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Optimum Arrangement Design of Compartments and Equipment of a Submarine Based on Expert System

전문가 시스템 기반 잠수함
구획 및 장비의 최적 배치 설계

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Abstract

Optimum Arrangement Design of Compartments and Equipment of a Submarine Based on Expert System

The arrangement design of a submarine is dependent on data of parent ships and experts' experiences. The delay in design can occur when there are data missing or the absence of experts. In addition, the arrangement design of a submarine is a difficult problem to be solved because various compartments and equipment are placed on the limited area called pressure hull and there can be numerous alternatives for the arrangement design. Thus, it is needed to accumulate data of parent ships, experts' experiences, and design rules as systematic structure, and a demand for optimization in the arrangement design is increasing these days. For this, an arrangement method of a submarine compartments and equipment based on expert system and optimization technique was proposed in this study. First, a template model for arrangement design of a submarine was made. Secondly, an expert system which can computerize quantitatively experts' experiences and knowledge was developed. Thirdly, an optimization method which can yield optimal arrangement design was established after formulating an arrangement problem of a submarine as an optimization problem and solving it with an efficient optimization algorithm. To evaluate the applicability of the proposed method, a prototype program which consists of the template model, expert system module, and optimization module was developed. Finally, this method was applied to a problem for arrangement design of a submarine. The result shows that the proposed method can be used as a new tool for arrangement design of submarine.

Keywords: Arrangement design, optimization, expert system, submarine

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1. Introduction

1.1. Chereteristics of the arrangment design of submarine

Arrangement design of submarine is similar to layout design of building. But when proceed arrangement design of submarine, weight restriction and center of weight of submarine must be considered (Bucher and Rydill, 1944). In addition, crew can operate inside of pressure hull only, so arrangement design of a compartments and equipment inside of pressure hull are considered with more caution and rigorously. Arrangement design is performed after main dimension of submarine has been decided. Then a draft arrangement of submarine is drawn up. After draft arrangement is drawn, detail arrangement of submarine is drawn include piping, wire, etc. 3D CAD model(digital mock-up) is used for check and modify the arrangement as occasion demands. Sometimes, real scale model is made for validation or improvement of the arrangement considering operability of equipment, accessibility of passage, etc. There are cases about check arrangement design using 1/4 scale model or 1/5 scale model (Shon and Park, 2001). Thus, it is very important that efficiency of space inside of pressure hull, so that efforts of design experts are reflected in the arrangement design of submarine.

Ideally, hull form of submarine should be teardrop form that is advantageous in underwater navigation. But commonly, hull form of submarine is longer and thinner than teardrop form, because of arrangement. As considering this, inside the pressure hull should be tight. Dominant components of length of pressure hull are torpedo room, propulsion system, battery, etc. Torpedo room and propulsion system is very hard to shorten because of characteristics of the equipment included in the system. So, there are many efforts for be piled up the dominant components of length such as, arrange space for battery under torpedo room. There are restriction of depth and breadth considering size of submarine and hull form, so that arrangement design of submarine should be performed take account of components of arrangement synthetically (Zimmerman, 2000).

Various tanks should be placed in pressure hull. Compensation tank placed in middle part of pressure hull and trim tank placed in front and rear part of pressure hull are installed in pressure hull in order to compensate weight variation of submarine while submerged. For example, fuel oil and auxiliary oil weight are changed during operation, and center of gravity is also changed. In various case of arrangement of submarine, Efforts to lower center of gravity is necessary. And also compensation tank and trim tank are arranged properly. Furthermore, fresh water tank and sanitary tank are installed for crew. Figure 1-1 shows arrangement of 212 class submarine that has diesel propulsion system.

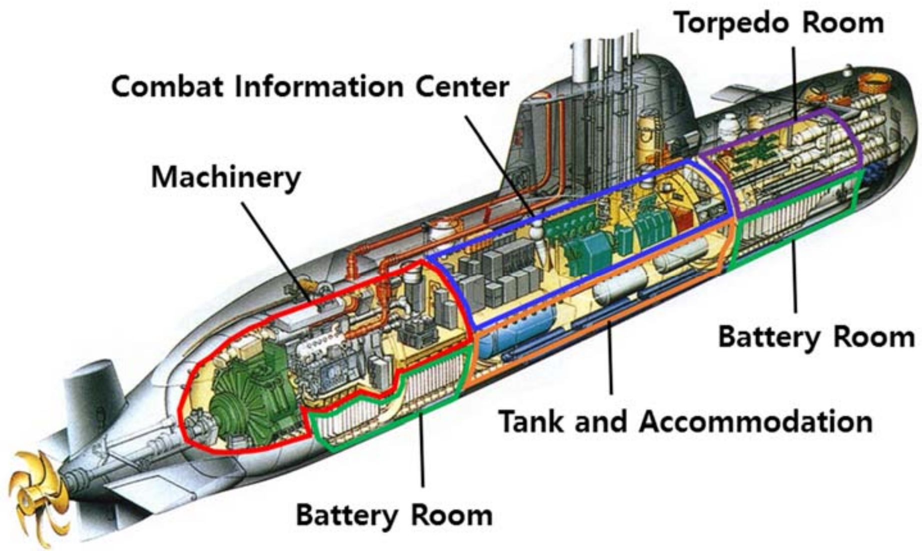

Figure 1-1 Arrangement of a submarine of 212 class

1.2. Motivation

The problems of arrangement design for a ships have been researched by many scholars. Equipment of submarine that is one of the special ships. Should be placed in a limited area called pressure hull. When an arrangement design of submarine is performed, more efforts are needed then ships. But a researches for arrangement design of submarine were rarely founded, because almost all submarines have been made for military purpose. So, in this study, a method for an arrangement design of submarine is presented.

Arrangement design of ships is performed refer to previous ships' then modified some parts needed to be changed. But in case of an arrangement design of submarine, there are few data about previous result, and many equipment should be placed in a limited area. So, the role of experts are extremely big. Therefore, in this study, an expert system was adopted to use similar way as arrangement design akin to experts'. To use quantitative factors calculated by computers add to qualitative factors produced by the expert system, optimization method was also adopted to proceed an arrangement design of submarine.

Experts of arrangement design can't calculate complicated value such as, quantitative values like material flows, space efficiency, etc. But experts can take account of many things such as efficiency of a submarine, practicality of manufacturing, utility of maintenance, consideration of future modifying based on previous data, experiences and knowledge. Therefore it is very difficult without previous data and experts that have ability to design for arrangement of a submarine. In this point of view, expert system that can evaluate alternatives without previous data and experts was adopted in this study.

Meanwhile, many compartments and equipment are arranged in the pressure hull, and there are many alternatives for arrangement. From many alternatives, one optimum should be selected considering operation performance of submarine, convenience of crew, and so on. For this, an optimization problem that can found an optimum based on evaluation results of alternatives from expert system was formulated in this study. At this time, it is very difficult to formulate the problem with all variables to be used in arrangement design of submarine. Thus, the optimization problem was divided into three parts and then formulated one by one in this study.

1.3. Related works

Almost all design data for submarine is secret to the public. So, there are few works for arrangement design of submarine. However, many studies for arrangement ships have been proceeded till now. But there were few researches that take into account of both the expert system and optimization. The examples of researches about arrangement design using expert system are as follows.

Jung et al. (2011) was used a rule-based expert system when proceeding arrangement design of submarine. Partition that divide the pressure hull into a compartments and sequence of the compartments were set to a design variables. Evaluation values of the alternatives from the expert system were applied to objective functions. If alternatives violate rules of experts', add penalty to objective function so that experts' knowledge were reflected in optimization process. However, optimization problem was formulated for two dimensional arrangement, and equipment were not taken into account for arrangement design. So, the method of the study has restriction when applying to the real problems.

Byun (1988) designed initial design supporting expert system for helping designer to perform arrangement design of compartments in initial stages of ship design. And using the system, a knowledge base for decide main dimension was constructed to get maximum cargo holds while meet the requirements of ship owner and regulations for ships. Then the knowledge base for arrangement of compartments was also constructed to determine arrangement design of compartments in comparison with existing systems. But expert system of the study was made for interactive mode with users. So, it is restricted to apply the system to optimization process.

Shin (2013) proposed new general process of an arrangement of a naval ships considering survivability in initial stage of design. SLP (Systematic Layout Planning) method was used for analyze relation between each equipment in the naval ships. Then, an arrangement method for the naval ships and a method for create alternative was proposed in the study. SLP method differ from the expert system, however the method decide arrangement using relation matrix made by expert. So, it has similarity to the expert system. But also, the study didn't consider about optimization process using expert system. So, it has limitation when doing automatically generate alternatives and find optimum alternative.

Helvacioglu and Insel (2005) proposed the multistage expert system in an arrangement design of container ships. Container ships divided to large block that is function group is arranged first, then re-arranged considering detail thing to be taken into account. Heuristic knowledge and rules for container ships were used in the expert system. But the study didn't consider arrangement of equipment and optimization.

Shin et al. (2002) used the expert system for layout design of machinery in ships. For layout design of machinery in ships, relations between each equipment, layout rules for machinery, requirement of ship owner and insight of designer should be considered. So, the study used the expert system consist of fuzzy rules. Then new algorithm for layout design of machinery was developed using the expert system. The study practically considered experts' rule in the system, however it is hard to make connection with optimization process and generate alternatives automatically.

There are researches about using the expert system in building architecture. Park (2009) defined frames for expressing experts' knowledge using requirement of space (area, position, etc.) and relations between spaces (adjacency, level difference, etc.). Then the study evaluate arrangement of buildings using the frame. But, the study just can evaluate arrangement of buildings made by hands. So, the study has limit to generate alternatives and find optimum alternative in the results.

Therefore, arrangement evaluation model (AEM) was proposed to systematically express experts' knowledge for arrangement design of submarine. Multistage optimization problems was formulated to perform optimization practically. And data structure for arrangement design of submarine was developed to connect expert system and optimization problems efficiently. Table 1-1 shows summary of the studies and this study.

Table 1-1 Summary of the studies and this study

Research	Application	Using expert system	Using optimization	Dimension
Chung et al.	Arrangement of submarine compartments	○	○	2D
Byun	Arrangement of ship compartments	○	×	3D
Shin	Arrangement of compartments of naval ship	△	×	3D
Helvacioglu and Insel	Arrangement of container ship	○	×	2D
Shin et al.	Arrangement of ship machinery	○	×	3D
Park	Arrangement of building	○	×	3D
This sstudy	**Arrangement of compartments and equipment of submarine**	○	○	**3D**

1.4. Summarystudy

In this study, a method of arrangement design of submarine using the expert system and optimization technique is proposed.

Firstly, the expert system that can systematically accumulate experts' knowledge and experiences and previous data and evaluate arrangement of submarine using the data is necessary. Secondly, optimization problem that can generate an alternatives automatically and find optimum from the results have to be developed. Thirdly, a data structure that can express various variables used in the expert system and optimization problem is needed. Finally, three components as explained previously can be used by users, so that user interface that can operate the system is needed. The method proposed in this study is like Figure 1-2.

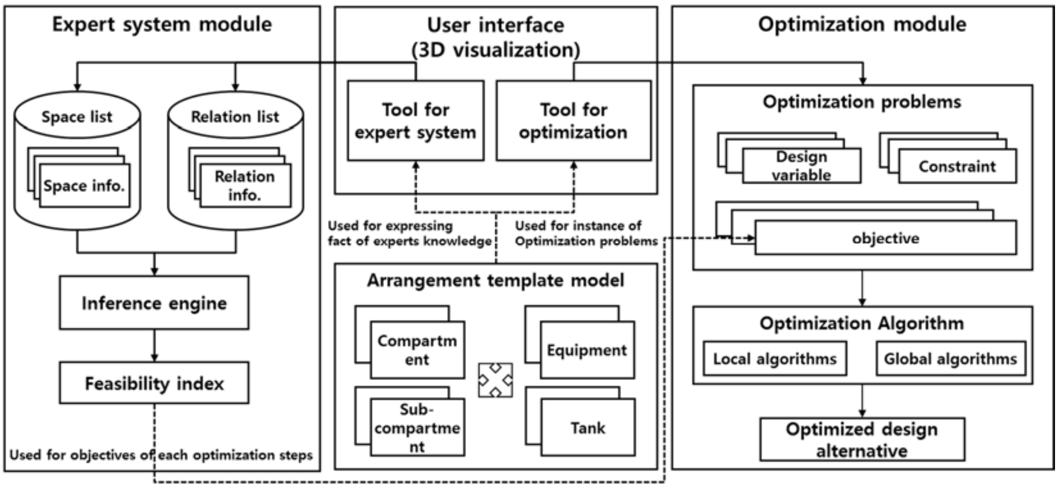

Figure 1-2 Configuration of optimum arrangement design of compartments and equipment based on expert system

In this study, optimum arrangement design of submarine based on the expert system was proposed, and computerize the system. Proposed system is consist of four part; Arrangement template model, expert system module, optimization module and user interface. Figure 1-3 is summary of each components used in the system.

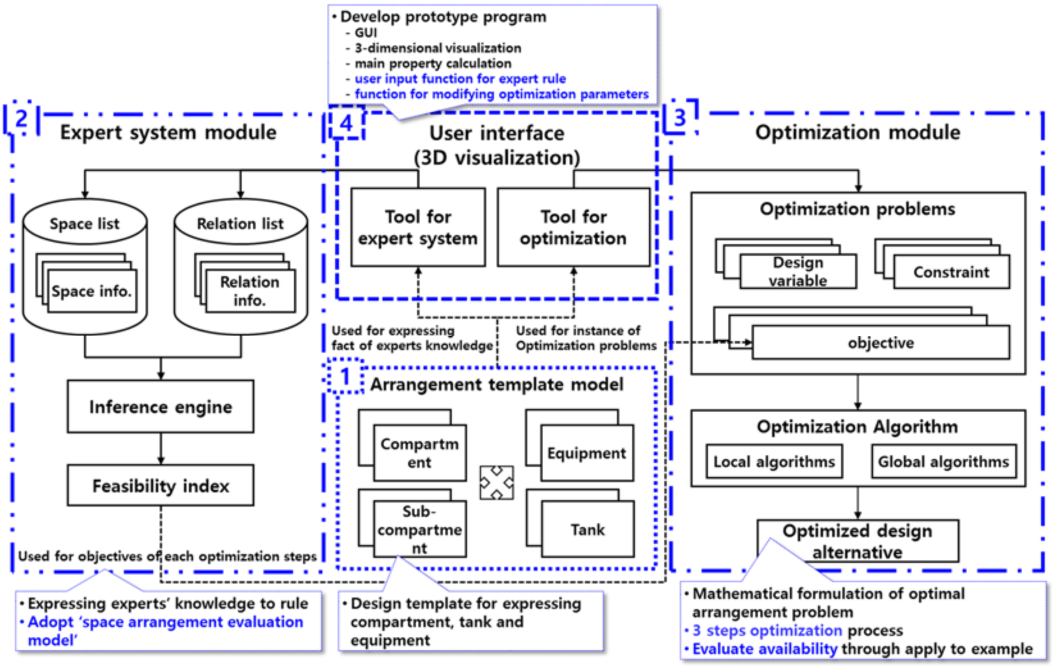

Figure 1-3 Summary of each components for the method of optimum arrangement of submarine based expert system

1.4.1. Arrangement template model

When proceed arrangement design of submarine, it is needed that a frame can contain various information about arrangement of submarine. The frame was defined to arrangement template model in this study. The template model can express various information about arrangement of submarine such as pressure hull, compartments, tanks, equipment, etc. And the information contained in the template model is used to define experts' rules in the expert system and variables in the optimization problems.

1.4.2. Expert system module

In artificial intelligence, an expert system is a computer system that emulates the decision-making ability of a human expert (Jacson, 1998). Among expert system, rule-based expert system is widely used. And in the system, a rule is presented by "IF-THEN phrase.

In this study, space information model (Park, 2009) was improved to adopt in this study. The name of improved model is AEM. And with this model, we can express experts' knowledge about arrangement design of submarine and evaluate suitability of alternatives.

1.4.3. Optimization module

Optimization module is composed of multistage optimization problem for arrangement of compartments, sub-compartments and equipment of submarine. And, to solve the problems effectively, optimization algorithm is contained in the module. Quantitative factors calculated in the expert system is considered in the optimization problems add to qualitative factors the can be calculated in the optimization process. This module is key components of the system to generate optimum arrangement of submarine. For practical perspective, the optimization problem was divided to three stages. And usability of the problems was confirmed with example.

1.4.4. User interface

User interface that was developed in this study has three key elements. First, tool for expert system was developed to create, edit and operate experts' rules. Second, tool for optimization was developed to set various parameters (the number of population, the number of evaluations, probability of mutation, etc.) that is used in the optimization problems and execute algorithm. Third, user interface also have 3D visualization panel for confirm the result of optimization.

2. Arrangement template model for submarine

2.1. Ontology

To express specific information in computers, we need a model for domain about specific subject. And the model is called ontology. In other words, ontology is specification of a conceptualization (Gruber, 1993). For arrangement design of ships, we need to have ontology for arrangement of ships. And For arrangement design of submarine, we need to have ontology for arrangement of submarine. Ontology gives concept of specific domain to object that have to share the information about the domain (Noy and McGuinness, 2001). Ontology's necessity is as follows:

- To share common understanding of the structure of information among people or software agents
- To enable reuse of domain knowledge
- To make domain assumptions explicit
- To separate domain knowledge from the operational knowledge
- To analyze domain knowledge

In many books about artificial intelligence, definition of ontology is vary with each other. There are many definition of ontology, so that clear concepts of ontology is treated in this study. Ontology is composed of a formal explicit description of concepts in a domain of discourse (classes or concepts), and properties of each concept describing various features and attributes the concept (slot or properties). In practical terms, developing an ontology includes:

- Defining classes in the ontology
- Arranging the classes in a taxonomic(subclass-superclass) hierarchy
- Defining slots and describing allowed values for these slots
- Filling in the values for slots for instances

Figure 2-1 shows example of ontology. In the example, car and ships (bulk carrier, container, and LNG carrier) are described. But it can change the structure as what the usage of.

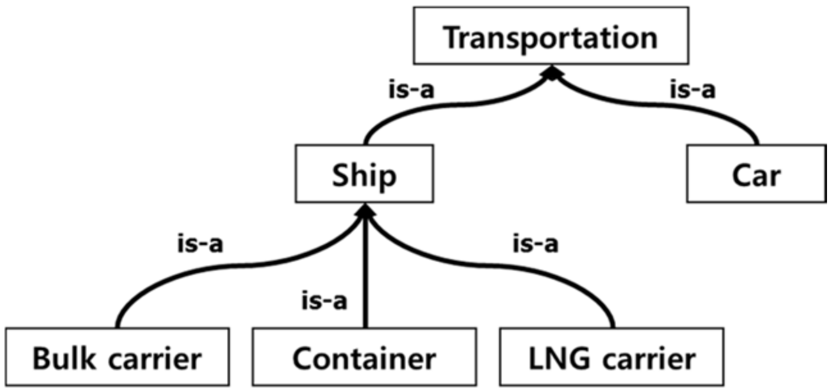

Figure 2-1 Ontology of transportation

2.2. Configuration of arrangement template model

In this study, an expert system and optimization technique were used for arrangement design of submarine. For this, a frame that can contain various information about arrangement of submarine is necessary. In other words, ontology is needed. So, the frame was defined to arrangement design of submarine template model in this study. Figure 2-2 appears main components of pressure hull.

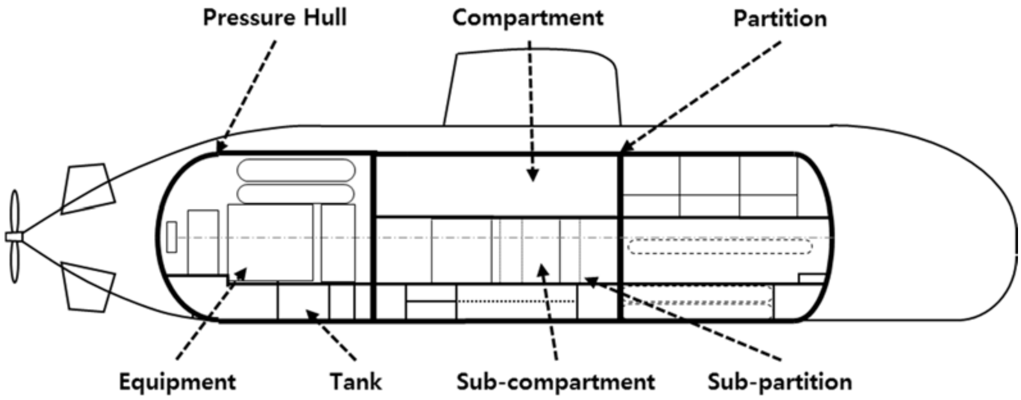

Figure 2-2 Main components of pressure hull of submarine

To express data about arrangement design of the submarine, pressure hull that has almost all equipment and has water tight space should be defined first. After, partitions that across the pressure hull should be defined. And the divided spaces are defined a compartments. As pressure does, the compartments are also divided by a sub-partitions, and the spaces divided by the sub-partition is defined to a sub-compartments. At last, an equipment that is placed in the compartments and the sub-compartments should be defined. The steps as previously mentioned is diagramed to Figure 2-3. And the steps also can be expressed by Figure 2-4.

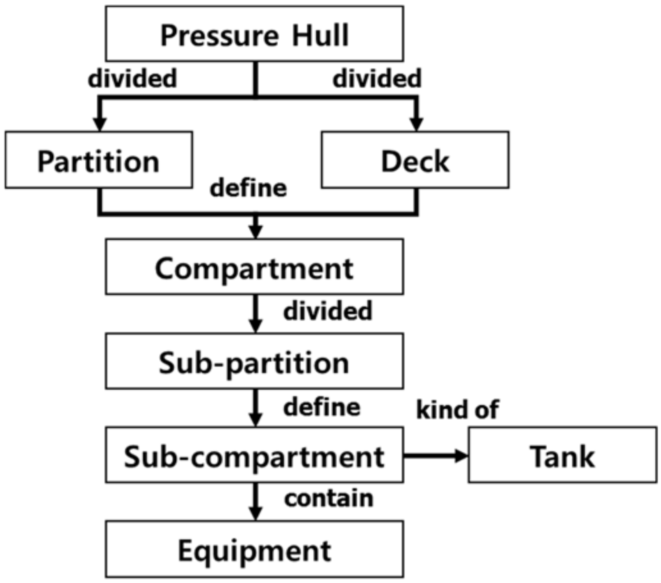

Figure 2-3 Relations between components in pressure hull

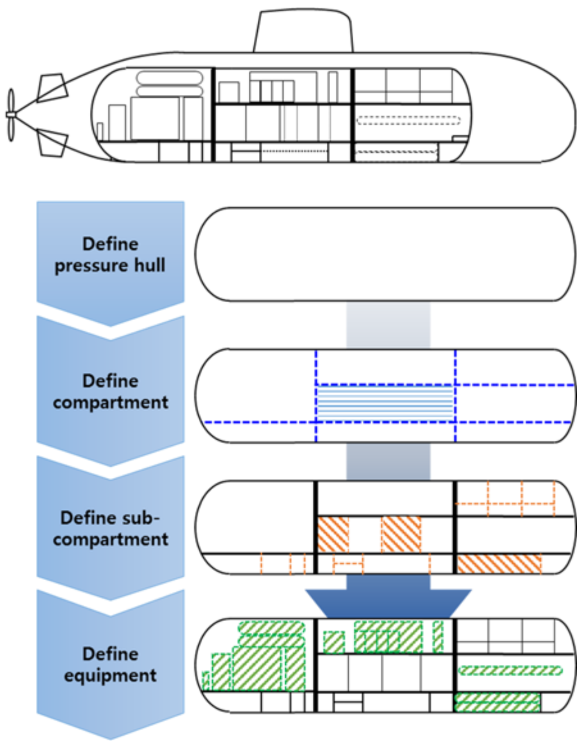

Figure 2-4 Steps for arrangement of pressure hull

2.2.1. Arrangement template model by UML

UML (Unified Modeling Language) is standardized modeling language enabling developers to specify, visualize, construct and document artifacts of a software system (O'keefe, 2006). As mentioned in 2.2, class diagram is needed to computerize the concept of arrangementtemplate model for a submarine. So, UML is used to define the template model in this study. In top of hierarchy, the pressure hull class is placed and properties of the pressure hull class is like Table 2-1.

Table 2-1 Properties of pressure hull class

Pressure Hull	
Properties	**Data type**
Name	String
Meshes	List<Mesh>
Volume	Double
Center of buoyancy	Point
Compartments	List<Compartment>
Partitions	List<Partition>

The pressure hull contains compartments and partitions. Partition class is abstract class, and sub-partition classes; X partition, Y partition and Z partition are defined by inherit partition class. Then transverse bulkhead partition class is defined by inheritance of X partition class, and deck class is also defined by inheritance of Z partition class. Properties of each classes previously mentioned are like Table 2-2, Table 2-3, Table 2-4, and Table 2-5.

Table 2-2 Properties of partition class

Partition(abstract class)	
Properties	**Data type**
ID	String

Table 2-3 Properties of sub-partition classes

X Partition, Y Partition, Z Partition	
Properties	**Data type**
Position	Double

Table 2-4 Properties of transverse bulkhead class

Transverse bulkhead	
Properties	**Data type**
Weight	Double

Table 2-5 Properties of deck class

Deck	
Properties	**Data type**
Weight	Double

To aggregate partition class in the compartment class or the sub-compartment class, a partition flag class is defined. Properties of the partition flag class is like Table 2-6.

Table 2-6 Properties of partition flag class

Partition flag	
Properties	**Data type**
Sign	bool
HasPartition	Partition

Compartment class below the pressure hull class is defined by inherit compartment base class, and the sub-compartment class is also defined by inherit the class. And a tank class that is kind of the sub-compartment class is defined by inheritance of the sub-compartment class. Properties of each classes are like Table 2-7, Table 2-8, Table 2-9, and Table 2-10.

Table 2-7 Properties of compartment base class

Compartment base	
Properties	**Data type**
ID	String
Name	String
Volume	Double
Center of buoyancy	Point
Meshes	List<Mesh>
Weight	Double
Relation matrix	DenseMatrix
Connection cost matrix	DenseMatrix
Discrete loads	List<Discrete Load>
Partition flags	List<Partition Flag>

Table 2-8 Properties of compartment class

Compartment	
Properties	**Data type**
Sub-compartments	List<SubCompartment>
Sub-partitions	List<Partition>

Table 2-9 Properties of sub-compartment class

Sub-compartment	
Properties	**Data type**
None	

Table 2-10 Properties of tank class

Tank	
Properties	**Data type**
Density	Double
Fill ratio	Double

At last, equipment class placed in the lowest part of hierarchy is defined, and properties of equipment class is like Table 2-11.

