공학석사 학위논문

Optimization of Crew Manning Considering Operation Scenarios of a Naval Ship

전투함의 운영 시나리오를 고려한 승조원 구성 최적화

2023 년 2 월

서울대학교 대학원
조선해양공학과
송 하 민

Optimization of Crew Manning Considering Operation Scenarios of a Naval Ship

지도 교수 노 명 일

이 논문을 공학석사 학위논문으로 제출함
2022 년 10 월

서울대학교 대학원
조선해양공학과
송 하 민

송하민의 공학석사 학위논문을 인준함
2023 년 2 월

위 원 장 ____ 우 종 훈 ____ (인)
부위원장 ____ 노 명 일 ____ (인)
위 원 ____ 김 도 균 ____ (인)

Contents

Figures

Tables

Abstract

Optimization of Crew Manning Considering Operation Scenarios of a Naval Ship

Hamin Song

Naval Architecture and Ocean Engineering

The Graduate School

Seoul National University

Currently, the military is planning to reduce the number of troops for reasons such as a decrease in the youth population and a shortened service period. However, battleships require more crew than before due to increased size, mounted weapons, and equipment. Therefore, deploying the appropriate number of crew members on the battleships is important. In addition, since battleships must consider various operating situations (combat, maintenance, etc.) and crew members have various specialties, it is essential to optimize the crew's composition to suit the battleships' characteristics. To this end, the Navy relies on experts with relevant know-how and data based on legacy ships. Still, additional optimization is required for reasons such as changes in military policy, enlargement of new battleships, and diversification of weapons.

In this paper, given the specifications of the design ship and major mounted equipment, the crew composition is primarily calculated using the data of the military's legacy ship currently in operation. Since the result was calculated based on the past, the expert system was additionally used to calculate the result reflecting the characteristics of the ship I designed and the current operation of the ship. Afterward, a method of optimizing the composition of the crew was studied using the simulation method.

The estimation method based on legacy ship data estimates crew members with various specialties in consideration of ship specifications and loaded weapons and estimates the crew composition suitable for the design ship using regression analysis. The estimation method of an expert system uses rule-based expert systems to re-estimate the crew member composition.

The estimation method based on simulation optimizes the composition of the crew by comparing and analyzing mission execution time and efficiency using Discrete Event System specification (DEVS) simulation in consideration of scenarios that mimic the actual operating situation of the ship.

Finally, a self-developed program was implemented for verification, and the performance was verified by inputting the specifications of the US Navy ship and the number of crew members into the program.

Keywords: Crew manning, Naval ship, Optimization, Simulation

Student number: 2021-21275

1. Introduction

1.1. Research background

Currently, the military has reduced the number of standing troops from 618,000 in early 2018 to 500,000 in 2022 in the ‘2327 Mid-term Defense Plan’ due to the decrease in available military resources due to the population cliff and changes in military strategy and will be maintained thereafter [1]. However, the Navy is currently next-generation destroyers, Aegis destroyers, and light aircraft carriers to enhance ship power, expand air operation missions, and establish the 7th Task Force. By 2030, it is expected that there will be a shortage of about 3,000 troops compared to today. (Hwang et al., 2019) Contrary to the growing shortage of troops, battleships are becoming larger and more complex than in the past, and various weapons and sensors mounted on ships to cope with complex warfare, such as anti-aircraft, anti-submarine, and anti-ship, are becoming more complex. Therefore, more operating personnel are required. In addition, optimizing crew composition contributes to operational effectiveness (Renee et al., 2016) and cost reduction (Tyson et al., 2006), and since soldiers' salaries are continuously increasing, the importance of optimizing crew composition is becoming more prominent. It is becoming. To this end, in this paper, based on the data based on the legacy ship data, the crew is calculated based on the current standard, supplemented with an expert system, and scenarios of various battleships are written and substituted to optimize the appropriate number of crew members for the battleship.

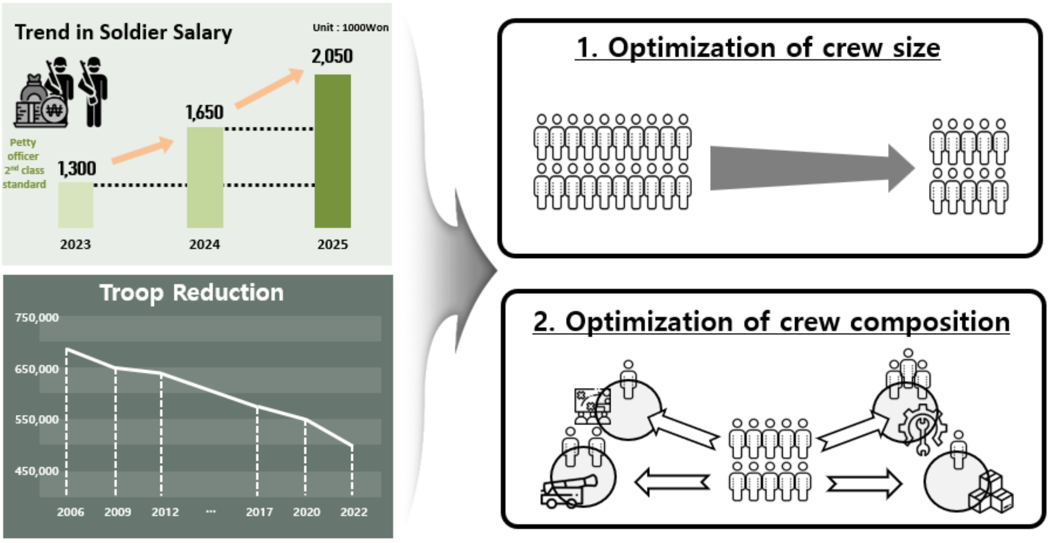


Figure 1. Motivation of research

1.2 Related works

Various studies have been conducted to estimate crew composition. John et al. (1997) estimated crew requirements through analysis with logs of crew activities and a shipboard task analysis of 4 oil tankers and 2 container ships. Tyson et al. (2006) estimated the size of personnel using empirical data and simulation for ship systems (propulsion, combat systems, communication, etc.), maintenance strategy, and level of automation. Later, Renaldo et al. (2014) developed and utilized IMPRINT (Improved Performance Research Integration Tool) PRO, a probabilistic simulation software program, to solve the crew member problem of the US Navy warship LCS (Littoral Combat Ship) and optimized the personnel. Renee et al. (2016) produced SCORE (Simulation for Crew Optimization and Risk Evaluation) tool to optimize the crew composition of future ships and evaluate the crew composition of current ships. In a study on the optimization of the crew composition of the Korean Navy, Hwang et al (2019) calculated the relationship between the weight of Korean Navy vessels and the number of crew members through regression analysis, and Kim et al. (2020) produced a scenario for the Korean Navy and calculated the composition and size of the crew using the Queue model and the Discrete Event System Specification (DEVS) model. Previous studies related to crew member estimation are summarized in Table 1.

Table 1. Previous studies related to crew estimation

Study	Crew estimation	Expert system	Optimization	Optimization tool
John et al. (1997) [2]	O	X	O	CSEM1)
Tyson et al. (2006) [3]	O	X	O	ISMAT2)
Renaldo et al. (2014) [4]	X	X	O	IMPRINT3) Pro
Renee et al. (2016) [5]	X	X	O	SCORE4)
Hwang et al. (2019) [6]	O	X	X	-
Kim et al. (2020) [7]	O	X	O	DEVS5)
This study	O	O	O	DEVS

There have been various studies, but no study has used optimization and expert systems at the same time for crew member estimation. Therefore, we propose an optimal crew member estimation method based on legacy ship data, expert system, and simulation.

1.3 Target of the study

The target of this study can be summarized as follows.

(1) First estimation based on legacy ship data

(2) Second estimation based on expert system

(3) Final estimation based on DEVS

Figure 2 summarizes the target of this study.

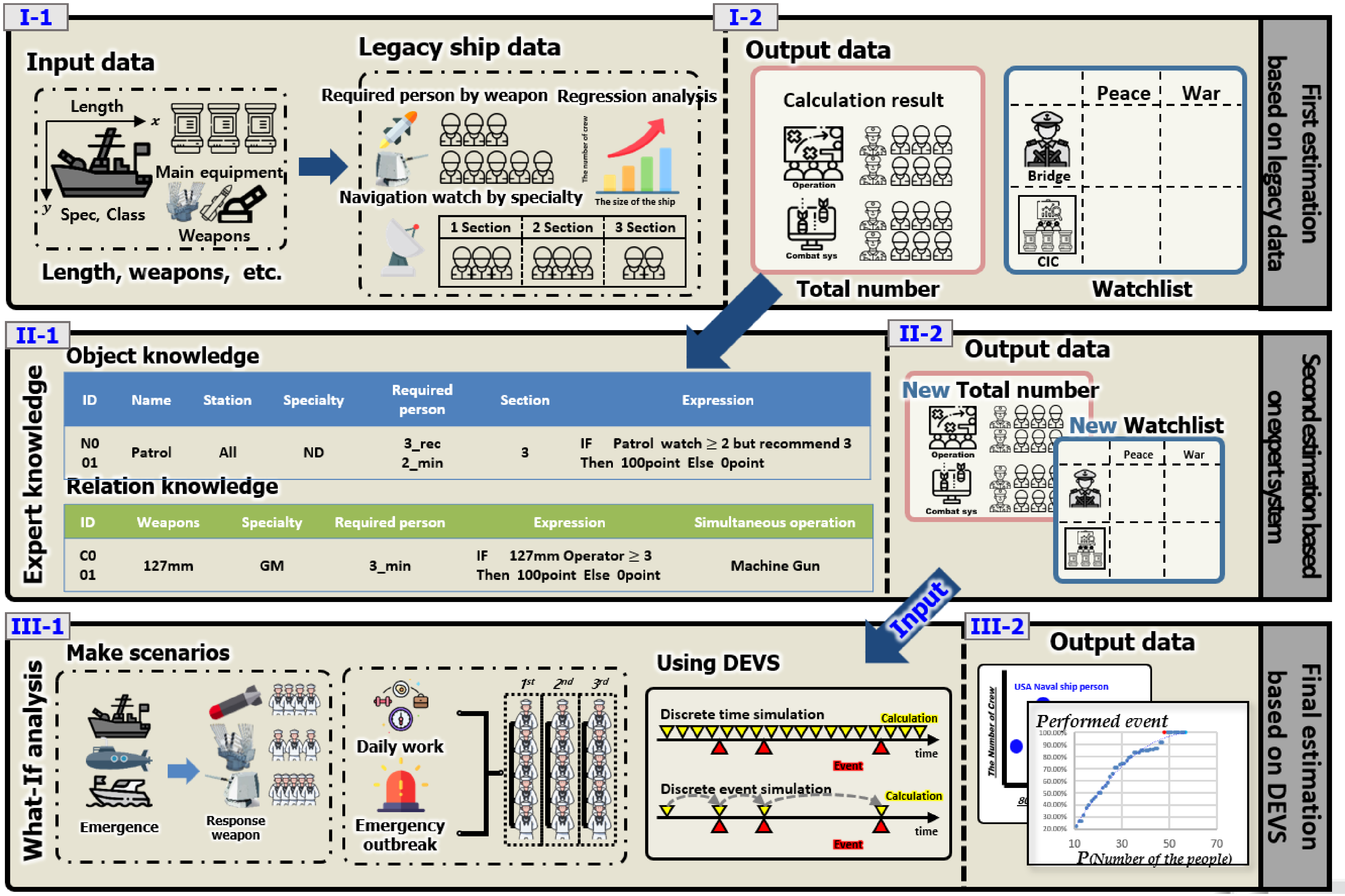


Figure 2. Summary of each component for the optimization of crew manning

I-1 and 2 of Figure 2 are Chapter 2 first estimations based on legacy ship data. In I-1, a crew estimation model is built using empirical data from past ships. When constructing, the special characteristics of the crew and the operating method of the ship were considered. After that, if the specification of the ship to be designed and the equipment to be designed are put into the system as input data, the composition of the crew and the mission and mission station in wartime and peacetime, which is the basis for calculating the result, is output as the calculation result, just like I-2.

II-1 and 2 of Figure 2 are Chapter 3 second estimation based on the expert system. In II-1, the user who sees the results of the first estimation classifies the characteristics and operation method of the ship currently being designed through the expert system into object information and related information and inputs them into the expert system. Then, the information is received, the user's opinion is reflected in the criteria of the first estimation, and the crew is calculated again with the reflected system. As a result, as in II-2, the composition of the crew and the mission and mission station in wartime, which is the basis for calculating the result, are recalculated. At this time, the user’s opinion is input by dividing it into object information and relational information, and the calculation result is the composition of the crew and the mission and mission station in wartime, which are reflected as expert opinions.

III-1 and 2 of Figure 2 are Chapter 4, the final estimation based on DEVS. In III-1, a scenario is set suitable for naval ship operation, and a simulation model is created using DEVS (Discrete Event System specification), and simulation is performed. Afterward, the results in III-2 are used to calculate the optimal number of people using the What-If Method.

In Chapter 5, the program composition using the finally developed method is briefly described, and in Chapter 6, the composition of the crew was calculated using the specifications and mounted equipment data of the US Navy ships, and the composition of the crew was compared with that of the US Navy ships. The significance of the result was confirmed. And in Chapter 7, a summary of the results and future research directions were described.

2. The first estimation based on legacy ship data

In this chapter, a method for estimating the composition of the crew using legacy ship data is explained. First of all, the crewman's specialties and ship operation characteristics are explained, and then the method of estimating the crew considering the characteristics is described [8].

2.1. Overview of the crew on board the naval ship

In the Navy, a crewman aboard ships is generally divided into 15 specialties within four divisions. Here, the specialty is a system that subdivides various tasks of the military into specialized fields and designates fields in which individuals can efficiently perform their duties based on their professional knowledge, abilities, and knowledge. A brief description of each department and specialty is provided below.

2.1.1. Boatswain’s Mate (BM)

The BM handles various equipment related to the entry and exit of ships, learns various deck technologies such as ship towing and maritime supply methods in order to carry out operations of combat ships, and is in charge of completing tasks such as assisting with various events for administrative duties.

2.1.2. Quartermasters (QM)

In order to promote safe navigation and carry out missions to assist navigation, QM learns various navigational techniques and acquires theories and techniques to maneuver ships as navigators, such as navigational equipment operation techniques and mastery of steering techniques. In addition, it is responsible for providing visual combat information by identifying aircraft and ships during operations and training.

2.1.3. Information Technician (IT)

It is in charge of tasks related to satellite communication equipment, digital professional processing system, network-oriented information communication infrastructure, wired and wireless communication equipment, and operation and maintenance of computer and peripheral devices.

2.1.4. Operation Specialist (OS)

OS acquires knowledge of the establishment procedure and evaluation of combat information and operates various radar and detection equipment in the combat information control room of the ship. In addition, it is in charge of assisting the commander by collecting and evaluating various information during general navigation, combat, and training situations.

2.1.5. Electronic Warfare (EW)

EW collects/analyzes/identifies/evaluates various electronic information and implements electronic countermeasures when necessary. It is also responsible for maintaining the equipment in peacetime.

2.1.6. Electronic Technicians (ET)

ET is in charge of efficiently using/maintaining the equipment by acquiring electronic technology for preventive maintenance and repair work of various electronic equipment in various fields of communication electronics.

2.1.7. Fire Controlmen (FC)

FC is in charge of the operation and maintenance of the fire control system, combat system, related equipment, repair parts, etc.

2.1.8. Sonar Technician (ST)

ST performs missions of operating and maintaining sonar and underwater intelligence equipment that detect targets using sound waves, detect submarines and mines through sound waves, and play a pivotal role in anti-submarine warfare and anti-mine warfare.

2.1.9. Gunner's Mate (GM)

GM is in charge of operating and maintaining marine firearms, ammunition/explosives, and related equipment, devices, and repair parts.

2.1.10. Gasturbine System (GS) / Enginermen (EN)

GS/EN is in charge of operating and maintaining engines, accessories, and control systems related to propulsion, such as gas turbines and internal combustion engines.

2.1.11. Electrician's Mate (EM)

EM is in charge of the maintenance and repair of motors, generators, gyros, inspection, maintenance, and repairs of other electric devices, circuits, propulsion control systems, etc.

2.1.12. Machinery Repairman (MR)

MR mainly performs repair and maintenance work of ships and is in charge of damage control work to restore the damage in case of fire, flooding, or hull damage.

2.1.13. Culinary Specialist (CS)

As the unit's nutritionist, the CS is in charge of billing, receiving, and storing all items related to unit members' menu preparation, restaurant hygiene management, and meal service.

2.1.14. Yeoman (YN)

YN is in charge of overall personnel/administrative support for the unit, including electronic document processing, law and regulation management, event work, personnel relations statistics and salary, and welfare work.

2.1.15. Hospital Corpsman (HM)

HM is in charge of medical-related duties, and as an assistant to the military surgeon, it is responsible for preventing and treating various injuries and managing and supervising the sanitary conditions of the unit.

2.1.16. Division of naval ship

Departments of Navy battleships are divided into four departments: Operation, Combat system, Engineering, and Supply division, according to the relevance of the work performed under the captain. The operation division is in charge of ships' basic operation and operational assistance and consists of BM, QM, IT, OS, and EW. The combat system division is in charge of the combat system and weapons operation and consists of ET, ST, FC, and GM. The Engineering division is in charge of engine and ship maintenance and consists of GS/EN, EM, and MR. Finally, the Supply division is in charge of in-ship administration and crew support and consists of CS, HM, YN, ETC (reinforced when necessary, such as supply, finance, and training).

