Study on rms integrated simulation modeling of multi-agent warship propulsion system

Chao Qian¹, Jingyuan Bao², Yong Tang³

¹College of Naval Ships and Oceanography, Naval University of Engineering, Wuhan 430033, China
²The Second Navy Representative Office in Wuhan of the Naval Equipment Department, Wuhan 430063, China
³School of Mechanical and Electrical Engineering, Wuhan Donghu University, Wuhan 430212, China

Abstract. As the key design characteristics of warship, reliability, maintainability, and supportability (RMS) are crucial to the successful completion of warship missions. To enrich the RMS design and analysis methods of warship equipment, this paper focuses on the voyage of warship propulsion system, and builds a theoretical model of RMS integrated assessment system for warship on the basis of multi-agent technology, so as to indicate how successfulness of the mission warship propulsion system is dynamically related to equipment and supporting resources. Furthermore, Anylogic is used as a platform to develop a RMS simulation system for warship propulsion system in the mission of voyage. By changing the RMS parameters of warship propulsion system and repeating the simulation of voyage, important factors are identified for the improvement of probability of mission completion success, which is of great military significance.

1. Introduction

Warship, as the major equipment in the modern sea battles, has become a technical field integrating the knowledge of multiple disciplines. A warship has a complicated structure which involves a great variety of professions and causes very high requirements for professionalism and technical performance. In the meanwhile, a warship must be far away from the shore base when it is performing a mission. During the period, it has to face such problems as long voyage, long-time cruising, unfathomable maritime environment, alternating altitudes, and difficult supply guarantee [1]. Considering its complicated structure and the specific problems during its mission, a warship requires higher reliability, maintainability, and supportability (RMS) than armored vehicles, tanks and other military equipment. Hence, the required RMS of warship must be studied to enhance its mission successfulness, but the lack of effective techniques and methods has made it very difficult to implement the RMS design, analysis, and assessment of warship. Additionally, traditional experience and mathematical analysis methods have some problems in effectively determining the technical indicators of RMS and plausibly guaranteeing the allocation and scheduling of resources [2].

With a complicated and giant system, a warship is often composed of hull, propulsion system, power system, navigation system, communication system, and combat system. Among them, propulsion system is an important shipboard system at the heart of warship, and plays a significant
role in the mission successfulness of warship [3]. For this reason, this paper will combine the computer-assisted modeling and simulation techniques with Anylogic software, and employ the method of multi-agent simulation to build a mission-based RMS simulation model of warship during the voyage of warship propulsion system, and assess the mission successfulness of warship on this basis.

2. Identification of indicators for comprehensive model assessment
Mission completion success probability (MCSP) is how possibly equipment could complete an assigned mission in a given mission section [4]. It is the basic measure of mission successfulness. MCSP is not only related to such factors as equipment reliability, maintainability, operation environment, and mission requirements, but also closely linked to supportability. Therefore, identifying the RMS indicators will provide an important basis and premise for further study.

2.1. Reliability indicator
Reliability is the ability of warship propulsion system to complete the assigned mission under the specified conditions and in a given period. It is normally denoted by R(t). Warship propulsion system belongs to repairable equipment, so that its reliability is often assessed in terms of mean time between failure (MTBF) [5].

MTBF represents the expected random variation of the time between two adjacent failures of equipment (including repair time).

MTBF could be determined by recording the time and number of equipment failures in the process of simulation and using the following Equation (1):

$$MTBF = \frac{\sum_{i=1}^{N} TBF_i}{N}$$  \hspace{1cm} (1)

where $TBF_i$ is the time between the $i$th failure of equipment and the previous failure; $N$ is the number of equipment failures in the simulation.

2.2. Maintainability indicator
Maintainability is the ability of warship to maintain or restore the specified state when it is maintained with the specific procedure and method under the specified conditions and in a given period. It is very important to warship. The common indicator for warship system maintainability is mean time to repair (MTTR).

MTTR represents the expected random variation of the time needed to repair equipment and restore its operation.

MTTR could be determined by recording the time and number of equipment repairs in the process of simulation. The statistical value of MTTR is calculated with the following Equation (2):

$$MTTR = \frac{\sum_{i=1}^{N} TCM_i}{N}$$  \hspace{1cm} (2)

where $TCM_i$ is the time when the $i$th repair of equipment occurs; $N$ is the number of equipment repairs in the simulation.

2.3. Supportability indicator
Supportability is the ability of the planned supporting resources to satisfy the needs of equipment during normal operation and wartime. It is a designed feature of warship system. Supportability is mainly indicated by resource sufficiency $P_c$, which is the probability of timely supply when any spare part is needed for equipment.

