공학박사 학위 논문

Optimal Arrangement Method of Equipment and Pipes in the Engine Room of a Ship

선박의 기관실 배치 자동화를 위한 장비 및 배관
최적 배치 방법

2023년 8월

서울대학교 대학원
조선해양공학과
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2023년 07월

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Abstract

Optimal Arrangement Method of Equipment and Pipes in the Engine Room of a Ship

The arrangement design of a ship's engine room must consider various factors, including interference from equipment and pipe located in the engine room, design rules, previous ship data, and expert knowledge. The arrangement design process for ships with many complex and customary areas relies on previous ship data and experts' design experience or know-how. During the pipe routing design process, pipe routing relies on experts' design experience and know-how. In order to complement the pipe routing of ships that rely on experts, this study propose a pipe routing optimization method by constructing an expert system that can systematize expert knowledge and combine it with optimization techniques. An Arrangement Template Model is constructed to represent the data structure, and an Arrangement Evaluation Model is used to evaluate the expert knowledge of real experts and computerize it systematically. The optimal arrangement results evaluated by the Arrangement Evaluation Model are used as the objective function of the optimization problem. For deriving an optimized design proposal by reviewing multiple designs in a short time, the optimization technique is combined with the expert system, and the optimization problem is formulated using it.

This study proposes a two-stage optimization method to perform the optimal arrangement design for the engine room effectively. The 1st stage performs the optimal arrangement of the deck's height and the equipment's location and orientation. In the 1st stage, objective functions are set to minimize the volume occupied by the equipment arranged in the engine room, minimize the length and bends of pipes and ducts, maximize the space availability, and maximize the feasibility of expert knowledge. In particular, to consider the results of the pipe routing design in the 1st stage, the optimal arrangement method is proposed that can consider pipe routing results together during the equipment arrangement stage of the ship. In addition, to effectively utilize the expert's knowledge and experience in the arrangement design, an expert system is used to calculate the feasibility of the expert's knowledge. As constraints, the installation availability of the equipment and a subset of the expert knowledge are considered. Various global optimization methods were compared for the optimization algorithm, and the most suitable algorithm to perform the optimal arrangement was selected.

The 2nd stage optimizes the routing of the pipes and ducts connecting the arranged equipment. In each step, the objective function is set to minimize the volume occupied by the equipment arranged in the engine room, minimize the length and bends of pipes and ducts, maximize the space availability, and maximize the feasibility of expert knowledge. As a route generation algorithm in the 2nd stage, various route generation algorithms were examined, and the Jump Point Search (JPS) algorithm was utilized to perform pipe routing in this study. To verify the effectiveness of the proposed method, the optimal layout of the

engine room of a 320,000-ton deadweight very large crude carrier (VLCC) was performed. The results showed that the proposed method could derive the optimal arrangement for the decks, equipment, and pipes inside the ship's engine room.

In future work, to improve the limitations of this study, which considers only major equipment, additional arrangement designs for equipment other than the major equipment will be considered. In the pipe routing process, various optimization methods and route generation methods will be evaluated to improve the calculation time. In addition, pipe routing methods that consider various bending angles will be studied, and additional expert knowledge that considers the characteristics of each pipe (flow rate, branch pipes, etc.) will be further developed.

Keywords: Engine room arrangement, optimal arrangement, pipe routing, expert system, optimization technique, pathfinding algorithm

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Introduction

1.1. Research Background

Vessel equipment/pipe routing design involves many considerations, such as selecting necessary equipment, selecting equipment location and direction, and selecting pipe routing. Due to the many variables, there are various arrangement designs, and optimization techniques are required to examine multiple design alternatives. In addition, due to the characteristics of ship arrangement design, where there are various design rules and requirements, ship arrangement design relies on previous ship data, expert knowledge, and experience. These extensive considerations make designers perform rigid designs that rely on previous designs. It also makes it difficult for designers to attempt and review various designs. Also, in the absence of experts, design modifications and iterations occur due to incorrect designs. The description is shown in Figure 1.

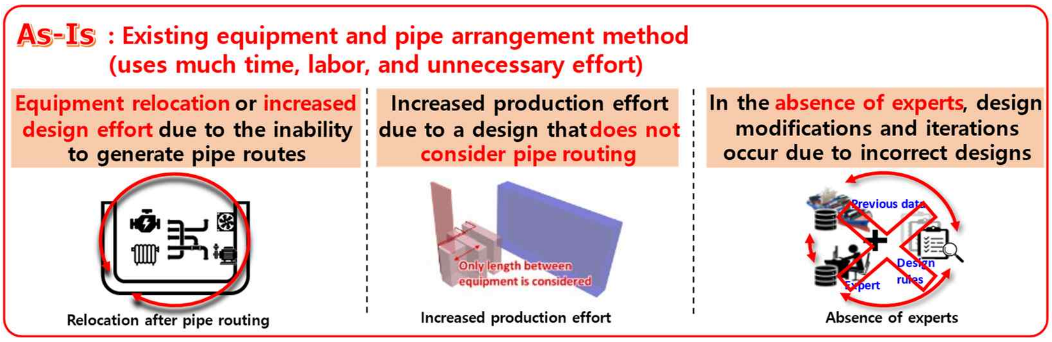


Figure 1. The necessity of the arrangement method

To improve the arrangement process, a system that can systemically express knowledge and experience and review various designs is required. In this study, an equipment and pipe arrangement method using a combination of optimization techniques and expert systems is proposed. In the optimal equipment arrangement process, to determine the position of decks and equipment, the occupied volume of the engine room, the length and the number of bends of pipes, space availability, and feasibility index by the expert system are set as objective functions. For estimating the length and number of bends of pipes, simplified pipe routing is performed. By performing simplified pipe routing in the equipment arrangement process, design modifications and iterations due to incorrect designs could be reduced. The description is shown in Figure 2.