Table 2-11 Properties of equipment class

Discrete Load	
Properties	**Data type**
ID	String
Center of gravity	Point
Width	Double
Breadth	Double
Height	Double
Weight	Double

Defined classes compose arrangement template model for a submarine. Expert system used the classes to define experts' rules, and optimization problems used the classes to set various design variables, a constraints, and an objective functions. Hierarchy of arrangement template model for a submarine is shown in Figure 2-5.

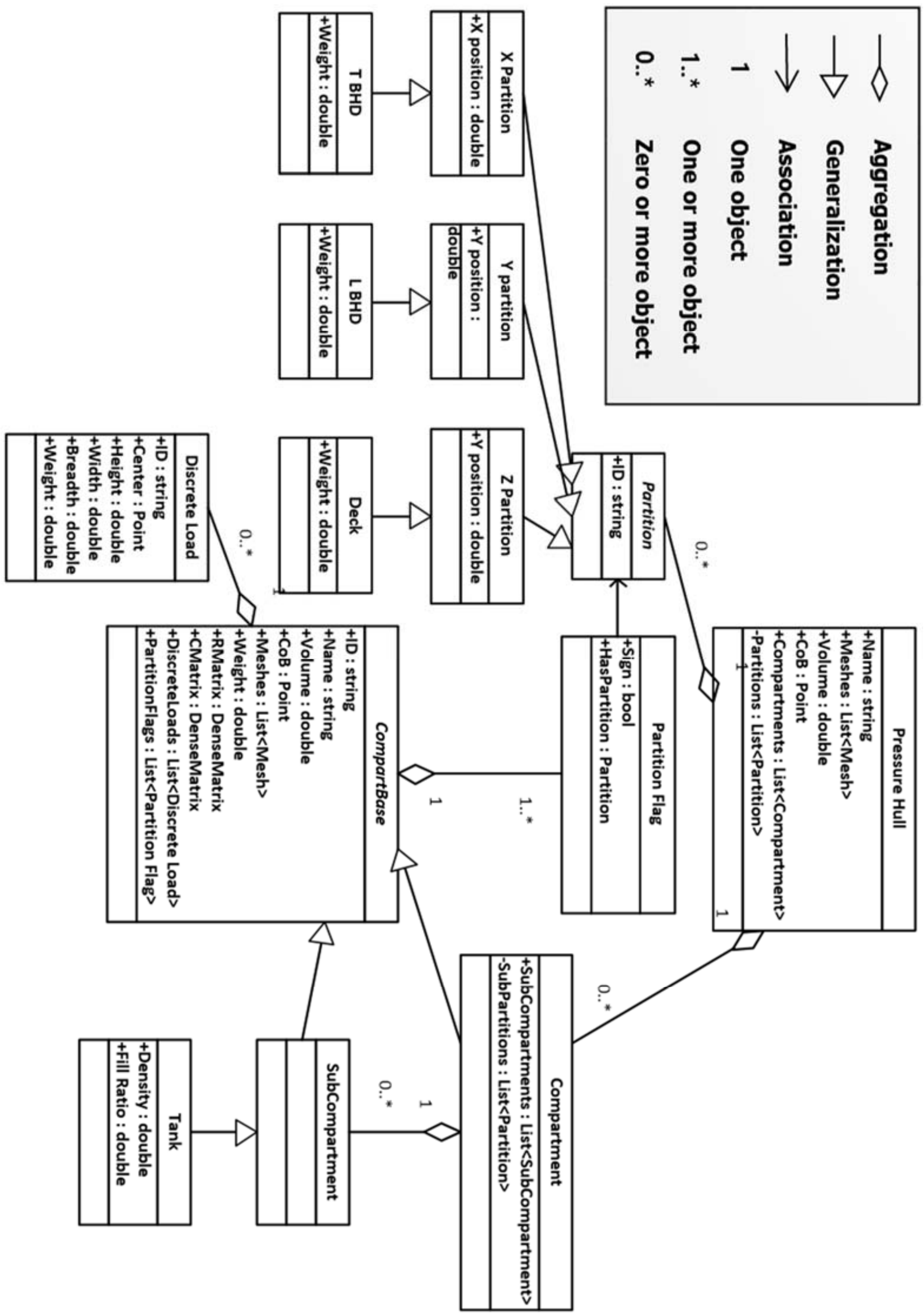

Figure 2-5 Arrangement template model expressed by UML

3. Expert system for arrangement design of submarine

3.1. Knowledge representation

In the 1970, people perceived that someone should be known a result to solve a problems that have to be solved with intelligence with computers. In other words, someone knows know-how about a specific domain. The know-how is that understanding a domains or concepts academically or actually (Negnevitsky, 2009). The person who has the knowledge is called expert. To acting like human experts, computer have to have a methods to express experts' knowledge. The methods are as follows.

3.1.1. Production rule

Production rule is widely known method to express knowledge. Production rule is composed of two parts. 'IF' part called antecedent (promise or condition) and 'THEN' part called consequent (conclusion or action) are the components of production rule. Common rules to use production rules are as follows:

- IF <antecedent>
- THEN <consequent>

Generally, one production rule can have various antecedent and consequent that is combination of logical product (AND) and logical sum (OR). An example for production rules about length for freeboard of ships are as follows:

Rule1

- IF '96% of waterline length at 85% of molded depth' < 'distance between in front of bow and after perpendicular at draft'
- THEN 'length for freeboard(L_f)' = 'distance between in front of bow and after perpendicular at draft'

Rule2

- IF '96% of waterline length at 85% of molded depth' > 'distance between in front of bow and after perpendicular at draft'
- THEN 'length for freeboard(L_f)' = '96% of waterline length at 85% of molded depth'

Relation, recommendation, instruction, strategy and heuristic can be expressed by using production rules (Durkin, 1994).

3.1.2. Semantic net

Semantic net is a method of expressing knowledge based on psychological model of memories relation of human. Semantic net use node and relation between nodes to express specific objects or concepts. Figure 3-1 shows an example of semantic net about 'Changsoo submit the paper to manager at may, 5'.

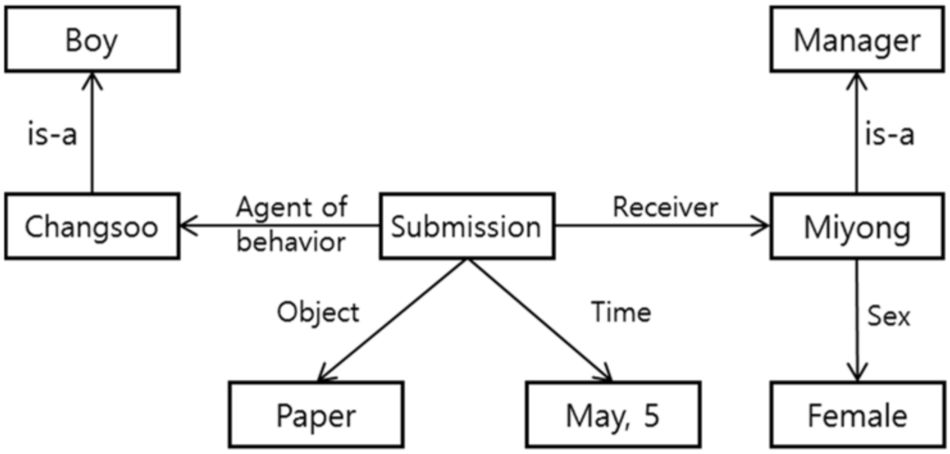

Figure 3-1 Example of Semantic Net

Semantic net is similar way to thinking of human. Using semantic net, it is easy to express relation about concepts or definitions of concepts and be understood by using flexible expression. However, attributes of objects are also expressed by one node. So, information that is expressed by one node are small. If the objects are complex, it is very hard to search the node of each objects.

3.1.3. Frame

Frame is a method of expressing knowledge using a frame based on object's structures and situations. Frame is systematization of the node structures of semantic net. Each frames can be an objects or have function of inheritance. Figure 3-2 is an example of frame for air plane tickets. Two tickets have same frame, but the frames for tickets have set of own slots.

Ticket for Qantas Airways	
Airline:	QANTAS AIRWAYS
Name:	MR N BLACK
Flight No.:	QF 612
Date:	29DEC
Seat No.:	23A
Departure:	HOBART
Arrival:	MELBOURNE
Boarding Time:	0620
Gate No.:	2

Ticket for Air New Zealand	
Airline:	AIR NEW ZEALAND
Name:	MRS J WHITE
Flight No.:	NZ 0198
Date:	23NOV
Seat No.:	27K
Departure:	MELBOURNE
Arrival:	CHRISTCHURCH
Boarding Time:	1815
Gate No.:	4

Figure 3-2 Frame example of air plane ticket

One entity gathers essential knowledge for specific entity or object. Frame use the slots to express knowledge, and frames can figure characteristics and features of object as using slots. As using frames to express experts' knowledge, it is convenient to modulate and capsulize the knowledge. However, there are many needless nodes or frames, so that information are too much to express necessary data and expandability and reusability are lower than other methods.

3.1.4. Logic

Logic is a method of expressing knowledge using symbol. All facts are expressed by symbols, so logic is also called mathematical logic or symbol logic. A declarative sentence that can assign one bool sign (true, false) to specific information is called statement or proposition. Statements whose form is a declarative sentence can have value (true, false). The following sentences are statements formed using a declarative sentence.

- 'Container ship is kind of ship'
- 'For arbitrary integer x, $x = x + 1$'

However, the following sentences are not statements.

- ‘Is container ship kind of ship?’ (not a declarative sentence)
- ‘This statement is true’ (cannot judge true or false)

Statement is sorted two kind of statements; basic statement that cannot be divided and synstudy statement that combine basic statements using a connection. A connection is used to statement operation, and the connection is denial, logical product, logical sum, condition, equivalent, etc. It is hard to know relations between statements using the logical expressions, and to quantization. So, the statements are supplemented by predicate logic. Table 3-1 shows expressions that is represented by predicate logic.

Table 3-1 Examples of predicate logic.

Sentence	Representation with predicate logic
Tom is man.	man(Tom)
Tom is college student.	collegestudent(Tom)
All college students are student.	$\forall_x$(collegestudent(x) → student(x))
All students likes sam or dislike sam.	$\forall_x$(student(x)→like(x,sam)∨dislike(x,sam)
All people likes someone.	$\forall_x \exists_x$like(x, y)
People blames actor that they don’t like.	$\forall_x \exists_x$(person(x)∧actor(y) ∧ blame(x, y) → ~like(x, y))
Man is person.	$\forall_x$(man(x)→person(x))

It is convenient to express knowledge using logics. And it has advantage of handling various conditions using inference. However, to use logic, operator that can be a role of inference engine must be needed. And once the operator is activated, all facts that can inferenced by the operator is deducted, so that it is inefficient from the point of computation.

As mentioned before, the rule-based expert system is commonly used among the four methods for express knowledge. Because, it is natural to express knowledge using production rule that has form of 'IF-THEN', and it is convenient to understand the rules because of unity of representing a knowledge. Also, knowledge base and inference engine can be divided to two parts, so that various application can be made by one expert system. Another advantage of production rule is that frame object and properties of semantic net can be added to one 'IF-THEN' rule, so that various knowledge can be expressed by one rule. Therefore, in this paper, expert system had made using production rule to express experts' knowledge. And as improve efficiency of the system, AEM was developed and adopted.

3.2. Rule-based expert system

To use experts' knowledge in the arrangement design sequence, expert system that can deal experts' knowledge in a computer is needed. As experts input a knowledge, expert system solve a problems in the specific domain instead of human experts. And a results of the problem should be satisfied to a criteria. Also, expert system can explain the process of inference sequence that is from the first fact to result (Negnevitcky, 2009). Expert system that use production rule to represent experts' knowledge is called rule-based expert system. Rule-based expert system is composed of knowledge base, database, inference engine, explanation mechanism and user interface, and configuration of the system is shown in Figure 3-3.

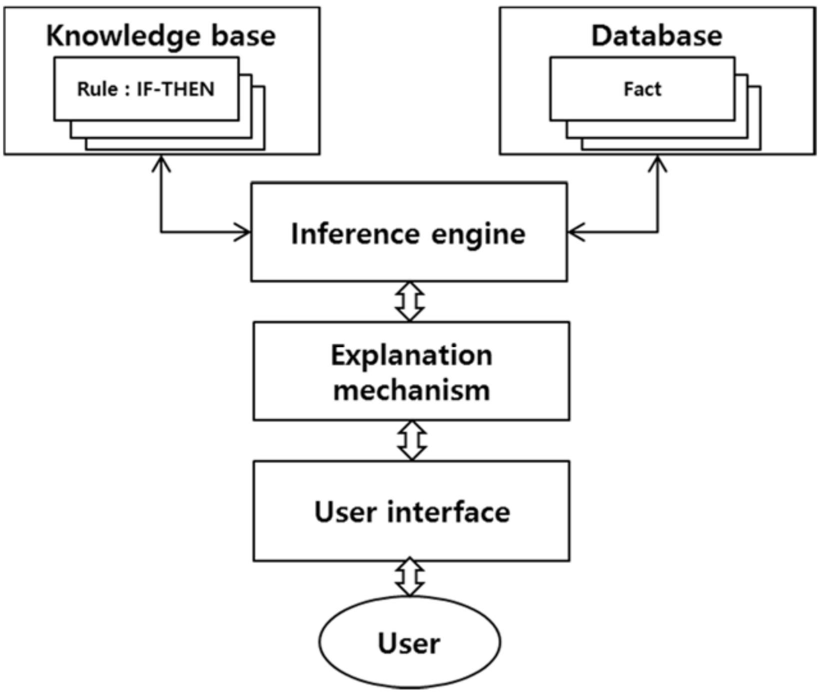

Figure 3-3 Configuration of rule-based expert system

3.2.1. Knowledge base

Knowledge base contains a knowledge for solving specific domain problems. In rule-based expert system, knowledge is made of rule set. Using each rule, recommendation, instruction, strategy and heuristic can be represented, and each rule has form of 'IF (condition)-THEN (action)'.

3.2.2. Database

Database is set of facts that is used to compare IF (condition) part of rule in knowledge base. The facts is saved in database. When inference is started in expert system, the facts in the database is used in the inference engine.

3.2.3. Inference engine

Inference engine is function as inference a result in the process of expert system. Inference engine link and compare a facts contained in database and rules contained in knowledge base. In expert system, inference is sequence of producing new facts from the experts' knowledge. Comparing a facts and rules, a new facts are fired, and this sequence is called pattern matching. Continuously, the process is executed in inference engine, then there is no facts that match the rules in knowledge base, the process is ended. Figure 3-4 how the process of inference as mentioned previously.

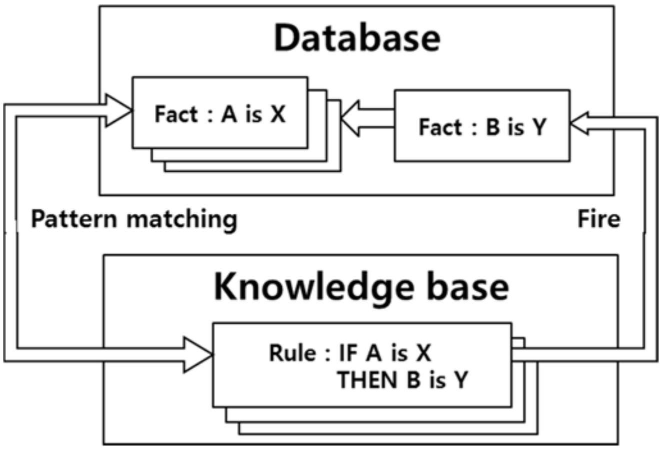

Figure 3-4 the process of inference engine

3.2.4. Explanation mechanism

Explanation mechanism explain the process from initial facts to final facts. In inference engine, it is saved that which fact is compared with which rule. So, the process of inference can be explained by using the information in inference engine. And validity of the result can be examined with explanation mechanism.

3.2.5. User interface

User interface is connection tool with user and expert system. User interface is various according to an application. User interface should be meaningful to user and easy to use.

3.3. Arrangement Evaluation Model (AEM)

Expert system which use production rule to express experts' knowledge is rule-based expert system as mentioned before. However, it is still hard to express complicated knowledge about arrangement design and thinking process, and needed to combine various rules. But experts' don't know how to combine various rule to represent their knowledge to expert system. Therefore, in this study, AEM was proposed. AEM is extended and advanced version of rule-based expert system, as use experts' knowledge about arrangement design.

In AEM, various knowledge about arrangement design is represented by space information and relation information, then they are used to evaluate alternatives of arrangement. And the set of space information is defined to space list, the set of relation information is defined to relation list. Configuration of AEM is shown in Figure 3-5.

Knowledge base, database, and inference engine is replaced by AEM. Using AEM, experts' can express various rules about arrangement design with space information and relation information. So, experts' don't have to consider about inference process when create rules for arrangement design in expert system. Relation between rule-based expert system and AEM is shown in Figure 3-6

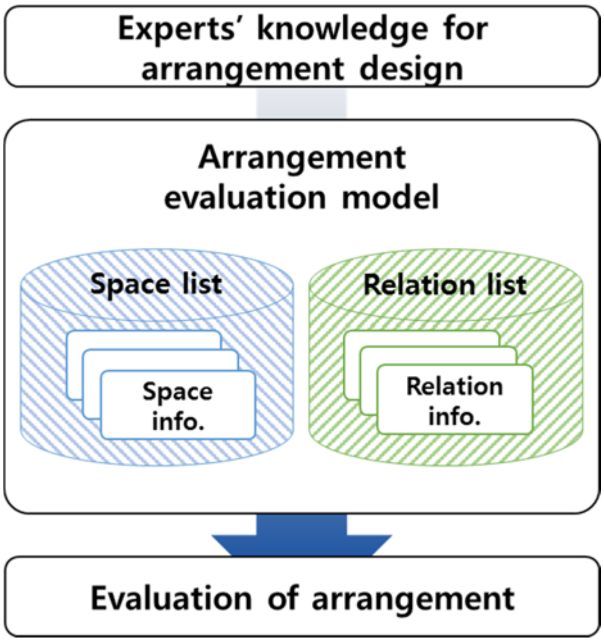

Figure 3-5 Configuration of arrangement evaluation model.

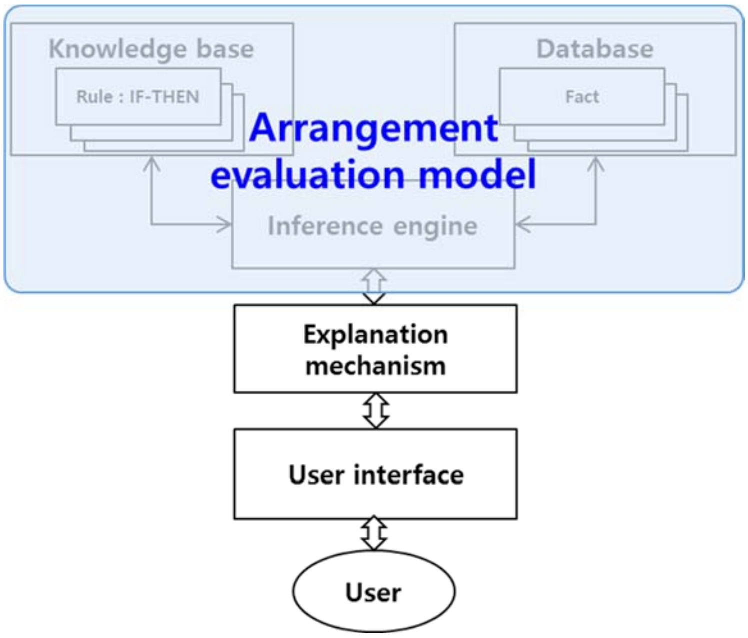

Figure 3-6 Role of arrangement evaluation model in the rule-based expert system.

3.3.1. Space information

Space information shows experts' knowledge for specific space about requirements of space area or volume. And the set of space information for all space defined in domain is space list. If expert have knowledge; 'machinery in a submarine should be larger than 100m^3, as considering equipment installed in machinery and maintenance space for machinery', then it is represented by one space information. Key words in the knowledge is objective space; 'machinery', and target value; 'minimum 100m^3'. Adding ID to distinct rules, one space information can be expressed by 3 properties; 'space information ID', 'objective space', and 'target value'. The example space information is shown in Figure 3-7.

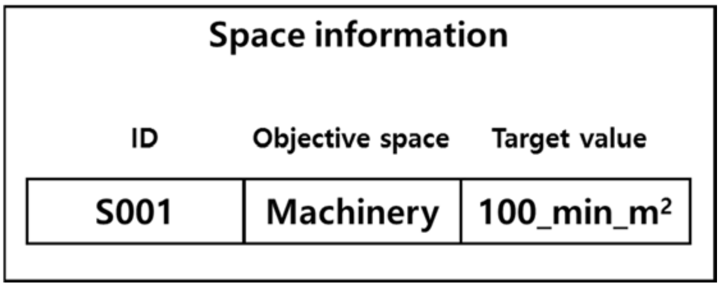

Figure 3-7 Configuration of space information

To realize three properties of space information, data type for each properties is needed. ID, and objective space can be expressed by string type. And target value can be expressed by new type named metric type. Data types for space information is listed in Table 3-2. Metric type was proposed by Park (2009). Metric type is composed of three component; standard value, boundary type, and unit type. Standard value is specific value for target value, and it is expressed by double type. Boundary type represents limit type of target value, and it can be a words like minimum, maximum, exact, and proposal. And unit type is unit of standard value. The properties of metric type is shown in Table 3-3. Therefore, using metric type, various target value can be defined like ‘minimum 100m^3’, ‘maximum 100m^3’, etc.

Table 3-2 Properties of space information

Properties	Data type
ID	String
Objective space	String
Target value	Metric type

Table 3-3 Properties of metric type

Properties	Data type
Standard value	Double
Boundary type	Selection type(min, max, ext, pro)
Unit type	Selection type(m, m^2, m^3, …)

3.3.2. Relation information

Relation information represents relations which experts’ think between one space and the other space. In this study, measurable values are object of relations. Relation information resembled space information is defined with information for expressing relation between two spaces. If the experts of arrangment of a submarine think ‘accommodation and CIC should be close considering operability for crew.’, then it can be represented by one relation information. Key word of the knowledge is objective space; ‘accommodation’, subjective space; ‘CIC’, and relation between objective space and subjective space; ‘close’. The example is one knowledge of relation information, so that for distincting relation information ID is needed. So, one relation information is composed of six properties; ‘ID’, ‘objective space’, ‘subjective space’, ‘relation type’, ‘perspective’, and ‘target value’. Perspective is used to express perspective of relations; ‘human perspective’, ‘material perspective’. Because, there are diffrences in two perspective when consider about relations. The example of one relation information is shown in Figure 3-8.

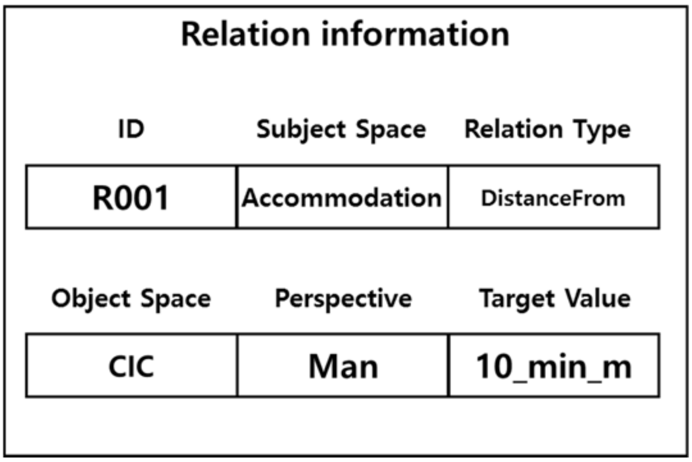

Figure 3-8 Configuration of relation information

To realize relation information in computer, data type is needed to express. ID, objective space, and subjective space can be represented by using string type. Relation type can be represented by using selection type. And target value can be represented by metric type. The relations that can be represented by relation type is listed in Table 3-4.

Table 3-4 Relations of relation type

Properties	Data type
ID	String
Subjective space	String
Relation type	Reference type(ConnectionTo, DepthFrom, …)
Objective space	String
Perspective	Selection type(Man, Material)
Target value	Metric type

When proceed arrangement design, relation type is needed to express relations between two spaces. The example explained previously use ‘closer’ to represent relation. ‘Closer’ can be one of relations between two spaces. Therefore, in this study, four types of relations were defined to relation types.

(1) Type “ConnectionTo”

ConnectionTo is one of relation type, and it represents physical connection of two spaces. If two spaces are connected, the value is ‘1’. And if two spaces are not connected, then the value is ‘0’. Using ConnectioTo, connectivity of two spaces can be expressed by experts’.

Figure 3-9 shows ConnectionTo of submarine spaces. In the example, space SP1 and SP2 is connected by passage, so ConnectionTo (SP1, SP2) is ‘1’. And SP1 and SP3 is not connected so ConnectionTo (SP1, SP3) is ‘0’.

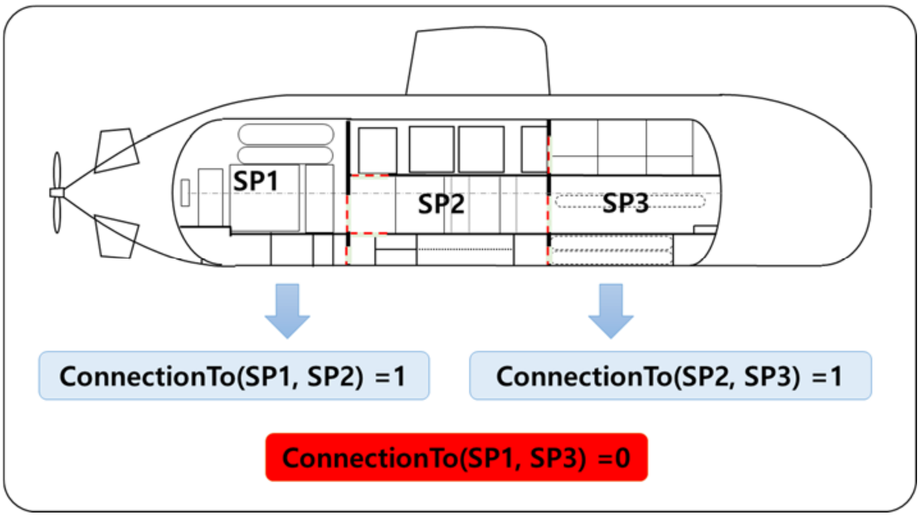

Figure 3-9 Example of type “ConnectionTo”

(2) Type “DepthFrom”

DepthFrom is expressed the number of spaces between objective space and subjective space. So, using DepthFrom, the minimum number of spaces between objective space and subjective space.