2.2. Key consideration for estimation of crew manning

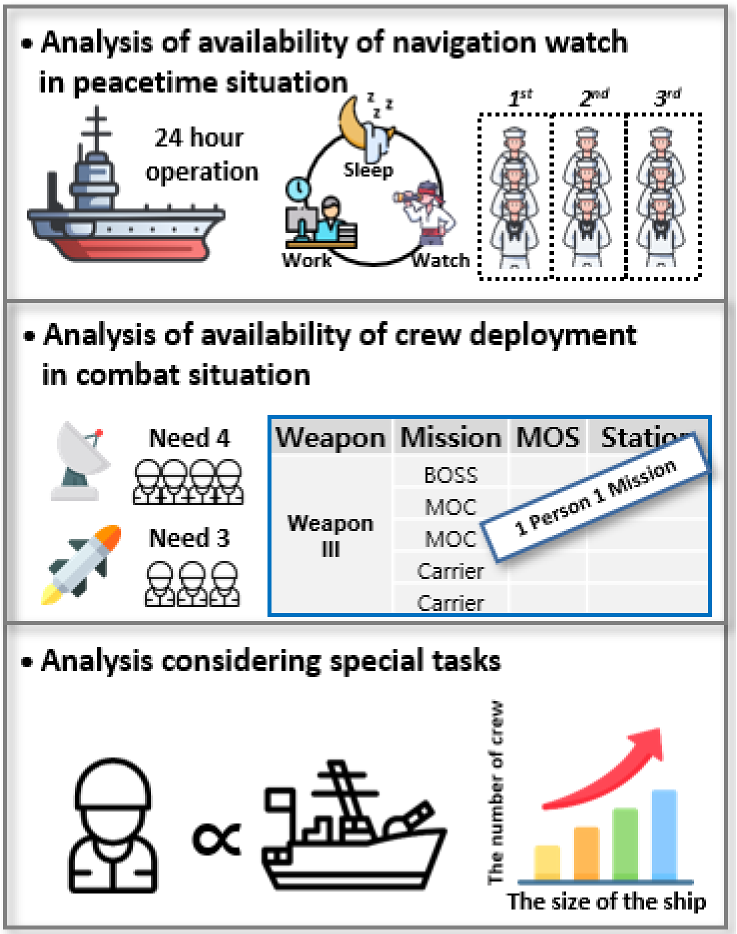


Figure 3. The main consideration of estimation of crew manning

As shown in Figure 3, when calculating crew members in the Navy, it is generally calculated by considering three things. The first is whether a navigation watch is available. Ships operate a navigational watch in a three-person system during peacetime, and personnel must be deployed to respond in an emergency. The second is whether it is possible to deploy personnel in a combat situation. In a combat situation, the crew must be deployed so that all sensors and ordnance can be operated.

The last is whether or not the ship can perform its tasks. A certain number of people are required to carry out the tasks given by the specialty within the set daily schedule, and in some specialties, more people than the above two cases are required.

The crew is calculated by selecting the largest value among the calculated values through the three criteria described above. However, in this paper, the number of people was calculated by applying one criterion for each specialty because the main standard with the largest result among the three criteria was generally established for each specialty.

2.2.13. Analysis of the availability of navigation watch

Ships operate a navigational watch in a three-person system in peacetime. At this time, the sensor and arming operation console should be staffed so that minimum response is possible in case of an emergency.

In the case of engine equipment, monitoring is carried out in the engine control room, and patrol watch officers are placed to check the status piece of equipment regularly.

In general, the navigation watch is set considering the class and operational scope of the ship and the specialties for which the navigation watch is the main factor are QM, IT, OS, EW, ET, and ST.

Table 2. Example of a navigation watch list of QM specialty

1st Class	**2nd Class**	**3rd Class**
Duty Petty Officer	Duty Petty Officer	Duty Petty Officer
Duty Petty Officer	Duty Petty Officer	Duty Petty Officer
Duty Petty Officer	Duty Petty Officer	Duty Petty Officer
Steersman	-	-
Steersman	-	-
Steersman	-	-

Table 2 is an example of a navigation watch list specializing in QM. In the system, data is organized for all specialties, and the navigational watch may change in relation to the operation of the ship according to the specialties.

2.2.14. Analysis of availability of crew deployment in a combat situation

The second is whether it is possible to deploy crew in a combat situation. All sensors and weapons must be operable during a combat deployment, and a crew for damage control is deployed in preparation for emergencies.

In general, personnel deployment in a combat situation is set mainly for each specialty and equipment operation, and the specialties for which the relevant matters are the main criteria are FC and GM.

Table 3. Example of crew deployment of a gun in a combat situation

127mm Gun		76mm Gun		40mm Gun	
Mission	**Specialty**	**Mission**	**Specialty**	**Mission**	**Specialty**
Commander	GM	Commander	GM	Commander	GM
Panel operator	GM	Panel operator	GM	Console operator	FC
Panel operator	GM	Console operator	FC	About ammunition	Anyone
Console operator	FC	About ammunition	Anyone	Ammunition mover	Anyone
About ammunition	Anyone	About ammunition	Anyone	-	-
About ammunition	Anyone	About ammunition	Anyone	-	-
About ammunition	Anyone	-	-	-	-
About ammunition	Anyone	-	-	-	-
About ammunition	Anyone	-	-	-	-
About ammunition	Anyone	-	-	-	-

The situation of the ship. In the system, data on all weapons are organized, and additionally, data is organized on all places that require personnel deployment in addition to weapons so that all crew members are given missions in combat situations.

2.2.15. Analysis considering the special task

The third is to consider the individual tasks of each specialty. In the case of the engineering division or CR specialty, it is more important to perform equipment inspection or meal preparation, which are one's own duties, rather than combat situations or navigation watch positions. Therefore, the engineering division performs maintenance, which is a unique task (the above two items are the main considerations, but consider their importance), and CR is calculated according to the total number of people who need to prepare meals.

In principle, a regression analysis should be performed on the number of crew members and the number of individual tasks, but due to the limitations of securing data, this study performed a regression analysis on the length of the ship and the crew members. The specialties for which the relevant matters are the main criteria are BM, Engineering division, CR, YN, and HM.

2.3. System configuration of the first estimation

As shown in Figure 4, the system of first estimation consists of four steps. The first step is to input the input data. Input data consists of the specification and weapons of the ship I want to design, which is currently used as a major factor in concept design and crew composition estimation by the Korean Navy. The second step is calculating the number of crew for each specialty through the key considerations described in Section 2.2. The third stage completes the navigation watch list and combat deployment list by designating specialties for missions where specialties were not specified in the navigation watch when the second stage was formed or when deploying crew in a combat situation. And with the output data, the specialties of the crew, the number of crew, the navigation watch list, and the combat deployment list are estimated.

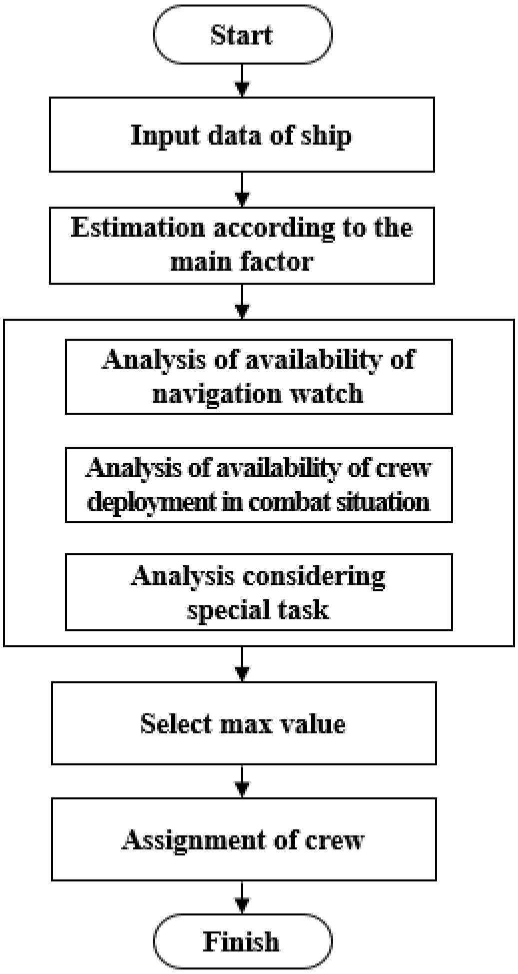


Figure 4. System configuration of the first estimation

2.3.13. Input data of the first estimation

Ship class				1 / 2 / 3
Ship length				00m
Weapon	Anti surface	GUN	127mm	Quantity
			76mm	Quantity
			40mm	Quantity
		Missile		Equiped or not
		MG		Quantity
	Anti air	Missile	SM-II	Equiped or not
		Defense	RAM	Quantity
			CIWS	Quantity
			Decoy	Equiped or not
	Anti submarine	Anti-sub rocket		Equiped or not
		Light torpedo		Equiped or not
		Depth charge		Equiped or not
		TACM		Equiped or not
Sensor	Electronic warfare			Equiped or not
	Anti air	Function		Equiped or not
		Aegis-radar		Equiped or not
	Anti submarine	HMS		Equiped or not
		Towed array sonar		Equiped or not

Figure 5. Format of input data

Figure 5 is the Format of the input data. It is divided into Weapon and Sensor, and each weapon is further divided into battles that are mainly performed. For the relevant contents, the input data was configured at a level that became the standard of concept design for use in concept design by the military later.

2.3.2. System configuration of the first estimation

As shown in Figure 4, the number of crew members is estimated by selecting the largest value among the major considerations when estimating the crew composition in Chapter 2.2.

2.3.3. Assignment of crew

All crew members must be committed to missions in combat situations or during navigation, but looking at the estimation results as shown in Figure 6, the QM's specialty, in which the navigation watch situation is the main factor, is sometimes not assigned a mission in a combat situation, and the combat situation is the main factor In GM's specialty, there are cases in which missions are not assigned in Navigation watch. In addition, since the number of personnel has not been assigned to missions that are not related to specialties, they are assigned to crew members capable of performing the mission, and the final result is shown to the user.

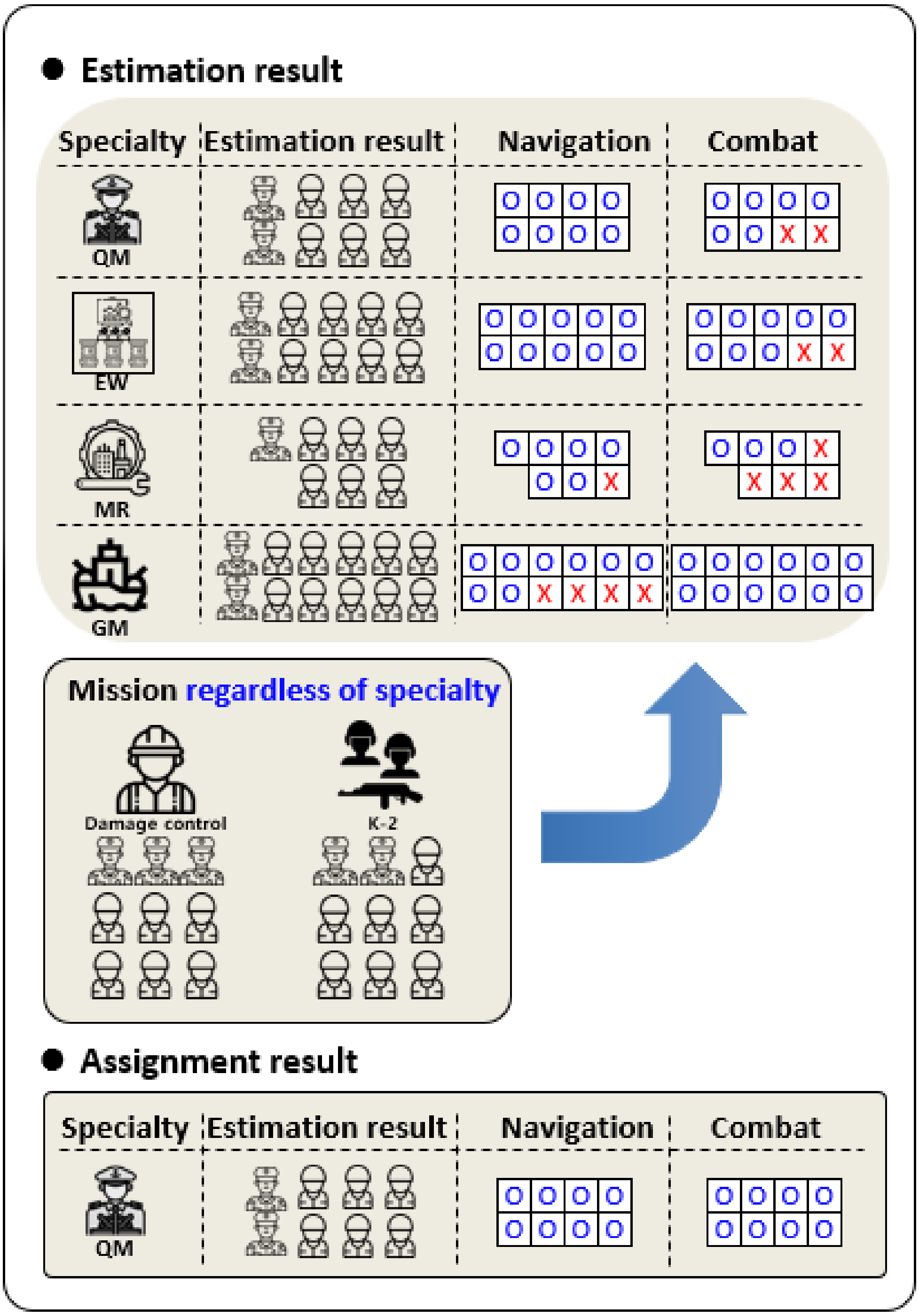


Figure 6. Assignment of crew

2.3.4. Output data of the first estimation

An example of output data is shown in Figure 7. The composition consists of departments, specialties, navigational watch positions, and missions and positions in combat situations.

Division	Specialty	Person	Navigation watch	Station	Combat watch	Station
Combat system	FC	FC 1	Weapon I	CIC	Weapon I	CIC
		FC 2	Weapon I	CIC	Weapon I	CIC
		FC 3	Weapon II	CIC	Weapon II	CIC
	GM	GM 1	Weapon I	Out-Board	Weapon I	Out-Board
		GM 2	Weapon II	Equip RM	Weapon I	CIC
		GM 3	Weapon II	CIC	Weapon II	CIC

Figure 7. Output data of the first estimation

3. The second estimation based on the Expert system

3.1. Knowledge representation

The dictionary definition of an expert system is a system designed to have the same or higher problem-solving ability than an expert by accumulating expert knowledge, experience, know-how, etc., in a computer.

The performance of an expert system is directly related to how to efficiently and effectively express and store the acquired knowledge to the extent that an expert system is composed of knowledge and inference mechanisms. In this section, we look at production rule, semantic net, and frame, which are currently widely used knowledge expression methods[9].

3.1.1. Production rule

Production rules are the most widely known knowledge representation method. It consists of an IF statement and a THEN statement, and if the condition of the IF statement is satisfied or occurred, the THEN statement is executed or becomes logically true. In general, the form is shown below.

- IF <antecedent>
- THEN <consequent>

In general, you can use AND, OR, or NOT to make statements clearer. An example of organizing the legacy ship data of the crew of a ship is as follows.

Rule1

- IF Acoustic detection equipment is mounted and (^) ship is 1st Class.
- THEN 6 crew with ST specialty boarded the ship.

Rule2

- IF Acoustic detection equipment is mounted and (^) ship is not 1st Class.
- THEN 3 crew with ST specialty boarded the ship.

Relation, recommendation, instruction, strategy, and heuristics can be expressed by using production rules (Durkin, 1994). But there are downsides too. Computers do not have semantic discernment capabilities and are at the level of having only literal comparison capabilities, so they recognize completely different rules even if they are the same sentence. To solve this problem, describing semantics can be a solution.

3.1.2 Semantic net

The semantic net is based on a psychological model of human associative memory. A semantic net is a network structure composed of arcs to express the relationship between nodes to express a specific entity or concept and has been mainly applied to the modeling of natural language processing in the 1960s. Figure 8 is a semantic network constructed of natural language, "On May 23rd, soccer player Heung-Min Son received the Golden Boot."

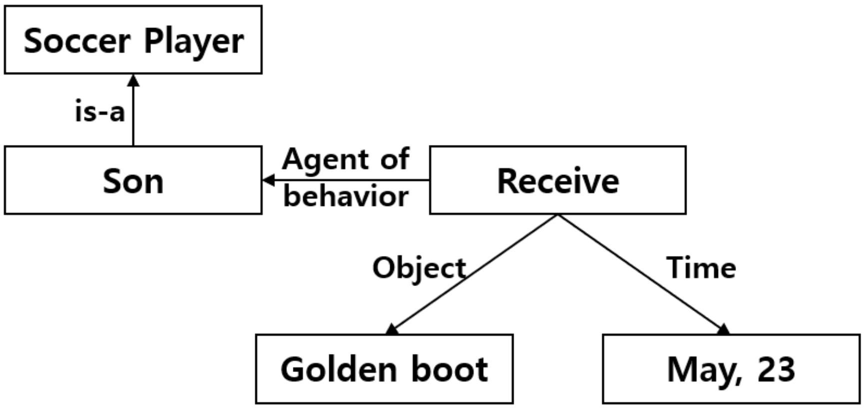


Figure 8. Example of semantic net

Semantic net has the advantage of being easy to understand and flexible in expression, but the node structure is simple, so even simple properties must be expressed as independent nodes like other objects. Therefore, even if the problem becomes a little complicated, it takes a long time to find the Semantic net.

3.1.3 Frame

The frame is a more systematized structure of nodes compared to the semantic net, and it is a data structure that can express several contextual pieces of information about a target or object as a structured frame. Specifically, expression using frames has a similar structure to a semantic net, but one frame is composed of several slots, and each slot represents each characteristic of an object. Figure 9 is an example of a frame for an airline ticket.

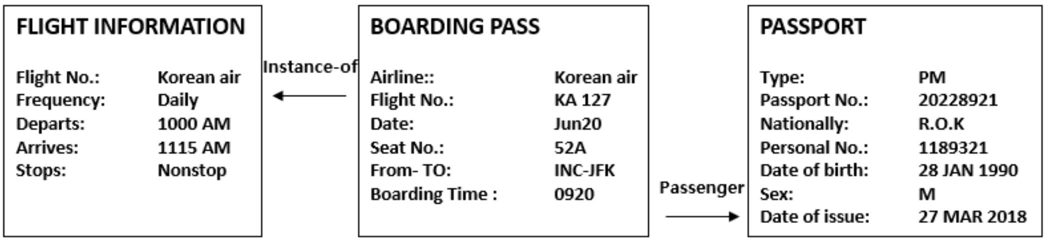


Figure 9. Example of a frame

Hierarchical structure formation and inheritance are possible between each frame, and a procedure can be attached that specifies what kind of action should be performed when contents are added, removed, or reinforced. However, there are too many unnecessary nodes or frames, so there is too much information to express the necessary data, and scalability and reusability are poor compared to other methods [9].

3.1.4 Hybrid knowledge representation

Depending on the characteristic of the problem, it may be difficult to express it with only one expression method. In this case, knowledge can be expressed by mixing various expression methods. The following is a partial process of ship design expressed in the corresponding method.