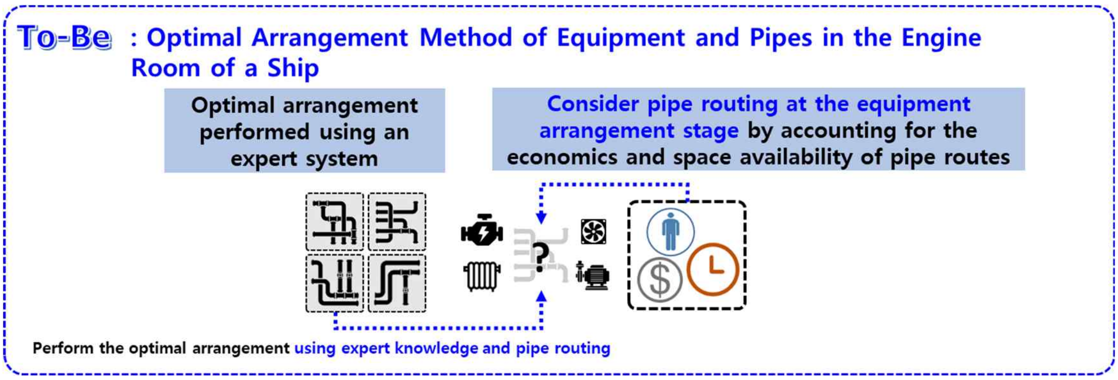


Figure 2. Improvement of the proposed arrangement method in this study

As for the optimization method, various global optimization algorithms are reviewed, and the most suitable method is selected for this study. In the pipe routing process, the nodes of pipes connecting the equipment determined in the previous process are constructed, and the objective functions are set as the total length of pipe routes, total number of bends, space availability, and the feasibility index for expert knowledge. As in the equipment arrangement process, pipe routing utilizes an expert system to apply a feasibility index for expert knowledge. For route generation, the most appropriate method for this study is selected to perform pipe routing. In this process, various methods are applied to perform pipe routing with appropriate speed and accuracy. The design area is proposed considering the space availability, and the dynamic grid method is utilized to improve the calculation speed of the grid-based pathfinding method. The entire arrangement process is summarized in Figure 3.

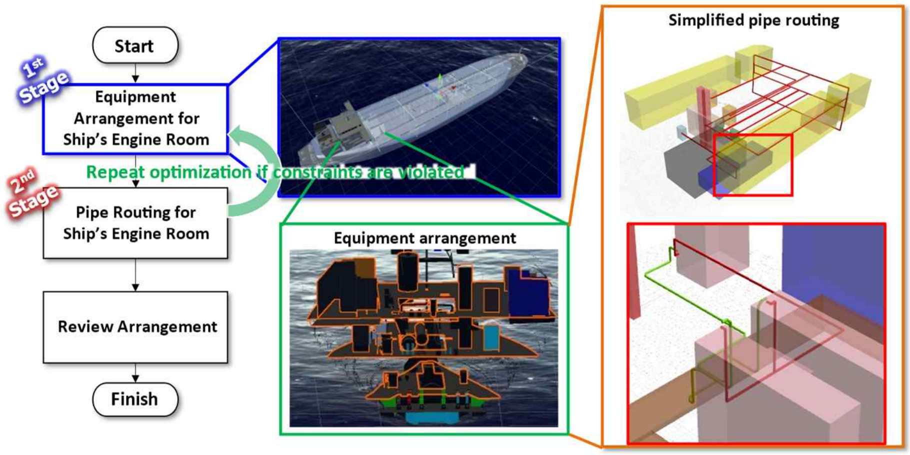


Figure 3. Arrangement process in this study

There are too many considerations and time to perform the equipment arrangement and pipe routing in the engine room at one time, which is the scope of this study. To improve the calculation speed of the arrangement design, decks, equipment, and pipes in the engine room are arranged through 2 stages. And to consider pipe rerouting in the 1st stage, a simplified version of pipe routing is performed in the 1st stage. However, the two-stage optimization method means that the optimization results may be different from the result calculated in a single stage. Therefore, if a constraint is violated in the 2nd stage, the 1st stage of the optimal arrangement is repeated again. With the proposed method, the designer will be able to present an optimized arrangement design. It is expected that the proper early-stage design, presented through this method, could reduce the production cost of the ship. (Shao et al., 2009).

1.2. Related Works

Related studies on ship arrangement and expert knowledge used in this study are classified into related works on arrangement design for a ship using expert knowledge, equipment arrangement for a ship, and pipe routing for a ship. There are several previous studies that have applied expert knowledge to ship arrangements. Kim and Roh (2016) performed optimal bulkhead arrangement and equipment arrangement using an expert system for a submarine. The study is significant in that it carried out an optimal design using a standardized expert system based on expert knowledge. Kim et al. (2017) proposed an expert system to apply expert knowledge to offshore topside arrangements. Li et al. (2019) performed an optimal arrangement considering expert knowledge to optimize the performance and stability of the cabin equipment. Lee et al. (2021) performed the optimal arrangement of equipment considering expert knowledge to maximize the coverage of the ship's firefighting equipment. The bulkheads and equipment arrangement inside the engine room were performed together, and pipe routing was performed together. In addition, in order to systematize expert knowledge and apply it, an expert system was used together to perform an optimal arrangement.

In order to improve previous studies, this study performed bulkheads and equipment arrangement inside the engine room together and performed pipe routing together. In addition, in order to systematize expert knowledge and apply it, an expert system was used together to perform an optimal arrangement. Table 1 summarizes studies that graft expert knowledge to vessel arrangement design.

Table 1. Comparison between related studies on arrangement design for ships using expert knowledge and this study

Studies	Target	Variables to consider	Bulkheads arrangement	3D equipment arrangement	Pipe routing	Expert knowledge	Optimization (method)
Kim et al. (2016)	Submarine	Design area and piping costs	O	O	△	O	O (GA)
Kim et al. (2017)	Offshore topside	Expert knowledge	X	X	X	O	X
Li et al. (2019)	Cabin equipment	Performance and stability	X	X	X	△	O (SLP, GA)
Lee et al. (2021)	Firefighting equipment	Coverage of equipment	X	X	X	△	O (MIDS)
This study	320K VLCC	Piping costs and space availability	O	O	O	O	O

There are various previous studies that have performed the optimal arrangement of equipment on ships. Li et al. (2019) performed an optimal arrangement considering expert knowledge to optimize the performance and stability of the cabin equipment. Gunawan et al. (2021) performed the optimal equipment arrangement for the ship's engine room. They optimized the locations of the equipment for each deck, and the piping cost considering the height of the deck was calculated and used as the objective function. Table 2 summarizes studies related to equipment arrangement design for a ship.