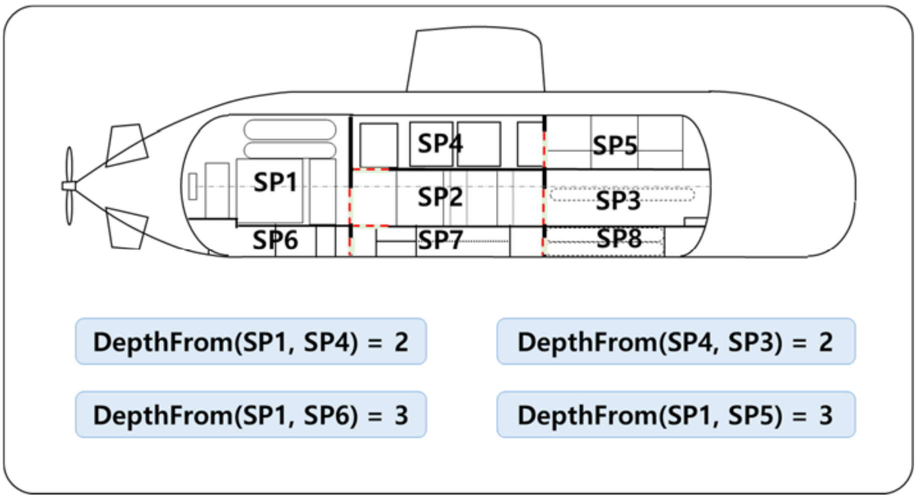

Figure 3-10 Example of type “DepthFrom”

Figure 3-10 shows DepthFrom values for submarine spaces. As seen in the example, shortest route from SP1 to SP4 start in SP1, go through SP2, then reach to SP4. So, DepthFrom (SP1, SP4) is ‘2’. For specific reason, knowledge about the number of two spaces; objective space and subjective space can be represented by using DepthFrom.

(3) Type “DistanceFrom”

DistanceFrom is relation type to express physical distance between two spaces. So, using DistanceFrom, minimum distance between objective space and subjective space can be calculated. And using the type, experts’ knowledge about distance between two spaces can be expressed.

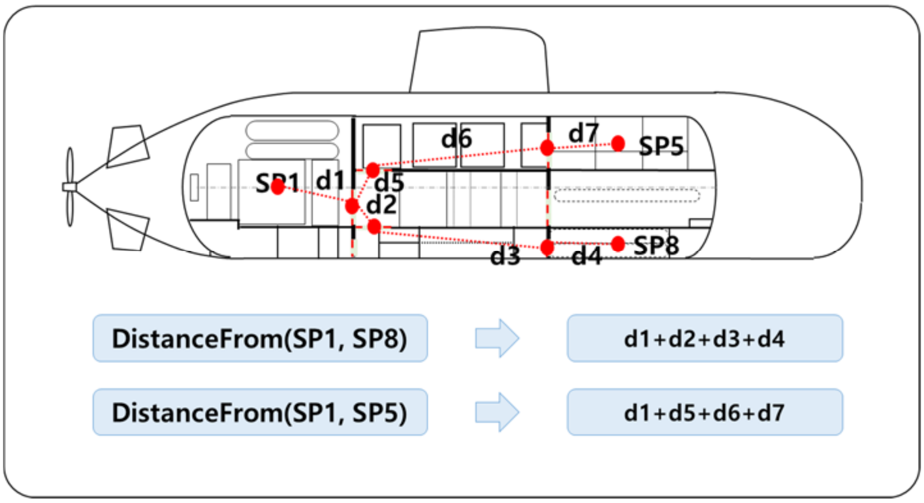

Figure 3-11 Example of type “DistanceFrom”

Figure 3-11 shows examples of DistanceFrom in submarine. As seen in the example, d1, d5, d6, d7 is needed to reach SP5 from SP1, so that DistanceFrom (SP1, SP5) is ‘d1+d5+d6+d7’. In case of previous example, minimum distance is for human. So, DistanceFrom value can be different with perspective.

(4) Type "LevelDifference"

LevelDifference is relation type about vertical position difference between two spaces. Using LevelDifference, the vertical distance between objective space and subjective space. So, experts' knowledge for vertical position differences can be represented by using LevelDifference.

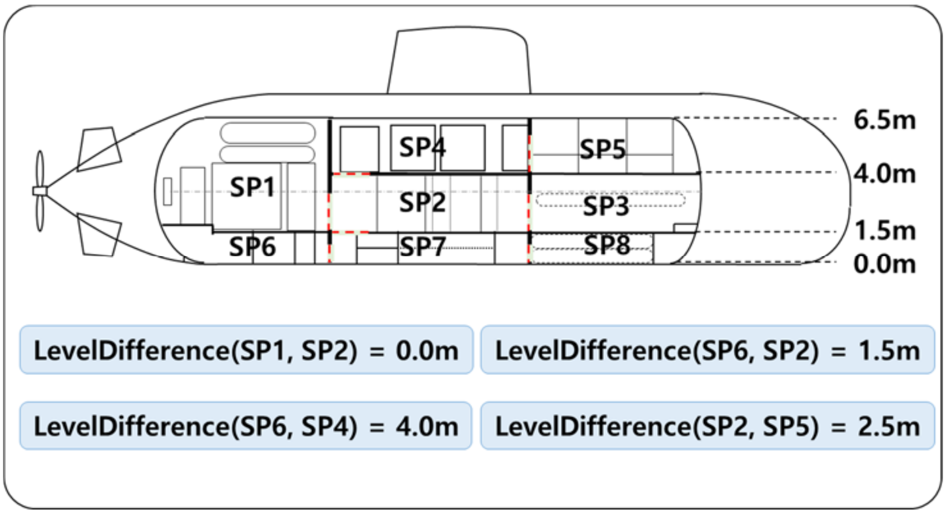

Figure 3-12 Example of type "LevelDifference"

Figure 3-12 show LevelDifference of submarine spaces. In the example, SP2 apart from SP6 by 1.5m vertical difference. So, LevelDifference (SP2, SP6) is '1.5m'.

3.3.3. Arrangement evaluation

As mentioned in 3.3.1 and 3.3.2, experts' knowledge about arrangement design of submarine are expressed. Then using the rules, specific alternatives are evaluated. And evaluated value is adopted in optimization process.

Space information and relation information is converted to the set of 'IF-THEN' rules, and it is used to evaluate alternatives. One space information or relation information can be defined differently by using boundary type of metric type. In case of 'maximum', the rule represents 'something is lower than some value'. Therefore, if calculated value from the expert system is lower than standard value, the rule is evaluated to '100' points. If the value is higher than standard value, the rule is evaluated to '0' points. 'Minimum' is similar with 'maximum'. Evaluation points calculated in contrast with 'maximum' points. In case of 'exact', if calculated value is same as standard value, the rule is evaluated to '100' points. But, if calculated value is different with standard value, then the rule is evaluated to '0' points. Three cases as mentioned previous are very easily calculated by using expert system. However, in case of 'proposal', it is ambiguous to evaluate the rules. Because, there are no criteria for the rules. This situation is called uncertainty.

Uncertainty is defined by the shortage of exact information that is used to reach the confident and reliable result (Stephanou and Sage, 1987). In traditional logic, it is permitted to infer some facts exactly. In that logic, exact result always exist, so that black and white logic is applied to process of inference. However, as mentioned before, it is insufficient to express 'proposal' of boundary type with Boolean logic. In other words, calculation is not that easy such as evaluating '100' points or '0' points depend on some value.

So, in this study, Fuzzy logic is adopted to represent 'proposal' of boundary type. Fuzzy logic is a form of many-valued logic which deals with reasoning that is approximate rather than fixed and exact, as comparing to traditional Boolean logic (Zadeh, 1965). The logical value of Boolean logic and Fuzzy logic is shown in Figure 3-13.

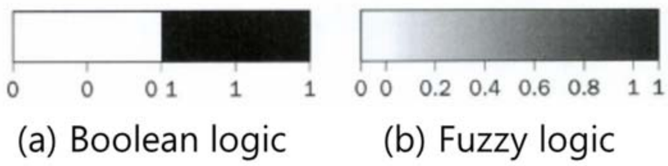

Figure 3-13 Range of logical value of Boolean logic and Fuzzy logic

In Fuzzy logic, particular value is defined by using linear fit function. Linear fit function can be various form defined according to specific objective. In this study, normal distribution whose variance is '2' is adopted to express value for proposal of boundary type. Therefore, by using proposal to boundary type, particular calculated value is same as standard value, then the rule is evaluated to '100' points. And the farther value difference between standard values the lesser the point evaluated according to normal distribution. Eq. (3-1) represents the function of normal distribution. In the equation, σ^2 is varience, and μ is mean value. Figure 3-14 shows the graph of normal distribution whose mean value is 0, and variance is 2.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{3-1}$$

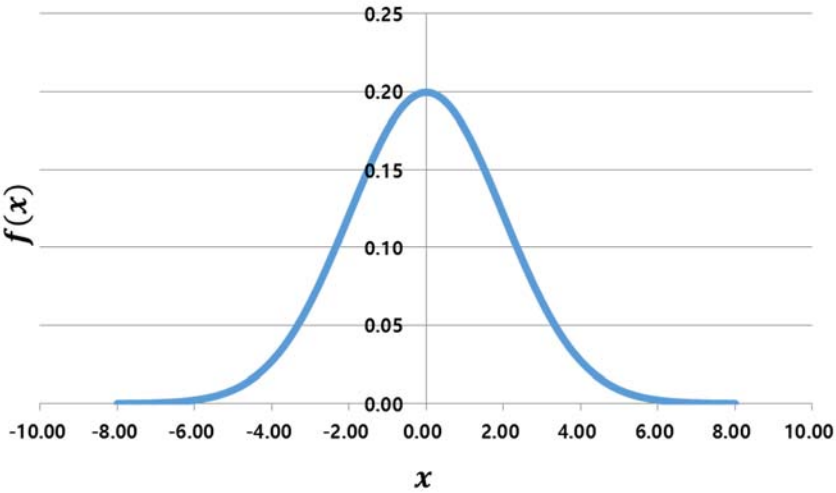

Figure 3-14 Normal distribution whose mean value is 0 and variance is 2

4. Multistage optimization method for arrangment design of submarine

4.1. Summary

In this study, a pressure hull where crew can carry out an operation and most compartments and equipment are placed is target of optimization problems. As processing an arrangement design of pressure hull, position and size of a compartment, sub-compartment that is placed in the compartment, and equipment should be determined. It is very difficult and complicated to considering the all variables in one optimization problem. Because, there are plenty of design variables and dependent variables in one optimization problem, so that the problem might not be solved practically. Therefore, in this study, the problems for an arrangement design of submarine is divided by three problems.

In the first stage, position and size of the compartments and partitions which is placed in pressure hull is determined. Using the compartment determined in the first stage, position and size of a sub-compartments which compose each compartments is determined. At last, an equipment in each compartments or sub-compartment is determined. After executing three stage of optimization and fixed the arrangement of submarine, the availability of submarine is checked by using equilibrium polygon and stability. If the alternative not meet to the criteria, third stage is retried for a while. Then if alternative continuously dissatisfy the criteria of the availability, optimization sequence take back to first stage, and proceed optimize once again. As mentioned process is continuously executed till meet the criteria. Figure 4-1 shows the configuration of the problems as mentioned above.

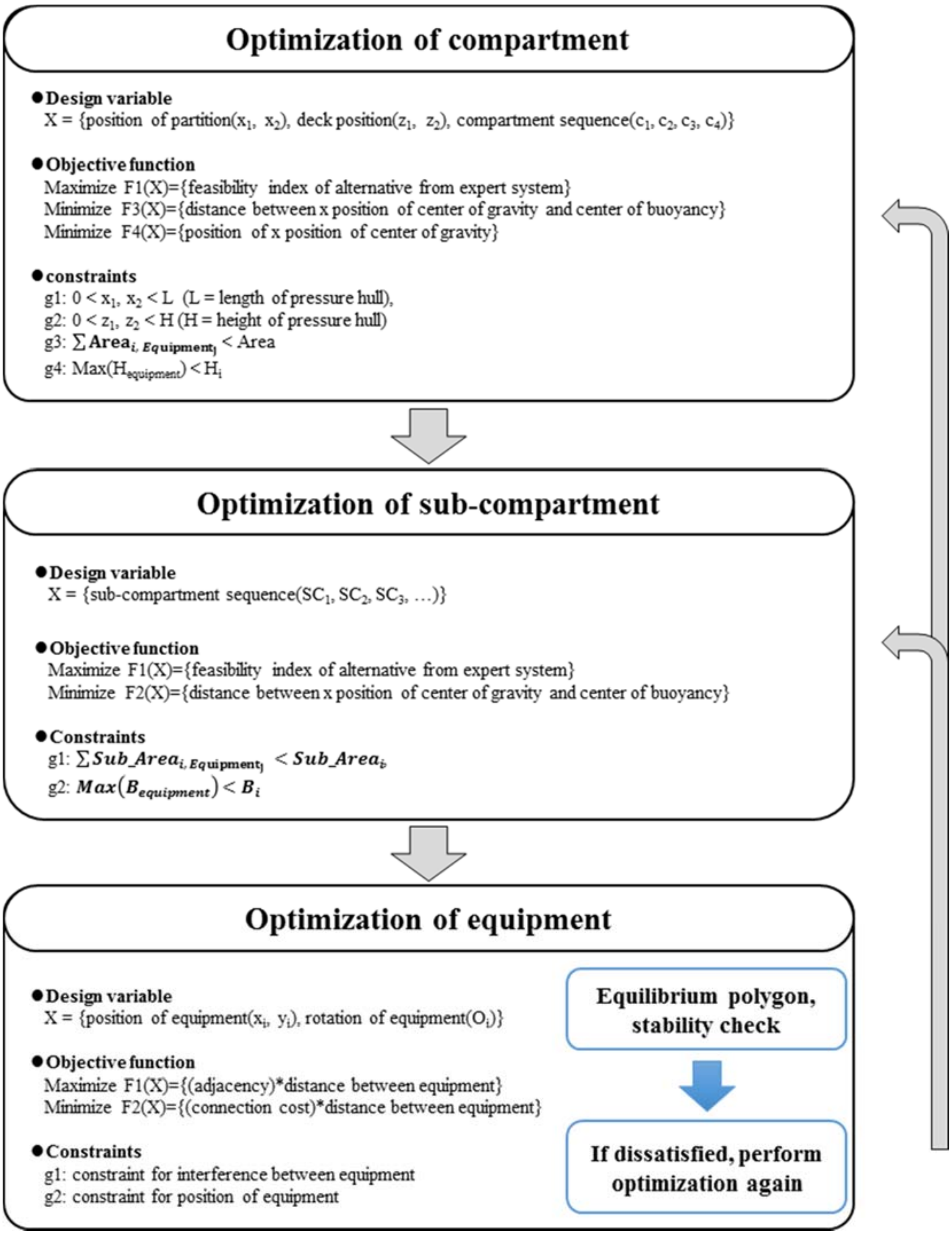

Figure 4-1 Summary of optimization method for an arrangement of submarine

As solving the problems, NSGAII (Nondominated Sorting Genetic Algorithm II, Deb et al., 2002) which is one of the multi-objective genetic algorithm was used. Multi-objective problems can be solved by using the NSGAII, so that the problems can be formulated diversely.

4.2. Optimization of main compartments

In the first stage, position and size of compartments and partitions are optimized. First, position of transverse bulkhead and deck is determined, then the space size which is surrounded by the partitions is fixed, and select compartments sequence using the spaces. Figure 4-2 shows variables determined in the first stage.

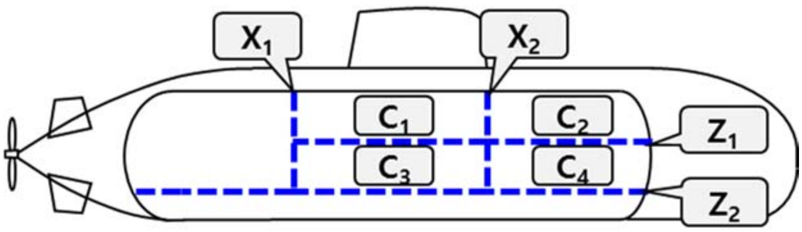

Figure 4-2 Components determined in the first stage

4.2.1. Input data

As proceed optimization of the first stage, pressure mesh model, the number of compartments, type of compartments, weight of each compartments, and center of gravity of each compartment are needed. And the number of partitions are also needed. To express exact shape of the pressure hull and calculate properties, mesh model of pressure hull is needed. The weight of each compartments are sum of equipment in the compartment. And center of gravity of the compartments is assumed to center of volume of compartment, because position of equipment which is placed in the compartment are not determined yet. Table 4-1 shows summary of input data for the first stage.

Table 4-1 Input data for optimization of compartments

Input data	
Mesh model of pressure hull	
The number of compartments	
Weight of each compartment	W_i
Center of gravity of each compartment	LCG_i, TCG_i, VCG_i
The number of partitions	

4.2.2. Design variables

In optimization of compartments stage, position of partitions, and sequence of compartments are set design variables as mentioned previously. Table 4-2 is shown the design variables for optimization of compartments and notation of the variables.

Table 4-2 Design variables for optimization of compartments

Design variable	
Position of transverse bulkheads	X_i
Position of decks	Z_i
Sequence of compartments	C_i

There are a lots of equipment for the propulsion and various functions in the machinery. And there have various tanks and batteries in the bilge compartment. The machinery and the bilge compartment must be placed in the specific position of pressure hull, because of operability and functionality about various point of view. So, two compartments is fixed (the machinery is placed in the back side of pressure hull and the bilge compartment is placed in the lower part of pressure hull). Position of the machinery and the bilge compartment are shown in Figure 4-3.

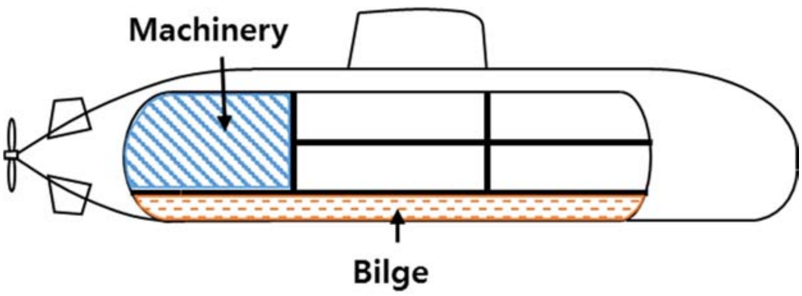

Figure 4-3 Position of machinery and bilge compartment

The design variables represents a chromosome for alternative in the genetic algorithms. That is called gene encoding. Figure 4-4 shows gene formed by the design variables. In the figure, $X_1,\ X_2,\ Y_1, and\ \ Y_2$ (position of the partitions) are expressed by using real variable, and $C_1,\ C_2,\ C_3, and\ C_4$ (sequence of the compartments) are expressed by using permutation variable.

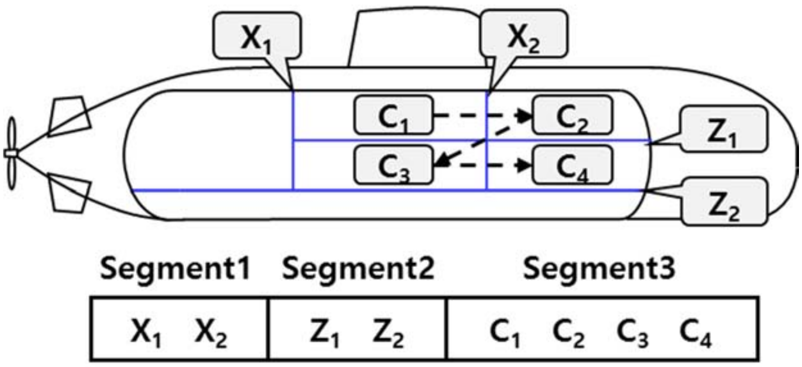

Figure 4-4 Gene encoding of the design variables for optimization of compartments

4.2.3. Objective functions

As optimization of compartments, three objective functions were determined. First objective is that maximize feasibility index that is evaluated by expert system. It is very important to maintain even trim condition for submarine. So, Distance between X position of center of gravity and X position of center of buoyancy should be equal when submerged. In this point of view, minimize the distance is set to second objective. It is also important to maintain stability in both surface condition and submerged condition. Therefore, third objective is determined to minimize Z position of center of gravity of submarine. Table 4-3 is summary of objective functions for optimization of compartments.

Table 4-3 Objective functions for optimization of compartments

Objective function		
Feasibility index from expert system	Maximize	$\sum R_k$ (R_k : Evaluation score for kth rule)
Distance between X position of CoG and x position of CoB	Minimize	$\lvert LCG - LCB \rvert$
Z position of CoB	Minimize	VCG

4.2.4. Constraints

As optimization of compartments in the first stage, three constraints were set. First, partitions should be placed in the pressure hull. So, design variables; X_i, and Y_i are constrained to have value within the pressure hull. Second, the area where equipment are placed should be larger than the area that is made by adding the area of each equipment in the compartment. So, the area of each compartments are constrained to have larger area then the area determined by optimization process. Third, each compartment have to have higher height then equipment which is equipped in the compartment. So, each compartment height is constrained to have higher height then equipment that is placed in the compartment. Table 4-4 shows summary of constraints and mathematical expression of constraints.

Table 4-4 Constraints for optimization of compartment

Constraints	
Position of transverse bulkhead and deck	$0 < X_i < L,\ 0 < Z_i < H$
Area of compartments	$\sum Area_{i,\, equipment_j} \leq Area_i$
Height of compartments	$Max(H_{equipment}) \leq H_i$

4.3. Optimization of sub-compartments

In the second stage, sub-compartment which is placed in the compartment determined in the first stage is target of optimization. It is purpose of this stage to determined position of sub-partitions and sequence of sub-compartments.

There is difference between calculating method of optimization in the first stage and the second stage. To optimize sub-compartments, the sequence of sub-compartments in each compartment is determined first. Then along the required volume set by space information of expert system, sub-partitions position is determined. The exact volume of the compartment and the volume that is assigned by expert system might be different. So, the difference between real volume and assigned volume is added or subtracted as same portion of difference. Figure 4-5 shows the components which is determined in the second stage.

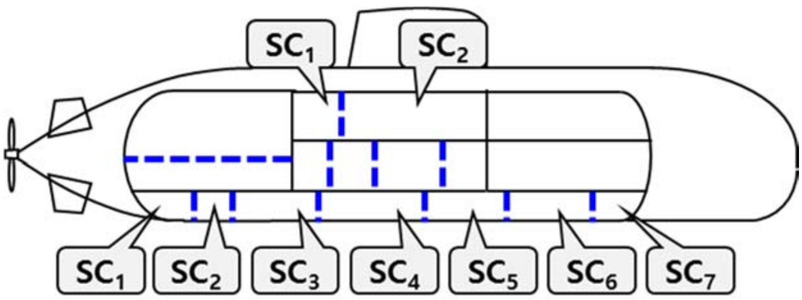

Figure 4-5 Components determined in the second stage

4.3.1. Input data

As proceed optimization of sub-compartments, required volume for each sub-compartment which set by expert system, the compartment that is divided by sub-partition, and the number of sub-compartment in the specific compartment are necessary. Table 4-5 is summary of input data for optimization of sub-compartments and notations of data.

Table 4-5 Input data for optimization of sub-compartments

Input data	
The number of compartment consisted of sub-compartment	
The number of sub-compartment in each compartment	
Demanded volume of each sub-compartment	SV_i

4.3.2. Design variables

In the second stage, sequence of sub-compartments is set to design variable. The variables is defined similar with the compartment sequence in the first stage. Table 4-6 shows design variable of the second stage and notation of the variable.

Table 4-6 Design variable for optimization of sub-compartments

Design variable	
Sequence of sub-compartments	SC_i

The most important compartment in the second stage is the bilge compartment, because there are lot of tank compartments in the bilge compartment. Among the tank compartments, after, and forward trim tank are included. From the position of the other compartment, it is good that trim tanks have smaller volume. To minimize trim tank's volume, trim tank must be positioned at the edge of the pressure hull, because functionality of trim tank can be maximized in that position. In other words, trim tank can act moment to the submarine using smaller ballast water when the tank place at the edge of the pressure hull. Therefore, trim tanks are placed at the bow side and after side of the pressure hull practically. In this study, after and forward trim tank are assumed to be fixed at the mentioned position. Figure 4-6 shows position of the trim tanks in the pressure hull.

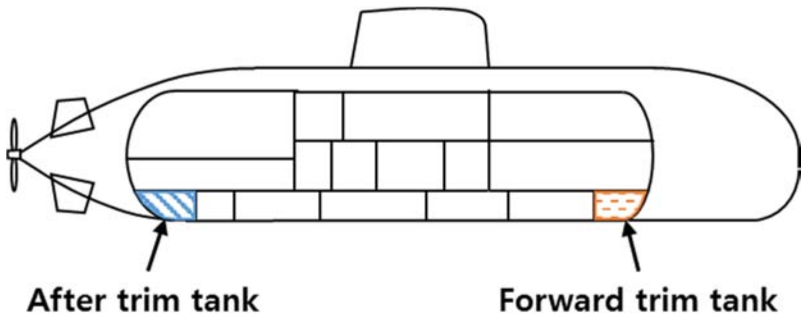

Figure 4-6 Position of after trim tank and forward trim tank

Sequnce of sub-compartment that is design variable for the second stage is expressed by using permutation variable; SC_i. Then to configure chromosome for the second stage, gene encoding is proceeded. Figure 4-7 shows the chromosome for the second stage.