Resource sufficiency is calculated for different types of resources at different levels of repair respectively using the following Equation (3):

$$P_c = \frac{\min(m,n)}{m}$$  \hspace{1cm} (3)

where $m$ is the total amount of a specific resource needed for a level of repair in the simulation; $n$ is the total number of the resources available for the level of repair.
3. Voyage mission successfulness of warship propulsion system

The mission of warship during voyage is to arrive at the designated sea area at a given time. At the beginning of a combat, the equipment of warship must be available (free of failure), e.g. propulsion and power system equipment, and shipboard guns. If any equipment failure occurs, it will adversely affect the operation of warship in combat. Considering the direct impact of its failure on combat, propulsion system equipment is regarded to be essential to combat [6].

3.1. Definition

According to analysis, the voyage mission failure of warship is divided into two types:

(1) The warship fails to arrive at the designated sea area at a given time;
(2) The combat equipment is in the failed state at the end of voyage.

Therefore, the voyage mission successfulness of warship propulsion system is defined as follows: the voyage mission of warship propulsion system is successfully completed when the system is able to support the warship with sufficient propulsion till its arrival at the designated sea area at a given period, and no equipment in the system is in the failed state at the end of the voyage [7].

3.2. Calculation

After taking equipment and warship as two agents, the voyage mission successfulness of propulsion system is simulated and calculated. It is represented by mission completion success probability (MCSP).

The voyage MCSP of warship propulsion system is denoted by \( D \),

\[
D = \frac{N_s}{N} = \frac{(N - N_f)}{N} \tag{4}
\]

where \( N_s \) is the number of successful voyages; \( N_f \) is the number of failed voyages; \( N \) is the total number of voyages.

3.3. Determination

According to its definition, mission successfulness is determined by two factors:

(1) Whether the warship arrives at the designated sea area at a given period

After warship stops for the repair of failed equipment, it must speed up to catch up the lost time caused by such stop. The speed is represented by \( v_n \), which must be less than the maximum constant speed of warship \( v_{max} \). Therefore, whether the warship arrives at the designated sea area at a given period could be determined by comparing \( v_n \) and \( v_{max} \).

\[
\begin{align*}
\text{successful arrival at the designated sea area at the given time, } v_n &\leq v_{max} \\
\text{failed arrival at the designated sea area at the given time, } v_n &> v_{max} \tag{5}
\end{align*}
\]

(2) Whether any equipment is in the failed state at the end of voyage

\( ① \) If any equipment has a critical failure during voyage, and is still in the failed state during combat since such failure is irreparable, the mission fails.

\( ② \) If any equipment has a failure during voyage, which is not critical, the time to repair such failure, that is, MTTR, is also subject to negative exponential distribution, and the time of the last equipment failure during voyage is \( T_f \), whether the equipment is in the failed state at the end of voyage is determined by:

\[
\begin{align*}
\text{equipment is in the normal state at the end of voyage, } T_f + \text{MTTR} &\leq T_0 \\
\text{equipment is in the failed state at the end of voyage, } T_f + \text{MTTR} &> T_0 \tag{6}
\end{align*}
\]

When both conditions (1) and (2) are satisfied simultaneously, the mission is successful.

4. Multi-agent modeling

Equipment in the warship propulsion system and the warship are regarded as agents to perform the modeling of the propulsion system based on the reliability, maintainability, and supportability of voyage mission, and determine the mission reliability of warship propulsion system during voyage.

4.1. Structure of warship propulsion system
Based on actual condition and references, it is determined that the propulsion system is composed of two gas turbines, two diesel engines, one set of surveillance equipment, one set of auxiliary equipment, two sets of speed reducing equipment, two shaft systems, and two shaft systems and two propellers. Considering the system functions and operating principles [8-11], two diesel engines could meet the needs of voyage mission. When both diesel engines fail, the warship could be driven by one gas turbine, and then enter any other mode as the case may be. There is only one set of surveillance equipment and one set of auxiliary equipment, so that no alternative is available if any failure happens to them. On this basis, the mission reliability of the system during voyage is given in Figure 1.

4.2. Creation of agents
First of all, warship propulsion system is further divided into warship equipment module, spare part module, and system module. Each module is defined as a type of agent.

4.2.1. Equipment module. The software Anylogic is employed as the development platform to simulate how the warship propulsion system fails and is restored to the normal state based on the actual condition of the system. The interface of the created system is presented in Figure 2.

![Figure 1. Reliability of warship propulsion system.](image1)

![Figure 2. Simulation interface of equipment module.](image2)
Based on the actual condition and theoretical analysis, the failures of warship system during voyage are categorized into:

a. Critical failure: It is the failure of warship system during voyage, which could not be repaired because of restrictive conditions. It exerts a direct effect on the mission completion of warship.

b. Noncritical failure: It is the reparable failure of warship equipment during voyage. It seems not to have any direct impact on the mission completion of warship, but may also lead to the voyage mission failure of warship.