Table 2. Comparison between related studies on arrangement design for and this study

Studies	Target	Variables to consider	3D arrangement	Pipe routing	Expert knowledge	Optimization (method)
Li et al. (2019)	Cabin equipment	Performance and stability	X	X	△	O (SLP, GA)
Gunawan et al. (2021)	Ship equipment	Piping cost	△	△	X	O (GA)
Lee et al. (2021)	Firefighting equipment	Coverage of equipment	X	X	△	O (MIDS)
Wang and Chen (2021)	Underwater detection ship	Adjacency and cost	X	△	X	O (GA)
Louvros et al. (2022)	Cruise ship	Adjacency, evacuation flow and sound pollution	X	X	X	O (GA)
This study	320K VLCC	Piping costs and space availability	O	O	O	O (Global optimization algorithm)

Various studies have been conducted on optimal pipe routing. Kimura and Ikehira (2009) performed pipe routing to minimize the piping costs and maximize the valve operationality. They considered the valve accessibility and feasibility of valve handling while calculating the valve operationality. Furuholmen et al. (2010) attempted to develop an optimal pipe route by minimizing the pipe length and the number of bends using a genetic algorithm (GA). Ando and Kimura (2011) performed pipe routing using the Dijkstra algorithm to minimize the pipe length, bends, and elbows. They performed tests by varying the diameter of the target pipe and verified that the proposed method could generate a path with minimal pipe bends and elbows. Jiang et al. (2015) used an ant colony optimization algorithm to generate optimal pipe routes to maximize space availability. As considered in previous studies, space availability is an index that evaluates the efficiency with which the space in which pipes are installed is used. Most studies have evaluated the space availability because pipes need to be close to the wall or equipment. Lee et al. (2019) generated an optimal pipe route by minimizing the pipe length and number of bends and maximizing the space availability using Dijkstra algorithm. Dong and Bian (2020) proposed the A*–GA Router algorithm. It combines the A* algorithm and GA to perform pipe routing in complex environments on a ship. They applied this method to pipe routing for a ship's fuel piping system and demonstrated that it could be improved compared with other existing methods. Gunawan et al. (2022) performed pipe routing in an engine room using Dijkstra algorithm, considering the piping cost. To consider the design procedure in conjunction, they used a GA to determine the best design procedure. Recently, research on pipe routing using reinforcement learning has been conducted. Shin et al. (2020) attempted to generate an optimal pipe route using reinforcement learning. They performed pipe routing for seven pipelines in a ship's engine room. Kim et al. (2023) proposed a method capable of frequent pipe-routing modifications using curriculum-learning-based reinforcement learning. They verified that the proposed method enables fast pipe routing compared to existing pathfinding algorithms. A comparison between studies related to pipe routing and this study is summarized in Table 3.

Table 3. Comparison between related studies on pipe routing and this study

Study	Considerations	Method for pipe routing
Kimura and Ikehira (2009)	Piping cost, valve operationality	Genetic algorithm
Furuholmen et al. (2010)	Pipe length, number of bends	Genetic algorithm
Ando and Kimura (2011)	Pipe length, number of bends	Dijkstra algorithm
Jiang et al. (2015)	Space availability	Ant colony algorithm
Lee et al. (2019)	Pipe length, number of bends, space availability	Dijkstra algorithm
Shin et al. (2020)	Pipe length, number of bends, space availability	Reinforcement learning
Dong and Bian (2020)	Pipe length, number of bends, space availability, sharing racks	A*–GA Router algorithm
Gunawan et al. (2022)	Piping cost, design procedure	Dijkstra algorithm
Kim et al. (2023)	Pipe length, number of bends	Reinforcement learning
This study	Pipe length, number of bends, space availability, feasibility index	Route generation algorithm

Most of the previous studies aimed to minimize the pipe length and the number of bends to minimize the piping costs. In addition, certain studies used valve operationality or space availability as additional objective functions. In this study, we proposed a method for optimal pipe routing based on the arrangement template model (ATM), arrangement evaluation model (AEM; e.g., expert system), and arrangement optimization model (AOM).

1.3. Configuration of the Study

The configuration of the proposed method for the optimal arrangement of equipment and pipes is illustrated in Figure 4.

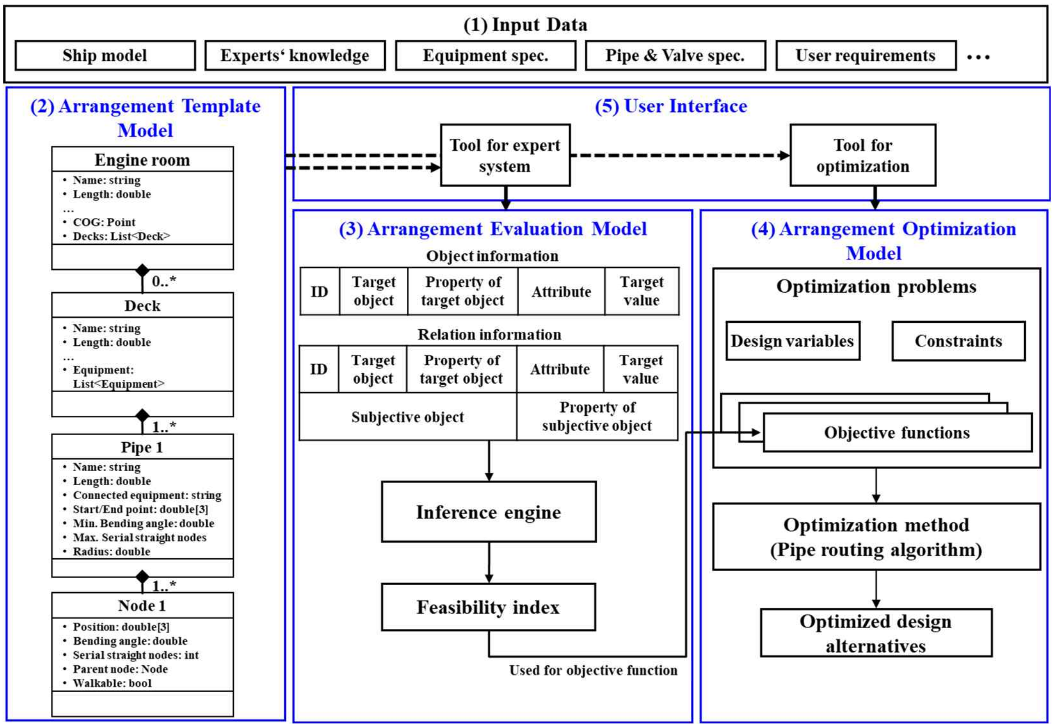


Figure 4. Configuration of this study

This study aimed to perform the optimal equipment arrangement and pipe routing for ship's engine room using an expert system and optimization technique. Figure 4 shows the configuration of the proposed method for pipe routing. The proposed method consists of an ATM (Figure 4 (2)), an AEM (Figure 4 (3)), an AOM (Figure 4 (4)), and a user interface (Figure 4 (5)).

In the process of the arrangement, data such as the ship model, expert knowledge, equipment specifications, and pipe and valve specifications are input through the user interface (Figure 4 (1)). The input data are stored according to the template in the ATM. Using this data, the AEM calculates the feasibility index of the proposed design. The objective functions of each design alternative in the AOM are evaluated using the calculated feasibility index. The optimized design alternatives are calculated based on the evaluated results. Each component is described in detail in Section 2. Section 3 describes the simulations performed on an example to verify the design variables and objective functions for optimization and the proposed expert system. Section 4 describes the application of the proposed method to actual examples to obtain optimal design alternatives. Finally, Section 5 summarizes the observations and discusses future work.

