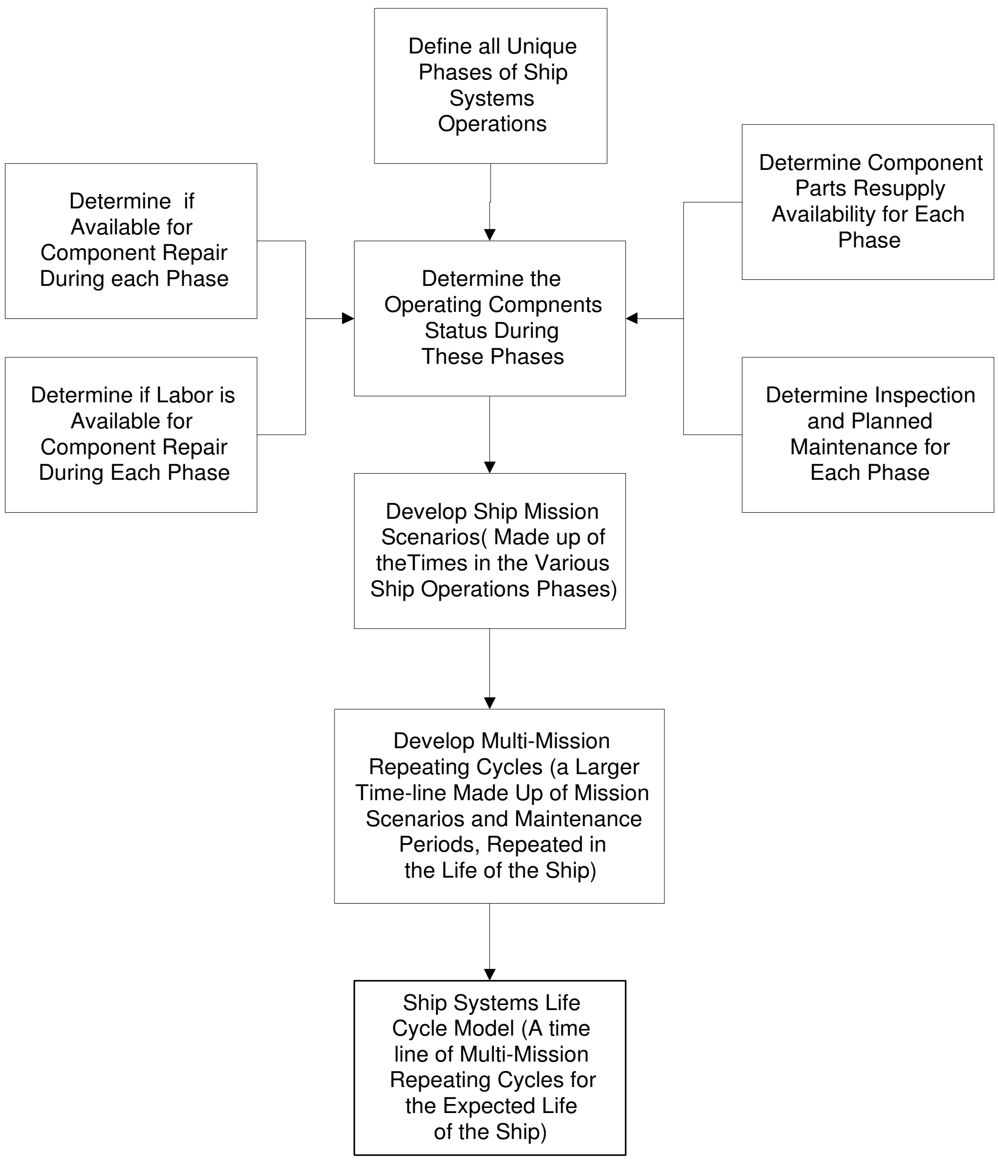
The component availability in our ship design RAM simulation models may be defined by using more complex methods. Some of these methods take into account the support- and scenario-driven associations of logistics delay times, and others generate more complex reliability and repair time probability functions. Monte Carlo simulation of the component failures is used repeatedly by our system fault tree analysis to determine overall system $A_{R\&M}$. For this paper, however, simple functions are used.