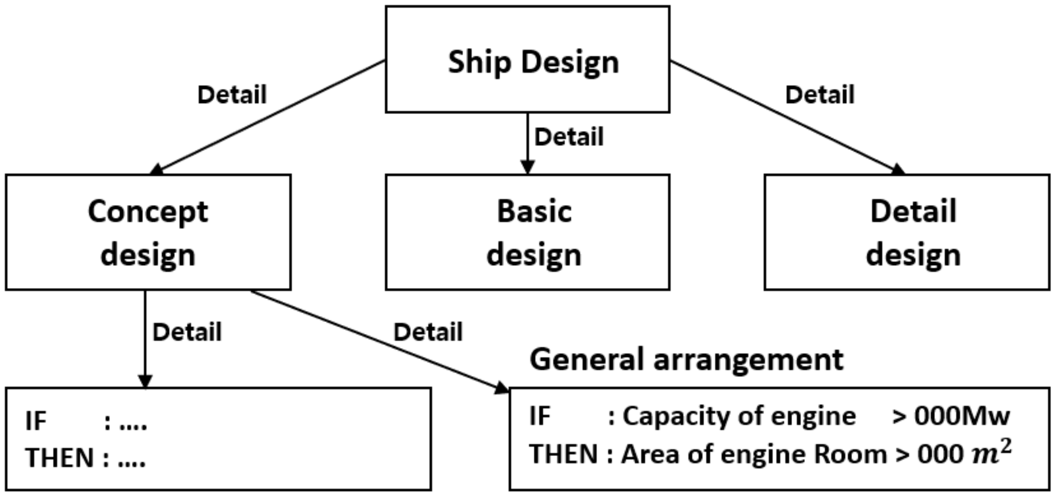


Figure 10. Example of hybrid knowledge

In rule-based knowledgebases, it is difficult to classify and search for knowledge when the number of rules increases, so it is necessary to organize them according to their contents or other criteria. To this end, rules can be classified using frames, and expressions can use IF slots and THEN slots.

As mentioned above, each knowledge expression has advantages and disadvantages, but among the four knowledge expression methods, the rule-based expert system is generally used. The reason is that it is natural to express knowledge using production rules in the form of ‘IF-THEN’, and it is easy to understand the rules with the unity of knowledge expression. Also, if the problem becomes complicated, it is possible to add frame objects and semantic network properties so that various knowledge can be expressed as one rule. Therefore, in this paper, an expert system was created using production rules to express expert knowledge.

3.2. Rule-based expert system

In order to utilize the knowledge of experts in estimating the composition of the crew, an expert system is needed to incorporate the expertise and experience of experts. The system uses the knowledge input by the expert to reason and solves the problem. Expert systems that use production rules to represent expert knowledge are called rule-based expert systems. The rule-based expert system consists of a rule-based system, explanation mechanism, and user interface, and the rule-based system consists of a knowledge base and reasoning engine in detail.

3.2.1. Knowledge base

A knowledge base is a database that stores expertise accumulated through intellectual activities and experiences by experts in a specific field, facts, and rules necessary for problem-solving and expression of expert knowledge; A rule that uses an IF-THEN format creation rule is included. The task of reflecting expert knowledge into a knowledge base is called knowledge acquisition.

3.2.2. Inference engine

The Inference engine derives results based on facts or rules accumulated as knowledge in the knowledge base and new facts or hypotheses input by users. In this model, results are derived by connecting Rules and Facts in the knowledge base and new information input by users. Figure 11 is the reasoning process mentioned above.

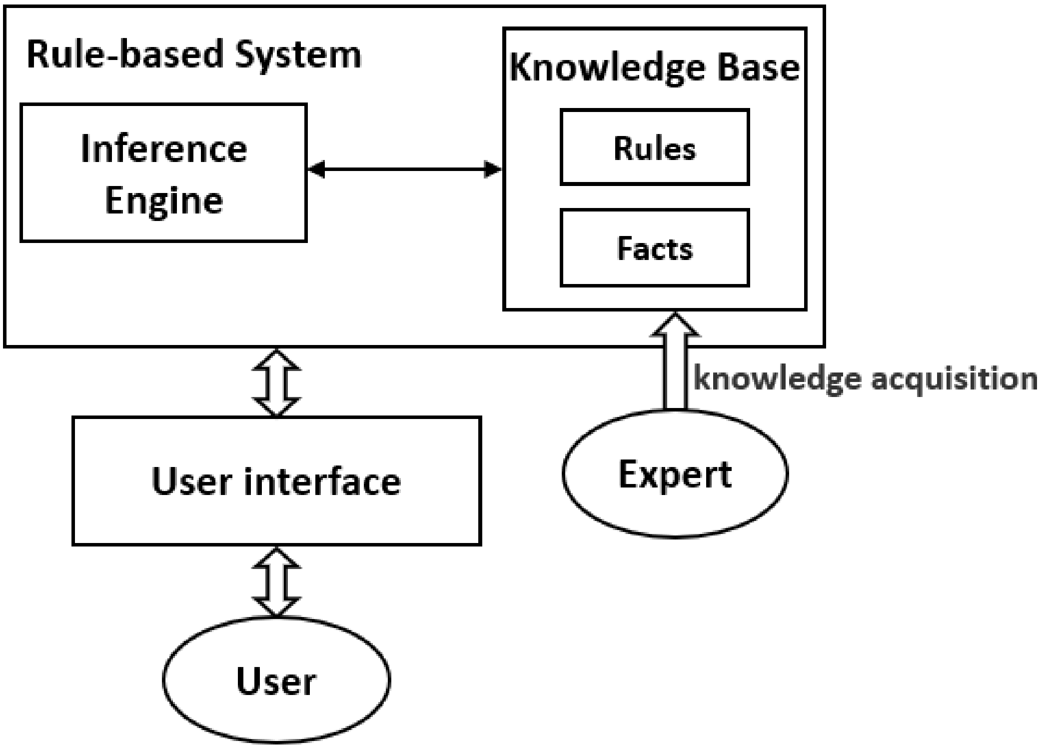


Figure 11. Configuration of the rule-based system

3.2.3. User interface

The user interface is the communication between the user and the expert system. This should provide users with an environment in which they can conveniently use the system.

3.3 Model using expert system

A model was created using the rule-based expert system mentioned above. Using the model, experts can express various knowledge about the crew's information as object information and relation information, and the model uses the knowledge to calculate the crew's number and composition.

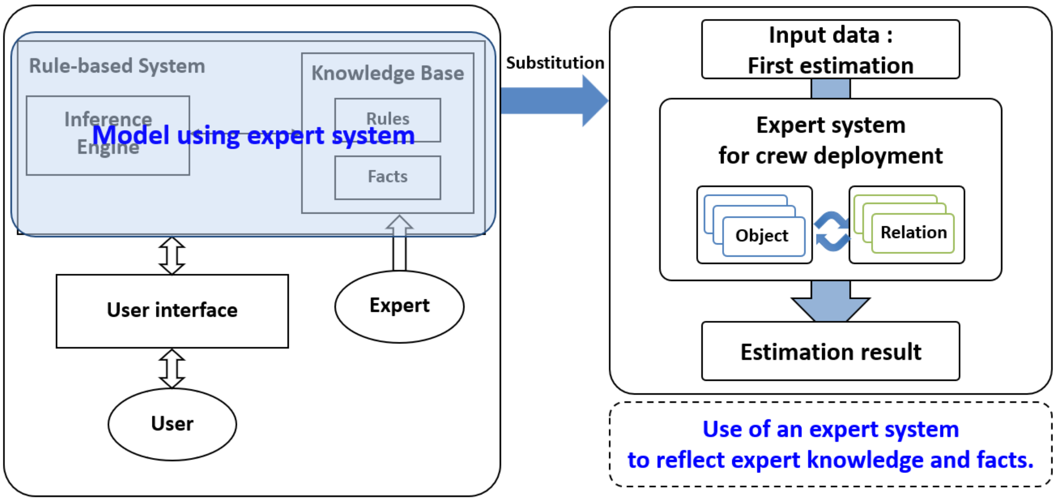


Figure 12. Model using expert system

As shown in Figure 12, the knowledge base and inference engine in the rule-based system are replaced with the corresponding model. In the model, the result value of the first estimation is received, and a new result is estimated using the expert system.

3.3.1. Object information

Object information is information expressing expertise applied to one object, and in this paper, it represents expertise on crew deployment in a navigational watch or combat situation for a specific crew member. Object information consists of ID, target object, specialty, and target value. If the expert says, 'the ship's steering watch should have at least two QM crew members assigned to each position considering the importance and size of the ship, and three are recommended if possible' expressed as object information.

Object information

ID	Object target	Specialty	Target value		
N001	Steering	QM	3_rec	2_min	3

Figure 13. Example of object information

As shown in Figure 13, data types for each property are required to implement the four types of object information. ID, object target, and specialty can be expressed in string type. And the target value is expressed as a list of integers, and the list is divided into minimum value, recommended value, and section to express the boundary type. If the ID is set to one value, the value can be defined by making the Minimum value and the Recommended value the same. Data types for object information are shown in Table 4 and Table 5.

Table 4. Properties of object information

Properties	**Data type**
ID	String
Object target	String
Specialty	String
Target value	List of integers

Table 5. Properties of the target value

Properties	**Data type**
Minimum value	Integer
Recommended value	Integer
Section	Integer

3.3.2. Relation information

Relation information represents missions that can be performed simultaneously when performing one mission in manning during combat and is defined as information to express the relationship between two object information. If an expert says, “two crew members with GM specialties operate 127mm, and one of them operates light torpedoes at the same time,” the system expresses the related content as relation information. When one ID is added, the keyword of knowledge consists of ‘Specialty’, ‘Object target’, ‘Object target value’, ‘Relation target’, and ‘Relation target value’, and related information is expressed as shown in the figure below.

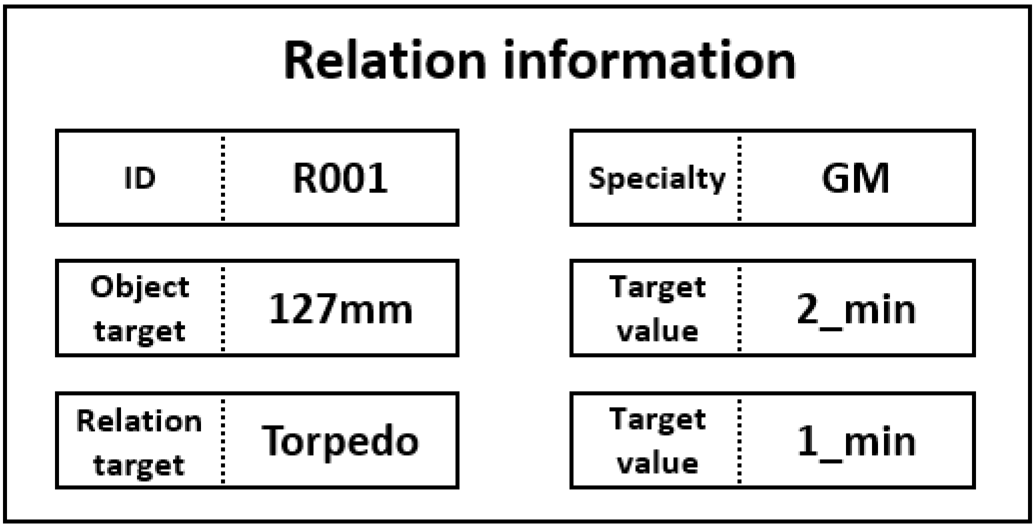


Figure 14. Example of relation information

As shown in Figure 14, data types for each property are required to implement the six types of relation information. ID, specialty, object target, and relation target can be expressed in string type. And the target value is expressed in a list of integers type, and the list is divided into minimum value and recommended value to express the boundary type. If the ID is set to one value, the value can be defined by making the Minimum value and the Recommended value the same. Data types for relation information are shown in Table 6 and Table 7.

Table 6. Properties of object information

Properties	**Data type**
ID	String
Specialty	String
Object target	String
Target value	List of integers
Relation target	String
Target value	List of integers

Table 7. Properties of the target value

Properties	**Data type**
Minimum value	Int
Recommended value	Int

3.3.3. Expert system for crew deployment

As mentioned in 3.3.1 and 3.3.2, the expert knowledge necessary to estimate the size and composition of the crew is expressed. As shown in Figure 15, when the information list is created and put into the model, the criteria necessary for calculating the crew members in the internal data of the first estimation are modified. The disadvantage of the existing expert system is that it takes a long time to accumulate expert knowledge, but the model uses the internal data of the first estimation as the basic expert knowledge, so it can save the initial accumulation time. If the standard of first estimation is modified in the model, the process of first estimation is repeated, and a new crew composition and mission list are calculated.

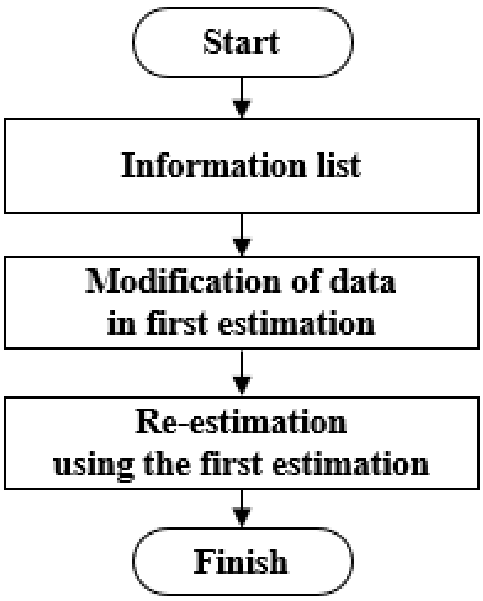


Figure 15. Expert system for crew deployment

4. The final estimation using DEVS

4.1. System specification formalisms

System specification formalisms are theories that model objects based on system theory and are classified into behavior and system structure. The external behavior of a system occurs between input time and output time within the system structure and changes the internal state. In other words, the system is defined in terms of inputs, internal states, and outputs, which are external actions, and this means that the inside and outside of the system are distinguished. One of the characteristics of Structure is decomposition. In other words, it has a hierarchical structure, and because it has the characteristics of composition, it has modularity and hierarchy[10].

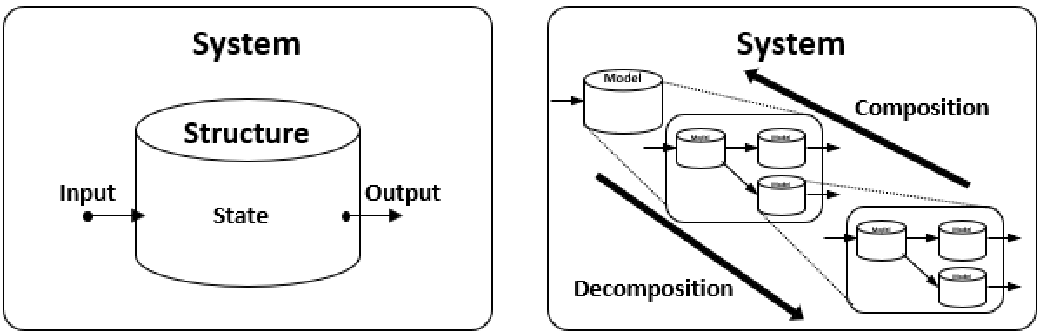


Figure 16. Feature of system specification formalisms

4.2. DEVS formalism

The DEVS formalism was introduced by ZEIGLER in the 1970s to model discrete event systems in a hierarchical manner. DEVS is a method for expressing the characteristics of a discrete event system that operates based on events in a formal way. An important feature of DEVS is hierarchical modularity. To put it simply, when DEVS models are combined like assembling Lego blocks, the resulting model can be expressed as DEVS. Therefore, a more complex and evolved model can be created using the verified model. In DEVS, behavior is expressed as an atomic model, and system structure is expressed as a coupled model. According to the purpose of the simulation, the simulation is composed by combining the atomic model and the coupled model.

4.2.1. Atomic model

An atomic model is the smallest model that does not divide in a simulation like the concept of an atom. As shown in Figure 17, when trying to perform an event in which oil is injected according to time at the gas station, the atomic model will be a gas tank, queue, etc.

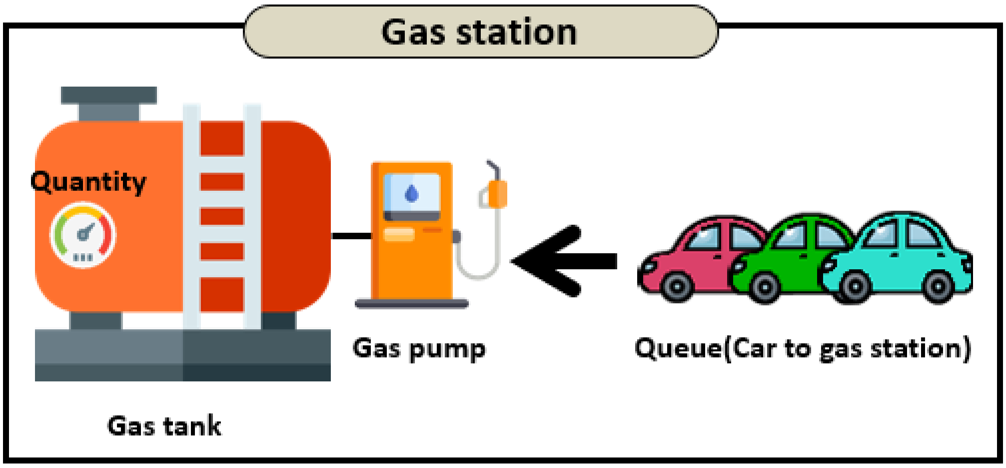


Figure 17. Example of the atomic model

The formal expression of the atomic model is as follows.

$$M = < X, S, Y, \delta_{int}, \delta_{ext}, \lambda, ta >$$

where,

X: Indicates "A set of input events from a model." In DEVS, it is a set of input events that can be used to express a model using a set. In the previous example, the input event that can occur in the gas tank is the 'arrival of a car.'

S: Indicates "A set of states that a model can have.". Represents a set of states that a model can have. In DEVS, the number of states a model can have is finite, which contrasts with a continuous system that has an infinite number of states. In the case of the gas pump connected to the gas tank in the previous example and refueling the vehicle, it can be modeled in the 'Idle' state if there is no vehicle currently being refueled and in the 'Busy' state if it is working. The condition of the tank can be expressed by the amount of oil remaining. "A set of states that a model can have.".

Y: Indicates "A set of output events from a model." An output event occurs when a certain purpose is satisfied after a certain period of time in a model state. The event will occur.

δ_{int}: "Internal state transition function."

δ_{ext}: "External state transition function."

State transition occurs when a model changes from one state to another. In DEVS, when an input event occurs or when the time for the model to stay in the current state runs out, a state transition occurs. The first case is called external state transition, and the second case is called internal state transition. The input of the external state transition is the input event, the current state, and the time spent in the current state, and the output is the next state. The input of the internal state transition is the current state, the time spent in the current state, and the output is the next state.

In the case of the previous example, an external state transition is an input event, and when a car comes, it changes from standby to supplying gas to the car as an output. And when that state is maintained and time passes (the input of the internal state transition), an internal state transition occurs, and the gas in the tank, which is the state, is reduced.

λ: It means an output function, and when a certain condition is satisfied when an internal state transition occurs, the output is determined in the existing state. In the previous example, when the time required to supply all the gas to the car is satisfied, the car generates output leaving the gas station.

ta: It means the time progress function, and it is a function that determines how long the model will stay in its current state. When the state of the model changes, the ta function is executed to determine the remaining time in the current state, and when the corresponding time elapses, the model's internal state transition function is executed. The input is the current state, and the output is the time the state is maintained.