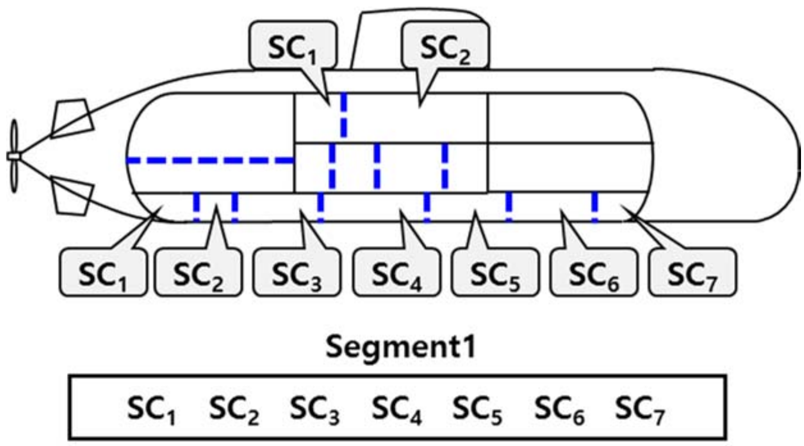

Figure 4-7 Gene encoding of the design variable for optimization of sub-compartments

4.3.3. Objective functions

For optimization of sub-compartments, two objective functions are determined. First, to maximize feasibility index from the expert system is objective of the problems. And second, there are chance to change X position of center of gravity of submarine when changing arrangement of sub-compartment, so that to minimize distance difference between X position of center of gravity and X position of center of buoyancy is set to objective. Table 4-7 shows summary of the objective functions and the mathematical expression of each objective function.

Table 4-7 Objective functions for optimization of sub-compartments.

Objective function		
Feasibility index from expert system	Maximize	$\sum R_k$ (R_k : Evaluation score for kth rule)
Distance between X position of CoG and x position of CoB	Minimize	$\vert LCG - LCB \vert$

4.3.4. Constraints

Two constraints are set to optimize the sub-compartments. In the sub-compartment, equipment can be placed similar with a compartment. The area of the sub-compartment is constrained to exceed the area of all equipment placed in the sub-compartment. And the breadth of the sub-compartment must be wider then equipment placed in that sub-compartment, so that the breadth of the sub-compartment is constrained to exceed breadth of the widest equipment in the sub-compartment. Table 4-8 shows summary of the constraints for the second stage and mathematical expression of each constraint.

Table 4-8 Constraints for optimization of sub-compartments

Constraints	
Area of sub-compartments	$\sum Sub\_Area_{i,\,equipment_j} \leq Sub\_Area_i$
Breadth of sub-compartments	$Max(B_{equipment}) \leq B_i$

4.4. Optimization of equipment

In the third stage, an equipment which is placed in the compartment and the sub-compartment determined in the first stage, and the second stage are arranged. In this stage, position and orientation of each equipment placed in the compartment and the sub-compartment are determined. To proceed this stage, the optimization sequence is done, so that the arrangement of submarine is determined. After the optimization sequence, the availability of alternatives are tested about stability and operability.

In this study, to check stability and operability, equilibrium polygon and ship stability is used. After optimize arrangement of equipment, the alternatives are confirmed to meet criteria. If the alternatives cannot meet the criteria, the third stage is performed again. In the first and second stage of optimization, the criteria are not considered, so that it might be not meet the criteria just optimize the third stage of optimization. Therefore, if the alternatives from the third stage not meet the criteria continuously, optimization stage is turning back to the first stage.

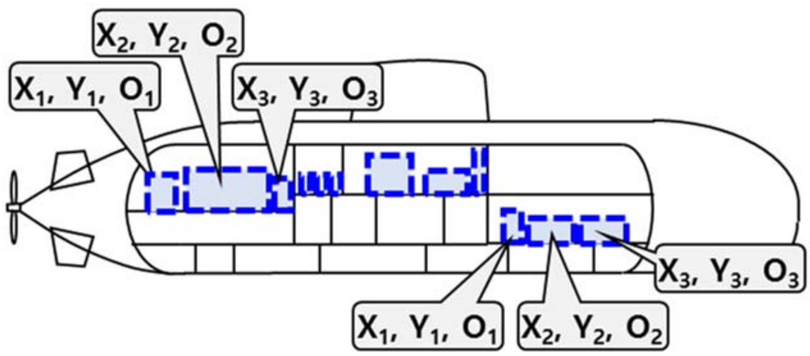

Figure 4-8 Components determined in the third stage

4.4.1. Input data

As perform optimization of equipment, the information of equipment placed in each compartment or sub-compartment. The information is weight, dimension, the compartment or sub-compartment that contain the equipment. There is a lot of equipment in the compartment or sub-compartment, so that it is troublesome task to set the rules for the equipment with using space information or relation information. Therefore, adjacency index and connection cost between each equipment in the same compartment or sub-compartment are made to consider the relations between equipment. Adjacency index matrix and connection cost matrix made by using adjacency index and connection cost between each equipment are also necessary to perform optimization of equipment. Table 4-9 shows summary of input data for the third stage and notation of each information.

Table 4-9 Input data for optimization of equipment

Input data	
The number of compartments or sub-compartment consisted of equipment	
Equipment dimension	el_i, ed_i, eh_i
Equipment weight	ew_i
Adjacency index matrix of equipment	$A_{i,j}$
Connection cost matrix of equipment	$C_{i,j}$

(1) Adjacency index

Adjacency index for equipment i and j; $A_{i,j}$ is digitized value for the equipment, and it can be calculated using antagonism and affinity of each equipment.

- Antagonism

Antagonism for each equipment describes level of far-off. Antagonism is appropriated from ‘0’ to ‘3’. Table 4-10 shows the example of antagonism index matrix for machinery. In the table, main propulsor should be farther from power generator then propulsion unit.

Table 4-10 Example of Antagonism index matrix

Antagonism matrix					
Equipment		MP	PU	SS	PG
Main propulsor	MP	-	1	1	2
Propulsion unit	PU		-	1	2
Support system	SS			-	2
Power generator	PG				-

- Affinity

Affinity of each equipment has reverse meaning with antagonism. In other words, affinity for each equipment describes level of nearby. Affinity of each equipment is also appropriated from ‘0’ to ‘3’. The example of affinity shown in Table 4-11. The example shows affinity for equipment placed in machinery.

Table 4-11 Example of affinity matrix

Affinity matrix					
Equipment		MP	PU	SS	PG
Main propulsor	MP	-	3	3	2
Propulsion unit	PU		-	3	2
Support system	SS			-	2
Power generator	PG				-

- Adjacency Index

Adjacency index is calculated by using antagonism and affinity between each equipment. Eq.(4-1) shows the equation for calculating adjacency index.

$$A_{i,j} = affinity_{i,j} - antagonism_{i,j} \tag{4-1}$$

After, objective function of optimization of equipment is set to maximize adjacency index value. So, if two equipment have to be nearby, adjacency index value must be set to higher value. Therefore, adjacency index is calculated by subtracting antagonism from affinity. In this study, adjacency index matrix that is composed by using two matrix (affinity matrix, and antagonism matrix) is used to calculate one of the objective function for optimization of equipment.

(2) Unit connection cost

In the submarine, there are many pipe lines, and electric wires. Especially, in the machinery, pneumatic and oil pressure equipment are exist even except the outfit as mentioned. So, the equipment must be connected between each other's. But, the kind of connections are different with each other's. And also the cost of the connection are different by kind of connections. Therefore, when perform arrangement of equipment, the connection cost should be considered. In this study, unit connection cost $C_{i,j}$ is used to calculate connection cost between equipment. Unit connection cost is quantified from '0' to '5'. Table 4-12 shows example of unit connection cost matrix of machinery.

Table 4-12 Example of unit connection cost matrix

Unit connection cost matrix					
Equipment		MP	PU	SS	PG
Main propulsor	MP	-	3	3	2
Propulsion unit	PU		-	3	2
Support system	SS			-	2
Power generator	PG				-

4.4.2. Design variables

As performing optimization of equipment, position and orientation of equipment is set to design variables. The equipment placed in each compartment or sub-compartment can be arranged by using position and orientation of the equipment. Theoretically, an equipment can rotate 360 degree. But, practically, there are few case of askew installation. Therefore, in this study, only 0 and 90 degree of rotation is dealt with. Table 4-13 shows the design variables for the third stage and notation of the variables.

Table 4-13 Design variables for optimization of equipment

Design variable	
Position of equipment	x_i, y_i
Rotation angle of equipment	O_i ('0' or '1', if rotated 90 degree, set '1')

Coordinate of position (x_i, y_i) can be represented by using real variable, and rotation of equipment (O_i) cab be represented by using binary variable. There are only two possibility for the rotation, so it is possible to represent rotation of equipment. Figure 4-9 shows chromosome of the design variables for the third stage.

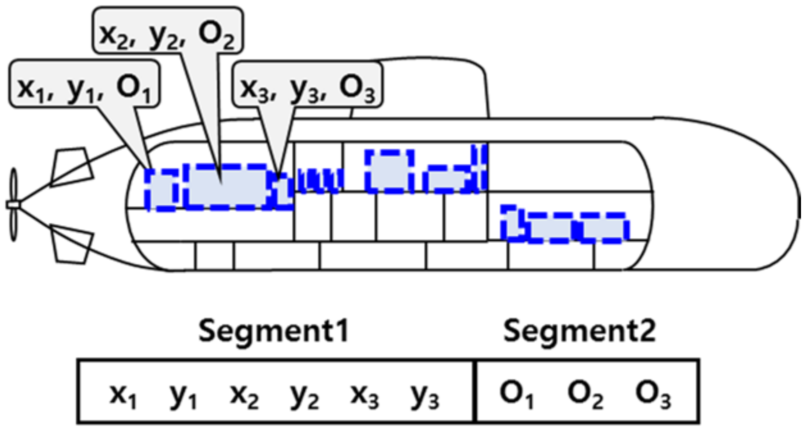

Figure 4-9 Gene encoding of the design variables for optimization of equipment

4.4.3. Objective functions

For optimization of compartment, two objective functions are defined. First objective function is that maximize adjacency relation using adjacency index matrix. Second objective function is that minimize total connection cost using unit connection cost matrix. The value of adjacency relation and connection cost between equipment can be calculated by multiplying adjacency index or unit connection cost by distance between two equipment. And as adding all values of each equipment, total adjacency index and connection cost can be calculated. Table 4-14 shows summary of the objective functions and mathematical expression of each objective function.

Table 4-14 Objective functions for optimization of equipment

Objective function		
Adjacency index between equipment	Maximize	$\sum(A_{i,j} \times TD_{i,j})$ $(TD_{i,j} = \lvert x_i - x \rvert + \lvert y_i - y_j \rvert)$
Connection cost between equipment	Minimize	$\sum(C_{i,j} \times TD_{i,j})$

4.4.4. Constraints

For optimization of equipment, two constraints are set in the optimization problem. First, interference between equipment which placed in one compartment or sub-compartment should not occur. So, it is constrained to interfere with each equipment. It is also should not occur that the equipment are arranged outside of compartment or sub-compartment. So, the position of each equipment are constrained as placing in the compartment or sub-compartment. In the two constraints, clearance between equipment are necessary to consider maintenance and repairing. So, design margin ϵ_i is added in each constraints. Table 4-15 shows summary of constraints and mathematical expression of each constraints. And Figure 4-10 shows notations of variables composing equations.

Table 4-15 Constraints for optimization of equipment

Constraints	
Position of each equipment considering Interference	$\lvert x_i - x_j \rvert \geq \frac{l_i - l_j}{2} + \epsilon_i \;\; or \;\; \lvert y_i - y_j \rvert \geq \frac{d_i - d_j}{2} + \epsilon_i$
Position of each equipment considering boundary of compartment or sub-compartment	$x_i \geq \frac{l_i}{2} + \epsilon_i + X_{min},\;\; y_i \geq \frac{d_i}{2} + \epsilon_i + Y_{min}$ $x_i + \frac{l_i}{2} + \epsilon_i \leq X_{max},\;\; y_i + \frac{d_i}{2} + \epsilon_i \leq Y_{max}$

In the constraints, l_i and d_i is length and breath of equipment considering size and orientation of equipment, and the variables can be calculated as shown in Eq.(4-2) and Eq.(4-3). Figure 4-11 shows l_i and d_i. Figure 4-12 and Figure 4-13 visualize each constraints.

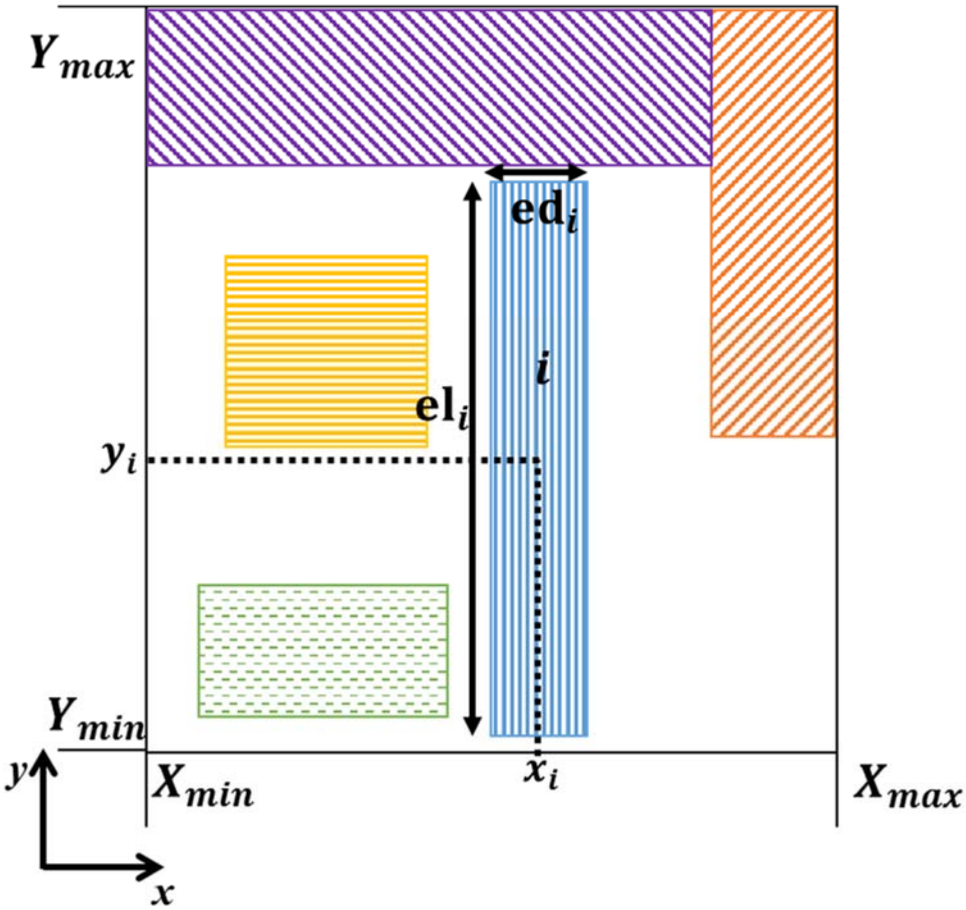

Figure 4-10 Notations for arranging equipment

$$l_i = el_i O_i + ed_i(1 - O_i) \tag{4-2}$$

$$d_i = el_i O_i + ed_i(1 - O_i) \tag{4-3}$$

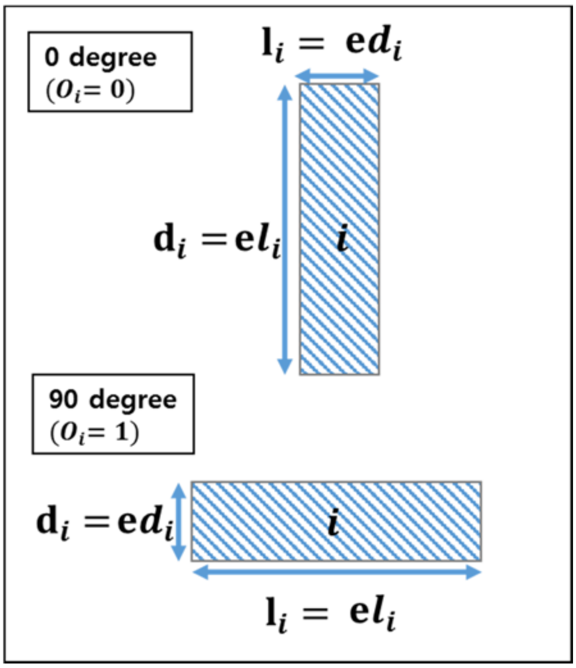

Figure 4-11 Variables considering size and orientation of equipment

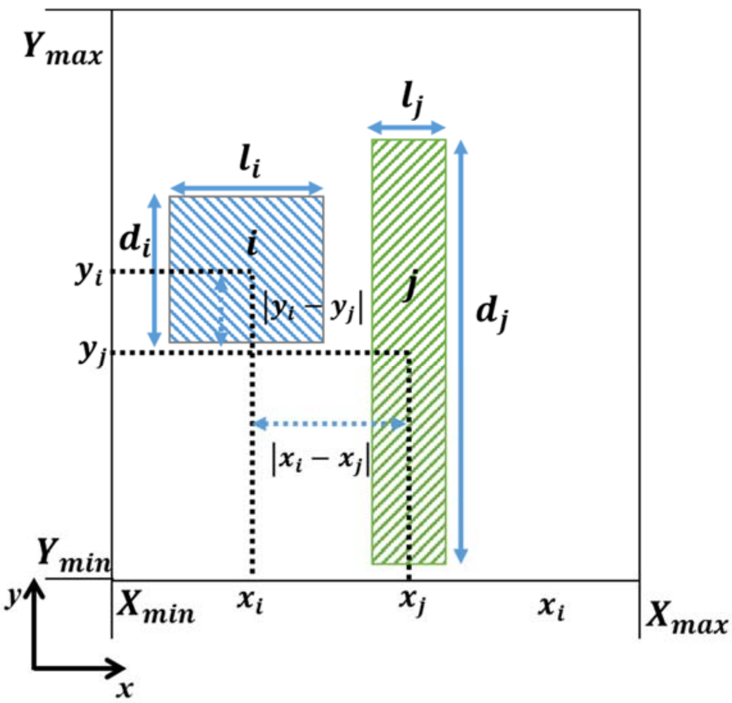

Figure 4-12 Constraint of inference between equipment

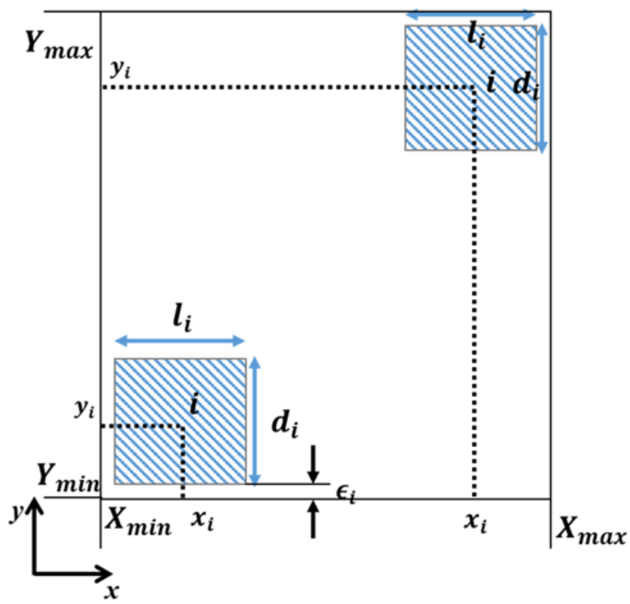

Figure 4-13 Constraint of position of equipment in the compartment or the sub-compartment

4.4.5. Evaluation of availability for alternative

After performing the optimization of equipment, the arrangement of submarine can be determined. Then it should be checked by evaluating availability for alternative. Thus, as mentioned before, the equilibrium polygon and stability of the submarine are tested here.

(1) Equilibrium polygon

Equilibrium polygon is graphical tool for checking that the submarine can maintain neutrally buoyant in the various weight condition (Shingler et al., 2005). To reduce moment exerted by operation in underwater, the submarine has compensation tank and trim tanks. Compensation tank and trim tanks should cancel out the change of weight and moment of submarine exerted by various situations (fire a torpedo, fuel consumption, accumulation of sanitary drain, etc.), and that is checked by using equilibrium polygon of the submarine.

Equilibrium polygon represent function of weight and moment change. Moment is set to X axis, and weight is set to Y axis. The origin point is longitudinal center of buoyancy of the submarine. After set the axis and the origin, weight and moment change are measured as ballasting sequence of forward trim tank, compensation tank, and after trim tank. After ballasting all tanks, weight and moment change are measured again as deballasting reversely. Then all the points measured are plotted in the graph composed of X, Y axis and the origin. As connecting the point by line, polygon of closed area is determined. This polygon is the area that is maintain the change of weight and moment. So, the submarine weight and moment must place in the polygon when operate in underwater. If extreme weight change or moment change occur, the submarine cannot cancel out the change, so that the submarine tilt forward or backward. Therefore, variable loads (crew, fresh water, sanitary drain, fuel oil, etc.) are surveyed, then all possible condition must be checked whether the point is in the polygon or not as variable loads change along the operating. Figure 4-14 shows general position of compensation tank and trim tanks. Figure 4-15 is example of equilibrium polygon, and Table 4-16 shows status changing of the example.

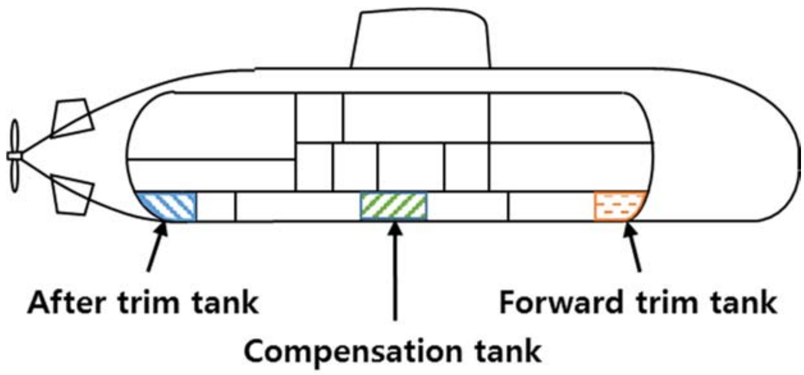

Figure 4-14 Location of compensation tank and trim tanks

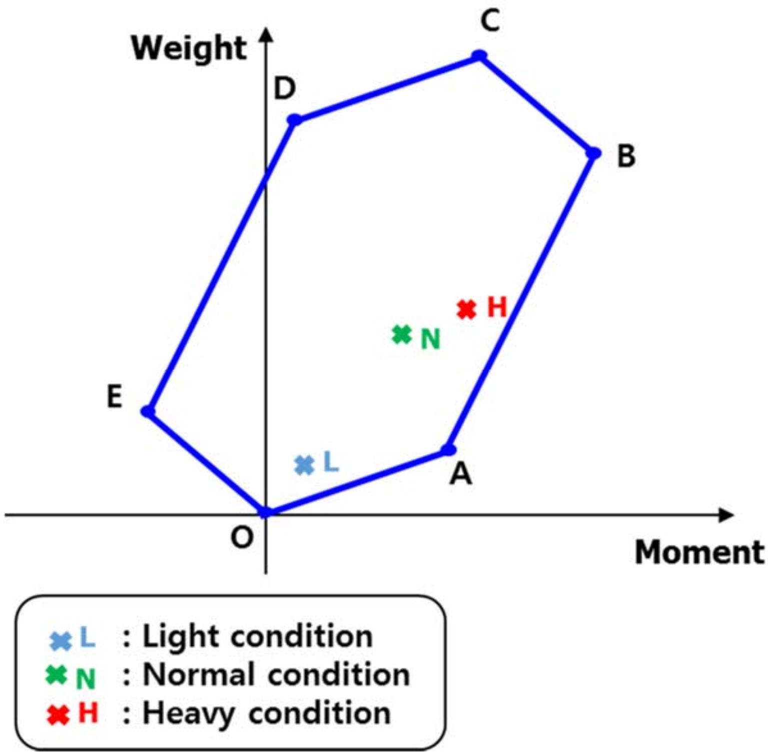

Figure 4-15 Example of trim polygon

Table 4-16 Status variation of equilibrium polygon

Sequence	Status variation
O → A	Ballasting forward trim tank
A → B	Ballasting compensation tank
B → C	Ballasting after trim tank
C → D	Deballasting forward trim tank
D → E	Deballasting compensation tank
E → O	Deballasting after trim tank

In this study, three conditions (light condition, normal condition, and heavy condition) which is regulated by U.S. navy are checked weather the conditions be in the polygon.

(2) Stability

When operating the submarine, both surface condition and submerged condition should be considered. Because, the submarine voyage in the two conditions, and the two condition have different hydrostatic characteristic. Therefore, in this study, both surface stability and submerged stability are evaluated.

- Surface stability

Surface stability of a submarine are evaluated by using transverse stability and longitudinal stability same as a surface ship. Surface stability can be calculated considering surface condition. As shown in Figure 4-16, (a) shows floating submarine, and (b) can be exerted by acting righting. If (b) is happened, the center of buoyancy and the center of gravity are not placed in the same line. Vertical line started at the initial center of buoyancy meet the new vertical line started at the changed center of buoyancy, and the point is defined to metacenter; M. Then M is the center of restoring force of the submarine. If M is positioned at the upper part of the center of gravity, the moment exerted by gravity and buoyancy of the submarine act like restoring force, so that the submarine can turn back to (a). The amount of restoring moment are calculated by multiplying displacement by GZ which is distance between the center of gravity and the vertical line started at the changed center of buoyancy. Then GZ is called righting arm. With small bank angle, righting arm GZ is approximated to $GM \cdot \sin\phi$. ϕ means rolling angle. However, if the center of gravity is position upper part of M, the moment exerted by gravity and buoyancy act like heeling moment, so that the submarine cannot be (a).