4.6. Mission Scenarios

Samples of ship mission scenario phases that we use in typical ship design RAM simulation are (a) in port on shore power; (b) in port on ship's power; (c) underway in transit; (d) underway on patrol; (e) underway engaging the enemy; and (f) underway training. Figure 3 shows the process for mission simulation scenarios as they make up the ship life cycle. The process allows us to assign low failure rates in cold standby, higher in hot standby and higher yet in heavy operation. Mission phase analysis also enables us to differentiate: repair accessibility, parts and labor availability, repair parts restocking and assessing the logistics delays.

We define systems' life cycle as a collection of repeated mission scenarios over the planned life of the ship. Life cycle mission scenarios enable us to simulate the effects of the age of component operating hours between major repair periods and restocking the ships, and to analyze their impact on availability. We also track the aging of components and the planned preventive maintenance schedules, and simulate the resultant aging reset. Due to scope constraints of this paper, we provided no examples of impacts of life cycle mission scenarios.

Figure 3 - Development of Life Cycle Scenarios for the Analysis of Ship Systems Availability



5. RESULTS OF ANALYTICAL ASSESSMENT OF AN EXAMPLE SHIP PROPULSION SYSTEM

5.1. Sample Ship Description

The ship is a small combatant with a displacement of over 3000 metric tons, LOA of 105 meters and beam of 12.5 meters. The propulsion plant is a CODAG plant employing two General Electric LM2500 marine gas turbines and two MTU 20V 1163 TB93 diesel engines. Each GE LM2500 gas turbine is arranged to drive a corresponding inboard port or starboard shaft line and Kamewa Series 200 waterjet via a reduction gear. Each propulsion gas turbine is connected to a double stage reduction gear via a flexible diaphragm coupling and SSS clutch.

The diesel engines are arranged to drive a corresponding port or starboard shaft line and a Kamewa Series 140 waterjet provided with directional control thrust.

Figure 4 illustrates the example ship vulnerability model. Ship spaces, structure and equipment are modeled as boxes. Decks and bulkheads are modeled as plates with thickness. Distributed systems are broken down into parts between two bulkheads and a slackness factor is assigned to flexible cables and piping.

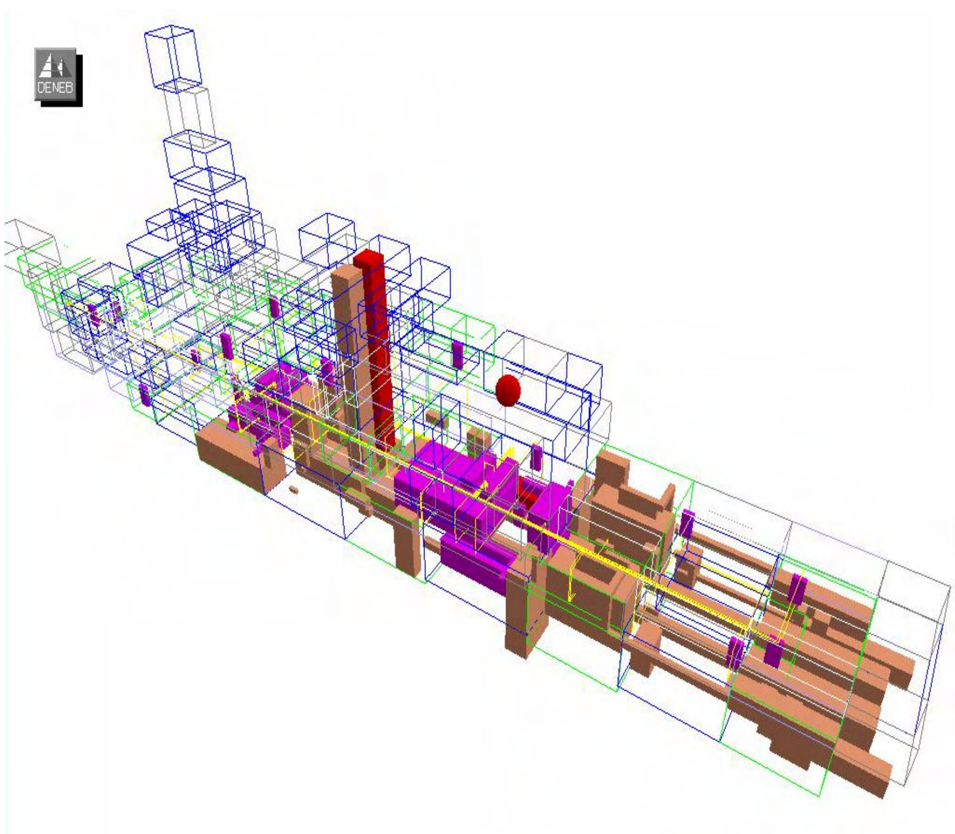


Figure 4 - JJMA SVM Graphic of a Small Combatant Propulsion Plant under SAP Attack