Considering the distribution of equipment failure, Anylogic simulation software could generate failures stochastically, making equipment enter the “failed” state. However, a process in the “maintenance state chart” is needed to restore the “normal” state of equipment. The maintenance state chart is shown in Figure 3.

![Maintenance state chart of equipment module.](image)

**Figure 3.** Maintenance state chart of equipment module.

Equipment maintenances are classified into preventive maintenance and breakdown maintenance. Preventive maintenance means that maintenance is performed prior to any failure or damage of warship equipment. Functional failure could be prevented by means of systematic product check, equipment test and replacement, so that equipment could perform all activities in the specified state. Breakdown maintenance, also known as corrective maintenance, refers to the maintenance performed to restore the state of warship equipment for the execution of the specified function after a failure is identified. As shown in the maintenance state chart, maintenances could be also categorized into maintenance requiring spare parts and maintenance not requiring spare parts. Hence, spare part storage should be created to meet the needs of maintenance, which is also achieved with the multi-agent modeling.

4.2.2. **Spare part module.** Spare parts refer to the modules, assemblies and parts used to replace the existing parts of equipment system. The spare parts of warship equipment are the modules or assemblies kept on board when the warship is executing the voyage mission, and used to replace the exclusive parts of warship equipment. They are important physical resources for guaranteeing the smooth implementation of warship equipment maintenance. The modeling of spare part module is mainly intended to simulate how spare parts are needed and consumed. The interface of simulation is presented in Figure 4.
4.2.3. **Warship propulsion system.** Warship propulsion system is a very complicated system. It is mainly responsible for the voyage mission, so that it is the subject of research in this paper. The model simulation interface in the software Anylogic is presented in Figure 5.

In the creation of agents for the warship system, it is necessary to specify the work relations of equipment in the system as well as the impact of their reliability on the system, which is most perfectly indicated in the reliability diagram of warship equipment. Based on the actual condition, warship propulsion system comprises 12 units of equipment. In the simulation, equipment agents are embedded into the agent of warship system. The variation of equipment state will cause the state change of warship propulsion system between “navigation” and “suspension” during the execution of the voyage mission.

After a voyage mission ends, the “state change chart” of the propulsion system judges the mission successfulness according to the judgment conditions, and records the number of “successful” or “failed” missions, so as to determine the mission completion success probability of the simulation system.

### Figure 4. Simulation interface of spare part module.

#### Figure 5. Simulation interface of warship propulsion system.

4.3. **Communication between agents**
In the warship propulsion system, the communication between equipment modules is needed. On this basis, the reliability diagram between equipment in the warship propulsion system is formed to affect the state of the system comprehensively. The communication between equipment module and spare module is needed to ensure the required maintenance and part replacement of failed equipment, so as to restore the “normal” state. The above communications must be achieved in the same way, that is, connecting two modules by communication line, and achieving information exchange by sending commands. The communication connection is shown in Figure 6.

![Figure 6. Communication connection of equipment and spare parts.](image)

**4.4. Model simulation process**

After creating the agents of equipment, spare parts, and warship system, the software Anylogic is employed for the integrated modeling of the reliability, maintainability, and supportability of warship propulsion system, and simulation calculation is carried out for the voyage mission successfulness. The general simulation process is presented in Figure 7.
4.5. Model simulation results
By combining the case study with the model study, the task success rate of the simulation model for the reliability, maintainability and supportability of the ship's power system can be obtained, as shown in Figure 8. The number of simulations was set to 100000. After 50000 simulations, the success results tended to be stable, and the number of simulations continued to increase without affecting the numerical convergence. Among them, the result obtained was the number of mission successes 82912 times, accounting for 82.9%. The number of mission failures was 17088, accounting for 17.1%.
5. Conclusions

Propulsion system, as one of the important shipboard systems, is studied in this paper. With the software Anylogic as the platform, the multi-agent simulation method is employed to develop the equipment RMS simulation model based on the voyage mission, and assess the mission successfulness. The voyage mission successfulness of warship propulsion system is defined and analyzed to identifying the indicators for the assessment of RMS simulation system. Considering the reliability relationship between its equipment, the entire system is divided into equipment module, spare part module, and system module. After determining the way of communication between these modules and the general modeling and simulation process, this paper presents the simulated process from the suspension of warship system because of the failed equipment of warship propulsion system during the voyage mission to the restoration of normal state and resumption of navigation thanks to the maintenance by the crew and the supporting resources including spare parts. Therefore, a complete RMS simulation model of warship propulsion system is formed, while the RMS parameters of equipment are generated including mean time between failures, mean time to repair, resource sufficiency, and mission completion success probability. On this basis, the entire simulation system is assessed. This simulation model is built to provide the reference and basis for the studies on other shipboard systems such as power system and communication system, and also lays a foundation for the RMS simulation modeling of the entire warship and the study of probability of mission completion success.

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