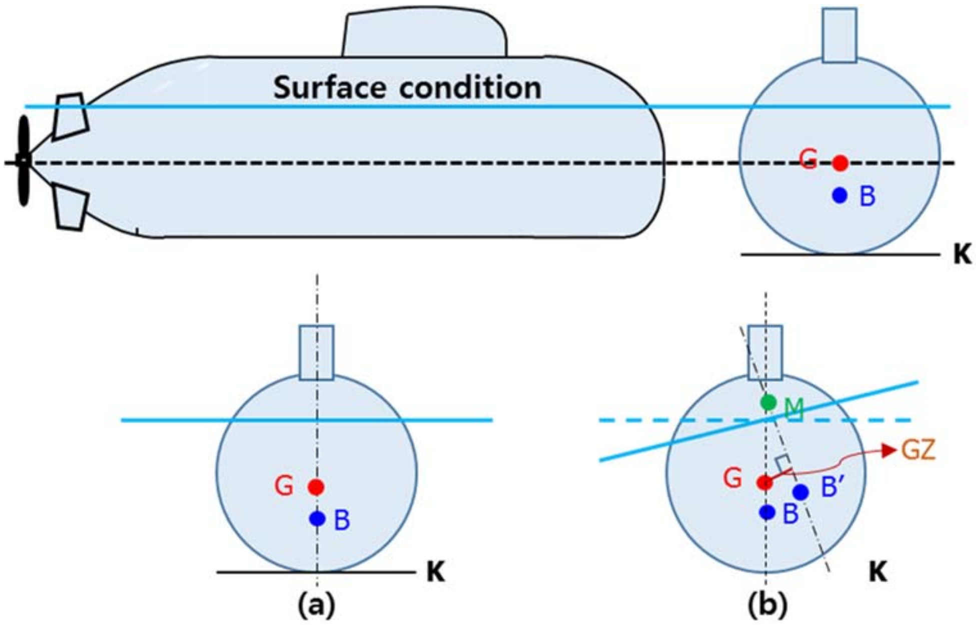

Figure 4-16 Surface stability of the submarine

Therefore, surface stability can be evaluated by calculating GM, so that occasionally GM is called initial stability. In this study, surface stability is evaluated by comparing specific requirement and GM as shown in Eq.(4-4). GM is calculated by using KB which is distance between lowest part of ship; keel and the center of buoyancy, BM which is distance between the center of buoyancy and metacenter, and KG which is distance between keel and the center of gravity as shown in Eq.(4-5).

$$GM_{requirement} \leq GM \tag{4-4}$$

$$\mathrm{GM} = \mathrm{KB} + \mathrm{BM} - \mathrm{KG} \tag{4-5}$$

Generally, longitudinal stability have more margin then transverse stability. So, if transverse stability meet the criteria, longitudinal stability also meet the criteria (The society of naval architects of Korea, 2012). In this study, total four stability (transverse stability, and longitudinal stability) are evaluated with two loading conditions (normal weight condition, full loading condition).

- Submerged stability

When the submarine submerged in underwater, the center of buoyancy is not changed, but the center of gravity can be changed. To generate restoring moment in various positions, the center of gravity have to be placed in the lower part of the center of buoyancy. If not, heeling moment are generated rather than restoring moment, so that the submarine incline more. Figure 4-17 shows ideal position of the center of gravity and the center of buoyancy of the submarine in underwater.

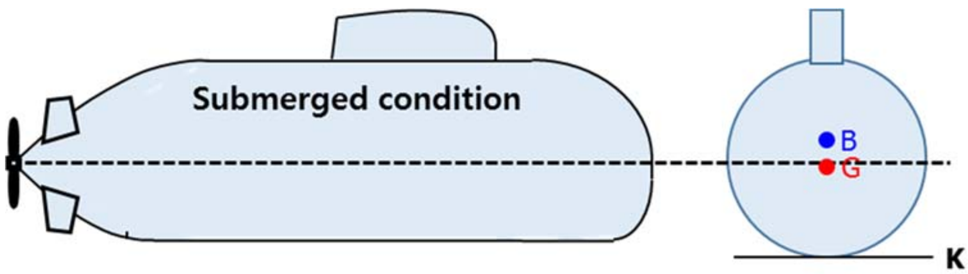

Figure 4-17 Submerged stability of the submarine

Therefore, submerged stability can be evaluated by using GB. In this study, when GB is larger than specific requirement, submerged stability is evaluated to satisfaction as shown in Eq.(4-6). GB is calculated using KB which is distance between keel and the center of buoyancy, and KG which is distance between keel and the center of gravity as described in Eq.(4-7).

$$GB_{requirement} \leq GB \tag{4-6}$$

$$\mathrm{GB} = \mathrm{KB} - \mathrm{KG} \tag{4-7}$$

In this study, submerged stability is evaluated by calculating GB in two loading conditions (normal weight condition, full loading condition).

5. User interface

5.1. Configuration of user interface

In this study, prototype program was developed to apply the method proposed in this study, and can be used easily by users. Using prototype program, user can confirm, manage, save the arrangement sequence of the submarine. Prototype program was developed based on C# language and WPF (Windows Presentation Foundation, http://msdn.microsoft.com/) in .Net 4.0 environment.

Prototype program has three main components. First, 3D visualization was developed. Using the panel, user can see the process of the arrangement with 3D view. Second, tool for expert system was developed. User can create, modify, and confirm a rules for arrangement of submarine by using the tool. Third, tool for optimization was developed, so that user can see the process of optimization with graph showing objective functions in real time. Also, after the optimization, user can check the availability of the alternative. Figure 5-1 shows the configuration of user interface.

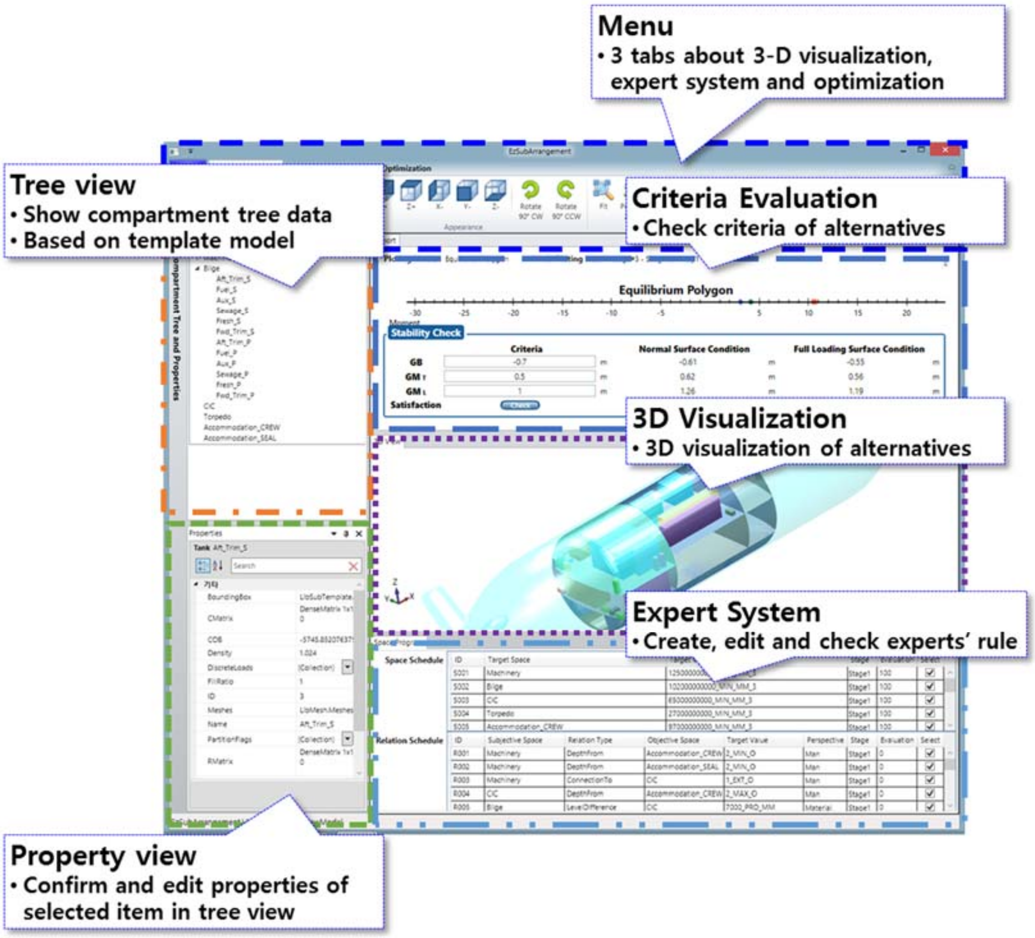

Figure 5-1 Configuration of prototype program

5.2. 3D visualization

In 3D visualization panel, user can see the alternatives of the submarine. In the menu, mesh models for pressure hull or external hull made by using CAD program can be saved, and imported. By using 3D view controller, user can freely change the viewpoint and zoom, and this task also can be done by using mouse control. In the tree view, user can confirm the compartments, the sub-compartments, and the equipment. Then properties (center of gravity, volume, weight, center of buoyancy, etc.) of each compartments, sub-compartments, and equipment can be confirmed in the properties view by selecting the items in the tree view. And selected item is colored in the 3D panel, so that user can confirm which item is selected. Figure 5-2 shows a 3D visualization panel and the libraries used in the panel.

For 3D visualization, WPF 3D which is provided by WPF and Helix 3D which is open source (http://helixtoolkit.codeplex.com/) are used to implement in the prototype program. To divide meshes by specific plane and union meshes, CSG (Constructive Solid Geometry) which is open source is wrapped to implement in the prototype program. And 3D meshes properties (center of buoyancy, moment, weight, etc.) can be calculated, so that mesh calculation library (in house code) was developed. Figure 5-2 shows 3D visualization panel and libraries used for the panel.

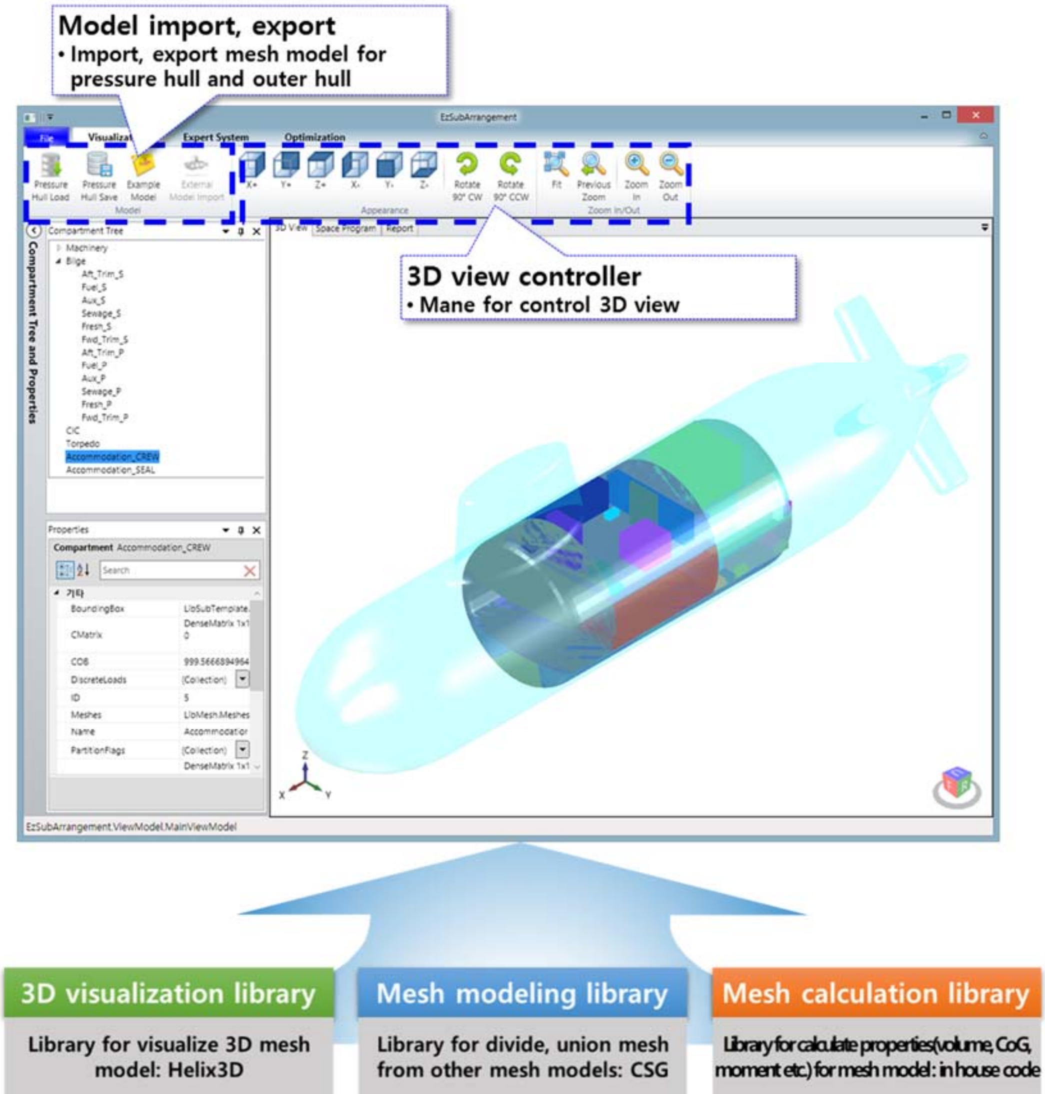

Figure 5-2 3D visualization panel

5.3. Tool for expert system

Tool for expert system is implementation of AEM which is mentioned in Chapter.3.3. And it is configured by using GUI (Graphic User Interface). In the menu, user can create space information and relation information. And also the rules can be saved, and loaded.

Expert system panel is composed of two tables which are space list and relation list. In space list, space information can be modified, confirmed. And in relation list, relation information can be modified, confirmed.

To connect with optimization problems and arrangement template model, in house code of AEM was developed. Figure 5-3 shows AEM in the prototype program and library used in the panel.

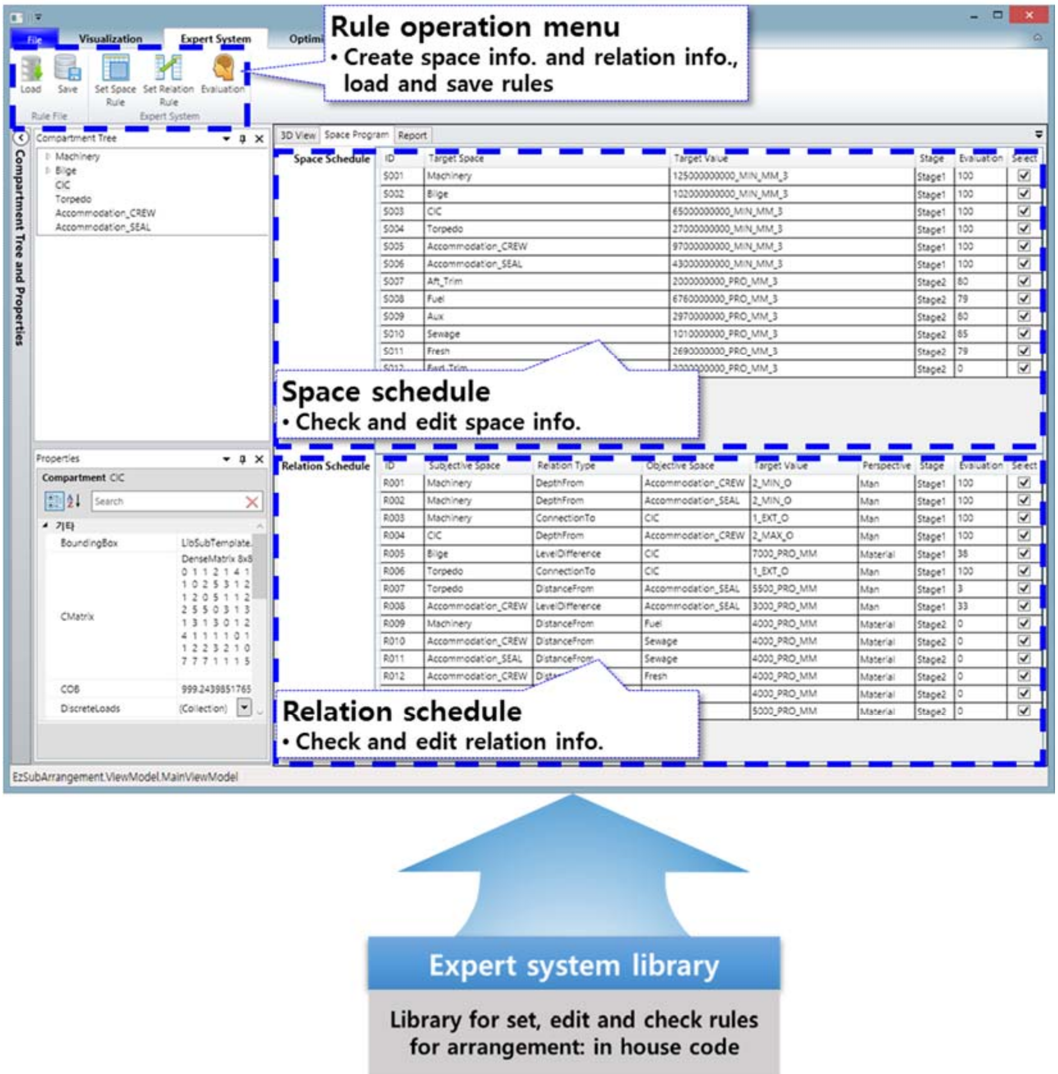

Figure 5-3 Tool for expert system

5.4. Tool for optimization

Tool for optimization is device to solve the optimization problems defined in Chapter.4, and adjust parameters in the algorithm. By using tool for optimization, user can perform each stages of optimization. And also user can confirm the value of objective function and overall constraint violation value in real time.

To solve the optimization problems, NSGAII is used. And open source library Jmetal.NET (http://jmetal.sourceforge.net/) which has the algorithm was used. To plotting the graph, open source library Oxyplot (https://oxyplot.codeplex.com/) was used. Figure 5-4 shows an optimization panel and libraries used in the panel.

After optimization, equilibrium polygon and stability of alternative are shown by using the panel. Using the menu, the variable loads used to determine points in equilibrium polygon and values of stability can be confirmed and modified. Stability requirement can be determined by user. Figure 5-5 shows the panel for evaluating the availability of alternative. In the figure, upper part is equilibrium polygon and lower part is stability values.

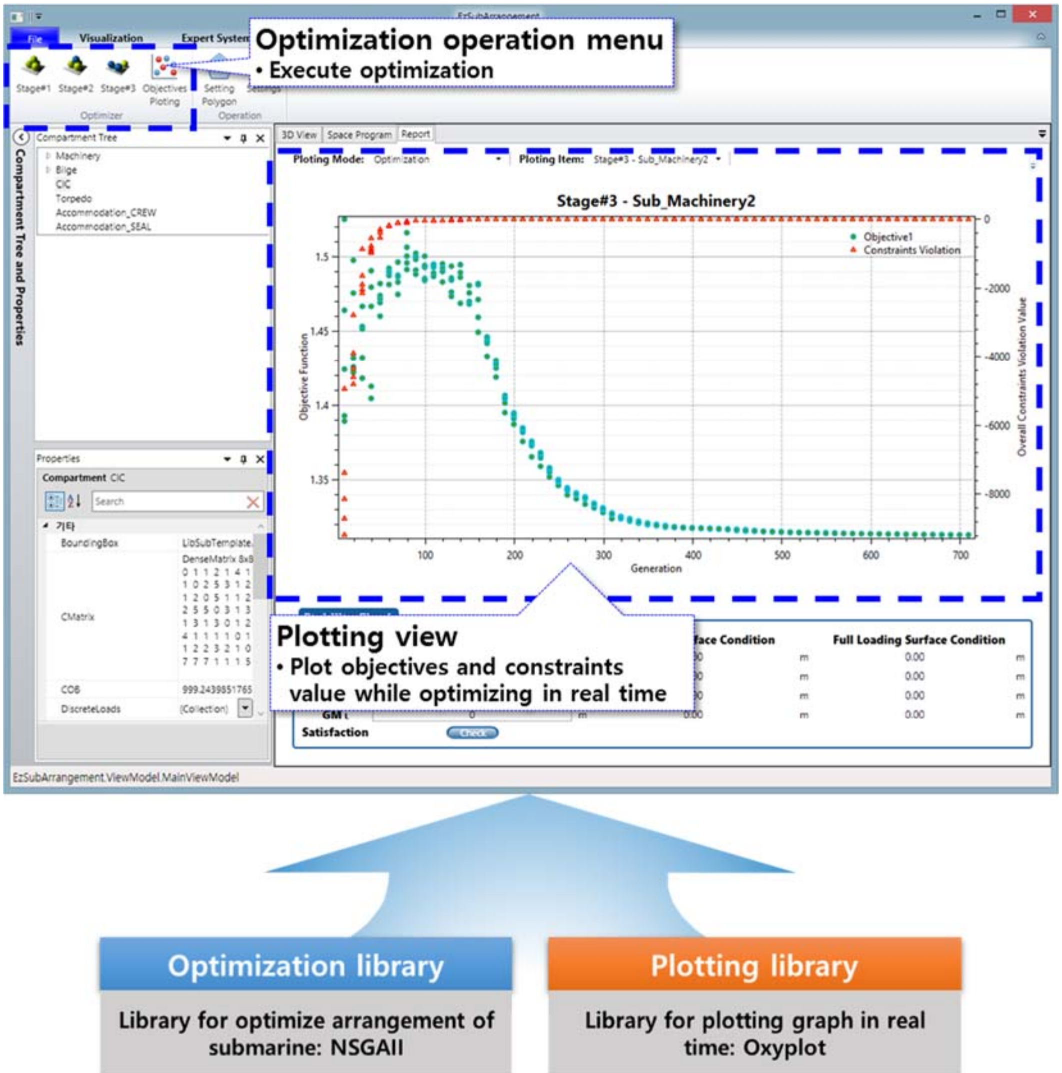

Figure 5-4 Tool for optimization

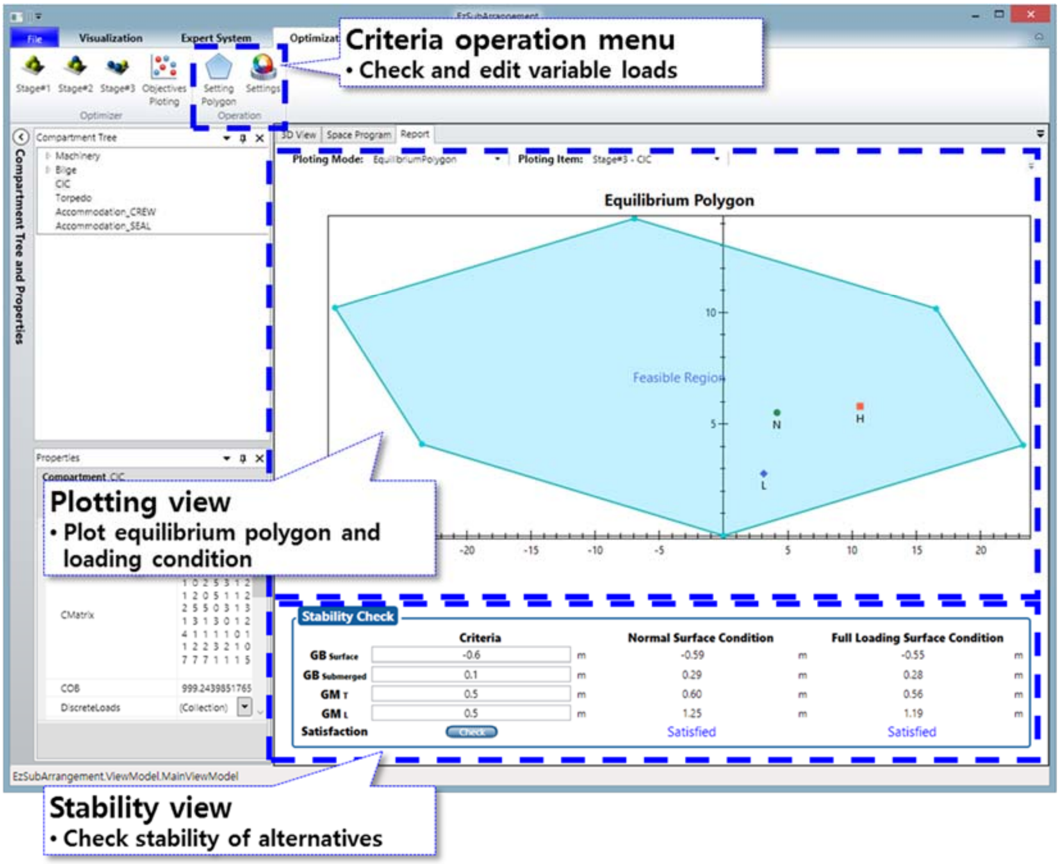

Figure 5-5 Evaluation of the availability

6. Application of the method for arrangement design of submarine

6.1. Description of an example

To verify the method for arrangement of submarine using the expert system and the optimization technique, littoral warfare submarine (SSLW) designed by U.S. navy was adopted (Shingler et al., 2005). The SSLW requirement is based on the need for a technologically advanced, convert, and small submarine capable of entering the littoral area. Mission requirements include Special Forces delivery, extraction and support, mine laying and countermeasures, anti-submarine warfare, search & salvage, and AUV (Autonomous Utility Vehicle) support. The submarine is required to have multiple and flexible mission packages. Figure 6-1 shows main configuration of the SSLW and the name of each parts. Table 6-1 shows main properties of the submarine.

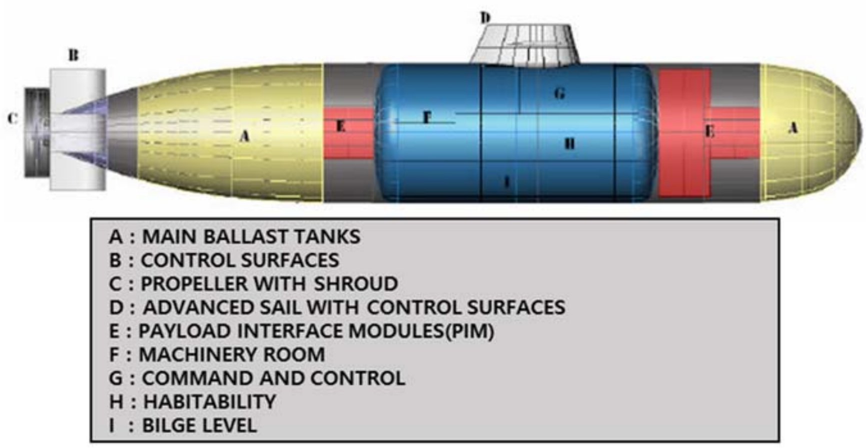

Figure 6-1 Configuration of Littoral warfare submarine (SSLW)

Table 6-1 Main characteristics of the submarine

Submarine Characteristic	Value
LOA(Length overall)	39.32 m
Breath	6.71 m
Depth	6.71 m
Displacement	795.36 m^3
Lightship weight	613.27 ton
Full load weight	727.35 ton
Sustained Speed	26.5 knots
Endurance Speed	10 knots
Sprint Range	31 nm
Endurance Range	1004 nm

In this study, the pressure hull is marked with blue in Figure 6-1 is main target of arrangement. The pressure hull is arranged by experts manually, and detail of the arrangement is shown in Figure 6-2.