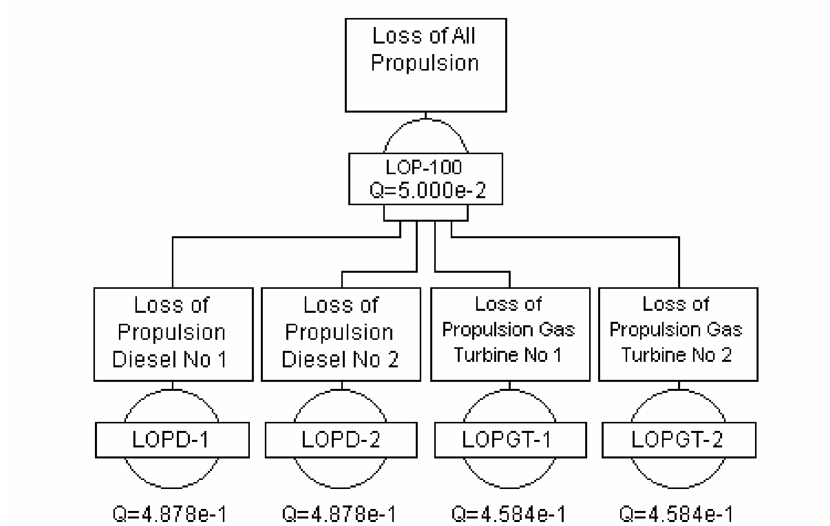


Figure 5 -Top Tier Fault Tree Diagram

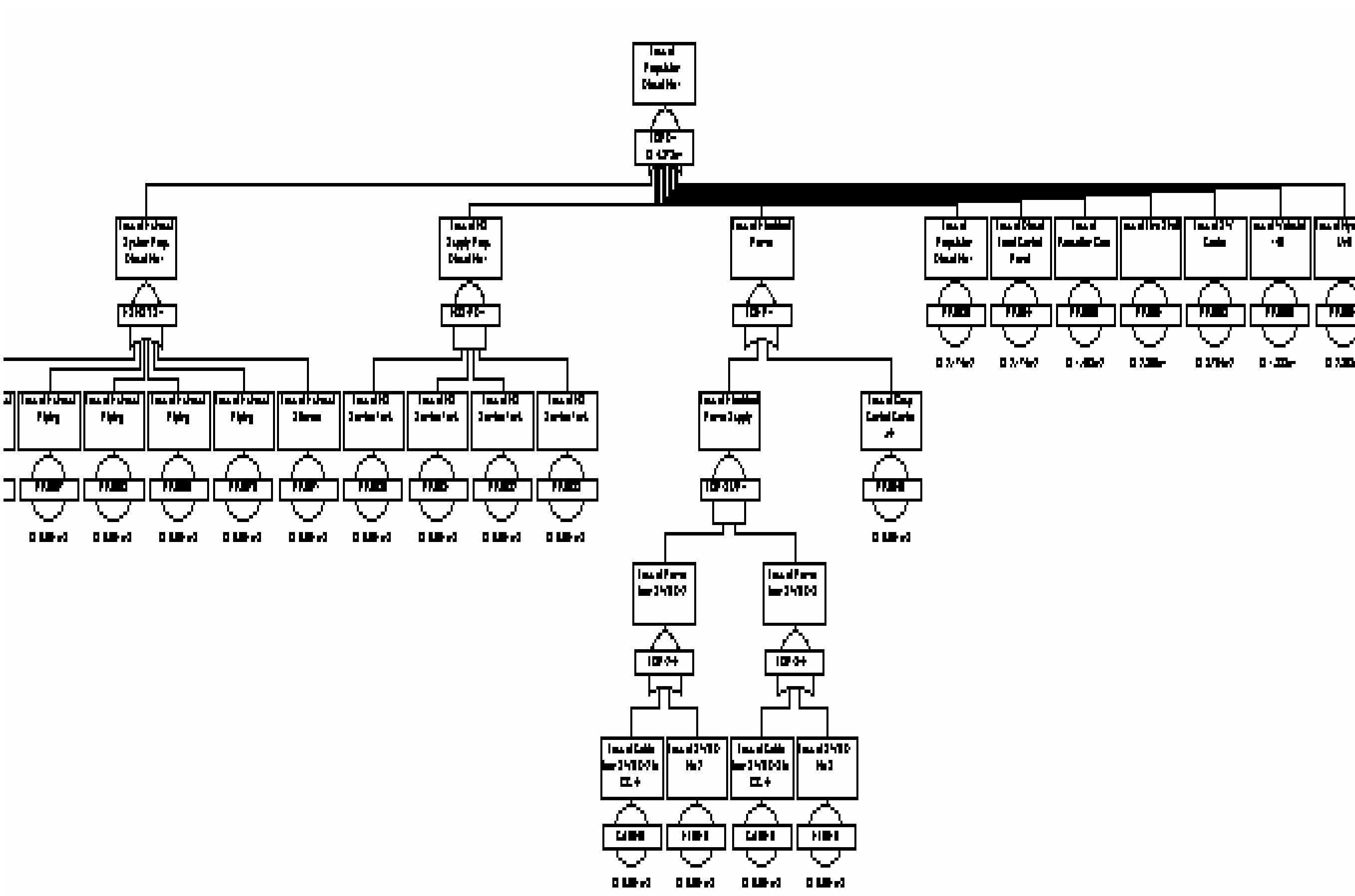


Figure 6 - Lower Tier Fault Tree Diagram

5.2. Vulnerability Analysis of a Fully Available Propulsion System.

We used the U.S. Navy BULLPUP missile as a design threat for our example vulnerability analysis. The overall weight of the warhead is 981 lbs. and it carries 370 lbs. of H-6 explosive charge. Figure 5 provides an example of a fault tree diagram at 50% propulsion availability. Figure 6 is a second tier level fault tree diagram related to the loss of propulsion diesel No 2.

We used dummy MTTF values for the purpose of generating “cut sheets” in the “Fault Tree” computer software. These values were ignored in assessing systems’ vulnerability after a hit. The components deactivated by the enemy action were then designated as failed on the fault tree diagram to determine the availability of the whole propulsion system. For example in case of 100% propulsion system loss all diesel and gas turbine units must be deactivated by a hit to result in 100% loss of ship propulsion