Figure 18 shows the contents schematically.

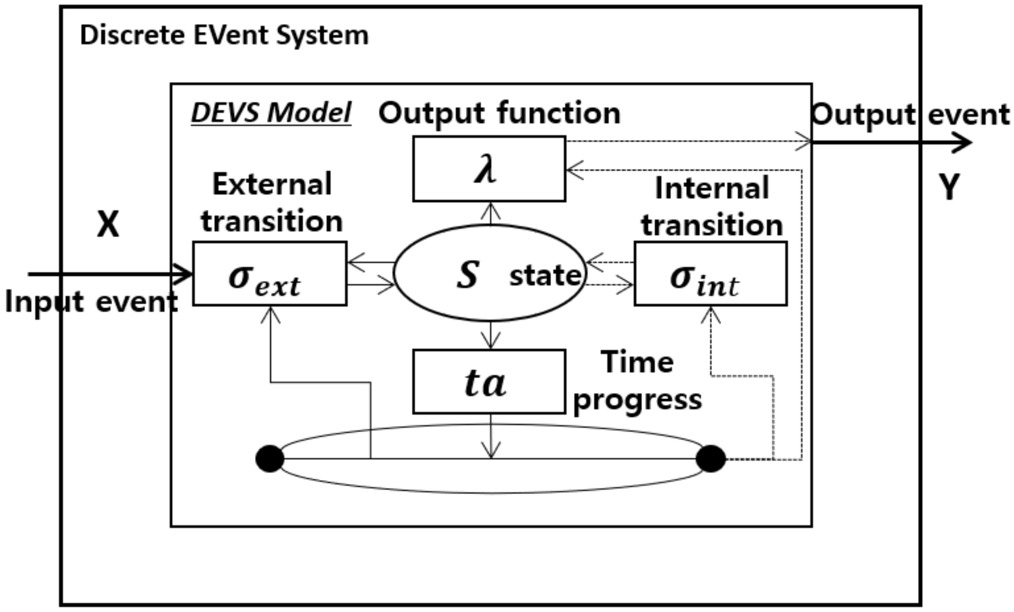


Figure 18. Configuration of the atomic model

4.2.2. Coupled model

The coupled model is a model formed by combining two or more atomic models, and the behavior is determined according to the connected form of the models. The formal expression of the coupled model is as follows.

$$\text{DN} = < \text{X}, \text{Y}, \text{D}, \{M_d\}, \{I_d\}, \{Z_{i,j}\}, select >$$

where,

X: In the same way as the atomic model, it represents “A set of input events from a model.”

Y: In the same way as the atomic model, it represents “A set of output events from a model.”

D: A set of names of sub-models that make up a combined model

$\{M_d\}$: set of sub-models

$\{I_d\}$: The set of models affected by the output of M_d

$\{Z_{i,j}\}$: A function that changes the output of the ith sub-model to the input of the jth model

It is simply explained through the example model in Figure 19.

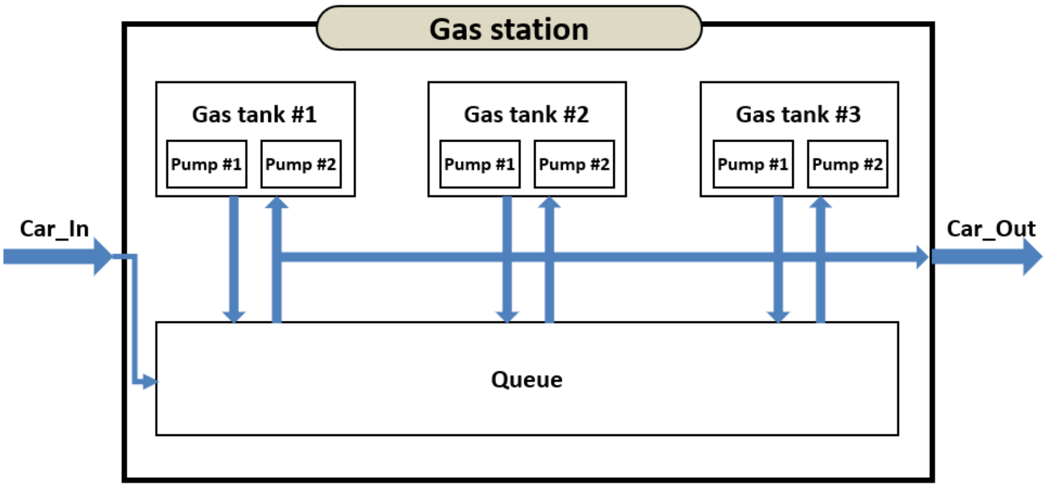


Figure 19. Example of the coupled model

This model is a combined model that includes three gas tanks and one queue model. Each gas tank has a different type of gas, and there are two gas pumps that can supply gas. When a new car arrives, an input occurs through the Car_In port, which is entered into the Queue model. The required gas is assigned to the car, and the queue model designates the tank according to the gas. If there is an empty pump in the tank, the car is assigned to the pump, and if not, the car is added to the waiting list. When a job is completed in one tank, an output occurs, which is simultaneously delivered to the output port, Car_Out, and the input port of the queue model. Here, the explanation of the above-coupled model is as follows based on an example.

X: A set of events when a car enters the gas station

Y: A set of events where a car leaves the gas station after refueling

D : { Gas tank #1, Gas tank #2, Gas tank #3, Queue} / simple string

$\{M_{\mathrm{n}}\}$: {Gas pump #1, Gas pump #2}

$\{I_{\mathrm{n}}\}$: {Queue, Car_Out}

$\{Z_{0\sim2,3}\}$: When gas refueling is completed, a new vehicle is put into Gas tank #n

4.3. Configuration of model

The simulation is constructed using the DEVS model mentioned in the previous chapter. Among the results estimated using the expert system, an optimized result is calculated using simulation for the size of the crew involved in the scenario. Below is the basic structure of the model.

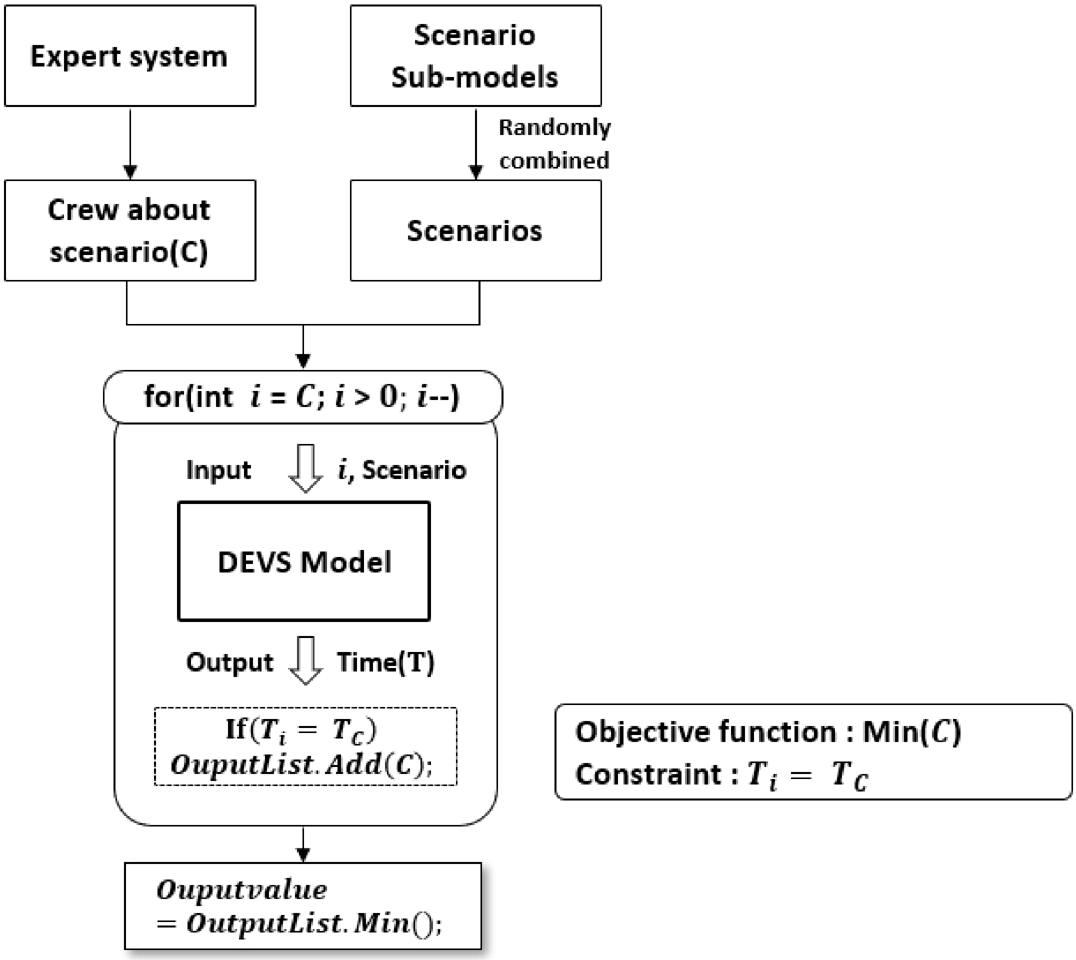


Figure 20. Total configuration of the model

The simulation is performed as shown in Figure 20. In the Expert system, the list of the crew (C) related to the scenario and scenario generated from scenario sub-models are used as input data.

As an optimization method, what-if simulation is used. What-If simulation is a data-intensive simulation that derives desired results by processing data obtained while changing various conditions. In the iterative statement, assume the value (C) from the expert system as the maximum value and measure the simulation execution time by reducing one person at a time.

The objective function is to minimize the number of crew members, and the constraint is set to maintain the scenario execution time in order not to deteriorate the capability of the ship. That is, the minimum number of people is calculated under the condition that the simulation execution time is maintained.

4.4. The first detailed DEVS model (For the naval ship's combat situation)

The first model is configured by changing the policy in the current naval combat situation. Currently, the Navy assigns one mission to one crew member in a combat situation. When assigning one mission to one crew member, there is no need to consider the congestion of personnel in various situations, and it is possible to fight systematically rather than individual abilities by minimizing the workload to individuals during battle.

However, there are many job vacancies, and in the case of a job performed by a specific specialty, the job method is similar, or two or more jobs can be performed through training. Therefore, in this problem, we estimate the effect of reducing the number of crew members involved in weapon operations in a combat situation when one or more missions are assigned.

As the input data, crew members' data and scenario composition, which are classified and configured based on the crew's specialties related to weapons in a combat situation, which is the result of the Expert system, and their location in a combat situation, are used.

.

4.4.1. Total scenario composition

Scenarios are composed in consideration of the missions of combat ships. Combat ship missions are generally Anti-Aircraft Warfare (AAW), Anti-Surface Warfare (ASUW), Anti-Submarine Warfare (ASW), and in the case of Aegis, anti-ballistic and anti-ballistic warfare as well. In the model, sub-scenarios for AAW (including ASUW using missiles), ASUW, and ASW using naval guns are constructed in consideration of weapons operations related to AAW, ASUW, and ASW, which are generally performed.

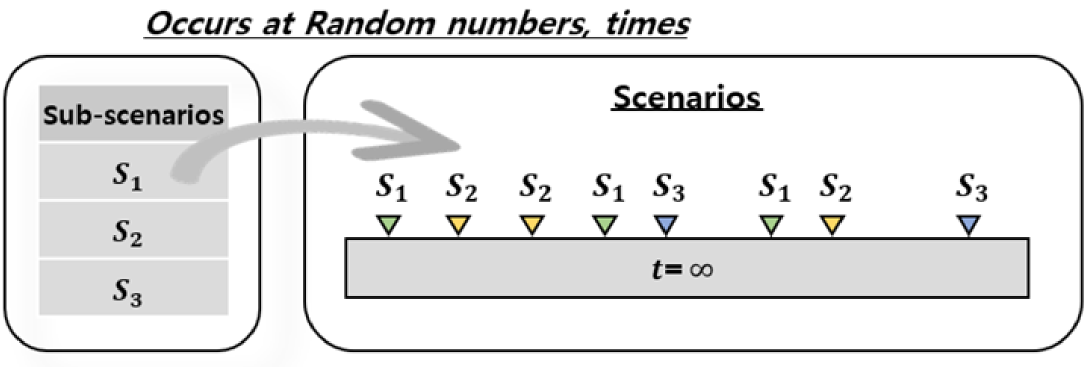


Figure 21. Composition method of simulation

Figure 21 and Sub-scenario are composed to take charge of the operation situation of the ship, and it is expressed as Mission 1 (M1). Whole scenario randomly selects missions in the List of Missions and configures scenarios by randomly setting intervals between missions. Simulation is performed in the DEVS Model using the configured scenario.

4.4.2. Sub-scenario composition – AAW

The basic scenario of AAW proceeds as shown in Figure 22 and Figure 23. First of all, if an enemy ship fires an anti-ship missile at this ship, it responds with the weapons of the ship I want to design. When an enemy ship appears and fires a missile, the ship launches an anti-ship missile at the enemy ship and, at the same time, fires an anti-aircraft missile in response to the enemy's anti-ship missile.

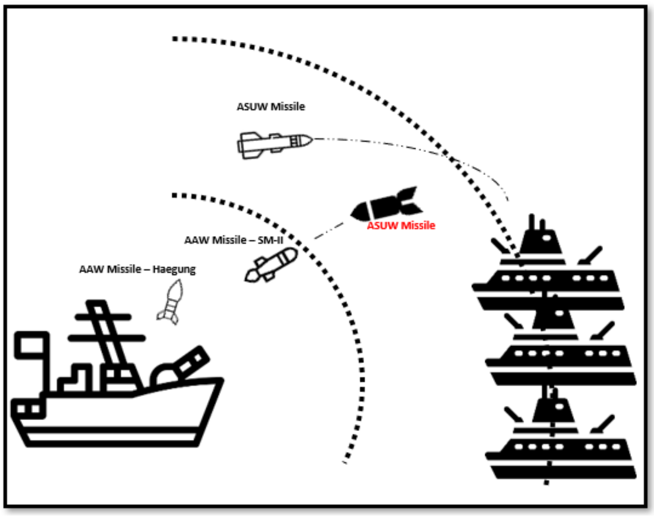


Figure 22. A schematic diagram of AAW

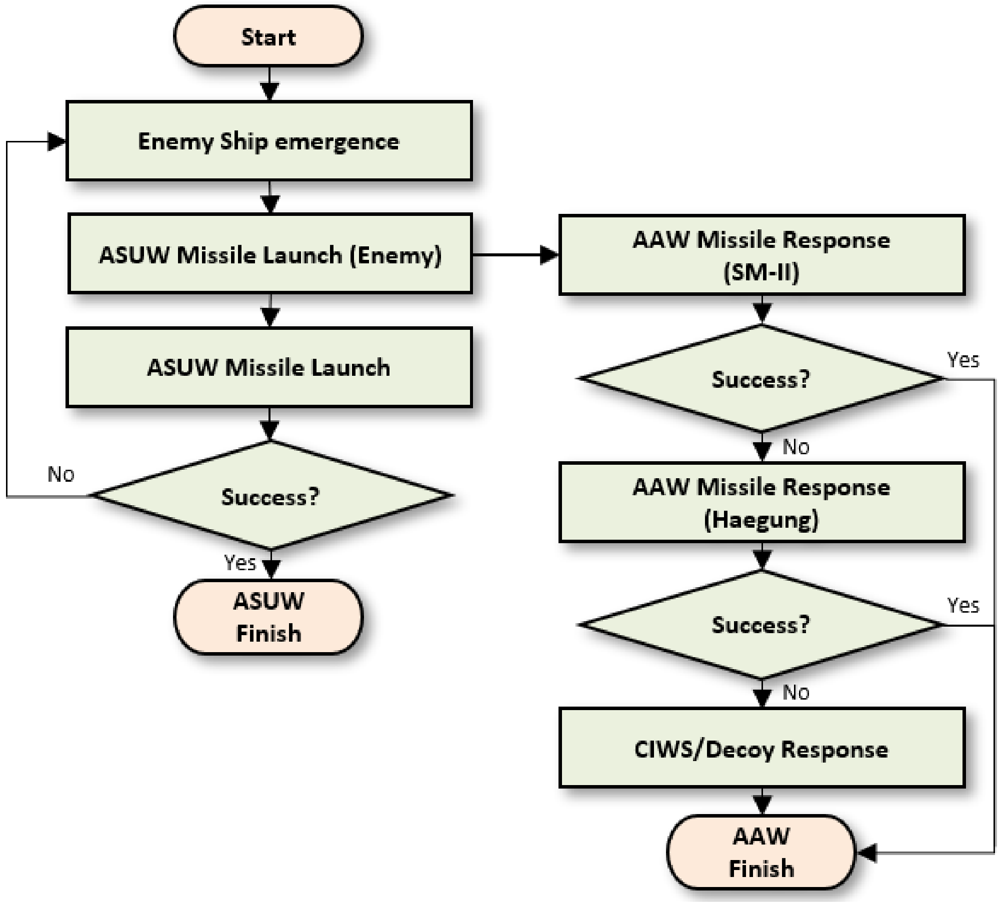


Figure 23. A diagram of AAW

If the missile launched by this ship does not hit, the enemy ship is set to fire the anti-ship missile again, and for the missile launched the second time, it is set to hit without condition considering the accuracy rate of the anti-ship missile. For the information on weapons used in the scenario, available information was used, and North Korea's new missile, the KH-35, was assumed as the enemy's missile.

4.4.3. Sub-scenario composition – Close ASUW

The basic scenario of a close naval gun battle is that when a small ship approaches within the range of a naval gun, it fires with the gun, and when it comes closer than that, it fires with CIWS. It is composed as shown in Figure 24, and the sub-scenario is composed according to randomly assigned hits. For the information on weapons used in the scenario, available information was used, and the enemy's naval guns were assumed to be 100mm naval guns mounted on Nampo, Seoho, and Najin-class ships, which are major North Korean ships.