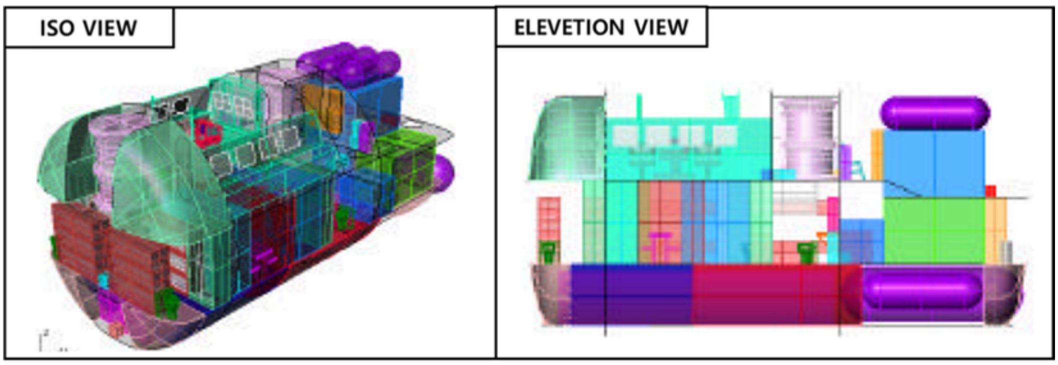

Figure 6-2 Arrangement of the pressure hull in the submarine

6.1.1. Components for optimization of compartment

The pressure hull of the example is composed of two transverse bulkhead, two deck, and six compartments divided by the partitions as shown in Figure 6-3. From the pressure hull top-left, torpedo room which has torpedoes and launching equipment, combat information center (CIC) where operations about the submarine are happened, machinery which has a lot of equipment for propulsion, generating, etc., accommodation for SEAL where the Special Force team reside, accommodation for crew where the crew reside, bilge compartment which has various tanks, and battery room exist in the pressure hull. Two transverse bulkhead, two deck, and six compartments are determined by the first stage (optimization of compartment).

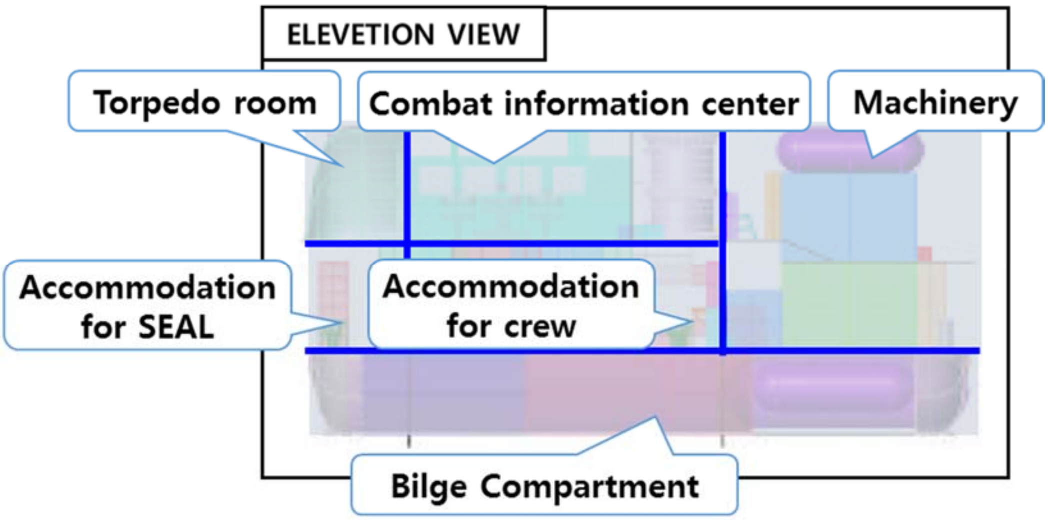

Figure 6-3 Target for optimization of main compartments

6.1.2. Components for optimization of sub-compartments

The bilge compartment which is one of the main compartments is composed of twelve sub-compartments, and the sub-compartments are placed in six apiece on either side of starboard and port as shown in Figure 6-4. From the left side, forward trim tank which exert moment by ballasting, sanitary tank which save the sanitary drains emitted by crew, fresh water tank which load fresh water used by crew, auxiliary tank which load auxiliary oil for various equipment, fuel tank which load fuel oil for propulsion, and after trim tank which act same as forward trim tank. The sub-partitions and sub-compartment of the bilge compartment are determined by performing the second stage (optimization of sub-compartments). The accommodations also have many sub-compartments, but the sub-compartment much lighter than the other sub-compartment. So, the accommodations are excluded in the second stage, because it is hard to improve operability of the submarine and change the center of gravity by re-arranging.

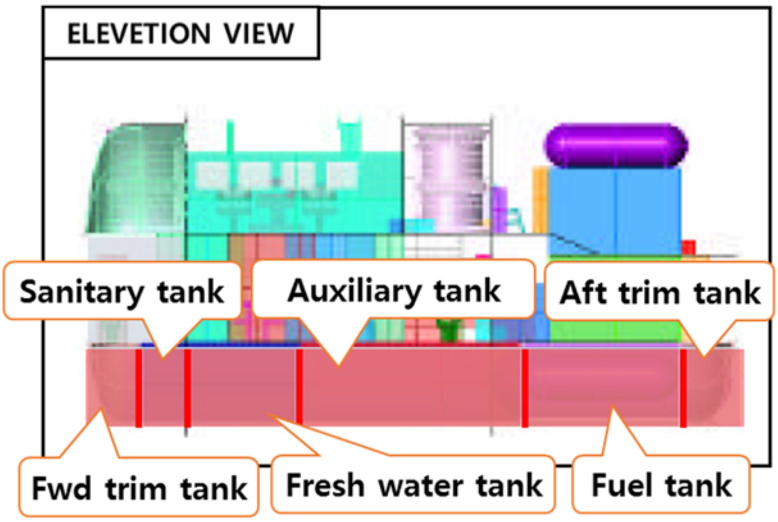

Figure 6-4 Target for optimization of sub-compartments

6.1.3. Components for optimization of equipment

There are many equipment in the pressure hull. Among the compartments, main machinery, sub-machinery, and CIC are set to target of arrangement, because most important equipment are included in the compartments and a lot of equipment exist in the compartments. There are ten equipment in the main machinery, fourteen equipment in the sub-machinery, and eight equipment in CIC. So, the position and orientation of thirty two equipment are determined by performing the stage three (optimization of equipment). There are also many equipment in the accommodations for cooking and living. But, the equipment in the accommodations are much lighter than the other equipment, so that it is very hard to change the center of gravity or operability of the submarine. Therefore, the equipment in the accommodations are excluded in the stage.

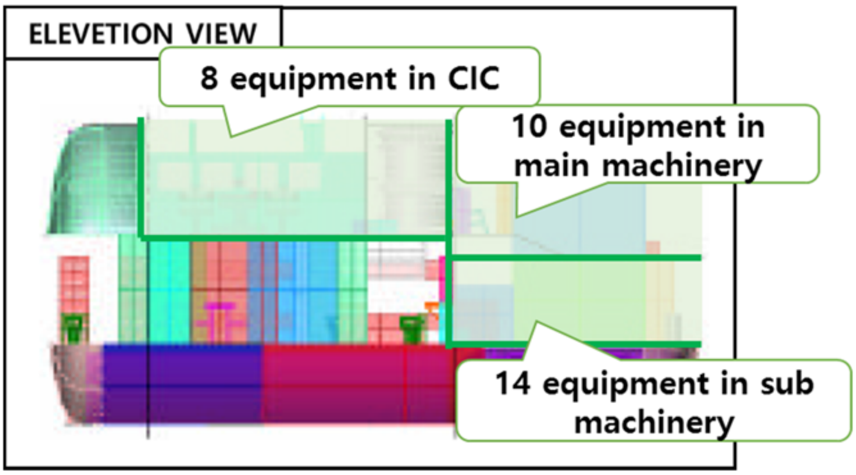

Figure 6-5 Target for optimization of equipment

(1) Equipment of the main machinery

The equipment for main machinery are mainly composed of two group. First one is for propulsion, and second one is for generating. Table 6-2 is list of the equipment in the main machinery. The table shows dimension and weight of the equipment.

Table 6-2 Equipment of the main machinery

Equipment	Length[m]	Breadth[m]	Height[m]	Weight[ton]
Polymer Electrolyte Membrane(PEM)	2.74	2.74	1.9	10.47
Oxygen tank	2.74	0.91	9.1	5.86
DC main switch board	0.3	1.83	1.83	1.29
Power conversion module1	0.3	0.3	0.91	1.29
Power conversion module2	0.3	0.3	0.91	1.29
Motor control center	0.3	0.3	0.91	0.84
Lighting load panel	0.3	0.3	0.91	1.29
DC/AC inverter controller	0.61	0.61	0.3	1.29
COH_2 burner	0.3	0.3	0.61	0.51
CO_2 scrubber	0.3	0.3	0.61	0.51

(2) Equipment of the sub-machinery

The sub-compartment also have many equipment for operating. Mainly, the equipment are for generating or operating the operating the other equipment. Table 6-3 shows dimension and weight of the equipment in the sub-machinery.

Table 6-3 Equipment of the sub-machinery

Equipment	Length[m]	Breadth[m]	Height[m]	Weight[ton]
Regenerator1	2.74	1.22	1.52	11.2
Regenerator2	2.74	1.22	1.52	11.2
High pressure air compressor	0.91	0.91	0.91	2
LP blower	0.91	0.91	0.91	3
Ventilation fan	0.3	0.61	0.3	0.51
Induction mast inlet	0.3	0.3	0.3	0.51
Trim and drain pump1	0.61	0.61	0.3	1.85
Trim and drain pump2	0.61	0.61	0.3	1.85
Seawater cooling pump1	0.3	0.61	0.3	0.09
Seawater cooling pump2	0.3	0.61	0.3	0.09
Main hydraulic pump	0.3	0.61	0.3	1.85
Fresh water pump	0.3	0.3	0.3	1.65
Hydraulic pressure accumulator	0.3	0.61	0.3	1.85
Trim accumulator	0.3	0.61	0.3	1.85

(3) Equipment of the CIC

The equipment placed in the CIC mainly are mainly for controlling the weapon system, sonar system, and steering. Table 6-4 shows the dimension and weight of the equipment in the CIC.

Table 6-4 Equipment of the CIC

Equipment	Length[m]	Breadth[m]	Height[m]	Weight[ton]
Sonar control system1	0.76	0.76	0.76	0.28
Sonar control system2	0.3	0.61	0.3	0.28
Sonar control system3	0.61	0.3	0.3	0.28
Command and surveillance1	4.51	0.61	1.37	3.02
Command and surveillance2	4.51	0.61	1.37	3.02
Command and surveillance3	0.61	1.52	2.13	3.02
Command and surveillance4	1.52	1.52	1.22	3.02
Command and surveillance5	0.15	1.52	2.13	3.02

6.2. Experts’ knowledges for the application

When calculate objective functions in the optimization process, feasibility index from expert system are included. So in this chapter, the rules adopted in the application are considered.

For the precise rules, experts of arrangement, data of the previous ship, and the regulations of the submarine are necessary. But, it is hard to be obtained, and also a lot of time will consumed to quantization of the data. Therefore, in this study, the knowledge from related books or studies were adopted to define the rules for expert system. If real experts define the rules in the future, the rules will be more realistic.

6.2.1. Space information

By referencing the arrangement of the example, the required volumes for the compartments and sub-compartments are determined, and twelve space information were defined by using the data. Table 6-5 shows the space list consisted of the space information.

Table 6-5 Space list for the application

ID	Objective space	Target value	Optimization stage
S001	Machinery	125_min_m^3	1 Stage
S002	Bilge Compartment	102_min_m^3	1 Stage
S003	CIC	65_min_m^3	1 Stage
S004	Torpedo room	27_min_m^3	1 Stage
S005	Accommodation_SEAL	43_pro_m^3	1 Stage
S006	Accommodation_crew	97_pro_m^3	1 Stage
S007	Aft trim tank	2_pro_m^3	2 Stage
S008	Fuel tank	6.76_min_m^3	2 Stage
S009	Auxiliary tank	2.97_min_m^3	2 Stage
S010	Sanitary tank	1.01_pro_m^3	2 Stage
S011	Fresh water tank	2.69_min_m^3	2 Stage
S012	Fwd trim tank	2_pro_m^3	2 Stage

6.2.2. Relation information

By analyzing the example arranged manually, and researching studies (Burcher and Rydill (1994), and Zimmerman (2000)), the relation information were defined.

When operating the submarine, the accommodations and the machinery should not be far, because of operability, maintenance, and repairing. And the CIC and the machinery also be closer for the same reason. For the rotation of crew and the emergency, crew should move quickly to the CIC, so that the accommodations and the CIC have to be close. The bilge compartment should be placed in the lower part of the pressure hull, because of the center of gravity. The machinery has a lot of equipment, so that the probability of fire are higher than other compartments. So, the torpedo room should be placed far from the machinery, because the torpedoes increase the risk of the fire.

For arrangement of the sub-compartment. Relations between sub-compartments should be considered. The machinery have to be close with fuel tank and auxiliary tank, so that the fuel oil or auxiliary oil can be supplied by the tanks to the equipment placed in the machinery. And, fresh tank and sanitary tank should be close with the accommodations, because the tanks mainly used in the accommodations. The knowledge mentioned can be expressed to the rules shown in Table 6-6.

Table 6-6 relation list for the application

ID	Objective space	Relation type	Subjective space	Target value	Perspective	Optimization stage
R001	Machinery	DepthFrom	Accommodation_crew	2_min	Man	1 Stage
R002	Machinery	DepthFrom	Accommodation_SEAL	2_min	Man	1 Stage
R003	Machinery	ConnectionTo	CIC	1_ext	Man	1 Stage
R004	CIC	DepthFrom	Accommodation_crew	2_max	man	1 Stage
R005	Bilge Compartment	LevelDifference	CIC	7_pro_m	Material	1 Stage
R006	Torpedo room	ConnectionTo	Accommodation_crew	1_ext	Man	1 Stage
R007	Torpedo room	DistanceFrom	Machinery	5.5_pro_m	Man	1 Stage
R008	Accommodation_crew	LevelDifference	Machinery	3_pro_m	Man	1 Stage
R009	Machinery	DistanceFrom	Fuel tank	4_pro_m	Material	2 Stage
R010	Accommodation_crew	DistanceFrom	Sanitary tank	4_pro_m	Material	2 Stage
R011	Accommodation_SEAL	DistanceFrom	Sanitary tank	4_pro_m[3]	Material	2 Stage
R012	Accommodation_crew	DistanceFrom	Fresh water tank	4_pro_m	Material	2 Stage
R013	Accommodation_SEAL	DistanceFrom	Fresh water tank	4_pro_m	Material	2 Stage
R014	Machinery	DistanceFrom	Auxiliary tank	5_pro_m	Material	2 Stage

6.2.3. Adjacency index matrix and unit connection cost matrix

Three compartments (main machinery, sub-machinery, and CIC) are optimized in the third stage. To calculate objective function in the third stage, adjacency index matrix and unit connection cost matrix are necessary as mentioned in Chapter.4.4.1. The matrixes are defined by using experts' knowledge about relations between each equipment.

In this study, the matrixes were defined by analyzing the example arranged manually, and researching the studies (Burcher and Rydill (1994), and Zimmerman (2000)). The data for the main machinery is shown in Table 6-7, and Table 6-8. The data for the sub-machinery is shown in Table 6-9, and Table 6-10. And the data for the CIC is shown in Table 6-11, and Table 6-12.

Table 6-7 Adjacency index matrix of the equipment of the main machinery

Adjacency matrix											
Equipment		P	OT	DM	PC1	PC2	MC	LL	DA	CB	CS
PEM	P	0	1	1	2	1	6	1	5	2	2
Oxygen tank	OT		0	2	2	4	1	2	1	2	2
DC main switch board	DM			0	2	1	2	2	6	2	2
Power conversion module1	PC1				0	1	2	4	1	2	2
Power conversion module2	PC2					0	1	2	1	2	2
Motor control center	MC						0	1	1	2	2
Lighting load panel	LL							0	7	2	2
DC/AC inverter controller	DA								0	2	2
COH_2 burner	CB									0	2
CO_2 scrubber	CS										0

Table 6-8 Unit connection cost matrix of the equipment of the main machinery

Unit connection cost matrix											
Equipment		P	OT	DM	PC1	PC2	MC	LL	DA	CB	CS
PEM	P	0	1	1	2	1	2	1	5	0	0
Oxygen tank	OT		0	2	2	2	1	2	1	0	0
DC main switch board	DM			0	2	1	2	2	4	0	0
Power conversion module1	PC1				0	1	2	2	1	0	0
Power conversion module2	PC2					0	1	6	1	0	0
Motor control center	MC						0	1	1	0	0
Lighting load panel	LL							0	3	0	0
DC/AC inverter controller	DA								0	0	0
COH_2 burner	CB									0	0
CO_2 scrubber	CS										0

Table 6-9 Adjacency index matrix of the equipment of the sub-machinery

Adjacency matrix															
Equipment		R1	R2	HP	LB	VF	IM	TD1	TD2	SC1	SC2	MH	FW	HP	TA
Regenerator1	R1	0	1	1	2	1	5	1	5	1	1	1	2	2	2
Regenerator2	R2		0	2	2	4	1	3	1	1	1	1	1	4	1
High pressure air compressor	HP			0	2	1	2	3	5	1	1	1	3	1	2
LP blower	LB				0	1	2	3	1	1	1	1	1	3	5
Ventilation fan	VF					0	1	4	1	1	1	1	5	5	1
Induction mast inlet	IM						0	1	1	1	1	1	1	2	3
Trimand drain pump1	TD1							0	5	1	1	1	2	3	1
Trimand drain pump2	TD2								0	1	1	1	2	1	2
Seawater collling pump1	SC1									0	1	1	2	1	3
Seawater collling pump2	SC2										0	1	3	1	1
Main hydraulic pump	MH											0	1	5	4
Fresh water pump	FW												0	1	3
Hydraulic pressure accumulator	HP													0	1
Trim accumulator	TA														0

Table 6-10 Unit connection cost matrix of the equipment of the sub-machinery

Unit connection cost matrix															
Equipment		R1	R2	HP	LB	VF	IM	TD1	TD2	SC1	SC2	MH	FW	HP	TA
Regenerator1	R1	0	1	1	2	1	3	1	5	1	1	1	2	2	2
Regenerator2	R2		0	2	2	2	1	1	1	1	1	1	1	4	1
High pressure air compressor	HP			0	2	1	2	1	5	1	1	1	3	1	2
LP blower	LB				0	1	2	3	1	1	1	1	1	5	5
Ventilation fan	VF					0	1	4	1	1	1	1	3	3	1
Induction mast inlet	IM						0	1	1	1	1	1	1	2	3
Trimand drain pump1	TD1							0	5	1	1	1	2	3	1
Trimand drain pump2	TD2								0	1	1	1	2	1	2
Seawater collling pump1	SC1									0	1	1	2	1	3
Seawater collling pump2	SC2										0	1	3	1	1
Main hydraulic pump	MH											0	1	3	4
Fresh water pump	FW												0	1	3
Hydraulic pressure accumulator	HP													0	1
Trim accumulator	TA														0

Table 6-11 Adjacency index matrix of the equipment of the CIC

Adjacency matrix									
Equipment		SC1	SC2	SC3	CS1	CS2	CS3	CS4	CS5
Sonar control system1	SC1	0	3	3	2	2	2	2	2
Sonar control system2	SC2		0	3	2	2	2	2	2
Sonar control system3	SC3			0	2	2	2	2	2
Command and surveillance1	CS1				0	5	2	2	2
Command and surveillance2	CS2					0	2	2	2
Command and surveillance3	CS3						0	1	1
Command and surveillance4	CS4							0	1
Command and surveillance5	CS5								0

Table 6-12 Unit connection cost matrix of the equipment of the CIC

Unit connection cost matrix									
Equipment		SC1	SC2	SC3	CS1	CS2	CS3	CS4	CS5
Sonar control system1	SC1	0	2	2	1	1	1	1	1
Sonar control system2	SC2		0	2	1	1	1	1	1
Sonar control system3	SC3			0	1	1	1	1	1
Command and surveillance1	CS1				0	5	1	1	1
Command and surveillance2	CS2					0	1	1	1
Command and surveillance3	CS3						0	1	1
Command and surveillance4	CS4							0	1
Command and surveillance5	CS5								0

6.3. Optimization result

By using prototype program as mentioned in Chapter.5, the example of Chapter.6.1 was optimized. All coordinates used in this study is defined with the center of buoyancy of the pressure hull as the center, and the axes is defined that + direction of the X axis is direction of bow, + direction of the Y axis is direction of starboard, and + direction of the Z axis is direction of the upward.

6.3.1. Result of the optimization of compartment (the first stage)

The parameters used in the first stage was as follows. The population was set to '10', and optimization was performed to '700' generations. SBX PMX crossover was used to crossover operator, and the probability of crossover was '0.9'. Polynomial swap mutation was used to mutation operator, and the probability of mutation was '0.01'. Selection operator was set to binary tournament. Table 6-13 is shown summary of the parameters.

Table 6-13 Parameters for the optimization of compartment

Parameter	Value
Population	10
Generation	700
Crossover operator	SBX PMX crossover
Crossover probability	0.9
Mutation operator	Polynomial swap mutation
Mutation probability	0.01
Selection operator	Binary tournament

Figure 6-6 shows the graph for showing the progress of the objective function and overall constraints violation value. Objective function was calculated by adding three objective functions normalized from '0' to '1' and defined in Chapter.4.2.3. After optimization, the objective function value was '0.85' and the overall constraints violation value was '0'.

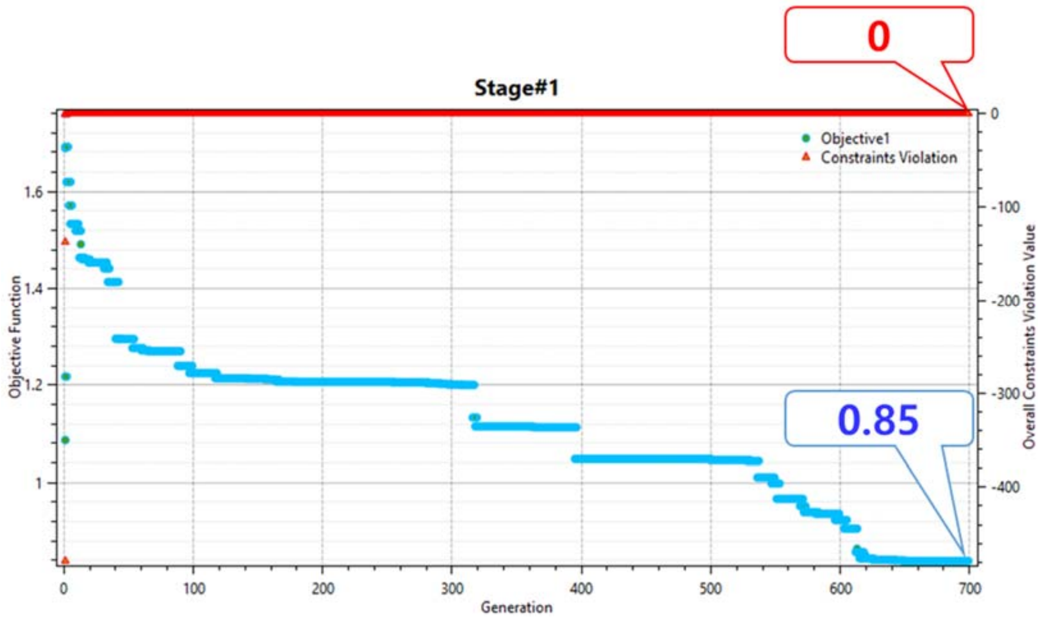

Figure 6-6 Progress of the objectives and overall constraints violation value while perform the first stage

(1) Comparison of the design variables

Before and after the optimization of compartment, the design variables were shown in Table 6-14, then by using gene decoding, the results were confirmed like Figure 6-7.

Compartment sequence (C_i) are from '0' torpedo room, CIC, accommodation for SEAL, accommodation for crew. Before and after the optimization of compartment, the sequence of the compartments were not changed, but the position of the transverse bulkhead and the deck were changed a little.