Figure 7 shows the availability estimates of the propulsion system after one, two or three SAP warhead hits. There is at least an 11.96% chance that the system will be fully available after a single hit and a 48.83% chance that at least 50% of the system will be available after the attack. As the number of hits increases these probabilities decrease, as shown on the figure. All system components are assumed 100% available at the time of the hit.

5.3. Vulnerability Analysis of Propulsion Systems with Various Availabilities.

Figure 8 outlines the process for assessing the effects of components’ de-activation (from combat and/or non-reliability causes) on systems’ availability after the hit.

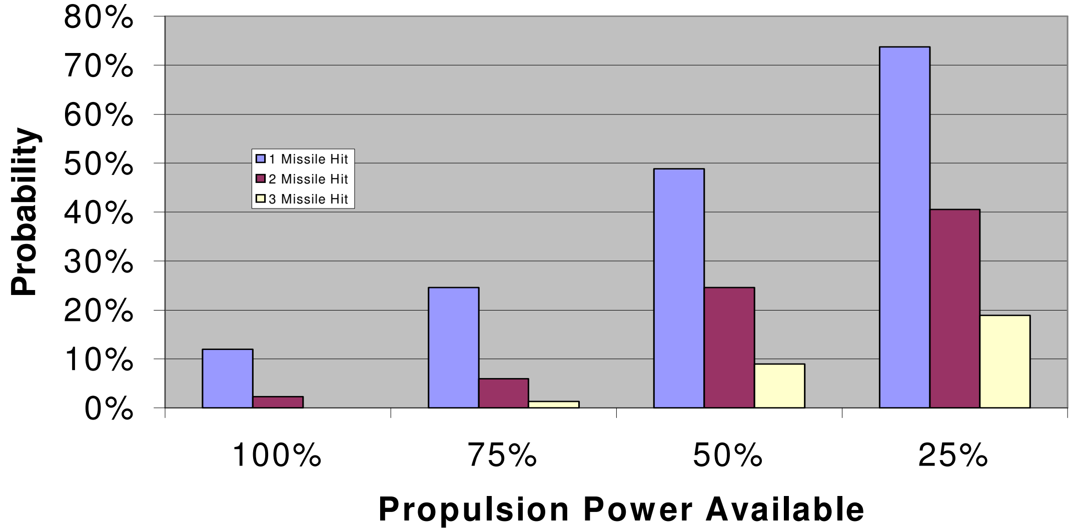
We performed components’ availability analysis for six different propulsion systems’ availability values (100%, 95%, 90%, 85%, 80% and 75%). The 100% availability case represents the condition traditionally used in ship vulnerability assessments. The other values are representative of systems’ availability design goals for non-combat causes of the components failures.