2. Theoretical Background

This study consists of the expert system for the arrangement of the ship's engine room, equipment arrangement for the ship's engine room, and pipe routing for the ship's engine room. Figure 5 expresses the configuration of this study.

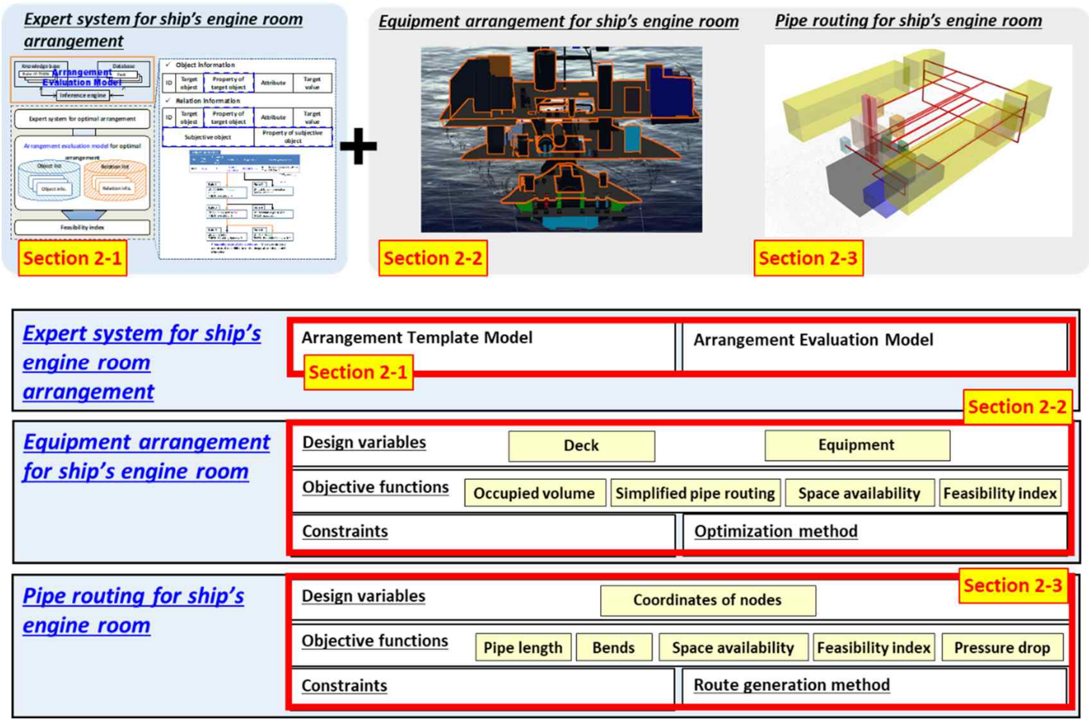


Figure 5. The theoretical background of this study

As shown in Figure 5, Section 2-1 describes the expert system for the ship's engine room arrangement. The section introduces a template for expressing an arrangement so that an expert system can be applied and an evaluation model that expresses and evaluates information about various rules, expert knowledge, and previous ship data according to defined rules. Section 2-2 describes the equipment arrangement for the ship's engine room, including design variables, objective functions, etc. The section introduces the equipment arrangement method, which is the first step of a two-step arrangement, introducing the problem formulated for optimal equipment arrangement and describing the reasons for selecting design variables, objective functions, and constraints and how they are calculated. Section 2-3 describes pipe routing for the ship's engine room. It describes the information required for pipe routing and the calculation process and results.

2.1. Expert System for Ship's Engine Room Arrangement

2.1.1. Arrangement template model for the arrangement

Expert systems enable computational design methods to replicate the decision-making processes of human experts Kendal and Creen (2007). In existing optimization methods, if expert knowledge is expressed using an objective function or constraint, it would be difficult to modify it subsequently. However, if an expert system is systematized and knowledge is expressed by it, the user can conveniently manage or modify the expert knowledge through the user interface.

Many attempts have been undertaken (Kim et al., 2015; Kim and Roh, 2016; Jung et al., 2018; Kim et al., 2017) to apply expert systems to ship arrangement design. This work utilizes the expert system proposed in the previous studies by improving it to be appropriate for an arrangement for a ship's engine room.

The expert system consists of ATM and AEM. ATM stores the data required for equipment arrangement and pipe routing. Figure 4 (2) shows an example of the data stored by ATM. A node that constitutes a pipe in an engine room represents the relationship between the deck inside the engine room, the pipe on the deck, and the nodes that constitute the pipe, as well as the information of each element. The stored information of the pipes and nodes is used by the AEM to calculate the feasibility index. Figure 6 shows an example of the ATM for the nodes in an engine room.