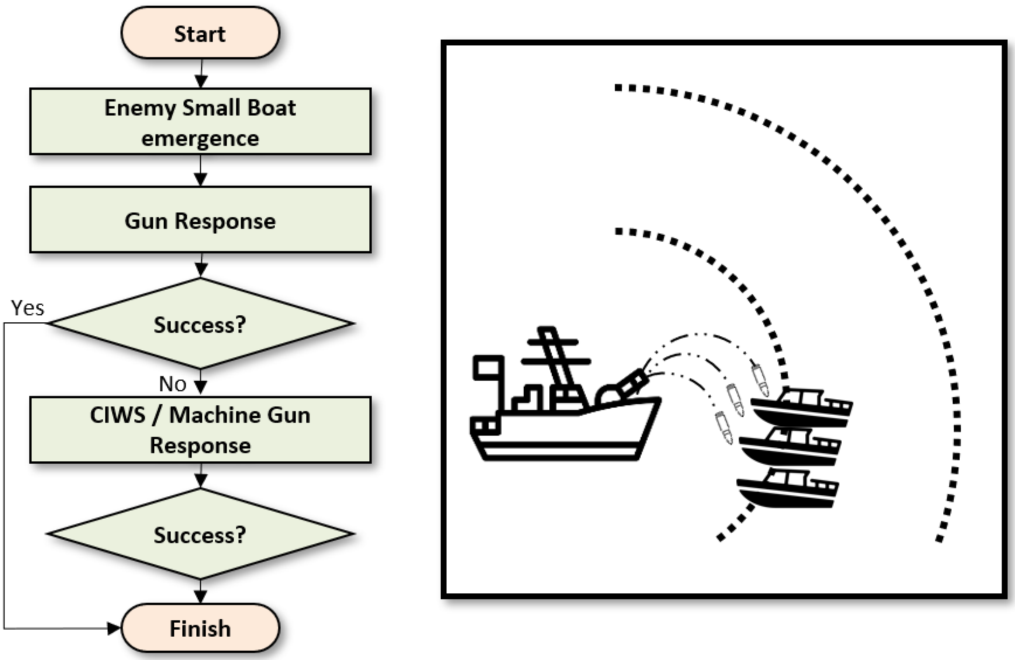


Figure 24. A schematic diagram of ASUW

4.4.4. Sub-scenario composition – ASW

As shown in Figure 25, the basic scenario of anti-submarine warfare consisted of a response scenario through the weapons of this ship when an enemy submarine appeared and fired a torpedo. The scenario progressed by assuming two scenarios: the case of detecting the location of the submarine and responding to it and the case of avoiding it by only checking whether the enemy fired a torpedo. The information on weapons used in the scenario used publicly available information.

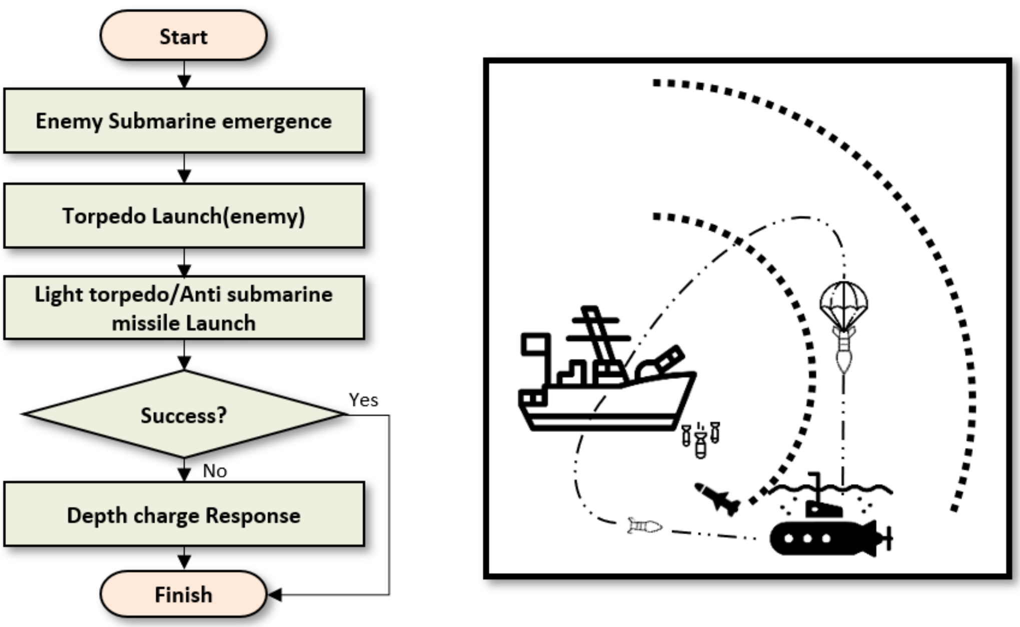


Figure 25. A schematic diagram of ASW

4.4.5. DEVS Model composition

Configure DEVS Model to operate Combat scenarios. The basic configuration of the DEVS Model is shown in Figure 26, and basically, the atomic model that performs the scenario in the combat situation and the atomic model that performs the scenario in the emergency situation is connected to the DEVS Simulation engine.

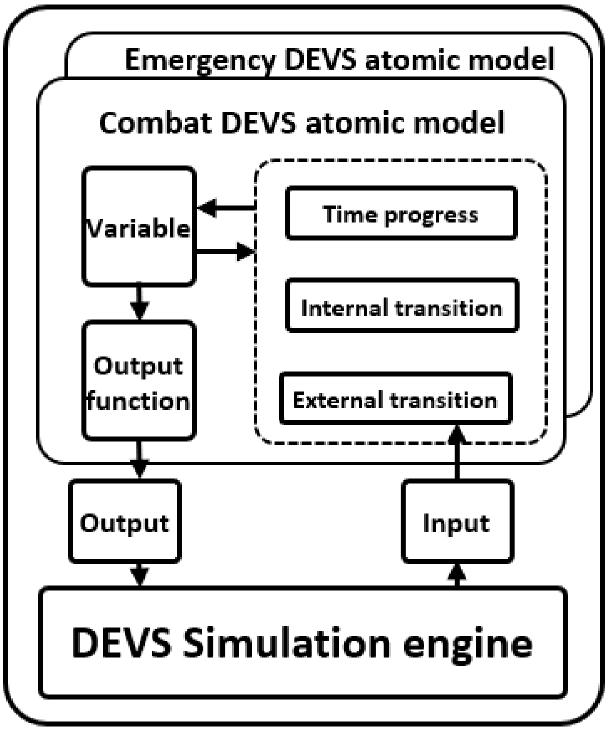


Figure 26. DEVS Model composition

In the DEVS Simulation engine, it plays the role of the blue part in Figure 27. The number and configuration of crew members and scenarios required for weapons operation received from the expert system are transferred to the atomic model, the completion time of the scenario is confirmed, and the result is calculated.

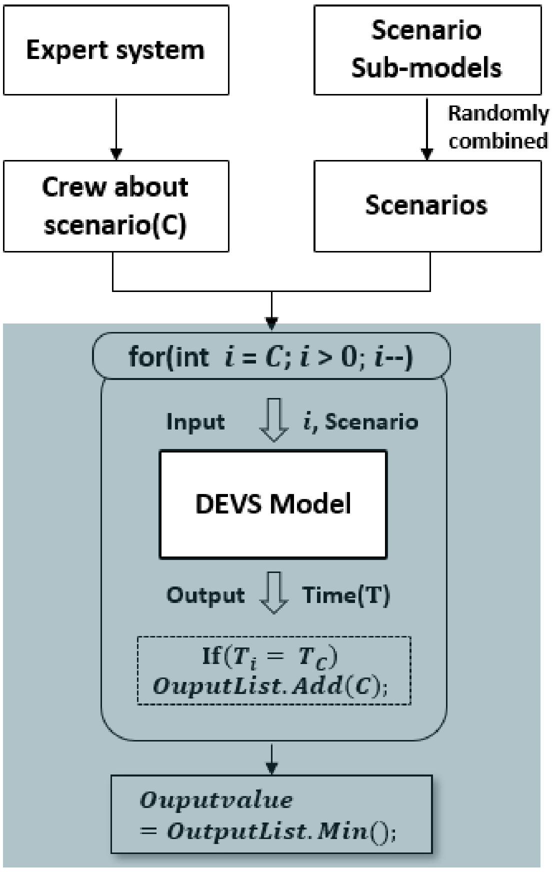


Figure 27. The part occupied by DEVS Simulation engine

As shown in Figure 28, an atomic model for the Combat scenario is constructed. The main components of the model are as follows.

X (A set of input events from a model): Scenario (Enemy attack), Crew about weapon

Y (A set of output events from a model): New crew, Completion time

δ_{int} (Internal state transition function): Crew allocation

δ_{ext} (External state transition function): Weapon allocation, Crew setting

λ (Output function): The end of events

To briefly explain the model, if the Crew about the weapon is input from the engine as an input event, δ_{ext} specifies the capacity of the atomic model of the crew member (the role corresponding to the number of crew members) set as shown in the lower box of Figure 28.

In addition, when an enemy attack comes in as an input event, the distance to the armed weapon is calculated, the required weapon is designated in δ_{ext}, and the data is received in δ_{int}, and a crew member suitable for the specialty and position required for the weapon is assigned. And when the enemy attack ends, the output function indicating that the event has ended is triggered, and when all the enemy attacks have ended, the completed time and the used crew about the weapon are sent to the engine as a result.

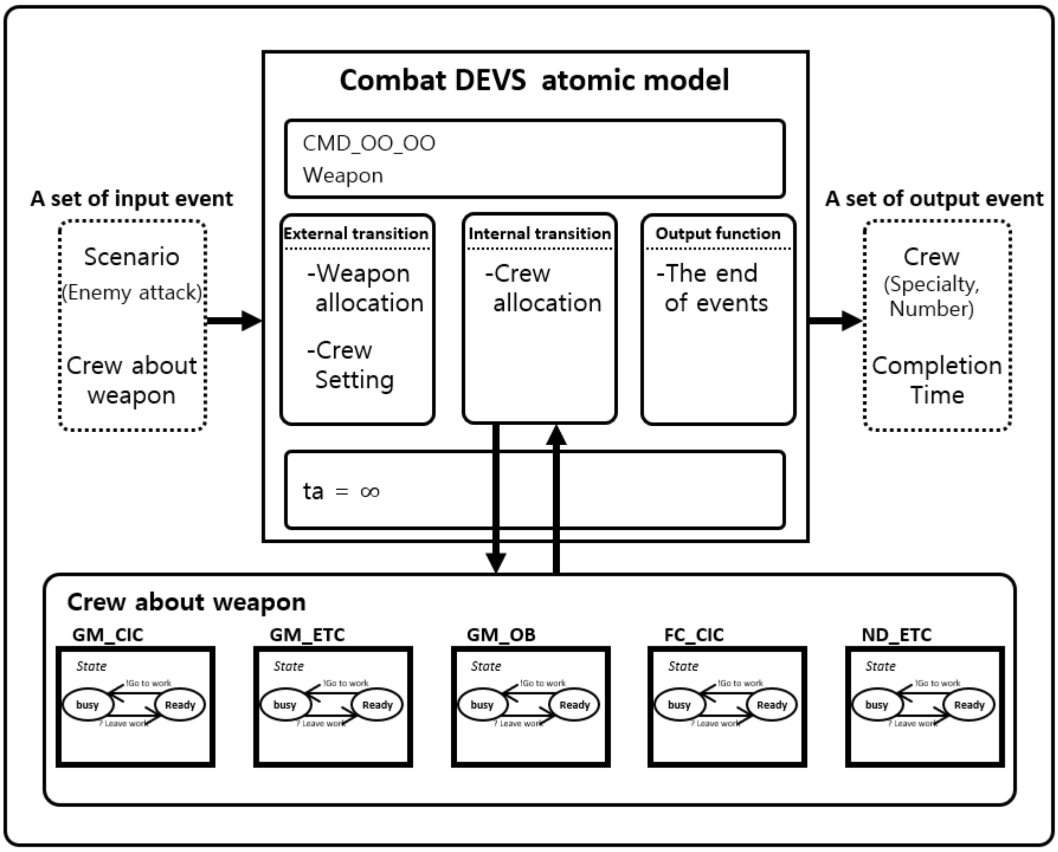


Figure 28. Atomic model DEVS simulation in a combat situation

4.5. The second detailed DEVS model (For the naval ship's emergency situation)

The second model measures the time to solve an engine failure when the ship's crew is performing their daily routine in peacetime. At this time, it is composed of changing the policy related to the maintenance of the navy. In the module that calculates personnel using legacy ship data, among the specialties calculated using regression analysis, maintenance time is a very important factor in calculating crew members because the number of crew members is determined according to maintenance time in the engine department. Therefore, at this time, the maintenance time is changed according to the level of maintenance performed on the ship, and the effect of the maintenance time on the number of crew members is confirmed while comparing the scenario execution time.

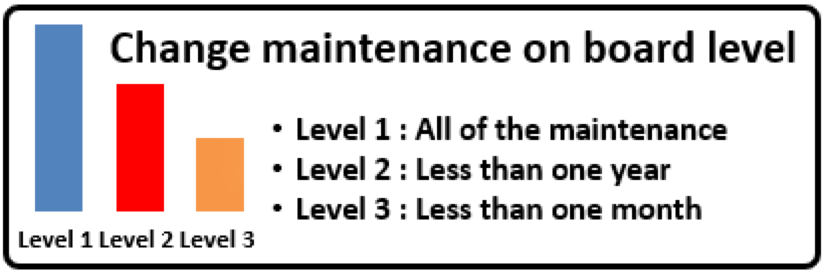


Figure 29. Maintenance on board level

As shown in Figure 29, it is assumed that all maintenance in case of Level 1, maintenance of less than one year in case of Level 2, and maintenance of less than one month in case of Level 3 are carried out on the ship, and the current level of maintenance is set as Level 1. Levels 2 and 3 were set at 0.7 and 0.5 levels of Level 1, respectively, as securing detailed data was limited.

4.5.1. Scenario composition

As shown in Figure 30, the problem was constructed by assuming an emergency situation. When the ship's crew is carrying out daily tasks as a third section, a situation arises when the engine breaks down. Accordingly, all personnel involved in the engine are committed to repairing the engine. When all the organs are repaired, they are put back into daily tasks, the overdue tasks are processed, and the processed time is measured to calculate the result.

The time to repair a broken engine was calculated by taking 0.5 times the preventive maintenance based on a Ship Manpower Document (OPNAVINST 1000.16K, Department of the navy, 2017.8.7.) of the US Navy [11].

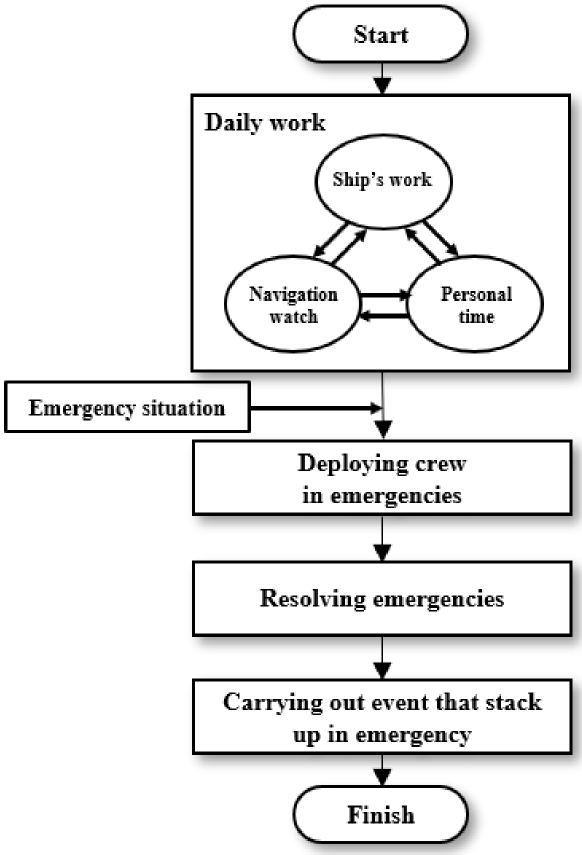


Figure 30. Composition of the DEVS model in an emergency situation

The crew proceeds according to the daily schedule in Figure 31, and this daily schedule follows the basic daily schedule of the US Navy, and the daily schedule was modified and applied to this model by applying the experience of boarding a naval vessel.

Unit : hour

Ship standard Workweek			81.00
Productive Workweek			**70.00**
Analysis of Duty Hours			
Total hours available weekly			168.00
Less Non-Available Time :			
Sleep	(56.00)	(87.00)	
Messing	(14.00)		
Personal needs	(14.00)		
Sunday (free time)	(3.00)		
Scheduled On Duty Hours Per Week			81.00
Less :			
Training	(7.00)	(11.00)	
Service diversion	(4.00)		
Total Hours Available for Productive Work			**70.00**

Figure 31. US Navy Basic work hours

4.5.2. Composition of the DEVS model

Configure DEVS Model to operate emergency scenarios. Basically, the atomic model that performs scenarios in emergency situations and the atomic model that performs scenarios in emergency situations are connected to the DEVS Simulation engine. The work done in the DEVS Simulation engine is the same as the combat scenario.

As shown in Figure 32, an atomic model for emergency scenarios is configured. The main components of the model are as follows.

X (A set of input events from a model): Emergency situation

Y (A set of output events from a model): End simulation

δ_{int} (Internal state transition function): Crew allocation

δ_{ext} (External state transition function): Crew setting

λ (Output function): The end of the event

To briefly explain the model, if the crew about an emergency is input from the engine as an input event, the capacity of the crew member atomic model (the role corresponding to the number of crew members) is set as shown in the lower box of Figure 32 is specified in δ_{ext}.

In addition, when an emergency situation comes in as an input event, an incident occurs at the time an emergency situation occurs in δ_{ext} and a crew member is assigned at that time in δ_{int}. And when the emergency situation ends, the output function sends a signal to δ_{int} again, and δ_{int} assigns crew members to daily tasks. And when the accumulated daily tasks are completed, the output function is triggered, and the completed time and used crew about weapons are sent to the engine as a result.