For this example, all propulsion systems are identical except for the reliability of the individual system components – and therefore the overall system expected availability. The components availability values on Figure 5-3 and Figure 5-4 have been adjusted to provide a specified overall system availability. In an actual ship design exercise the MTTF will be determined using manufacturer’s or U.S. Navy data sources, and the system will be designed to meet the system availability requirements set forth in ship specifications.

This generally means providing a greater components redundancy or selecting more reliable system components, or modifying the maintenance and parts replacement schedules, or combination of all the above.

Each of the six systems’ availability cases is then analyzed for the vulnerability to the warhead using the process described in Figure 8. For each hit, we perform the Monte Carlo simulation to determine system components’ failures due to combat and non-combat causes and their impact on the system’s availability. If the results show that our availability values fall below the specified goals then the system is redesigned and the process is repeated until the design requirements are met.

Figure 7 – JJMA SVM Results for Propulsion Plant Post-Hit Availability Assuming 100% Pre-Hit Availability



5.4. Impact of Systems' Reliability on Vulnerability Assessments

Figure 9 presents a curve showing the sensitivity of the propulsion system's vulnerability estimates at 50% or less capability retention after the hit.

Modern ship survivability requirements generally specify the percentages of various ship capabilities that must be retained after one or more hits. As can be seen from Figure 9, these capabilities may be significantly overestimated if actual system reliability parameters are ignored.

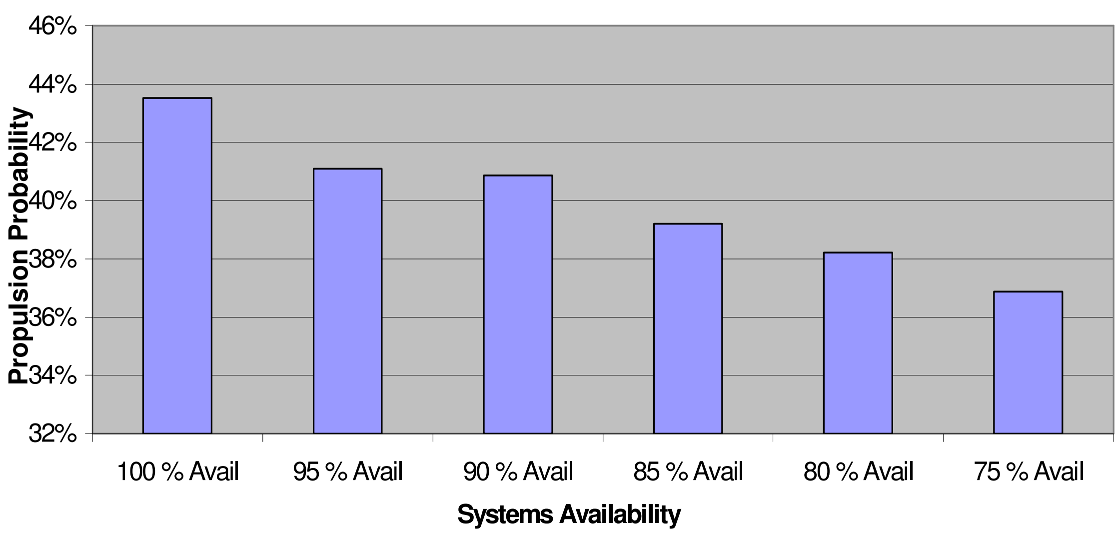


Figure 9 - Probability of Having at Least 50% of Ship's Propulsion Available after One SAP Hit for Given System RAM Design Goal Availability

5.5. Systems' Design Options for Meeting Availability and Vulnerability Requirements.

The initial step is to select a systems design that meets availability requirements. To achieve this the designer may exercise one or a combination of the following alternatives:

- More reliable (and more costly) system's components
- Greater component redundancy
- More frequent maintenance and parts replacement schedule