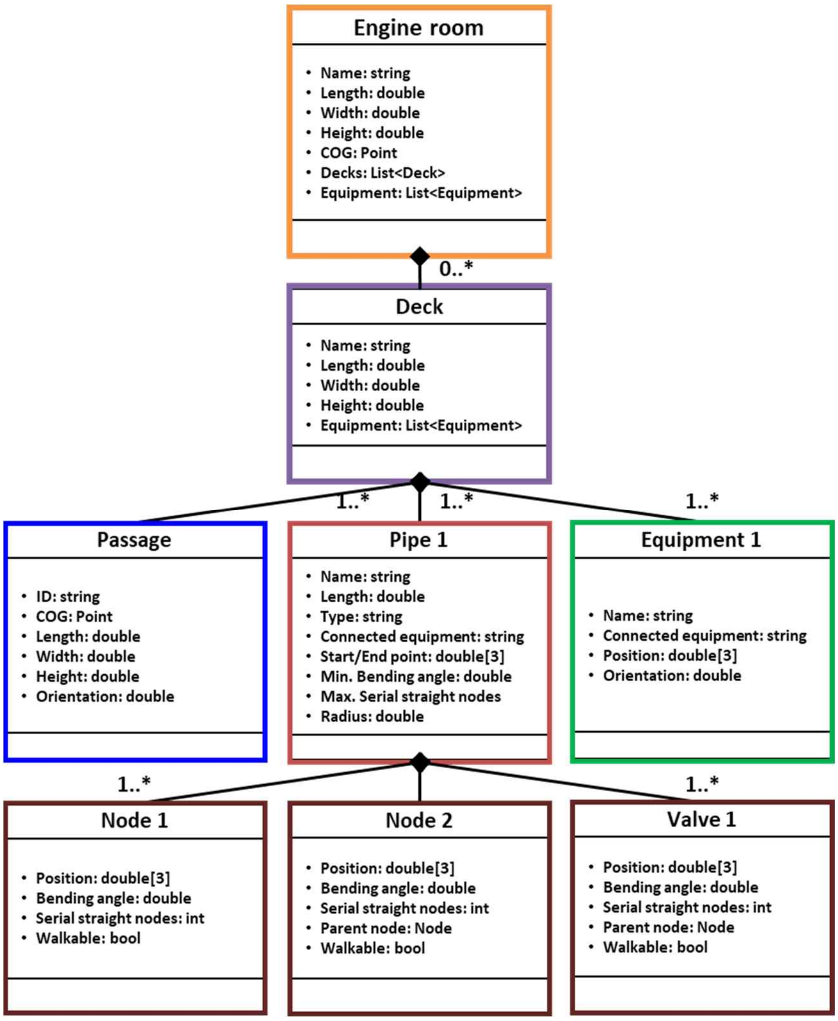


Figure 6. An example of ATM

In Figure 6, the engine room is composed of several decks, each of which has components such as pipes, equipment, and passages. Among them, a pipe consists of several nodes, and each node has properties such as bending angle, number of serial straight nodes, information of parent node, walkable information, etc. These attributes are used to evaluate expert knowledge in AEM, introduced in Section 2.1.2. By expressing the arrangement design of this study in such a formatted framework, it is easier for the expert system to calculate the feasibility index, which in turn facilitates the application of optimization techniques.

2.1.2. Arrangement evaluation model for the arrangement

The AEM stores and evaluates the information related to expert knowledge. The stored information is classified into object and relationship information. Object information expresses expert knowledge applied to an individual object. The format for object information expert knowledge is shown in Table 4.

Table 4. The format of the object information

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type

As shown in Table 4, object information consists of an object ID, a target object, the properties of the target object, an attribute, a target value, knowledge expression, and a Consideration type of the information. An example of expert knowledge expressed as object information is presented in Table 5.

Table 5. Examples of the object information

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type
B004	Node	Exposed to passage	Node *z*-coordinate	150_MIN_mm	IF Node *z*-coordinate ≥ 150 mm THEN 100 ELSE 0	2
B005	Node	Exposed to passage	Node *z*-coordinate	300_MAX_mm	IF Node *z*-coordinate ≤ 300 mm THEN 100 ELSE 0	2

In the example in Table 5, the object ID refers to characters that can identify information. Target object refers to the object that is the target of the information. In this study, a node or pipe was the target object. The property of a target object is a value that distinguishes target objects under a specific condition from objects of the same type. Unlike template models used in previous studies, our model was improved by adding the properties of the target object to apply expert knowledge targeting specific target objects. The example in Table 5 shows expert knowledge that could be collectively applied to the nodes exposed to passages. An attribute is a value that is the target of knowledge, and the target value is a value we aim to satisfy a condition. This example expresses expert knowledge of the *z*-coordinates of the nodes. Other attributes used in the examples of this study include Distance, Node z-coordinate, Minimum straight pipe length, Bending angle, Whether exposed to passages, Vertical Distance, and Whether the object passes the support. In addition to these examples, every attribute such as node coordinates and number of bends, can be defined and used. The target value is determined by the attributes of the target object. In the example, 150_MIN_mm indicates a minimum of 150 mm, and 300_MAX_mm indicates a maximum of 300 mm. Five conditions were used to express the target value: MIN, MAX, EXT, true, and false. MIN is the minimum value, MAX is the maximum value, EXT is the exact value, and true/false indicates whether knowledge is satisfied or not. Knowledge expression is expert knowledge expressed by the "IF–THEN" rule. The knowledge expressed by this rule is used by the inference engine to calculate the feasibility index of the design alternatives. (Kim et al., 2015; Kim and Roh, 2016) In the example in Table 5, this implies that a feasibility index of 100 is obtained if the knowledge is satisfied. Otherwise, a feasibility index of zero is obtained for the design alternative. Finally, the Consideration type indicates the consideration type of expert knowledge. The Consideration type can be one of Constraint, 1, 2, or 3. In this study, to improve the expert system, we separated the expert knowledge into objective functions and constraints so that more diverse knowledge can be represented. The smaller the number, the more important the knowledge. In the case of Constraint, it means that the expert knowledge acts as a constraint and must be satisfied. Expert knowledge with a consideration type of 1 is the next most important expert knowledge, and the final feasibility index multiplied by 1.0 is applied to the objective function. Expert knowledge with a priority of 2 is multiplied by 0.9, and a priority of 3 is multiplied by 0.8 so that it affects the objective function, the feasibility index, differentially.

Table 5 presents expert knowledge of the nodes exposed to the passage. For example, if the height (*z*-coordinate) of the node constituting the pipe exposed to a passage is exceptionally low, interference with the passage structure or flange may occur. Conversely, more pipe support is required if the height of the nodes is excessively high. However, it is inconvenient to install additional support owing to the presence of the passage. Table 5 indicates that the proposed AEM can represent expert knowledge.

Relation information expresses the object and expert knowledge acting between the object. The format for relation information expert knowledge is shown in Table 6.

Table 6. Example of the relation information

Relation ID	Target object	Property of target object	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type

It consists of the relation ID, target object, property of the target object, subjective object, property of the subjective object, attribute, relationship type, target value, and knowledge expression. In relation information, expert knowledge of the relationship between the target and subjective objects is defined through the relationship type. The composition of the relation information is similar to that of the object information. However, the subjective object and subjective object properties are added. Because relation information expresses the relationship between two objects, the subjective object is the target of the related information. In the example shown in Table 7, the subjective object is the equipment that expresses its relationship with the target object node. The subjective object properties express the conditions of the subjective object to which expert knowledge is applied. In the example in Table 7, the property implies that expert knowledge applies to all equipment. An example of expert knowledge expressed as relation information is presented in Table 7.

Table 7. Example of the relation information

Relation ID	Target object	Property of target object	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type
R003	Node	All	Distance	400_MIN_mm	Equipment	All	IF distance from all nodes to all equipment ≥ 400 mm THEN 100 ELSE 0	Constraint

The expert knowledge expressed in Table 7 is that of the minimum separation distance between the equipment and pipe. For equipment maintenance, the nodes constituting the pipe should be at least 400 mm from the equipment. For calculating distance between objects, it is calculated by the minimum of the distances between all nodes. In addition, Table 7 shows that relation information can be represented by our ATM.