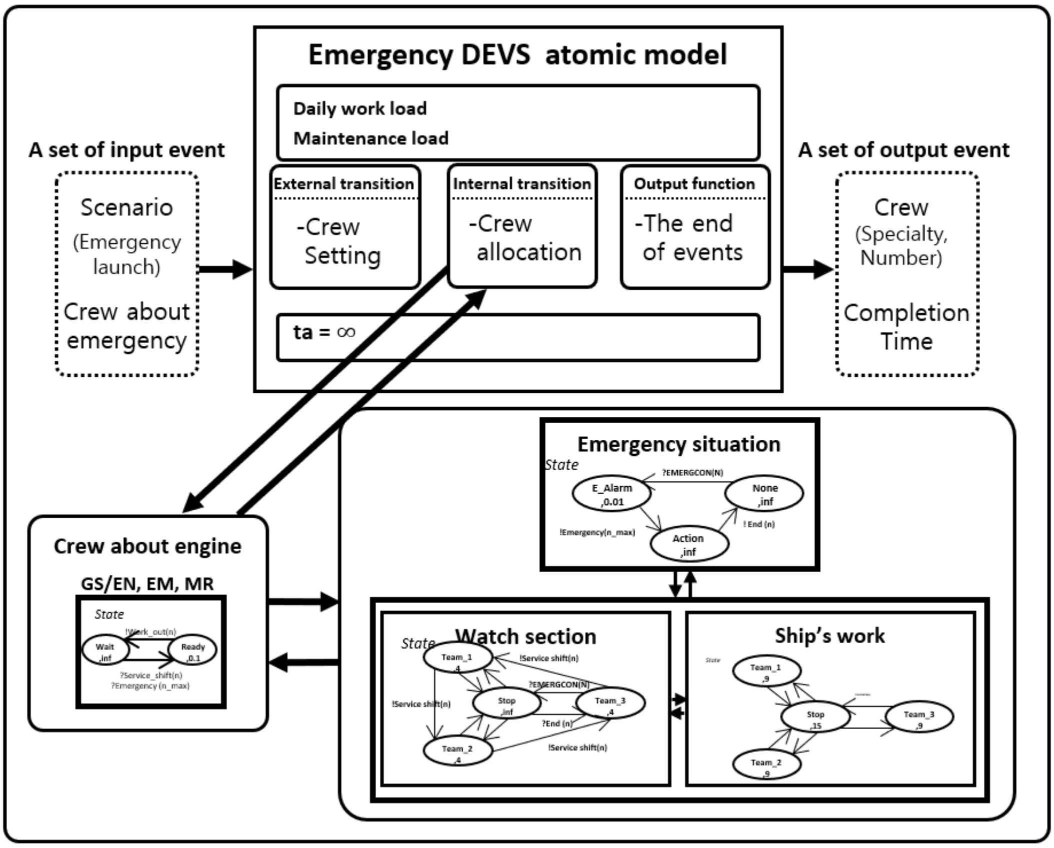


Figure 32. Atomic model DEVS simulation in an emergency situation

5. User interface

In this paper, a prototype program was developed by applying the proposed method. Using the Prototype program, the user can estimate the number and composition of the crew, and manage and store the data. The prototype program was developed based on Unity using C# language.

The prototype program is divided into three parts like this study. First, a tool for estimation based on legacy ship data was developed. The user can use the tool to fill in the specifications of the ship he/she wants to design and the mounted weapon, and in the case of future equipment without legacy ship data, the number of personnel can be calculated by linking with the next step, the expert system. Second, a tool for estimation based on an expert system was developed. The user writes rules for the ships designed using the tool and calculates the number and composition of crew members suitable for the ship. In the last stage, estimation based on DEVS, after the simulation was performed, the number of personnel for each position in the engine department was visualized in the deployment of personnel in a combat situation and in an emergency situation.

5.1. Tool for estimation based on legacy ship data

In the Tool for estimation based on legacy ship data, users can estimate the number and composition of crew members. It is possible to enter the specification of the ship, the quantity of equipment, and whether or not it is loaded, and as a result, the number and composition of the crew are estimated. In addition, it shows the user the deployment of personnel during combat situations and the deployment of personnel during navigation watch.

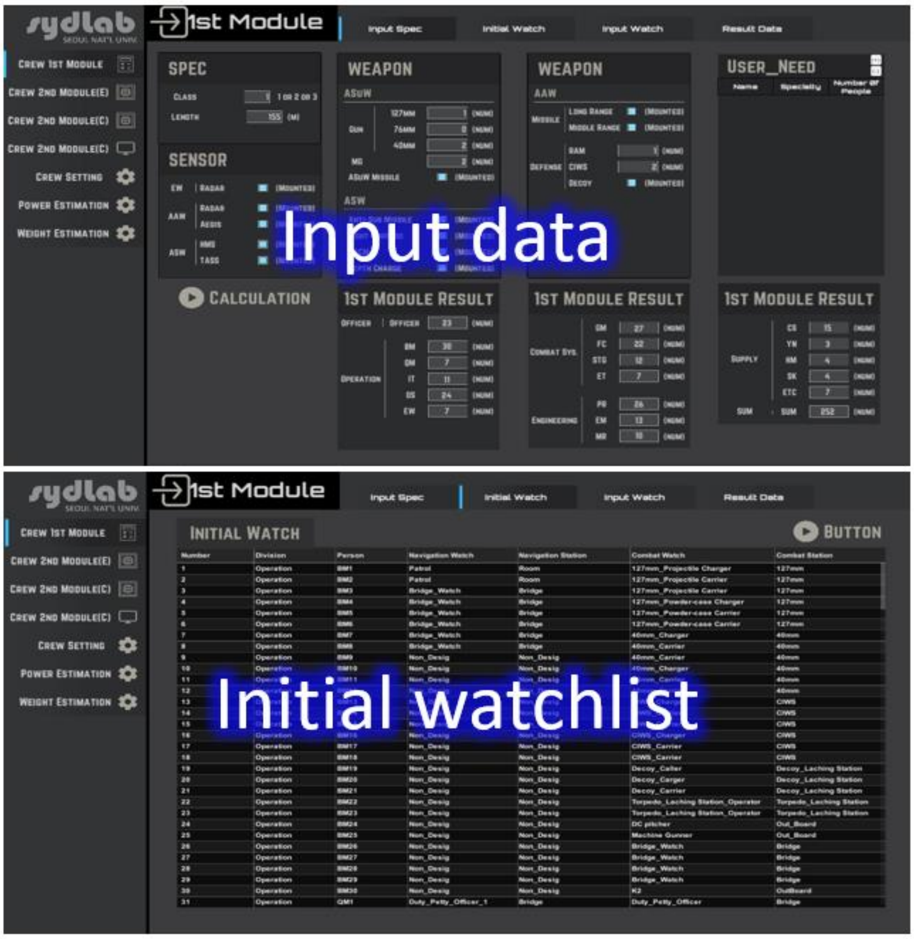


Figure 33. The user interface for the first estimation

5.2. Tool for estimation based on expert system

In the Tool for estimation based on an expert system, the user checks the results from the Tool for estimation based on legacy ship data and reflects the characteristics of the ship the user wants to design through Rules to obtain the desired result.

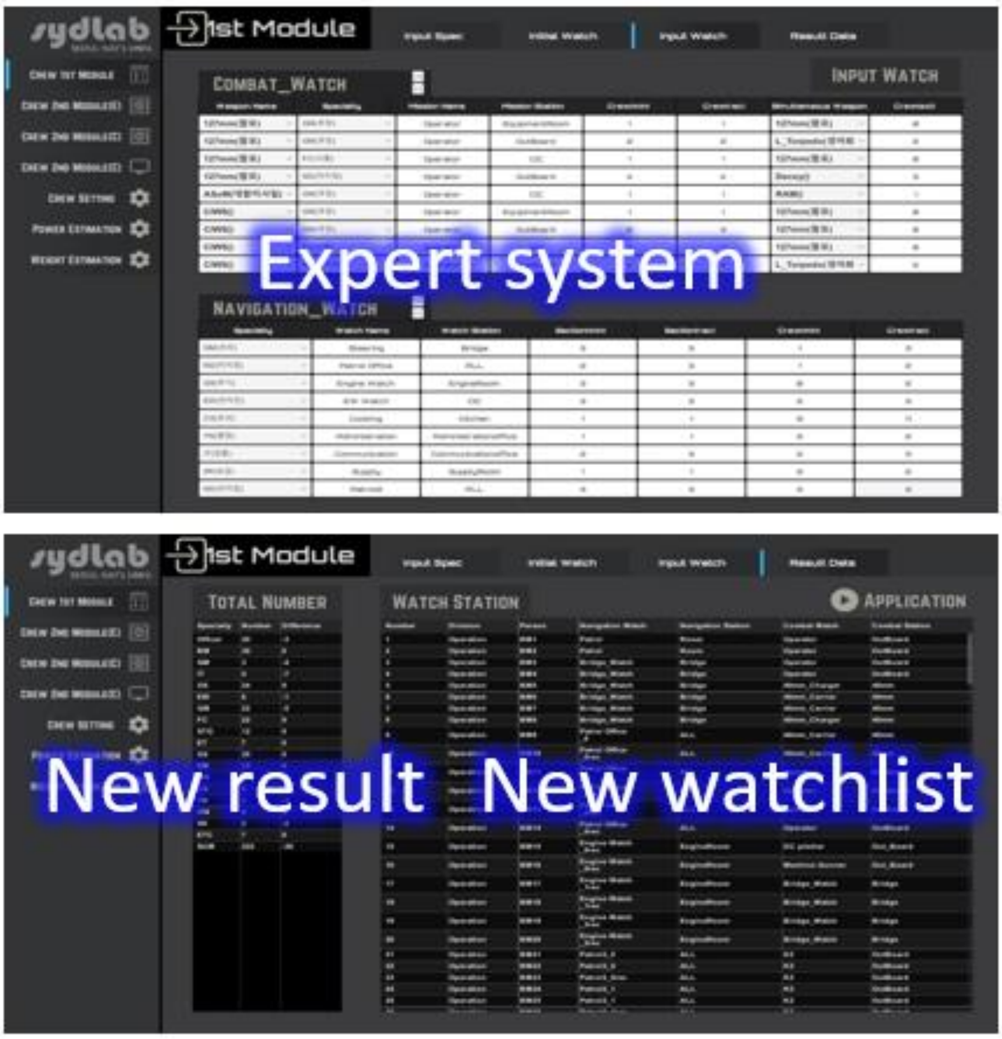


Figure 34. The user interface for the second estimation

5.3. Tool for estimation based on DEVS

In the Tool for estimation based on DEVS, the user performs a simulation, checks the result, and modifies the composition of the crew in the vessel I designed. The result of performing the combat scenario and the mission performed by each crew member can be checked by the user through a graph.

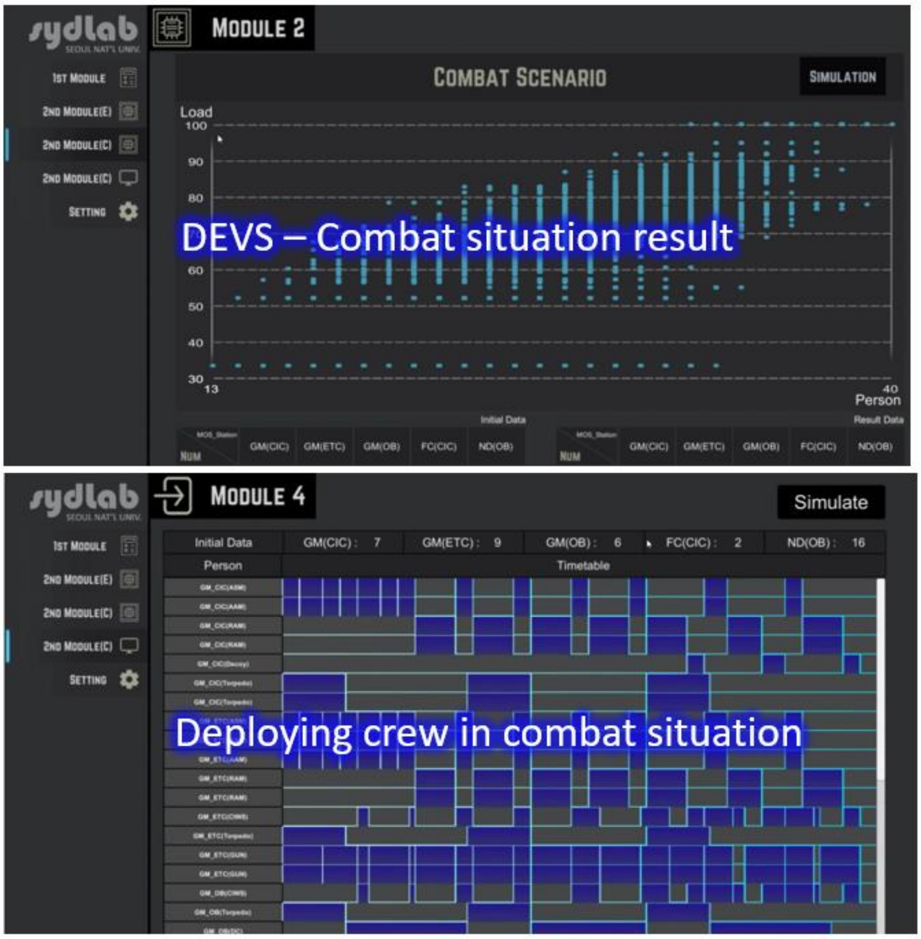


Figure 35. The user interface for final estimation-1 (In combat situation)

In addition, the result of performing the emergency scenario and the load value of the overall work were checked by the user through the graph.

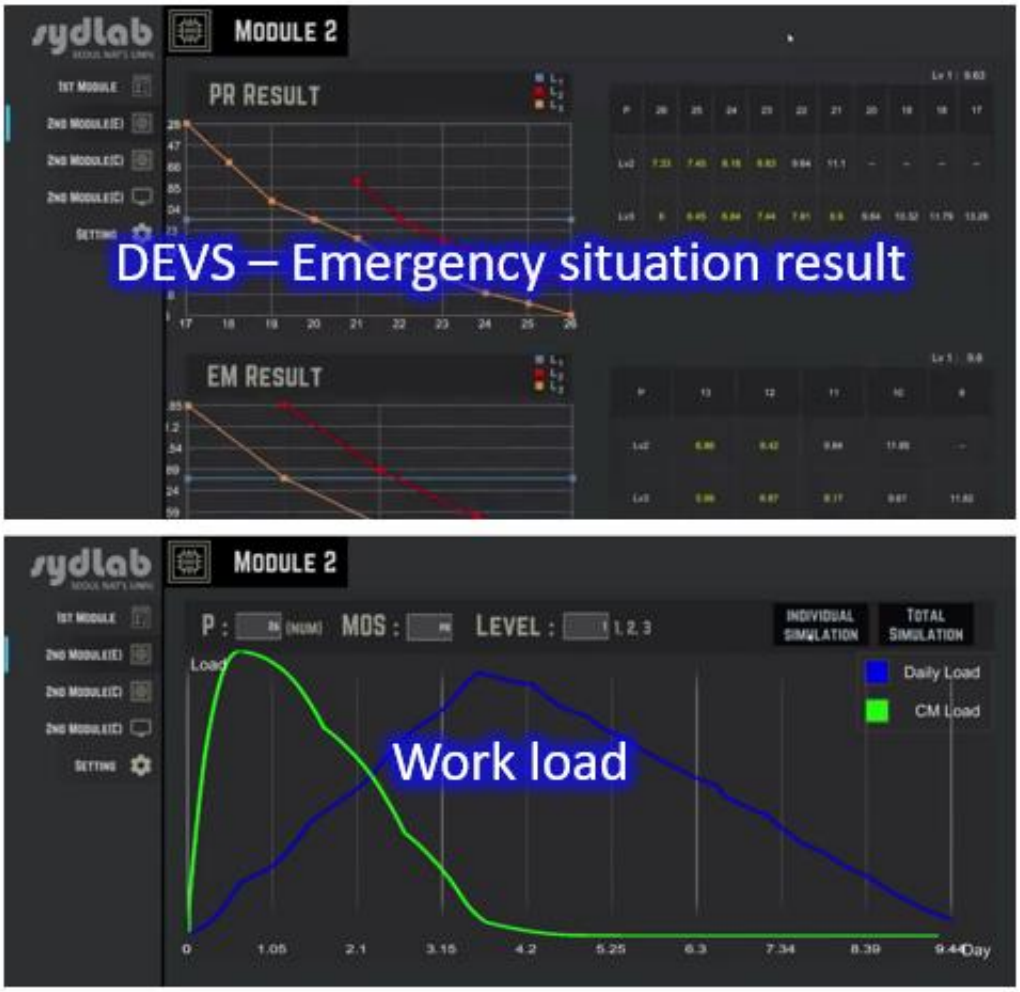


Figure 36. The user interface for final estimation-2 (In an emergency situation)

6. Application of the method for crew deployment

6.1. Description of an example

To verify the estimation based on legacy ship data, expert system, and DEVS of this study, the Arleigh Burke-class Destroyer Flight IIA (DDG) designed by the US Navy was adopted. This warship is a multi-mission destroyer that performs many missions, such as AAW using Aegis radar and anti-air missile, towed array sonar, ASW using anti-submarine rocket, and ASuW using the guns of a warship and CIWS.

6.2. The first estimation based on legacy ship data for application

For the current estimation method, a database was constructed using the experience of boarding a naval vessel. Although the data cannot be disclosed for security reasons, the data is classified as shown in Table 8. and the system is configured.

Table 8. The factor for each specialty

Division	Specialty	1st Class	2nd Class	3rd Class
Operation	BM	Regression analysis		
	OS	$F_{OS\_anti\_surface}(\text{Class}) + F_{OS\_anti\_air}(\text{Class})$		
	QM	A+4	A	A
	EW	3B	2B	B
	IT	C+6	C+3	C
Combat system	GM	$F_{GM\_weapon}(\text{Weapon\_list})$		
	FC	$F_{FC\_weapon}(\text{Weapon\_list})$		
	STG	D+3	D	D
	ET	$F_{ET\_equipment}(Equpiment) + F_{ET\_base}(\text{Class})$		
Engineering	GS&EN	Regression analysis		
	EM	Regression analysis		
	DC	Regression analysis		
Supply	CS	Regression analysis		
	HM	E+2	E+1	E
	YN	F+2	F+1	F
	SK	G+2	G+1	G

Information on the Arleigh Burke-class Destroyer, which is an example, is organized as shown in Table 9 according to the format of the input data of the first estimation.

Table 9. Input data of Arleigh Burke-class Destroyer for the first estimation

Ship Characteristic	Value
Ship Class	Second class
LOA (Length overall)	155m
127mm (5 inch) Gun	1
76mm Gun	0
40mm Gun	2
Anti-ship Missile	Equipped
Anti-air Missile (Over 100km range)	Equipped
Anti-air Missile (Less than 100km range)	Equipped
RAM	1
CIWS	2
Decoy	Equipped
Lightweight Torpedo	Equipped
Anti-submarine Rocket	Equipped
Depth charge	Equipped
TACM	Equipped
Equipment for electronic warfare	Equipped
Anti-air Detection Function	Equipped
Aegis Function	Equipped
Hull-mounted sonar	Equipped
Towed array sonar system	Equipped

Since information on the exact organization of DDG-51 could not be obtained, as shown in Table 10, US Navy albums around 2010 were counted and compared with this result. [12]

Table 10. Comparison of results with the US Navy

Division	Specialty	DDG-80	DDG-84	DDG-86	DDG-92
Operation	BM	21	25	23	28
	OS	25	19	16	21
	QM	3	7	14	6
	EW	11	24	20	5
	IT	12	11	12	12
	Subtotal	**72**	**86**	**85**	**72**
Combat system	GM	14	13	8	8
	FC	27	38	21	21
	STG	14	14	18	18
	ET	15	23	20	19
	Subtotal	**70**	**88**	**67**	**66**
Engineering	GS&EN	36	31	43	37
	EM	6	8	7	6
	DC	16	17	20	11
	Subtotal	**58**	**56**	**70**	**54**
Supply	CS	16	12	15	15
	HM	2	3	4	4
	YN	3	6	3	3
	SH	13	17	10	10
	Subtotal	**34**	**38**	**32**	**32**
Total Sum		**234**	**268**	**254**	**224**

For security reasons, the composition of the crew estimated through the study cannot be disclosed, so an example of the results in what form the results come out is prepared in Table 11.