The next step is to perform vulnerability analysis of the system using a combined RAM Life Cycle to Vulnerability Simulation analysis. If the analysis indicates that the system will have a higher than specified vulnerability, the designer could exercise the following options:

- Provide a greater separation between redundant components. Adding more components will improve a system's availability but will not be effective from the vulnerability standpoint without sufficient separation between redundant components.
- Increase weapon effects tolerance of the system by protecting its components by means of armor, shock mitigation, more robust component design etc. This option is exercised when the ship is too small relative to the vulnerability area of the threat weapon. For the cases where exclusion armor is provided, it is desirable to keep the number of components as few as possible to limit the target area and the impact of armor weight on ship system. For this special condition, choosing the most reliable components will make sense from both availability and vulnerability standpoints.

To arrive at an optimal system's design it is essential that all these options or their combination be analyzed with regard to their ship impact and cost. The methodology we described in this paper provides ship designers with this capability.

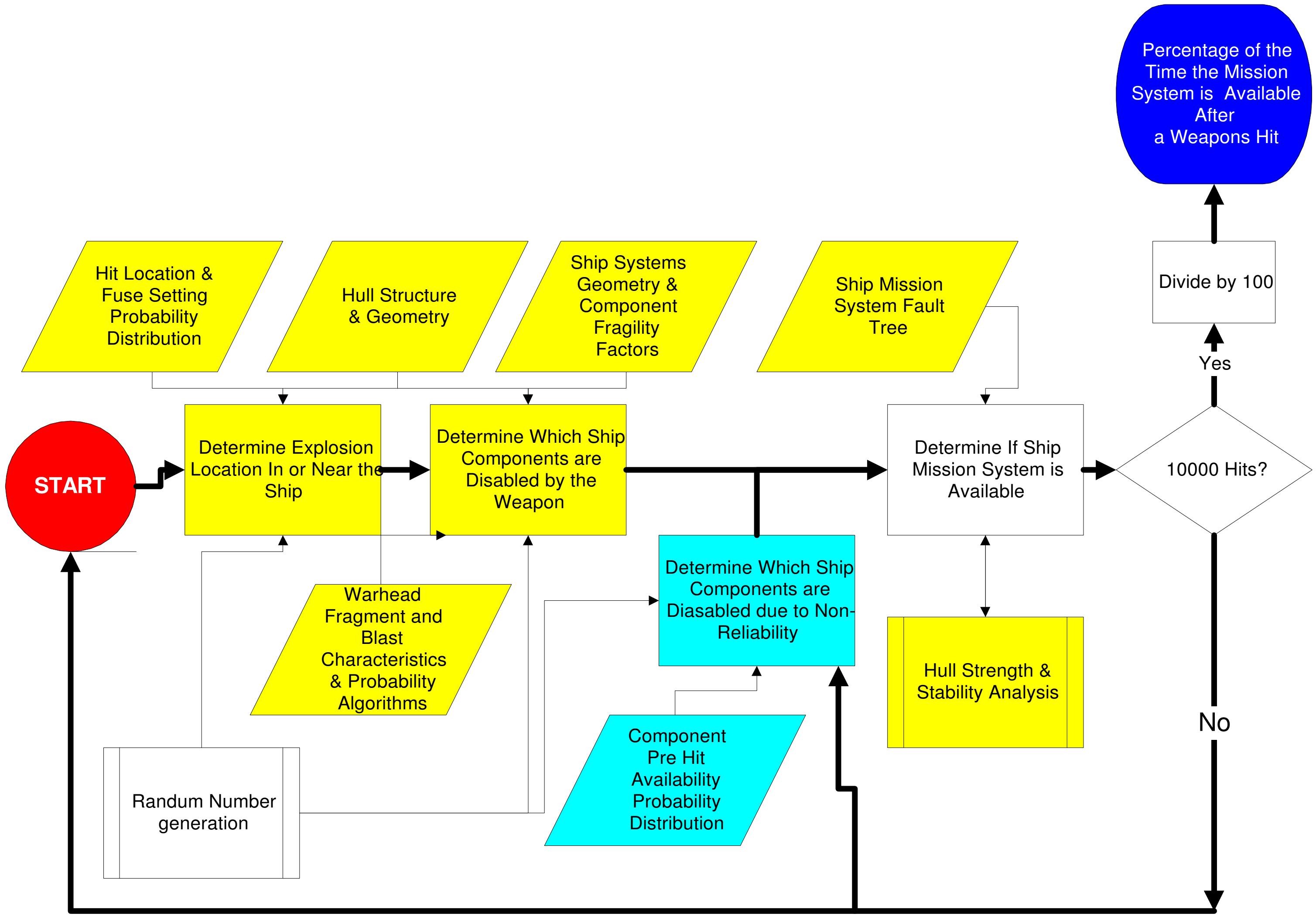


Figure 1. Process for Assessing the Effects of Component's Deactivation on Systems' Availability after the Hit.