Table 6-14 Design variables before and after the optimization of compartment

	Manually	**Optimized**
Design variable	**Value**	**Value**
TBHD($\boldsymbol{X_1}$)	-1.53	-0.95
TBHD($\boldsymbol{X_2}$)	4.57	4.69
Deck($\boldsymbol{Y_1}$)	0.94	0.89
Deck($\boldsymbol{Y_2}$)	-1.32	-1.49
Sequence($\boldsymbol{C_1}$)	0	0
Sequence($\boldsymbol{C_2}$)	1	1
Sequence($\boldsymbol{C_3}$)	2	2
Sequence($\boldsymbol{C_4}$)	3	3

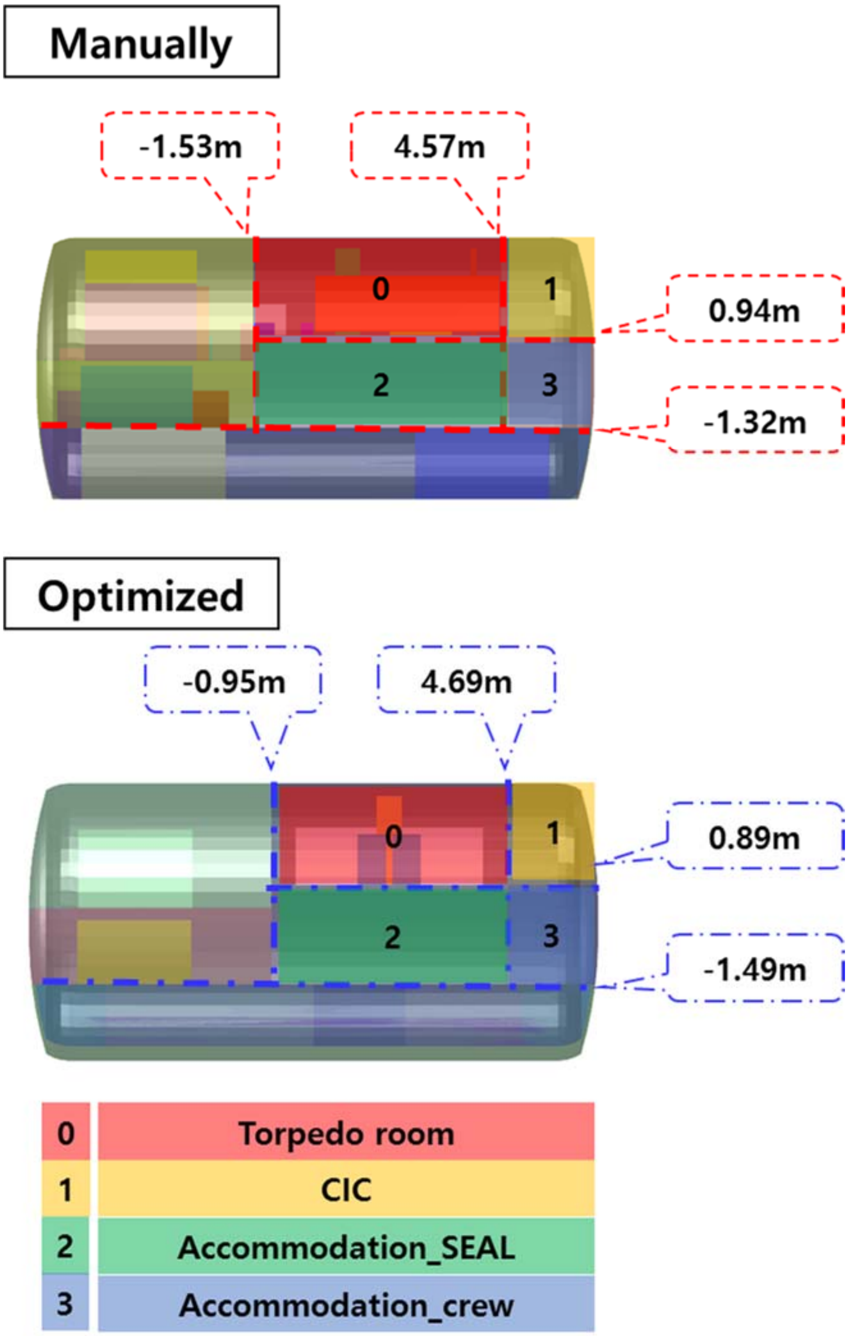

Figure 6-7 Before and after the optimization of compartment

(2) Comparison of the objective functions

When optimize the arrangement of the compartments, feasibility index from expert system, distance between X position of CoG and x position of CoB, and Z position of CoB are calculated as the objective functions. The feasibility index from expert system was normalized from '0' to '1', and the objective was optimized towards maximize. Distance between X position of CoG and X position of CoB was optimized toward minimize. And Z position of CoB was optimized towards minimize also.

After the optimization of compartments, first objective function was improved by 17% '0.64' to '0.75'. Second objective function was improved by 49% '1.02m' to '0.63m'. And third objective function was also improved by 73% '1.95m' to '0.52m'. Table 6-15 shows summary of the objective functions before and after the first stage.

Table 6-15 Objective functions before and after the optimization of compartment

Objective function		Manually	Optimized	Ratio
Feasibility index from expert system	Maximize	0.64	0.75	1.17
Distance between X position of CoG and x position of CoB	Minimize	1.02m	0.63m	0.61
Z position of CoB	Minimize	1.95m	0.52m	0.27

6.3.2. Result of the optimization of sub-comparment (the second stage)

The parameters used in the second stage was as follows. The population was set to ‘10’, and optimization was performed to ‘200’ generations. PMX crossover was used to crossover operator, and the probability of crossover was ‘0.9’. Swap mutation was used to mutation operator, and the probability of mutation was ‘0.25’. Selection operator was set to binary tournament. Table 6-16 is shown summary of the parameters.

Table 6-16 Parameters for the optimization of sub-compartments

Parameter	**Value**
Population	10
Generation	200
Crossover operator	PMX crossover
Crossover probability	0.9
Mutation operator	Swap mutation
Mutation probability	0.25
Selection operator	Binary tournament

Figure 6-8 shows the graph for showing the progress of the objective function and overall constraints violation value. Objective function was calculated by adding two objective functions normalized from ‘0’ to ‘1’ and defined in Chapter.4.3.3. After optimization, the objective function value was ‘0.40’ and the overall constraints violation value was ‘0’.

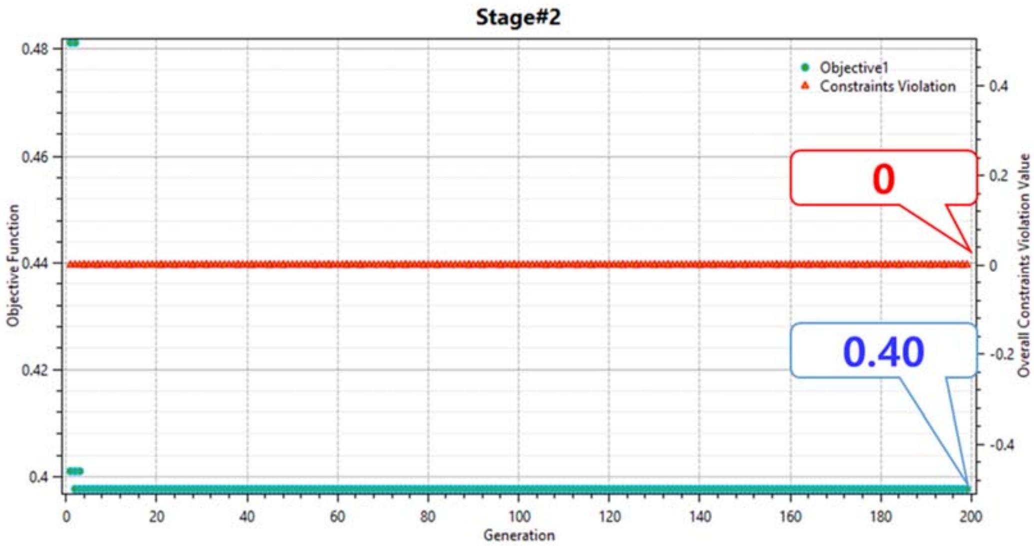

Figure 6-8 Progress of the objectives and overall constraints violation value while perform the first stage

(1) Comparison of the design variables

Before and after the optimization of sub-compartments, the design variables of the second stage were shown in Table 6-17. And then by using gene decoding, the results were shown like Figure 6-9.

Table 6-17 Design variables before and after the optimization of sub-compartments

	Manually	Optimized
Design variable	**Value**	**Value**
Sequence($\boldsymbol{SC_1}$)	0	1
Sequence($\boldsymbol{SC_2}$)	1	0
Sequence($\boldsymbol{SC_3}$)	2	3
Sequence($\boldsymbol{SC_4}$)	3	2

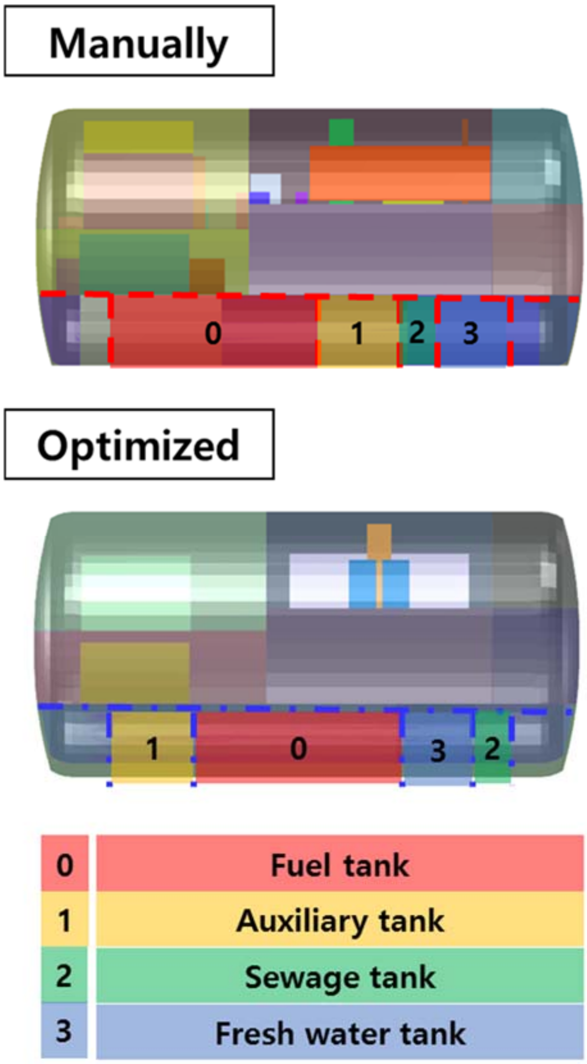

Figure 6-9 Before and after the optimization of sub-compartments

(2) Comparison of the objective functions

When optimize the arrangement of the sub-compartments, feasibility index from expert system, and distance between X position of CoG and x position of CoB are calculated as the objective functions. The feasibility index from expert system was normalized from '0' to '1', and the objective was optimized towards maximize. And distance between X position of CoG and X position of CoB was optimized toward minimize.

After the optimization of compartments, first objective function was improved by 103% '0.33' to '0.67'. And second objective function was improved by 82% '1.02m' to '0.18m'. Table 6-18 shows summary of the objective functions before and after the second stage.

Table 6-18 Objective functions before and after the optimization of sub-compartments

Objective function		Manually	Optimized	Ratio
Feasibility index from expert system	Maximize	0.33	0.67	2.03
Distance between X position of CoG and x position of CoB	Minimize	1.02m	0.18m	0.18

6.3.3. Result of the optimization of equipment

As mentioned in Chapter.6.1.3, the main machinery, the sub-machinery, and the CIC were target of optimization. And the target were optimized individually.

The parameters used in the third stage was as follows. The population was set to '100', and optimization was performed to '4000' generations. SBX single point crossover was used to crossover operator, and the probability of crossover was '0.9'. Polynomial bit flip mutation was used to mutation operator, and the probability of mutation was '0.05'.

Selection operator was set to binary tournament. Table 6-19 is shown summary of the parameters.

Table 6-19 Parameters for the optimization of equipment

Parameter	Value
Population	100
Generation	4000
Crossover operator	SBX single point crossover
Crossover probability	0.9
Mutation operator	Polynomial bit flip mutation
Mutation probability	0.05
Selection operator	Binary tournament

Figure 6-10, Figure 6-11, and Figure 6-12 show the graph for showing the progress of the objective function and overall constraints violation value of each compartment or sub-compartments. Objective function was calculated by adding two objective functions normalized from ‘0’ to ‘1’ and defined in Chapter.4.4.3. In case of the main machinery, the objective function value was ‘1.48’ and the overall constraints violation value was ‘0’ after the optimization. In case of the sub-machinery, the objective function value was ‘1.30’ and the overall constraints violation value was ‘0’ after the optimization. And in case of the CIC, the objective function value was ‘1.05’ and the overall constraints violation value was ‘0’ after the optimization.

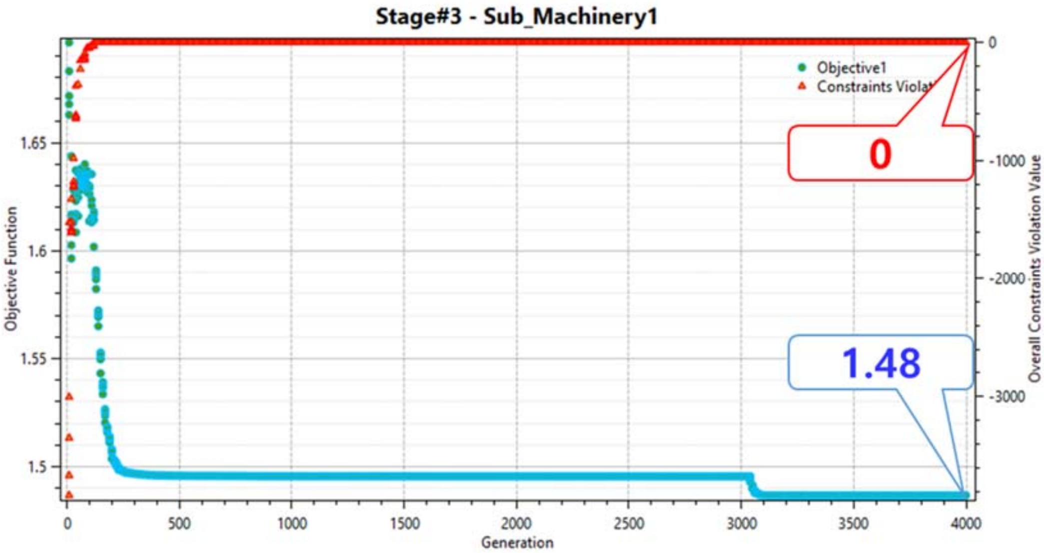

Figure 6-10 Progress of the objectives and overall constraints violation value while perform the third stage (main machinery)

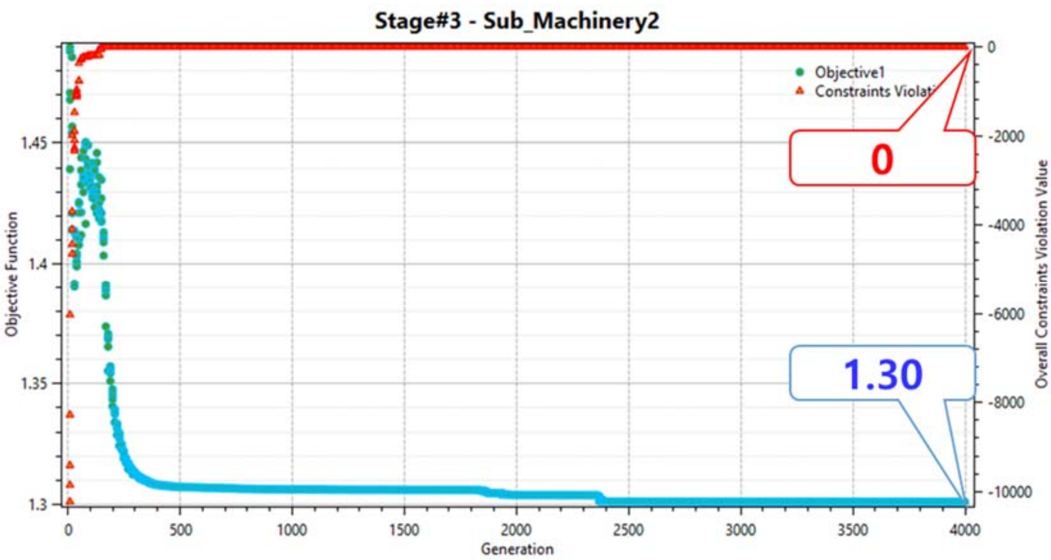

Figure 6-11 Progress of the objectives and overall constraints violation value while perform the third stage (sub machinery)

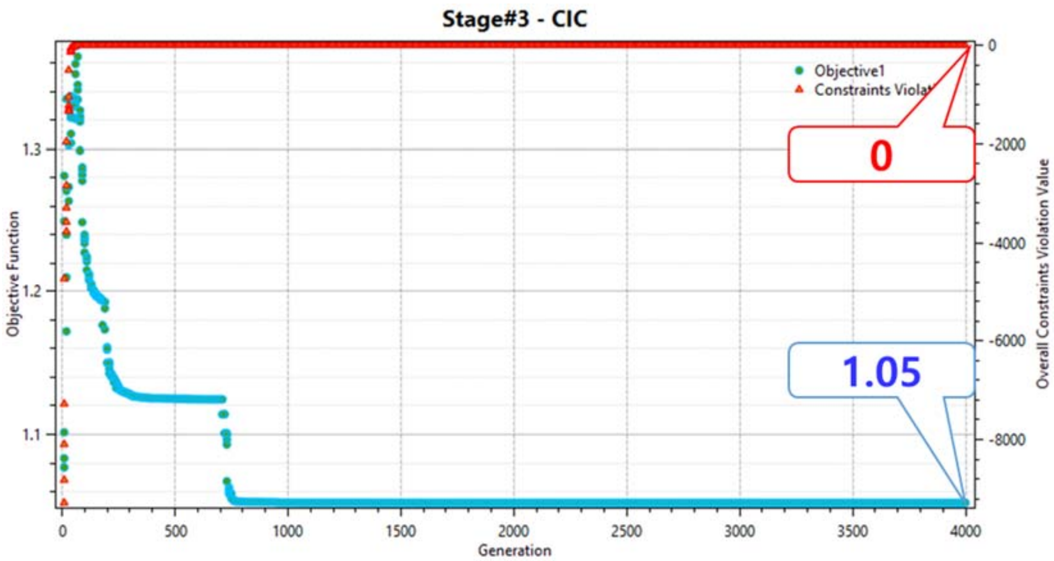

Figure 6-12 Progress of the objectives and overall constraints violation value while perform the third stage (CIC)

(1) Comparison of the design variables

- Design variables of the main machinery

Before and after the optimization of the main machinery, the design variables of the third stage were shown in Table 6-20. And then by using gene decoding, the results were shown like Figure 6-13.

Table 6-20 Design variables before and after the optimization of the main machinery

	Manually			Optimized		
Equipment	x_i	y_i	O_i	x_i	y_i	O_i
Polymer Electrolyte Membrane(PEM)	-4.23	0	0	-3.57	1.13	1
Oxygen tank	-4.23	0	0	-6.04	0.95	1
DC main switch board	-2.77	0.2	0	-3.11	-2.41	1
Power conversion module1	-1.7	-2.3	0	-2.35	-0.59	0
Power conversion module2	-1.7	2.4	0	-2.35	2.96	0
Motor control center	-1.7	-1.4	0	-6.34	-2.96	1
Lighting load panel	-1.7	2.1	0	-5.84	-2.96	1
DC/AC inverter controller	-6	0.1	0	-6.19	2.82	1
COH_2 burner	-2.7	-2.2	0	-2.36	-2.98	0
CO_2 scrubber	-2.7	-1.2	0	-2.86	-2.98	0

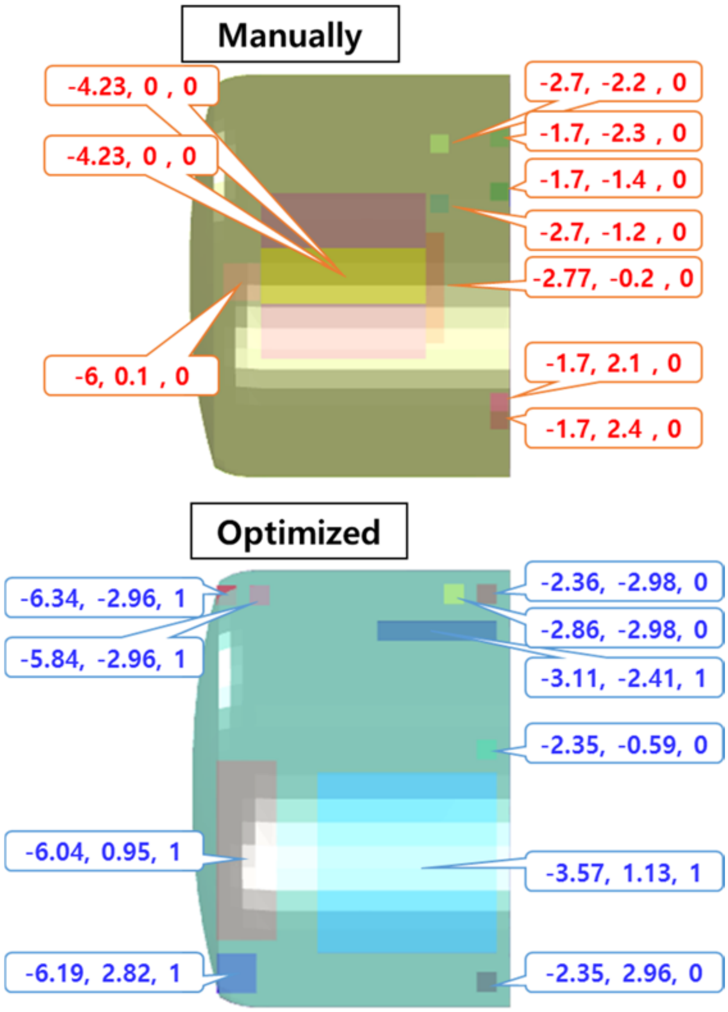

Figure 6-13 Before and after the optimization of the main machinery

- Design variables of the sub-machinery

Before and after the optimization of the sub-machinery, the design variables of the third stage were shown in Table 6-21. And then by using gene decoding, the results were shown like Figure 6-14.

Table 6-21 Design variables before and after the optimization of the sub-machinery

	Manually			Optimized		
Equipment	x_i	y_i	O_i	x_i	y_i	O_i
Regenerator1	-4.4	-2.1	0	-4.59	0.96	0
Regenerator2	-4.4	2.1	0	-5.09	2.38	0
High pressure air compressor	-2.6	-2.2	0	-3.77	-2.53	1
LP blower	-5.9	-0.2	0	-2.66	-2.53	0
Ventilation fan	-5.3	0.99	0	-2.35	-1.57	0
Induction mast inlet	-4.2	0.2	0	-2.35	2.83	0
Trim and drain pump1	-4.6	0.99	0	-6.31	1.42	1
Trim and drain pump2	-3.9	0.99	0	-6.16	-2.68	1
Seawater cooling pump1	-5.9	-1.18	0	-3.01	-1.57	1
Seawater cooling pump2	-4.98	-0.5	0	-6.31	0.76	0
Main hydraulic pump	-3.2	-0.99	0	-5.35	-2.84	1
Fresh water pump	-5.1	0.4	0	-2.51	2.33	1
Hydraulic pressure accumulator	-5.3	-1.18	0	-2.5	1.82	1
Trim accumulator	-4.7	-1.2	0	-6.31	-1.87	0

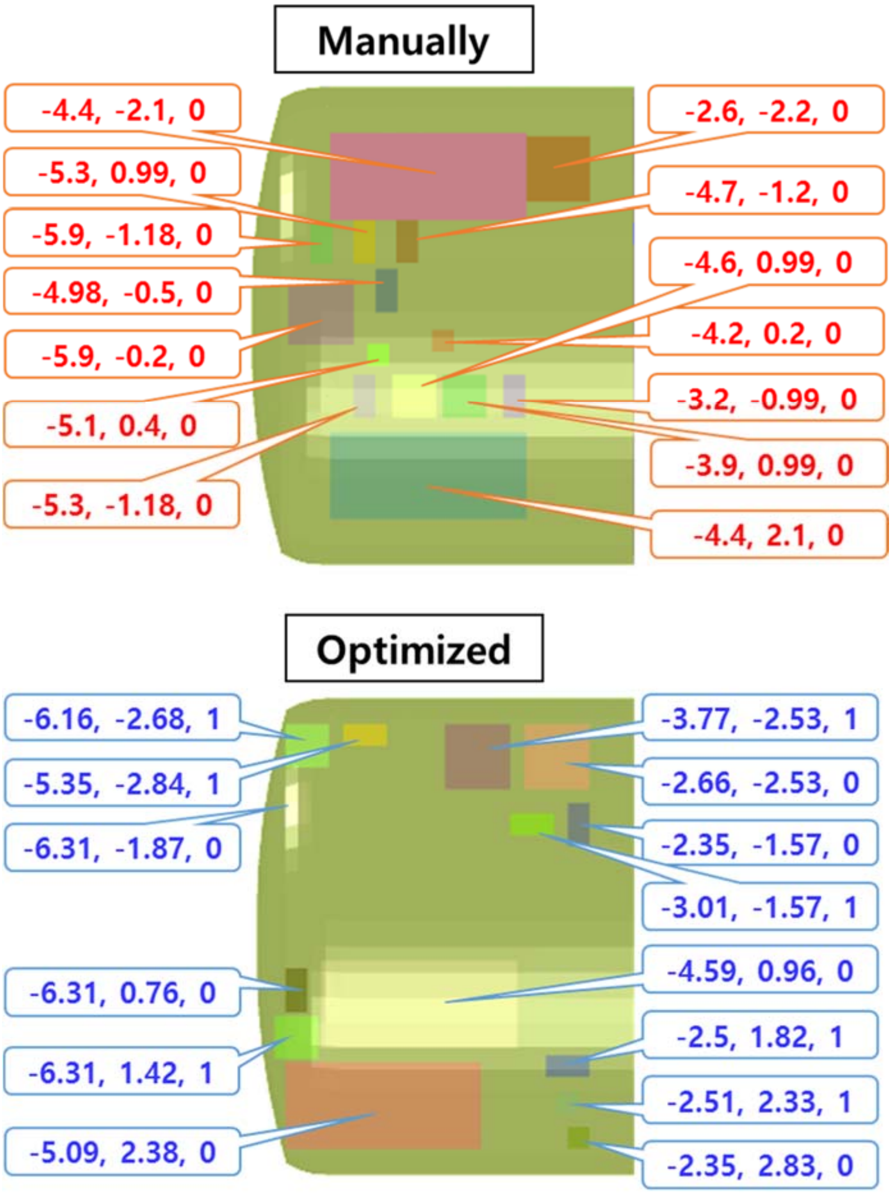

Figure 6-14 Before and after the optimization of the sub-machinery

- Design variables of the CIC

Before and after the optimization of the CIC, the design variables of the third stage were shown in Table 6-22. And then by using gene decoding, the results were shown like Figure 6-15.