Table 11. Example of the first estimation result

Number	Division	Crew	Navigation		Combat	
			Mission	Station	Mission	Station
1	Operation	BM-1	Patrol	Ship Overall	Projectile charger	127mm
2		BM-2	Patrol	Ship Overall	Projectile carrier	127mm
3		BM-3	Bridge watch	Bridge	Projectile carrier	127mm
4		QM-1	Duty petty officer-1	Bridge	Duty petty officer	Bridge
5		QM-2	Duty petty officer-2	Bridge	Broadcasting	Bridge
6		QM-3	Duty petty officer-3	Bridge	Signalman	Bridge
11	Combat System	GM-1	127mm_Watch	127mm	Captain of the gun	127mm
12		GM-2	Console operator	CIC	Panel operator	Equipm ent room
13		GM-3	Console operator	CIC	Panel operator	Equipm ent room

The number of crew members estimated through the study is shown in Table 12.

Table 12. The number of the crew of the first estimation result

<table>
<tr><th>Division</th><th>Specialty</th><th>Number</th><th>Division</th><th>Specialty</th><th>Number</th></tr>
<tr><td colspan="2">Officer</td><td>23</td><td rowspan="3">Engineering</td><td>PR</td><td>26</td></tr>
<tr><td rowspan="5">Operation</td><td>BM</td><td>30</td><td>EM</td><td>13</td></tr>
<tr><td>QM</td><td>7</td><td>MR</td><td>10</td></tr>
<tr><td>IT</td><td>11</td><td rowspan="5">Supply</td><td>CS</td><td>15</td></tr>
<tr><td>OS</td><td>24</td><td>YN</td><td>3</td></tr>
<tr><td>EW</td><td>7</td><td>HM</td><td>4</td></tr>
<tr><td rowspan="4">Combat System</td><td>GM</td><td>27</td><td>SK</td><td>4</td></tr>
<tr><td>FC</td><td>22</td><td>ETC</td><td>7</td></tr>
<tr><td>ST</td><td>12</td><td colspan="2" rowspan="2">Total Sum</td><td rowspan="2">252</td></tr>
<tr><td>ET</td><td>7</td></tr>
</table>

In addition, data and results for past ships of the Arleigh Burke-class Destroyer in Table 10 were compared. The comparison result is shown in Figure 37.

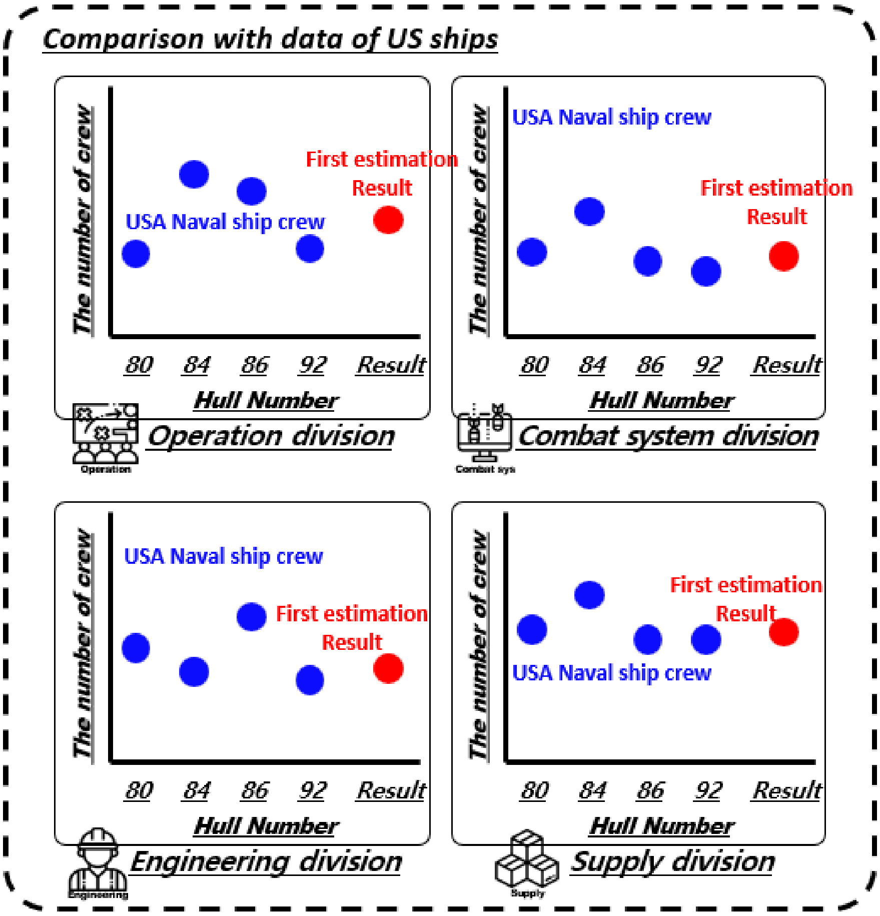


Figure 37. Comparison of results with the US Navy

The blue dot in Figure 37 is the data from Arleigh Burke-class Destroyer's past ships, and the red dot is the result of the first estimation. As a result of the comparison, it can be confirmed that the result of the first estimation is within the range of the past ship.

6.3. The second estimation based on experts' knowledge for application

In the second estimation, the user checks the result value of chapter 6.1, adds and reflects the rules necessary for the ship I want to design, and transfers the value to the final estimation.

For accurate rules, experts in calculating the crew composition, legacy ship data, and ship regulations are needed. Since the input data of the current expert system is the result value calculated using legacy ship data in the first estimation, the legacy ship data can be replaced in this paper, but it is generally difficult to obtain, and it takes a lot of time to quantize the data. Therefore, in this paper, the rules of the expert system were defined by borrowing the knowledge of the study. Later, if real experts define the rules, the rules will become more realistic.

By referring to the result of the example, the object information necessary for the ship to be designed is defined. Object information is divided into navigation watch and combat watch, and the format of result is the same as the first estimation.

By referring to the result of the first estimation, the object information necessary for the target ship is defined. Object information is divided into navigation watch and combat watch, and the results are shown in Table 13.

Table 13. Expert knowledge for application (Object information)

Object ID	Target object mission	Target object station	Specialty	Target Value
N001	Steering	Bridge	QM	2_MIN_man / 3_Section
N002	Patrol officer-1	Ship Overall	ND	2_REC_man / 1_MIN_man / 2_Section
N003	Engine watch	Engine Room	GS/EN	2_REC_man / 0_MIN_man / 3_Section
N004	EW watch	CIC	EW	3_REC_man / 2_MIN_man / 3_Section
N005	Galley watch	Galley	CS	11_REC_man / 8_MIN_man / 1_Section
N006	Administration	Administration office	YN	2_REC_man / 2_MIN_man / 1_Section
N007	Communication	Communication office	IT	3_REC_man / 2_MIN_man / 2_Section
N008	Supply	Supply Room	SK	2_REC_man / 2_MIN_man / 1_Section
N009	Patrol officer-2	Ship Overall	ND	3_REC_man / 2_MIN_man / 3_Section
C001	127mm	Equipment Room	GM	1_MIN_man / 1_Section
C002	127mm	CIC	FC	1_MIN_man / 1_Section
C003	CIWS	Equipment Room	GM	1_MIN_man / 1_Section
C004	CIWS	Outboard	GM	3_REC_man / 2_MIN_man / 1_Section
C005	CIWS	CIC	FC	1_MIN_man / 1_Section

As shown in Table 14, the relation information necessary for the ship to be designed was defined by referring to the results of the example.

Table 14. Expert knowledge for application (Relation information)

Relation ID	Target object mission	Target object station	Specialty	Subjective object	Subjective Object value
R001	127mm Gun	Outboard	GM	Torpedo	1_MIN_man
R002	127mm Gun	Outboard	ND	Decoy	3_MIN_man
R003	Anti-surface missile	CIWS	GM	RAM	1_MIN_man
R004	CIWS	Outboard	ND	Torpedo	2_MIN_man

For security reasons, composition of the crew estimated through the study cannot be disclosed, the number of crew members estimated through the study is shown in Table 15Table 12.

Table 15. The number of crew of the second estimation result

Division	Specialty	Number	Division	Specialty	Number
Officer		23	Engineering	PR	26
Operation	BM	30		EM	13
	QM	7		MR	10
	IT	11	Supply	CS	15
	OS	24		YN	3
	EW	7		HM	4
Combat System	GM	27		SK	4
	FC	22		ETC	7
	ST	12	Total Sum		252

	ET	7		

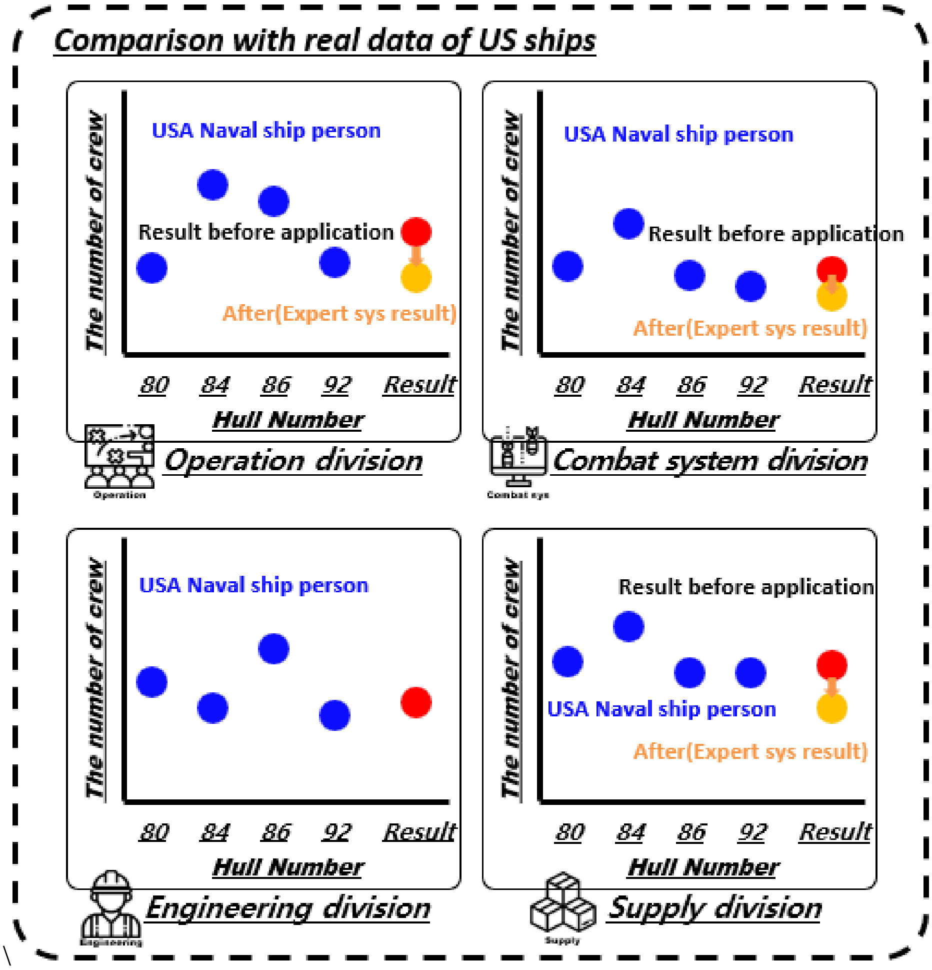


Figure 38. Comparison of results with the first estimation

Figure 38 compares the results with Figure 37. The blue dot is the Arleigh Burke-class Destroyer's past ship data, the red dot is the Result of the first estimation, and the orange dot is the Result of second estimation. As a result of the comparison, it can be seen that the knowledge is reflected, and the number of personnel may increase due to the knowledge.

6.4. The final estimation based on DEVS for application

Simulation using DEVS is performed based on the results from the expert system. Simulation is performed with combat situations and emergency situations. Among the results from the expert system, combat situation is for weapons-related specialty, and emergency situation is for the crew members of the engine department. The target crew members are shown in Figure 39.

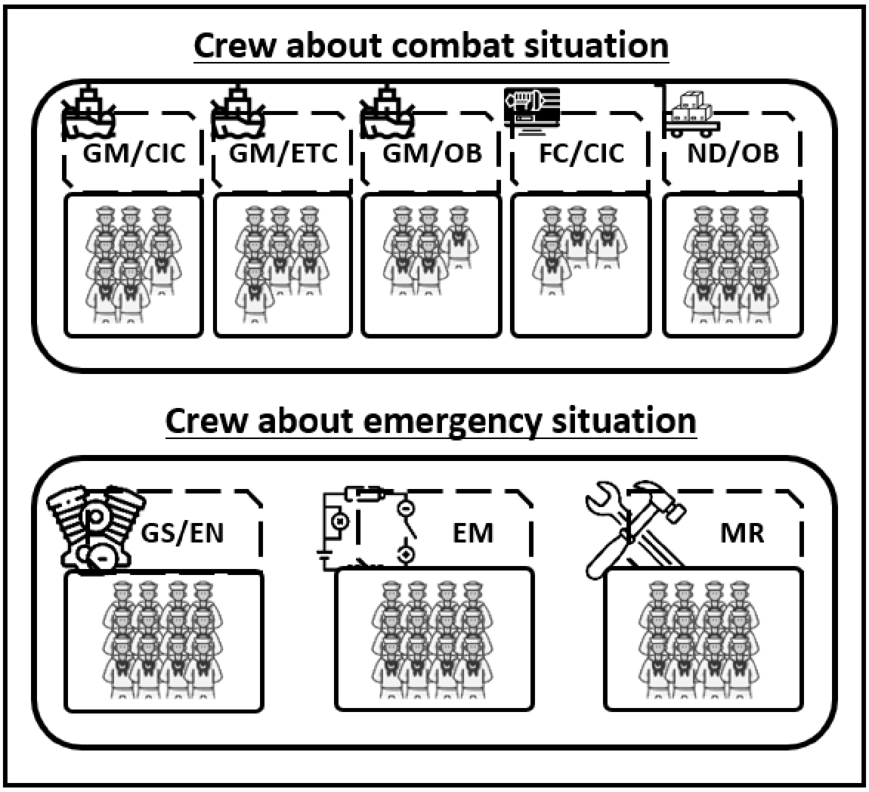


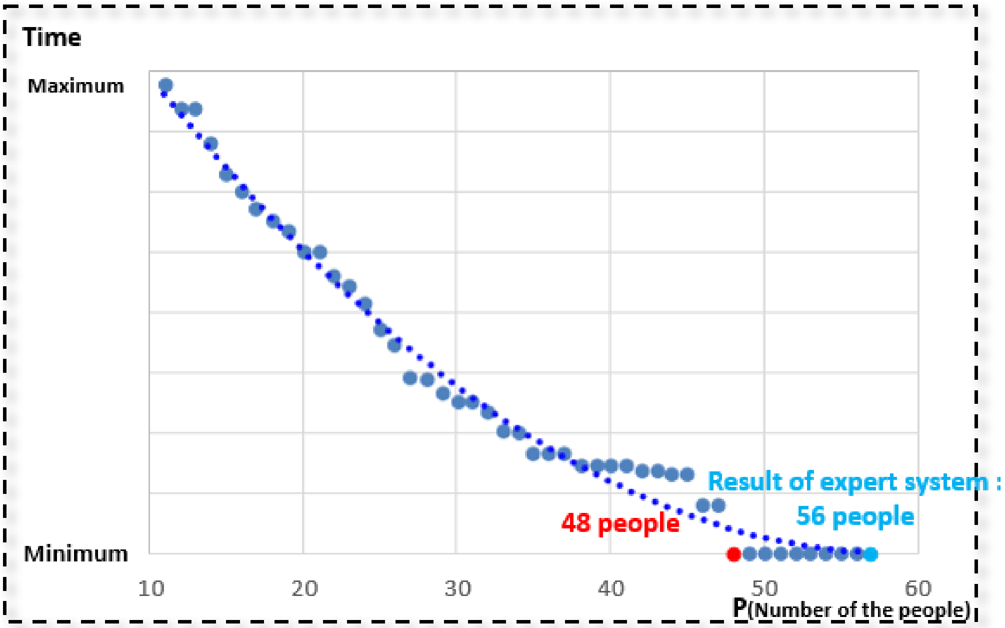
Figure 39. Target crew for simulation

6.4.1. Result of DEVS model for a combat situation

Simulation is performed using the crew about combat situations from the expert system as input data. The specialty of the crew consists of GM, FC, and ND (Non-Designation: Crew whose mission is not related to the specialty). The purpose of performing the simulation is to perform multiple missions, not one mission, by one crew member, and to make the matter realistically possible, only missions performed in the same similar location were performed simultaneously. Therefore, the crew members from the expert system were classified into detailed groups based on the positions in which missions were performed during combat situations. Therefore, it is divided into GM/CIC, GM/ETC (equipment room, etc.), GM/Outboard, FC/CIC, and ND/Outboard.

A total of 100 cases were performed in the simulation. Each case is divided into scenario composition, the interval between scenarios, and hit rate of weapons for each scenario, and information on each case is included in Appendix.

For each case, the minimum number of people was calculated under the limiting condition that the execution time does not decrease, and the method calculates the minimum number of people whose execution time does not decrease while reducing one person in the classified crew group, as shown in Figure 40.



Time	GM_{CIC}	GM_{ETC}	GM_{OB}	FC_{CIC}	ND_{OB}	SUM
100%	7	10	9	5	25	56
100%	6	11	8	5	26	55
...						
100%	4 (-3)	9 (-1)	7 (-2)	5 (-)	23 (-2)	48 (-8)
111.98%	4	9	7	5	22	47

Figure 40 Result of a case

After performing 100 times, the final number was selected by selecting the maximum value for each crew member's specialty/station. The detailed results of the corresponding results are included in Appendix A, and the main results are shown in Table 16.

As shown in Table 16, the specialties and placement positions were classified and classified, and the maximum value was calculated for each column to calculate the minimum value for all simulations. As a result of the performance, 2 people and 3.5% decreased compared to the Result of the second estimation.

Table 16. Results of simulation in a combat situation

Case Number	GM/CIC	GM/ETC	GM/OB	FC/CIC	ND/OB	Sum
Result of the second estimation	7	11	9	5	25	57
27	7	10	9	4	24	54
63	7	10	9	4	24	54
35	7	9	9	3	25	53
85	7	10	8	4	23	52
50	7	9	8	3	24	51
61	7	10	9	4	21	51
75	7	7	9	3	25	51
3	7	9	9	3	22	50
6	7	10	8	3	22	50
8	7	10	9	4	20	50
43	6	8	9	3	24	50
57	6	7	9	3	25	50
78	7	10	9	3	21	50
79	7	9	9	4	21	50
98	7	7	8	4	24	50
Max	7	10	9	4	25	55

6.4.2. Result of DEVS model for emergency situation

Simulation is performed using the crew about the emergency situation from the second estimation as input data. The number of personnel in the engine department is 26, 13, and 10, respectively, for GS/EN, EM, and MR, and the daily schedule for the simulation is shown in Figure 41.