6. CONCLUSIONS AND RECOMMENDATIONS

Reliability analysis is a logical and necessary addition to ship vulnerability assessment process. Armed with an analytical capability such as is described in this paper, the ship designer will be capable of making rational decisions with regard to system components' reliability and redundancy, redundant component separation, and component hardening and protection features.

The JJMA-SVM enables analyzing a wide range of air- and water-delivered weapons and conditions. It serves as a tool to be used at all stages of ship design, enabling the designers to converge on the most reliable and survivable ship within size and budget constraints.

We now have the capability of assessing ship vulnerability to detonation of weapons in ship magazines from accidental causes or enemy action, and for providing means for minimizing these effects. JJMA-SVM can be extended to assess ship crews' vulnerability to enemy action and the impact of crew losses on ship's mission-keeping capability. In this case, we will include the statistical variations of the human body, location in the ship, individual personnel postures during attack, and man-machine interface considerations.

We have used our methodology for assessing ship vulnerability to non-combat conditions such as grounding and collision.

We have developed an approach for assessing ship loss probabilities from hull girder damage from combat or natural causes.

There has been a considerable interest regarding the use of Commercial off the Shelf (COTS) systems in ship design. The majority of these systems cannot withstand shock without relying on some form of shock mitigation. Our methodology can be adopted to evaluate vulnerability of both protected and unprotected COTS components to shock damage from a non-contact torpedo or mine attacks and for minimizing the number of costly equipment shock mitigation features.

Enemy hit distributions are determined in part by ship signature attributes and active countermeasures such as use of flares and chaff. Our probabilistic approach can be used to evaluate the efficacy of these techniques and to determine the best way to allocate limited budget between susceptibility and vulnerability reduction features.

The threat environment is constantly changing. It is essential that it be carefully evaluated for both new ship designs and existing ships in need of survivability enhancement modifications. JJMA has developed powerful analytical tools which could lead to more reliable, less vulnerable and more cost-effective ship designs. We recommend that these or similar tools be used in all ship design applications including those concerned with non-combat effects such as collision and grounding.

Definitions:

(1) Susceptibility: This area is concerned with reducing probability of a ship being hit e.g., ship signature reduction, use of flares and chaff to seduce incoming threats away from the target vessel, use of ship's self defense weapons, etc.

(2) Vulnerability: This area covers the ship's vulnerability to threat damage. It is concerned with the extent of impairment of ship's mission-keeping capability and its ability to remain afloat.

(3) Recoverability: This area addresses equipment and procedures to contain spread of fire and flooding and to recover ship's mission keeping capability after the hit. Unlike "susceptibility" and "vulnerability", which analyze an instant event, recoverability involves a time factor.

(4) Reliability R (t): The probability that a system/component has performed its function until a specified time t.

(5) Unreliability F(t): The probability that a system/component will fail prior to a specified time t. $F(t) = 1 - R(t)$

(6) Availability: The average time the system/component is in a usable condition divided by the total time.

(7) Failure: System/component perform outside the specified tolerance boundaries.

(8) Instantaneous Rate of Failure: ($\lambda(t)$) The probability of failure in time *dt* about a given survival time t. For totally random failures, $R(t) = e^{-\lambda t}$

(9) Mean Time To Failure, MTTF = $\int_0^\infty R(t)dt = \int_0^\infty -1/\lambda dt$

(10) Instantaneous Rate of Repair: $\mu(t)$. This is the probability of repair in *dt* about time t. It describes the instantaneous repair rate as λ (t) describes the instantaneous failure rate.

(11) Mean Time To Repair, MTTR = $\int_0^\infty -1/\mu \, dt$

(12) Mean Time Between Failures, MTBF = MTTR + MTTF where $\lambda(t) = \lambda$; $\mu(t) = \mu$ and $\lambda << \mu$

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