The AEM evaluates information based on the arrangement template model and calculates a feasibility index. The feasibility of expert knowledge in the design proposal is evaluated according to the "IF–THEN" phrase. Table 8 presents an example of expert knowledge of pipe nodes exposed to passages. The pipe node exposed to the passage should be arranged at the pipe height (z-direction) at 150 mm–300 mm for maintenance and connection with the support.

Table 8. Examples of expert knowledge for pipe nodes exposed to passages

Object ID	Target Object	Property of target object	Attribute	Target Value	Knowledge expression	Consideration type
B006	Node	Exposed to passage	Node z-coordinate	150_MIN_mm	IF Node z-coordinate ≥ 150 mm THEN 100 ELSE 0	2
B007	Node	Exposed to passage	Node z-coordinate	300_MAX_mm	IF Node z-coordinate ≤ 300 mm THEN 100 ELSE 0	2

The process of calculating the feasibility index using expert knowledge is illustrated in Figure 7.

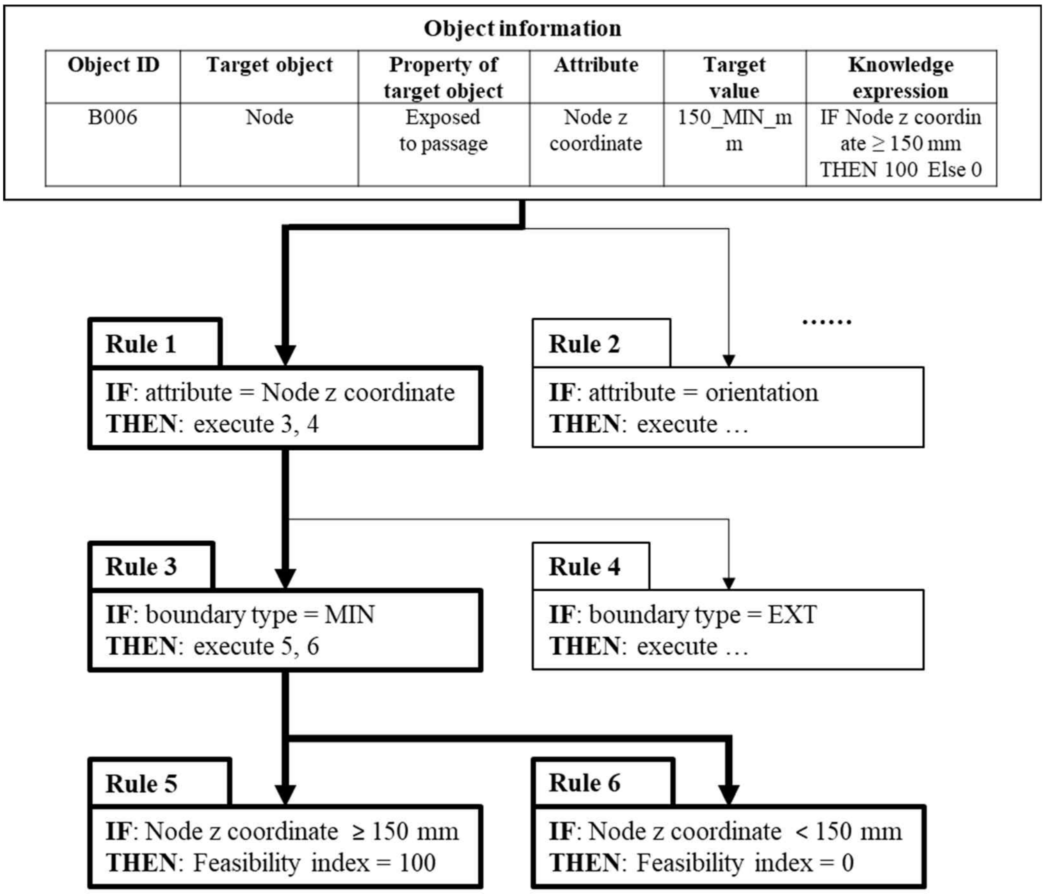


Figure 7. Process of calculating feasibility index

This process was applied to a target object that satisfied the properties of the target object. First, we examined the attribute and applied Rule 1 because it contained the object information of the *z*-coordinate of the node. Next, Rule 3 was applied because the boundary type of the information was MIN. Finally, the *z*-coordinate of the corresponding node was examined. The feasibility index was 100 when the *z*-coordinate was larger than 150 mm. Otherwise, a value of zero was assigned to this index. Examples of expert knowledge used in this study can be found in the appendix.

2.2. Equipment Arrangement for Ship's Engine Room

2.2.1. Input information

For equipment arrangement for ship's engine room, 3D model of the ship, List and specification (weight, size, etc.) of equipment, specifications of compartments, and pipes are required as input information. A 3D model of the ship is required to check for equipment or piping conflicts with the hull structure and to apply expert knowledge. Information about equipment, compartments, and pipes is utilized to calculate the objective function and constraints while performing an optimal arrangement of them.

2.2.2. Design variables

In this study, the height of each deck and the coordinates of the center and orientation of each equipment in an engine room are set as design variables. The three decks to be designed are the lower deck, 1st deck, and 2nd deck in the engine room, as shown in Figure 8.

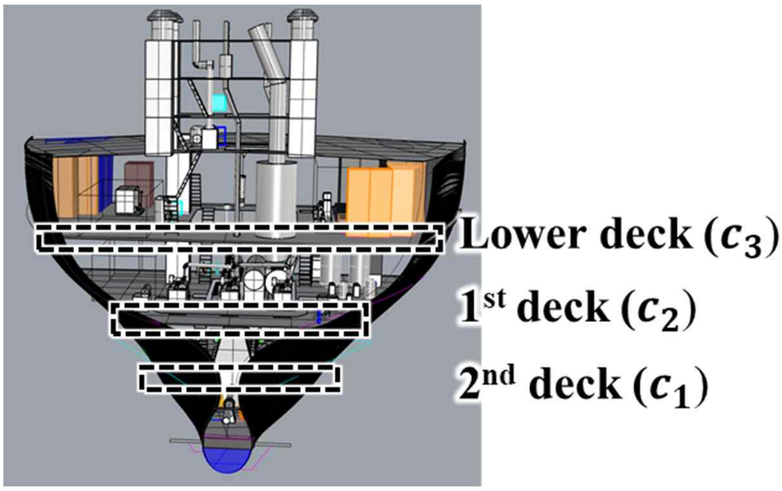


Figure 8. Three decks in the engine room to be designed

c_1 is the height of the 2nd deck, c_2 is the height of the 1st deck, c_3 is the height of the lower deck. For equipment, the design targets are the (x, y, z) coordinates of the center of each equipment, and the orientation rotates at 90-degree intervals. The equipment to be deployed is as follows in Figure 9.