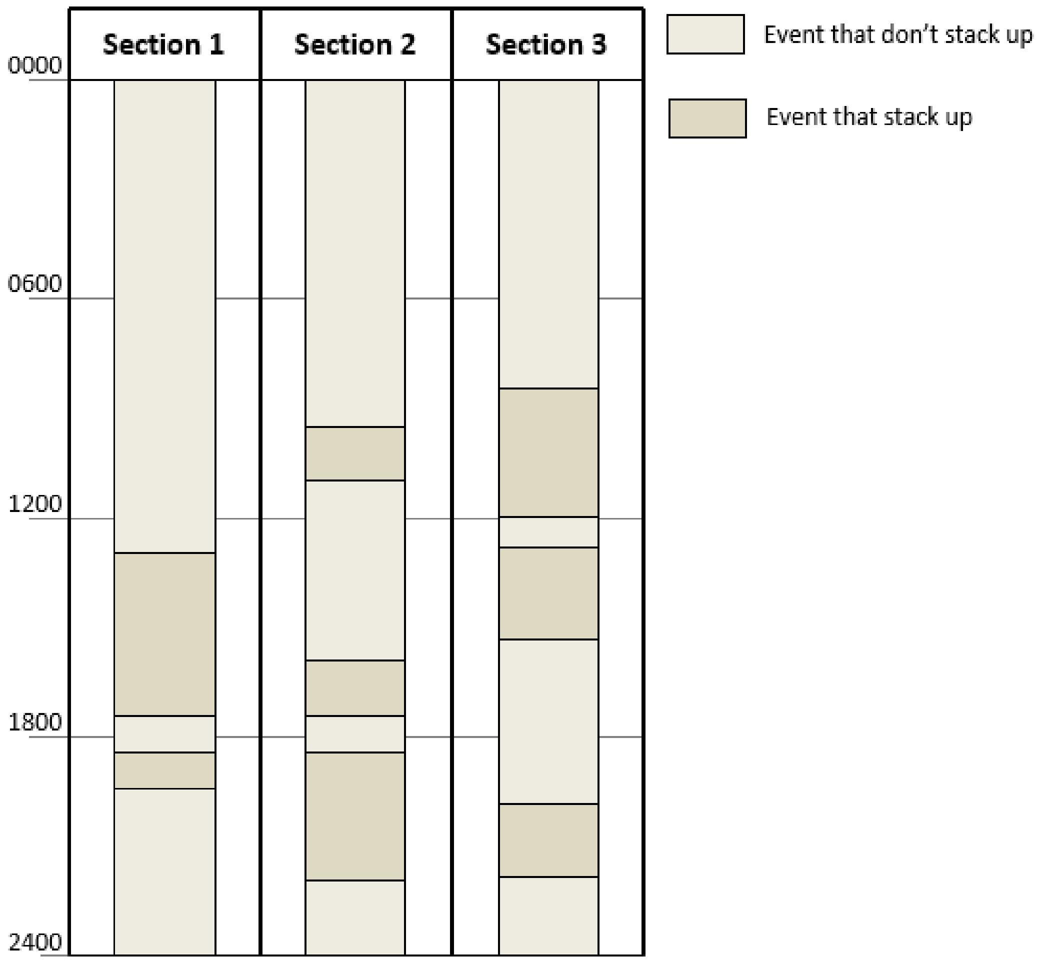
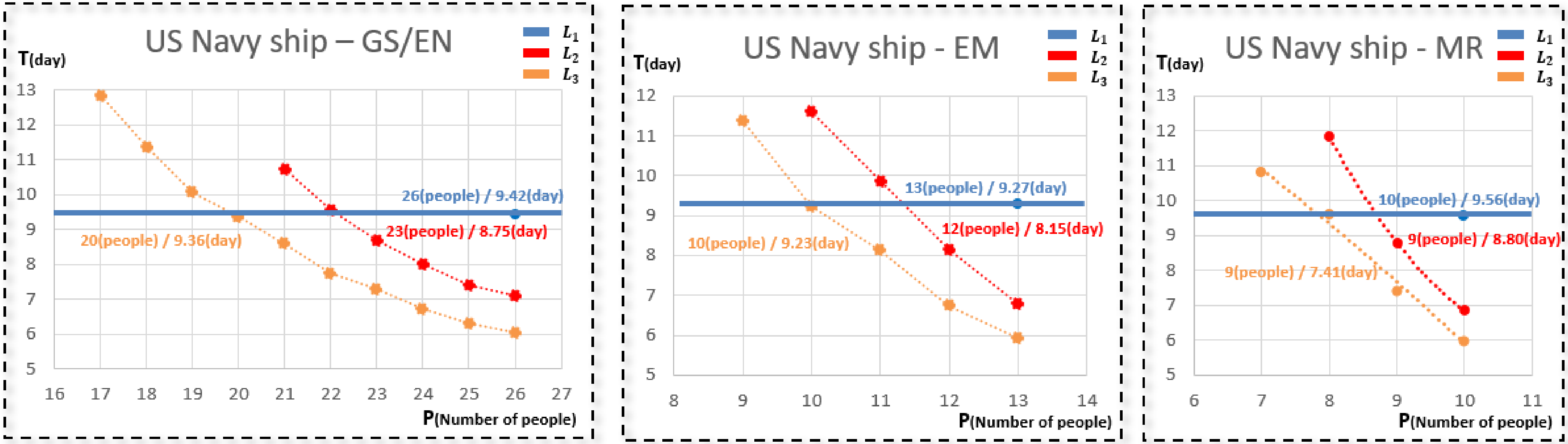


Figure 41. Daily schedule for conducting simulations

The daily schedule must be performed indispensably even when an emergency situation occurs, and it is not performed when an emergency situation occurs, and the event that doesn’t stack up does not accumulate even after the emergency situation is over, and it must be performed after the emergency situation is over. It is divided into Events that stack up. The event that doesn’t stack up consists of Sleeping / Messing / Watching / Meal, and the Event that stacks up consists of Training / Education / Administration / Maintenance.

When carrying out daily tasks, an emergency situation occurs, and the crew solves the emergency situation while performing the Event that doesn’t stack up, and after the completion of the emergency situation, the Event that stacks up is completed and then checks and compares the time. The result of the simulation is shown in Figure 42.

As a result, GS/EN reduced the number of employees from 26 to 23 when Level 2 was applied and 20 when Level 3 was applied, and EM reduced from 13 to 12 when Level 2 was applied and 10 when Level 3 was applied MR decreased to 9 when Level 2,3 was applied. This resulted in a decrease of 8 to 12% from the default value when Level 2 was applied and 10 to 23% when Level 3 was applied.



Lv	26	25	24	23	22	21	20	19	18	17
Lv2	7.09	7.39	8.01	8.71	9.55	10.7	-	-	-	-
Lv3	6.04	6.31	6.71	7.29	7.74	8.59	9.36	10.05	11.36	12.85

Lv	13	12	11	10	9
Lv2	6.81	8.15	9.86	11.62	-
Lv3	5.93	6.74	8.12	9.23	11.39

Lv	10	9	8	7
Lv2	6.86	8.80	11.82	-
Lv3	5.99	7.41	9.6	10.8

Figure 42. Results of simulation in an emergency situation

7. Conclusions and future works

The Navy needs to optimize the number of crew members who board the ships due to the decrease in military service resources due to the population cliff and the increase in the number of ships, which has a great impact on operational effectiveness and cost reduction. In addition, a detailed study was necessary because the operation of the ship and the specialties of various crew members had to be considered.

In this paper, we propose a method for estimating the composition of the crew in three stages. In the first step, a method using crew member composition data of the legacy ship data was adopted to reflect the matters related to the operation of the ship. After datafication of the relevant data in accordance with the standards in consideration of the crew's specialties and operation of the ship in wartime, the composition of the crew and the mission and mission performance position in the wartime situation is calculated considering the weapons and equipment of the ship to be designed.

In the second step, an expert system was adopted to reflect the changing ship design policy and new ships. Using the expert system, the expert's knowledge is reinforced on the result value from the previous step to produce a suitable result for the ship to be designed.

In the third step, simulation using DEVS was adopted, which can confirm the change in crew composition in advance when the military implements a policy change. The method consists of a whole combat situation and an emergency situation (Engine failure), and it is possible to calculate the crew composition optimized for the situation.

In addition, the method proposed in this paper was adopted and used to organize the crew of the Arleigh Burke-class Destroyer Flight IIA (DDG) of the US Navy, and the results were summarized. The validity of the proposed method was demonstrated through an example.

However, the current Expert system in this paper cannot handle all the knowledge of the composition of the crew. Therefore, it will be improved to handle various knowledge as well as the method through mission assignment in wartime, which is the format currently used.

In addition, in this paper, the most lethal situation was dealt with when performing the simulation, but we plan to study to calculate the optimal number of people in all situations by adding modules in other special jobs.

In this paper, the human factor was not considered during the simulation. Since the crew members are not robots, fatigue accumulates as the voyage continues, which reduces work efficiency. In future studies, the human factor will be considered.

References

[1] Ministry of National Defense (Korea), 2022, '23~'27 Mid-tern National Defense Plan Press Release

[2] John D. Lee, 1997. Validation and Sensitivity Analysis of a Crew Size Evaluation Method, Battle Seattle Research Center.

[3] Tyson Scofield, 2006. Manning and Automation Model for Naval Ship Analysis and Optimization, The Faculty of Virginia Polytechnic Institute and State University.

[4] Hollins and Renaldo N., 2014. A case study using imprint pro to validate the LCS core crew manning solution, Naval Postgraduate School.

[5] Renee Chow and Matthew Lamb, 2016. Evaluation of Current and Future Crew Sizes and Compositions: Two RCN Case Studies, DRDC Toronto Research Centre.

[6] In ha Hwang, 2019. A Study on a Manpower Forecasting Model for Naval Ships, Korea University.

[7] Ki-Su Kim, 2020. "A Method of the Evaluation and Optimization for the Crew Manning of Naval Ships", The Annual Autumn Conference, pp. 257.

[8] "Navy recruitment - Specialty Introduction", 대한민국 해군. accessed Jan 18, 2023, https://www.navy.mil.kr/mbshome/mbs/navy/subview.do?id=navy_050102010000

[9] Ki-Su Kim, 2015. Optimum Arrangement Design of Compartments and Equipment of a Submarine Based on Expert system, Master Thesis, Seoul National University.

[10] Zeigler, B., 1984, Multifacetted Modeling and Discrete Event Simulation. Academic Press, London; Orlando.

[11] Department of the navy (USA), 2017. OPNAVINST 1000.16K

[12] "E-YEARBOOK.COM-Navy Cruise Books", E-YEARBOOK.COM. accessed Jan 18, 2023, https://www.e-yearbook.com/navy-cruise-books.html

APPENDIX

A. Detailed data of combat scenarios

Case	GM/CIC	GM/ETC	GM/OB	FC/CIC	ND/OB	SUM	AAW	ASUW	ASW
1	5	6	7	3	20	41	6	6	3
2	6	6	8	3	20	43	6	6	2
3	7	9	9	3	22	50	7	7	3
4	7	6	7	3	17	40	7	7	5
5	7	8	7	3	21	46	6	6	4
6	7	10	8	3	22	50	7	7	6
7	6	6	8	3	22	45	6	6	2
8	7	10	9	4	20	50	7	7	4
9	7	7	8	3	22	47	8	8	5
10	6	6	8	3	22	45	9	9	5
11	7	6	7	3	16	39	8	8	3
12	6	7	7	3	16	39	7	7	6
13	5	6	8	3	22	44	9	9	7
14	7	6	9	3	23	48	8	8	4
15	5	6	7	3	18	39	7	7	4
16	6	6	7	3	20	42	7	7	6
17	7	7	7	3	17	41	8	8	4
18	5	7	7	4	21	44	7	7	5
19	5	6	7	3	17	38	7	7	5
20	5	6	7	3	19	40	7	7	4
21	7	6	9	3	21	46	8	8	5
22	6	6	7	3	21	43	7	7	5
23	5	6	7	3	16	37	7	7	5
24	5	6	7	3	16	37	6	6	4
25	6	7	8	3	25	49	7	7	5
26	6	6	7	3	16	38	7	7	4
27	7	10	9	4	24	54	7	7	3
28	5	6	7	3	16	37	8	8	7
29	6	7	7	3	17	40	8	8	5
30	6	10	7	3	20	46	7	7	2
31	7	6	7	3	17	40	7	7	4
32	5	6	7	3	17	38	8	8	5
33	6	7	8	4	20	45	8	8	4
34	6	6	9	3	21	45	7	7	4
35	7	9	9	3	25	53	7	7	5
36	6	6	7	3	21	43	8	8	5
37	5	6	7	3	19	40	7	7	6
38	7	10	7	3	20	47	8	8	5
39	5	6	7	3	21	42	6	6	5
40	6	7	7	3	16	39	9	9	6
41	6	6	7	3	19	41	6	6	1
42	6	6	7	3	16	38	8	8	4
43	6	8	9	3	24	50	7	7	5
44	6	6	7	3	17	39	8	8	5
45	7	6	9	3	23	48	7	7	5
46	6	6	8	3	22	45	6	6	3
47	5	9	7	3	20	44	8	8	6
48	6	6	7	3	16	38	8	8	5
49	7	6	9	3	22	47	6	6	4
50	7	9	8	3	24	51	8	8	5

51	7	7	9	3	22	48	9	9	5
52	5	6	7	3	18	39	7	7	5
53	6	6	8	3	22	45	8	8	5
54	6	6	9	4	19	44	7	7	5
55	5	6	8	3	22	44	6	6	5
56	5	6	7	3	16	37	7	7	3
57	6	7	9	3	25	50	8	8	4
58	7	7	7	3	20	44	8	8	4
59	7	6	9	3	21	46	6	6	4
60	5	6	7	3	18	39	7	7	3
61	7	10	9	4	21	51	7	7	4
62	7	9	7	3	19	45	8	8	5
63	7	10	9	4	24	54	7	7	2
64	5	6	7	3	24	45	8	8	5
65	7	6	8	3	16	40	8	8	5
66	7	6	9	4	23	49	6	6	5
67	5	6	7	3	19	40	7	7	5
68	7	6	7	3	16	39	8	8	5
69	6	7	7	3	20	43	6	6	2
70	7	10	9	4	19	49	8	8	5
71	7	8	9	4	20	48	8	8	7
72	5	6	7	3	17	38	8	8	4
73	5	6	8	3	21	43	7	7	4
74	5	6	7	3	20	41	8	8	4
75	7	7	9	3	25	51	6	6	4
76	7	6	9	3	23	48	6	6	4
77	6	6	7	3	16	38	9	9	5
78	7	10	9	3	21	50	7	7	4
79	7	9	9	4	21	50	8	8	5
80	7	8	7	3	19	44	6	6	5
81	7	6	9	3	21	46	8	8	6
82	6	6	7	3	18	40	9	9	5
83	6	7	8	3	22	46	7	7	5
84	7	8	7	3	16	41	9	9	5
85	7	10	8	4	23	52	7	7	5
86	5	6	7	3	16	37	8	8	5
87	7	6	7	3	16	39	8	8	4
88	6	6	8	4	23	47	9	9	7
89	7	6	7	3	16	39	8	8	4
90	5	6	7	3	18	39	7	7	5
91	6	6	9	3	20	44	8	8	4
92	7	8	7	3	20	45	8	8	4
93	5	7	8	3	22	45	8	8	4
94	5	6	7	3	21	42	8	8	7
95	7	10	7	3	21	48	7	7	4
96	6	6	7	3	18	40	9	9	7
97	7	6	7	3	16	39	10	10	6
98	7	7	8	4	24	50	10	10	6
99	7	6	8	3	21	45	10	10	6
100	7	8	7	3	17	42	10	10	6

국문 초록

전투함의 운영 시나리오를 고려한 승조원 추정 최적화

현재 군은 청년 인구 감소, 복무기간 단축 등을 이유로 병력 감축의 계획의 세우고 있다. 하지만 전투함은 대형화, 탑재 무장, 장비의 증가 등으로 인해 이전보다 많은 운영 인원이 필요하다. 그러므로 적절한 승조원의 수를 전투함에 배치하는 것이 중요하다. 또한 전투함은 여러 운용 상황(전투, 정비 등)을 고려해야 하고 승조원의 특기가 다양하므로 승조원의 구성을 전투함의 특성에 맞게 최적화하는 것이 필수적이다. 이를 위해 해군은 관련 노하우를 갖춘 전문가와 실적선 기반의 자료에 의존하고 있으나, 군 정책의 변화, 신형 전투함의 대형화, 무장의 다양화 등의 이유로 추가적인 최적화가 필요하다.

본 논문에서는 설계 함정의 제원과 주요 탑재 장비가 주어질 때, 현재 군이 시행 중인 실적선 자료를 활용해 운영 기반의 승조원 구성을 일차적으로 산출하였다. 해당 결과는 과거기반의 승조원 구성을 산출하였기 때문에 추가적으로 전문가시스템을 활용하여 내가 설계하는 함정의 특성과 현재 함정 운영에 대한 사항을 반영한 결과를 산출하였다. 이후 그 결과를 시뮬레이션 방법을 이용하여 전투함의 승조원 구성을 최적화하는 방법을 연구하였다. 실적선 자료 기반의 승조원 추정 방법은 다양한 특기를 가진 승조원을 함정의 제원, 탑재된 무장 등을 고려하여 분류하고, 회귀 분석 등을 이용하여 설계 함정에 맞는 승조원 구성을 추정하게 된다. 전문가 시스템 기반의 승조원 추정 방법은 Rule-based expert systems를 활용하여 함정 운용을 고려하여

설계한 CEM(Crew manning Expert system Model)을 통해 승조원 구성을 재추정하게된다. 시뮬레이션 기반의 최적화 방법은 함정의 실제 운영 상황을 모사한 시나리오를 고려하여 이산 사건 (DEVS: Discrete EVent System specification) 시뮬레이션을 이용해 임무 수행 시간 및 효율을 비교 분석하여 승조원 구성을 최적화한다. 최종적으로 검증을 위해 자체 개발 프로그램을 구현하였고, 미 해군의 함정의 제원 및 승조원의 수를 프로그램에 입력하여 성능을 검증하였다.

Keywords: Crew manning (승조원 구성), Naval ship (함정), Optimization (최적화), Simulation (시뮬레이션)

Student number: 2021-21275