Table 6-22 Design variables before and after the optimization of the CIC

	Manually			Optimized		
Equipment	x_i	y_i	O_i	x_i	y_i	O_i
Sonar control system1	-1.11	-2.5	0	-1.22	-2.39	0
Sonar control system2	-0.21	-2.6	0	3.29	-2.62	1
Sonar control system3	-1.31	-1.3	0	3.45	2.49	1
Command and surveillance1	2.25	-2	0	0.66	2.05	0
Command and surveillance2	2.25	2	0	1.34	-1.41	0
Command and surveillance3	0.79	0	0	2.84	0.86	1
Command and surveillance4	2.59	0	0	-0.84	0.69	1
Command and surveillance5	3.89	0	0	-0.84	-0.73	1

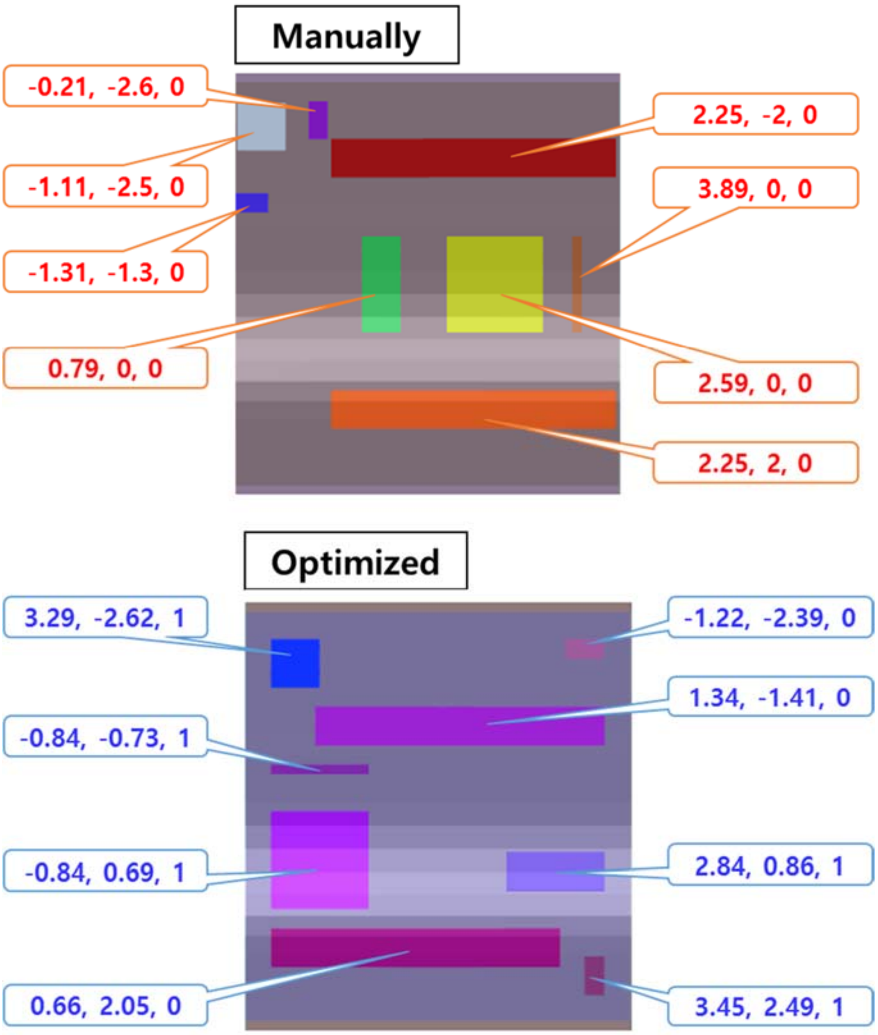

Figure 6-15 Before and after the optimization of the CIC

(2) Comparison of the objective functions

When optimize the arrangement of the equipment, adjacency index between equipment, and connection cost between equipment are calculated as the objective functions. The two objective functions were normalized from ‘0’ to ‘1’. The adjacency index was optimized towards maximize. And unit connection cost was optimized toward minimize.

After the optimization of equipment, the objective functions of the three compartment and sub-compartments were compared to before the optimization. In case of the main machinery, first objective function was improved by 7% ‘0.84’ to ‘0.90’. And second objective function was improved by 16% ‘0.66’ to ‘0.56’. In case of the sub-machinery, first objective function was improved by 46% ‘0.52’ to ‘0.76’. And second objective function was improved by 5% ‘0.84’ to ‘0.80’. And in case of the CIC, first objective function was improved by 45% ‘0.31’ to ‘0.45’. And second objective function was improved by 3% ‘0.61’ to ‘0.59’. Figure 6-15 shows summary of the objective functions before and after the third stage.

Table 6-23 Objective functions before and after the optimization of equipment

Objective function		Manually	Optimized	Ratio
Main machinery				
Adjacency index between equipment	Maximize	0.52	0.75	1.46
Connection cost between equipment	Minimize	0.84	0.80	0.95
Sub machinery				
Adjacency index between equipment	Maximize	0.31	0.45	1.45
Connection cost between equipment	Minimize	0.61	0.59	0.97
CIC				
Adjacency index between equipment	Maximize	0.84	0.90	1.07
Connection cost between equipment	Minimize	0.66	0.56	0.84

6.3.4. Comparison between the result and the example

As shown in Chapter.6.3.1, Chapter.6.3.2, and Chapter.6.3.3, the result of the optimization was better than the example arranged manually in terms of the objective functions., Table 6-24 is made by summing-up the all objective functions before and after the optimization of each stages. And the arrangement of the result and the example arranged manually can be confirm by using prototype program. It is shown in Figure 6-16.

Table 6-24 Summary of the objective functions before and after the optimization

Objective function		Manually	Optimized	Ratio
Stage #1				
Feasibility index from expert system	Maximize	0.64	0.75	1.17
Distance between X position of CoG and x position of CoB	Minimize	1.02m	0.63m	0.61
Z position of CoB	Minimize	1.95m	0.52m	0.27
Stage #2				
Feasibility index from expert system	Maximize	0.33	0.67	2.03
Distance between X position of CoG and x position of CoB	Minimize	1.02m	0.18m	0.18
Stage #3				
Main machinery				
Adjacency between each equipment	Maximize	0.52	0.75	1.46
Connection cost between each equipment	Minimize	0.84	0.80	0.95
Sub machinery				
Adjacency between each equipment	Maximize	0.31	0.45	1.45
Connection cost between each equipment	Minimize	0.61	0.59	0.97
CIC				
Adjacency between each equipment	Maximize	0.84	0.90	1.07
Connection cost between each equipment	Minimize	0.66	0.56	0.84

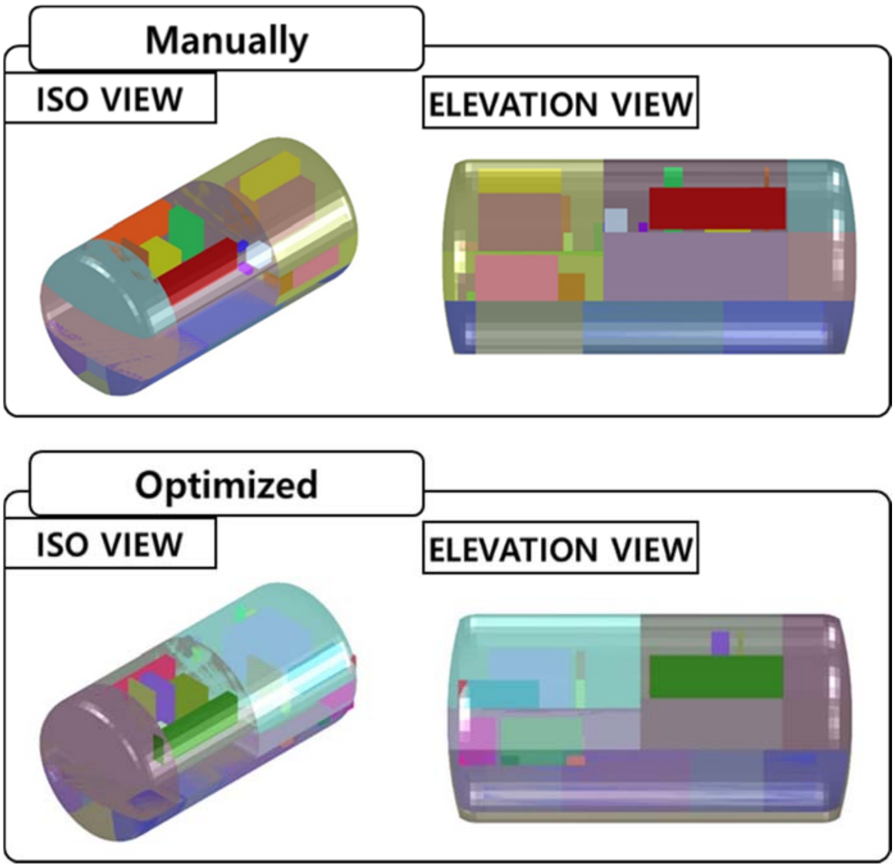

Figure 6-16 Arrangement of the submarine before and after the optimization

(1) Evaluate availability of the result of the optimization

As mentioned in Chapter.4.4.5, the alternative optimized using proposed method should be checked whether the submarine can operate in underwater. Therefore, in this study, the equilibrium polygon and the stability were evaluated to check the availability.

- Equilibrium polygon

The equilibrium polygon is the criterion of the weight and moment change of the submarine. As shown in Figure 6-17, the equilibrium polygon before and after the optimization both satisfy. But in the optimization procedure, there are no consideration for the equilibrium polygon, so that the shape of the equilibrium polygon after the optimization was little dented despite of satisfying.

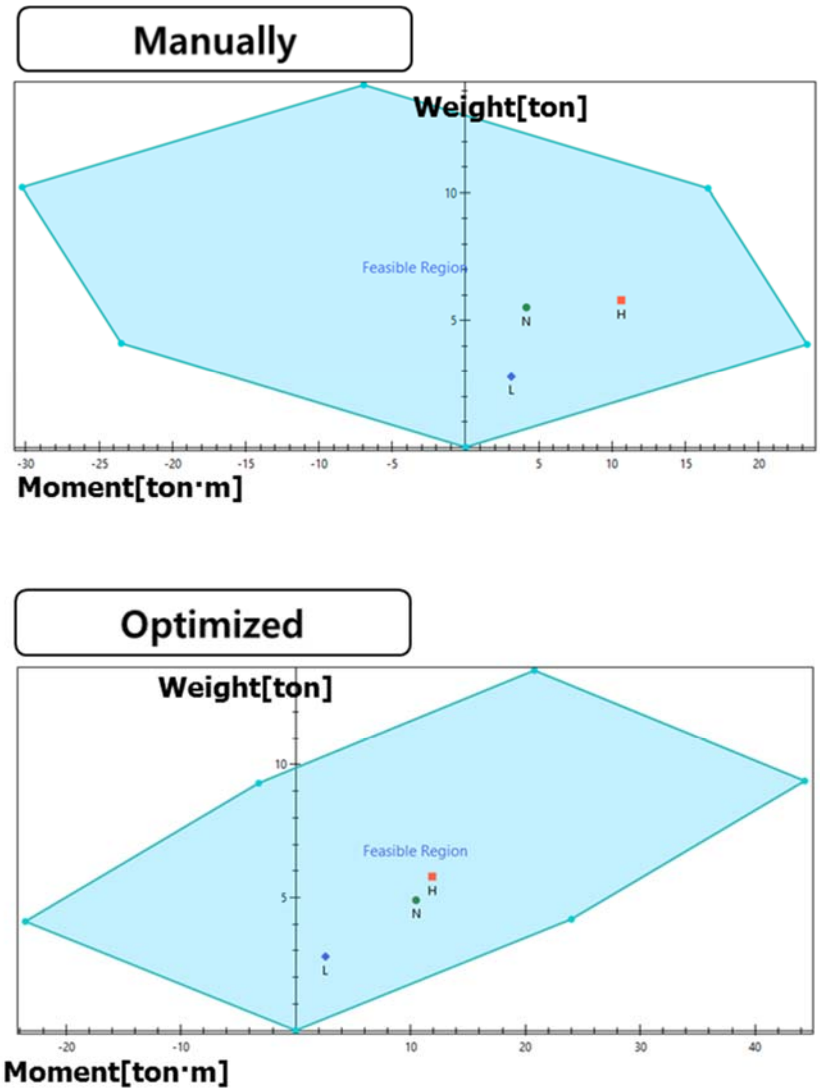

Figure 6-17 Equilibrium polygon before and after the optimization

- Stability

Stability is criteria of the safety for incline the submarine when operate in underwater condition or surface condition. In this study, two cases regulated by U.S. navy (normal condition, and full loading condition) were checked to confirm the stability. In two cases, GB, transverse GM, and longitudinal GM for surface condition, and GB for submerged condition were calculated. Table 6-25 shows comparison of the stability before and after the optimization.

In both cases, the stability satisfy. In the optimization process, distance between X position of CoG and X position of CoB, and distance between keel and CoG were considered. So, as distance between X position of CoG and X position of CoB is shorten, longitudinal GM was increased drastically. And GB was also increased slightly.

Table 6-25 Stability before and after the optimization

		Manually		Optimized	
	Criteria	Normal condition	Full loading condition	Normal condition	Full loading condition
$\boldsymbol{GB_{surface}}$	-0.6m	-0.59m	-0.57m	-0.59m	-0.55m
$\boldsymbol{GM_T}$	0.5m	0.57	0.56	0.60	0.56
$\boldsymbol{GM_L}$	0.5m	0.79	0.69	1.25	1.19
$\boldsymbol{GB_{submerged}}$	0.2m	0.28	0.28	0.29	0.28

7. Conclusions and future works

In this study, the expert system was adopted to evaluate arrangement of a submarine. For the expert system, the methodology which systematize the experts' knowledge about arrangement of a submarine, and used when absence the experts or previous ship data was proposed. By using AEM to existing rule-based expert system, user could easily defined various experts' knowledge.

For optimize arrangement of a submarine, multi-stage optimization of arrangement of a submarine was proposed. The optimization problems were consisted of three parts; the optimization of compartment, the optimization of sub-compartments, and the optimization of equipment. In the optimization problems, experts' knowledge were considered by adopting expert system, so that it could deduct realistic alternatives against the existing methods.

And the method proposed in this study was adopted to arrange the example arranged by U.S. navy. As adopted to the example, availability of the methods was proved.

However, AEM cannot handle the all knowledge for arrangement of a submarine. Therefore, it is expected that AEM will be improved for handle the other various knowledge.

And the example arranged by U.S. navy was simple as compared with the other submarines operated by actual navy. So, in the future, the proposed method will be adopted to the realistic examples. And by adopting, the proposed method will be validated. Also, the availability of the proposed method will be improved.

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APPENDICES

A. Weight information of the example

the LCG is taken about the center of buotancy at a distance 21946mm from aft

SWBS	component	wt-ton	vcg-mm	moment(ton-mm)	lcg-mm	moment(ton-mm)	tcg-mm	moment(ton-mm)
	full load weight+margin	783.55	-288.36	-225945.40	140.14	109809.84	-2.77	-2166.68
	lightship weight+margin	612.54	-312.61	-191484.87	-36.92	-22614.15	-0.09	-54.69
	lightship weight	576.17	-130.74	-75331.54	-415.51	-239404.14	0.67	388.64
	margin	36.36	-3194.30	-116153.33	5961.89	216789.99	-12.19	-443.33
100	**hull structures**	**316.50**	**-15.77**	**-4991.99**	**2065.16**	**653631.20**	**0.00**	**0.00**
110	shell+support	180.36	0.00	0.00	3048.00	549738.26	0.00	0.00
120	pressure hull structural hulkhds	81.70	0.00	0.00	762.00	62252.78	0.00	0.00
140	pressurehull platforms/flats	6.30	-792.48	-4991.99	762.00	4799.99	0.00	0.00
150	conning tower	0.19	0.00	0.00	1545.34	298.31	0.00	0.00
160	special structures	3.90	0.00	0.00	762.00	2972.90	0.00	0.00
180	foundations	40.22	0.00	0.00	762.00	30650.26	0.00	0.00
190	special purpose systems	3.83	0.00	0.00	762.00	2918.70	0.00	0.00
200	**propulsion plant**	**126.27**	**-1010.23**	**-127560.52**	**-5059.98**	**-638915.88**	**0.00**	**0.00**
220	main propulsor	57.30	-2316.48	-132739.86	3002.28	172037.85	0.00	0.00
230	propulsion units	10.47	457.20	4789.15	-3505.20	-36716.83	0.00	0.00
240	propulsion power transmission	37.57	0.00	0.00	-21031.20	-790177.52	0.00	0.00
250	support systems, uptakes	20.07	0.00	0.00	762.00	15290.29	0.00	0.00
290	special purpose systems	0.85	457.20	390.19	762.00	650.32	0.00	0.00
300	**electric plant, general**	**28.84**	**364.12**	**10502.69**	**-2636.43**	**-76045.78**	**0.00**	**0.00**
310	electric power generation	22.39	457.20	10237.92	-3505.20	-78490.68	0.00	0.00
320	electrical distribution system	4.94	0.00	0.00	762.00	3762.57	0.00	0.00
330	lighting system	0.93	0.00	0.00	762.00	712.26	0.00	0.00
340	powergeneration support system	0.54	457.20	246.19	-3505.20	-1887.48	0.00	0.00
390	special purpose systems	0.04	457.20	18.58	-3505.20	-142.45	0.00	0.00
400	**command+surveillance**	**16.64**	**1829.26**	**30442.75**	**3073.87**	**51155.51**	**0.00**	**0.00**
420	navigation systems	1.52	1929.38	2940.38	3200.40	4877.41	0.00	0.00
430	interior communications	1.31	1929.38	2528.73	3200.40	4194.57	0.00	0.00
440	exterior communications	0.97	1929.38	1862.24	3200.40	3089.03	0.00	0.00
450	surf surveillance system(radar)	0.93	1929.38	1803.43	3200.40	2991.48	0.00	0.00
460	underwater surveillance system	10.38	1929.38	20033.80	3200.40	33231.42	0.00	0.00
480	fire control systems	0.86	0.00	0.00	762.00	658.06	0.00	0.00
490	special purpose systems	0.66	1929.38	1274.17	3200.40	2113.54	0.00	0.00

500	**auxiliary system, general**	**46.64**	**189.30**	**8829.78**	**-6132.59**	**-286051.77**	**0.00**	**0.00**
510	climate control	5.04	0.00	0.00	762.00	3839.99	0.00	0.00
520	sea water systems	0.17	0.00	0.00	762.00	131.61	0.00	0.00
530	fresh water systems	1.68	-1219.20	-2043.87	7010.40	11752.23	0.00	0.00
540	fuels/lubricants, handling+stowage	0.58	396.24	229.47	3200.40	1853.42	0.00	0.00
550	air,gas+misc fluid system	16.99	0.00	0.00	762.00	12944.49	0.00	0.00
560	ship control system	14.30	0.00	0.00	-20046.70	-286569.92	0.00	0.00
580	anchor, mooring, handeling+stowage	2.38	0.00	0.00	-20046.70	-47659.82	0.00	0.00
590	environmental+aux system	5.52	1929.38	10644.18	3200.40	17656.22	0.00	0.00
600	**outfit+furnishing, general**	**37.64**	**31.75**	**1195.23**	**907.57**	**34163.54**	**10.32**	**388.64**
610	ship fittings	0.87	0.00	0.00	762.00	665.81	0.00	0.00
620	hull outfit	0.73	0.00	0.00	762.00	557.42	0.00	0.00
630	personal outfit	15.59	0.00	0.00	762.00	11876.11	0.00	0.00
640	living spaces	0.74	-216.41	-160.51	4876.80	3617.03	609.60	452.13
650	commissary+laundry spaces	0.07	-228.60	-16.26	4876.80	346.84	-1676.40	-119.23
660	control station furnishings	0.72	1929.38	1391.78	3200.40	2308.64	0.00	0.00
670	lockers+special storage	0.09	-216.41	-19.79	4876.80	445.93	609.60	55.74
690	marine+hull outfitting	18.83	0.00	0.00	762.00	14345.78	0.00	0.00
700	**armament**	**3.63**	**1723.27**	**6250.52**	**6247.12**	**22659.05**	**0.00**	**0.00**
750	torpedoes handling	3.54	1767.84	6250.52	6400.80	22631.18	0.00	0.00
760	seals	0.09	0.00	0.00	304.80	27.87	0.00	0.00
	full load condition							
f00	loads	151.17	0.00	0.00	762.00	115192.03	0.00	0.00
f10	ship personnel	1.85	0.00	0.00	762.00	1409.03	0.00	0.00
f31	provisions+personnel stores	0.91	-228.60	-209.03	2438.40	2229.67	-1676.40	-1532.90
f32	general stores	0.35	-228.60	-78.97	2438.40	842.32	-1676.40	-579.10
f47	sea water	2.18	-2042.16	-4460.89	762.00	1664.51	0.00	0.00
f52	fresh water	14.55	-2042.16	-29711.63	762.00	11086.43	0.00	0.00

B. Capacity information of the example

Requirement	Area(m2)	Volume(m3)	Volume Percent	Hull Env Volume %	P Hull Volume %
$A_{COberth\&san}$		10.19	1.05	1.13	2.18
$A_{offberth\&san}$		28.88	2.99	3.19	6.17
A_{offwr}		6.80			
A_{offhab}		45.87			
A_{galley}		10.19			
$A_{crewmess}$		6.80			
$A_{crewberth}$		20.22			
$A_{crewsanitary}$		9.23			
$A_{crewhab}$		46.43	4.8	5.13	9.92
A_{hab}		92.31	9.54	10.19	19.73
V_{stores}		10.19	1.05	1.13	2.18
A_{p4}		29.34	3.03	3.24	6.27
A_{cont}		44.94	4.65	4.96	9.6
A_{7}		12.26	1.27	1.35	2.62
A_{sf}		54.93	5.68	6.07	11.74
A_{ops}		141.47	14.62	15.62	30.23
V_{2fuel}		15.57	1.61	1.72	3.33
V_{2ox}		25.68	2.65	2.83	5.49
V_{lo}		1.73	0.18	0.19	0.37
V_{w}		2.49	0.26	0.28	0.53
V_{sew}		0.91	0.09	0.1	0.19
$V_{aux\&trim}$		28.97	3	3.2	6.19
V_{tk}		75.35	7.79	8.32	16.1

V_{pib}	10.476862	17.08	1.77	1.89	3.65
A_{phmarg}	9.5244197	22.34	2.31	2.47	4.77
$A_{phpassage}$		16.82	1.74	1.86	3.6
$V_{battery}$		21.72	2.24	2.4	4.64
V_{mb}		69.63	7.2	7.69	14.88
$V_{machroom}$		131.81			
$V_{auxmach}$		34.77	3.59	3.84	7.43
V_{ph}		501.66	51.86	55.39	107.21
V_{pim}		108.74		12.01	
V_{pob}		12.15		1.34	
$V_{pobtotal}$		120.88		13.35	
V_{prop}		15.23		1.68	
V_{sailob}		13.82		1.53	
V_{miscob}		90.16		9.95	
V_{ob}		240.10		26.51	
V_{eb}		741.76		81.89	
$V_{mbt\ aft}$		241.68			
$V_{mbt\ forw}$		310.15			
V_{mbt}		364.21		40.21	
V_{sub}		1105.94		122.1	
$V_{bareHullenv}$		1003.15		110.76	
V_{sailob}		58.79			
V_{envtot}		1077.17			
V_{ff}		-28.77		-3.18	

C. Variable loads of the example

Variable Load Items for Each Condition

		Normal Condition			Light #2			Heavy #2		
Group	**Item**	**Weight**	**Distance from LCB**	**Moment**	**weight**	**Distance from LCB**	**Moment**	**weight**	**Distance from LCB**	**Moment**
1	Crew and effects	1.72	2.50	4.30	1.72	2.50	4.30	1.72	2.50	4.30
	Sanitary tanks	0.00	21.00	0.00	0.00	21.00	0.00	0.07	21.00	1.47
	Sanitary Flush Waste	0.96	21.00	20.16	0.96	21.00	20.16	0.96	21.00	20.16
	Residual water	0.55	-24.67	-13.57	0.00	-24.67	0.00	0.55	-24.67	-13.57
	Nitrogen	0.23	2.50	0.58	0.23	2.50	0.58	0.23	2.50	0.58
	Oxygen candles	0.13	-11.15	-1.45	0.13	-11.15	-1.45	0.13	-11.15	-1.45
2	Potable Water	0.82	5.07	4.16	0.41	5.07	2.08	0.82	5.07	4.16
3	Provisions	0.46	8.00	3.68	0.00	8.00	0.00	0.46	8.00	3.68
	General Stores	0.17	8.00	1.36	0.00	8.00	0.00	0.17	8.00	1.36
	Oxygen candles	0.13	-11.15	-1.45	0.00	-11.15	0.00	0.13	-11.15	-1.45
4	Lubricating oil in storage	1.50	-10.00	-15.00	0.75	-10.00	-7.50	1.50	-10.00	-15.00
5	Torpedoes	3.39	25.00	84.75	0.00	25.00	0.00	3.39	25.00	84.75
6	Passengers	1.29	2.50	3.23	0.00	2.50	0.00	1.29	2.50	3.23
	Total and CG's	11.35	7.99	90.74	4.20	4.32	18.16	11.42	8.07	92.21

국문 초록

전문가 시스템 기반 잠수함 구획 및 장비의 최적 배치 설계

잠수함의 배치 설계를 진행함에 있어서 실적선 자료와 전문가의 경험이 매우 중요하다. 각 나라별로 잠수함 배치 설계 철학이 다르고, 새로운 잠수함을 설계할 때 실적선의 자료를 참고하여 전문가들이 변경해야 할 부분만 수정하는 방향으로 설계를 진행하기 때문이다. 따라서 실적선 자료가 부족하거나, 전문가가 부재할 경우, 잠수함의 배치 설계 과정이 지연될 수 있다. 또한, 잠수함에서는 다양한 구획 및 장비를 내압 선체라는 한정된 공간 내에 배치하여야 하고, 다양한 배치 안 중에서 최적의 배치 안을 선정하여야 하기에, 잠수함의 배치 설계 문제는 풀기가 그리 쉽지 않다. 그러므로 실적선 자료와 전문가의 경험 그리고 다양한 설계 규정들을 체계화하여 축적할 필요가 있고, 짧은 시간 내에 다수의 대안을 검토함으로써 보다 나은 결과를 도출할 수 있는 잠수함의 최적 배치 설계에 대한 요구가 꾸준히 증가하고 있다.

이를 위해, 본 논문에서는 전문가 시스템 기반 잠수함의 구획 및 장비의 최적

배치 설계 방법을 연구하였다. 첫 번째로, 전문가의 지식을 표현하거나, 잠수함 배치 최적화 과정에서의 다양한 변수를 표현하기 위해 '잠수함 배치 템플릿 모델'을 설계하였다. 두 번째로, 전문가의 지식과 경험, 다양한 설계 규정을 체계화하여 컴퓨터에 저장, 활용할 수 있도록 전문가 시스템을 개발하였다. 세 번째로, 전문가 시스템을 활용하여 다양한 잠수함 배치 설계 안 중에서 최적의 대안을 찾아낼 수 있는 최적화 문제를 정식화 하였다.

본 논문에서 제시한 방법의 유효성을 검증하기 위해, 잠수함 배치 템플릿 모델, 전문가 시스템 모듈, 최적화 모듈과 사용자 인터페이스로 구성된 프로토타입 프로그램을 개발하였다. 그리고 프로토타입 프로그램을 이용해 미 해군 700 톤급 잠수함 배치 설계에 본 논문에서 제시한 방법을 적용해 보았다. 그 결과, 본 논문에서 제시한 방법이 잠수함의 배치 설계를 진행하는데 있어 하나의 새로운 방법이 될 수 있다는 가능성을 발견하였다.

Keywords: 배치 설계, 최적화, 전문가 시스템, 잠수함

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