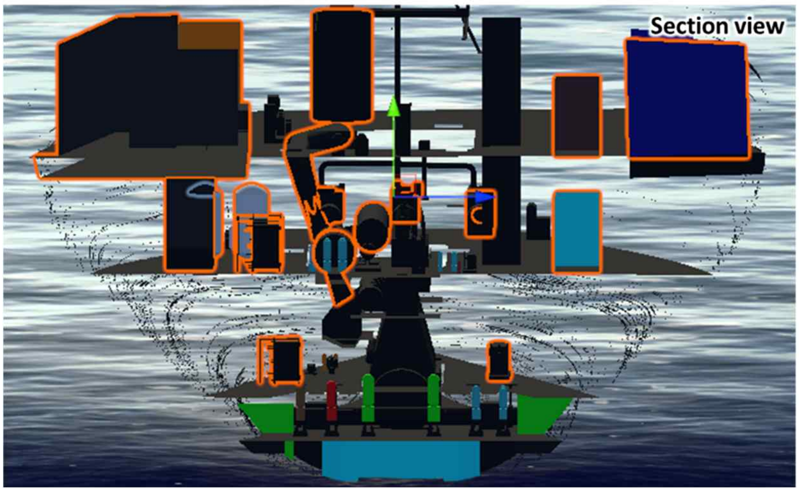


Figure 9. Target equipment for arrangement

2.2.3. Objective functions

The minimization of the occupied volume of the engine room (F_1), length of major pipes and ducts (simplified results) (F_2), number of bends of major pipes and ducts (F_3), space availability of equipment (F_4), and feasibility index of arrangement (F_5) were set as the objective functions.

F_1 minimizes the space occupied by equipment in the engine room. F_2 and F_3 are used as objective functions to minimize the piping costs. However, since it takes too much computation time to perform detailed pipe routing in the 1st stage, simplified results are used. F_4 is the objective function used for maximization of the efficiency of the design space, and F_5 is used to apply expert knowledge to design alternatives. Each objective function is explained in detail in this section.

(1) Occupied volume of the engine room

In order to minimize the space occupied by the engine room or equipment inside the engine room in a ship, the occupied volume of the engine room (F_1) is set as the objective function. Occupied volume is the total volume that is unavailable due to the location of equipment in the engine room. The occupied volume of the engine room is calculated by Eq. (1).

$$F_1 = \sum_{j=1}^{N_{equipment}} V_{e_j} = \sum_{j=1}^{N_{equipment}} L_j \times W_j \times c_i \tag{1}$$

In Eq. (1), $N_{equipment}$ means the number of equipment in the engine room, V_{ej} means the volume of the equipment e_j. L_j means the length of the equipment e_j, W_j means the width of the equipment e_j, and c_i means the height of the deck on which the equipment is located. The calculation of F_1 is described in Figure 10.

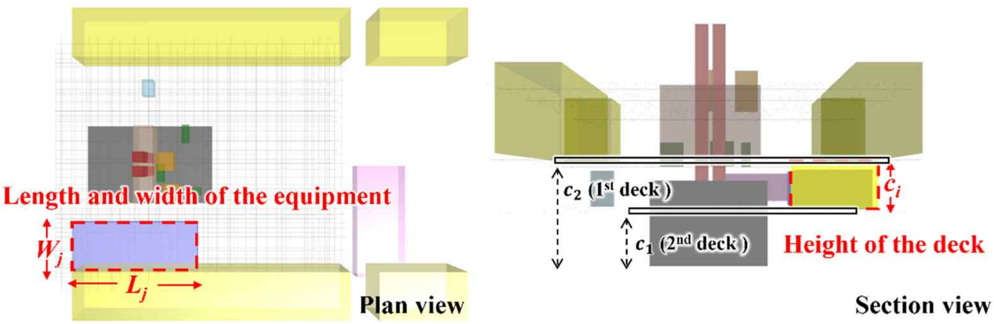


Figure 10. Calculation of the occupied volume of the engine room by equipment

The defined V_{ej} includes the space in the z direction between the deck and the equipment in the engine room, and therefore represents the volume in which new equipment can not be installed. In this study, the occupied volume defined in Eq. (1) is used to define how the equipment can efficiently utilize the space inside the engine room. In arrangement design, the more the occupied volume (F_1) is minimized, the more equipment can be mounted inside the engine room, or the volume of the engine room can be minimized.

(2) Length and number of bends of pipes and ducts

The length of major pipes and ducts (F_2) and number of bends of major pipes and ducts (F_3) are set as the second and third objective functions. These objective functions are calculated from the simplified results of pipe routing introduced in Section 2.3. A comparison of the pipe routing for simplified results in the 1st stage and the pipe routing in the 2nd stage is shown in Table 9.

Table 9. Comparison of pipe routing in the 1st stage and the 2nd stage

Stage	Design variables	Route generation method	Objective functions	Grid space	Computation time
1st stage	Coordinates of nodes	Pathfinding algorithm	Total length and	Large	0.5 [sec]

			number of bends, and feasibility index		
2nd stage	Coordinates of nodes	Pathfinding algorithm	Total length and number of bends, and feasibility index	Small	21.1 [sec]

In the 1st stage, all pipe routing must be performed for a single equipment arrangement during the optimization process. This is very computationally demanding and is one of the reasons why previous studies have not considered pipe routing in equipment arrangements. In order to perform pipe routing for all equipment arrangements within a reasonable computation time, this study performs simplified pipe routing with the differences shown in Table 9. The pipe routing in the 1st stage utilizes a wider grid space and more aggressively utilizes the dynamic grid in the grid configuration introduced in Section 2.3. This simplification of pipe routing allows us to perform very fast simplified pipe routing.

(3) Space availability of equipment

Space availability refers to the efficiency with which the compartments, equipment, and pipes are used. It should be considered in multiple-pipe routing when arranging for other equipment or pipe routing. It is also important for the convenience of installation and frequent maintenance (Jiang et al., 2015; Wang et al., 2018). The space availability used by Lee et al. (2019) was applied in this study. They defined the vertical distance from a wall or an obstacle as the space available to a node. If there is an adjacent node, the space availability is the smaller value obtained by adding one to the space availability of the adjacent node and the vertical distance to the obstacle. The space availability (F_4) is calculated by an integer value, space factor, defined for each node. It describes the space availability in the study of Lee et al. (2019). The smaller the space factor, the closer the node is to a wall or obstacle, and the higher the space availability of the equipment location. We performed the equipment arrangement that maximized the space availability by minimizing the space factor as the fourth objective function (F_4).

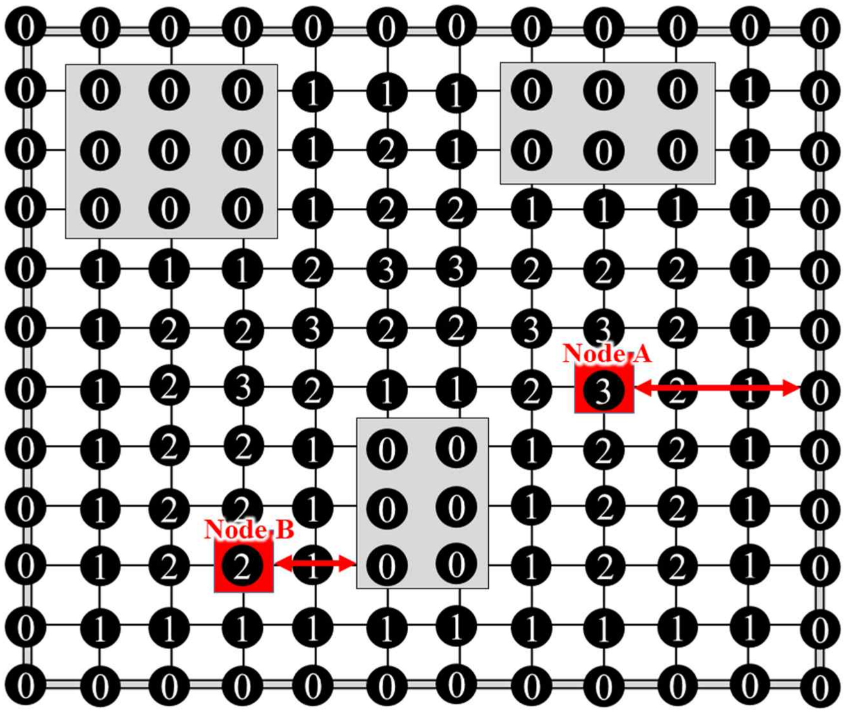


Figure 11 Example of calculation of space factor in design space

Figure 11 shows an example of calculating the space factor in a design space. The gray parts represent obstacles or equipment to be avoided or a wall that is the boundary of the design space. The wall and obstacle parts have a space factor of zero. Meanwhile, the space factors of Nodes A and B are three and two, respectively. Space availability can be calculated using the equations

$$\textbf{Space availability} = \textbf{Space factor}_{max} - \textbf{Space factor} \quad (2)$$

$$Space\ factor = Min(Distance_{wall},\ Distance_{obstacle},\ Space\ factor_{adjacent\ node} + 1) \quad (3)$$

$Distance_{wall}$ is the distance to the nearest wall, and $Distance_{obstacle}$ is the distance to the nearest obstacle. $Space\ factor_{adjacentdnode}$ is the space factor of the adjacent node. While space availability does not increase with closeness to all obstacles, we consistently define space availability as increasing with closeness to an obstacle and utilize the expert system in Section 2.1 for exceptional cases to determine the distance from equipment or obstacles.

(4) Feasibility index of equipment

The feasibility index of equipment (F_5) is the output of the expert system in Section 2.1 concerning how effectively it satisfies the expert knowledge. A higher feasibility index indicates that the design alternative is suitable for expert knowledge. This index was calculated using Eqs. (4) and (5):

$$F_5 = \sum_{i=1}^{N_{equipment}} F(e_i) \quad (4)$$

$$F(e_i) = \sum_{n=1}^{N_{\exp}} FI_n \cdot W_n \quad (5)$$

In Eq. (4), $F(e_i)$ is the feasibility index of the ith equipment (e_i). In Eq. (5), it is calculated as the sum of the products of the feasibility index of the *n*th expert knowledge (FI_n) and its weight factor (W_n). The weight factor has a value between zero and one. It is set according to the importance of the expert knowledge intended by the user. As a result of Eq. (5), we can calculate the feasibility index and its sum for all equipment (i = 1 to $N_{equipment}$). The calculated feasibility index is used for equipment arrangement for the ship's engine room through the process shown in Figure 12.

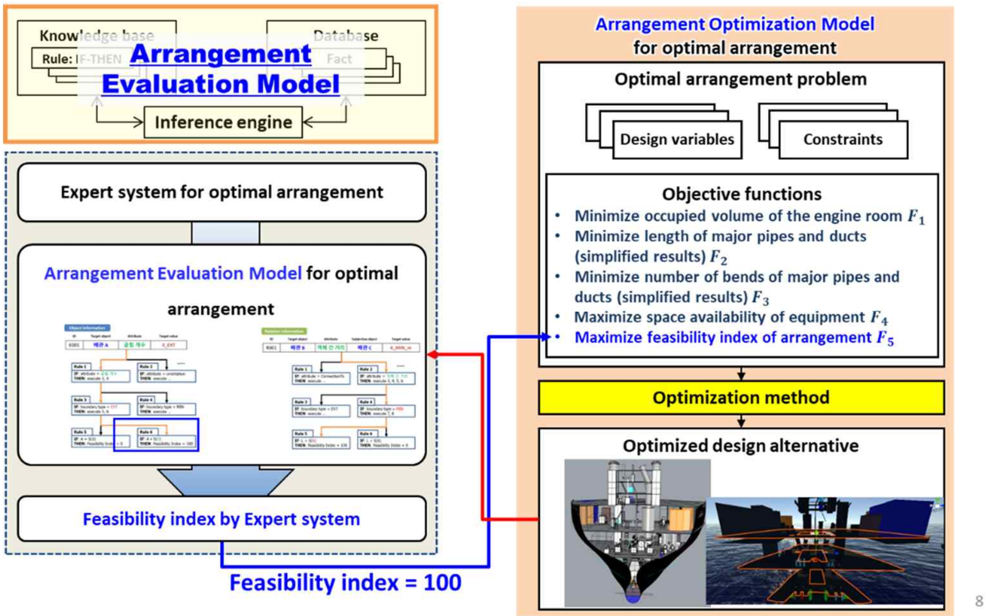


Figure 12. Using the objective function of the calculated feasibility index

By AEM introduced in Section 2.1, the design alternative is evaluated, and the feasibility index is calculated. The feasibility index is a value between 0 and 100 and is used as the 5th objective function among the five objective functions of the optimization process.

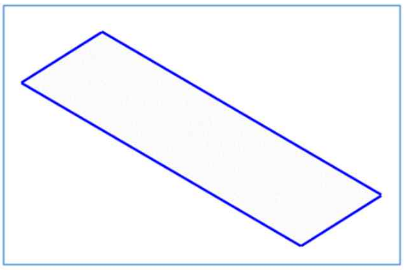
2.2.4. Constraints

(1) Equipment installation available area

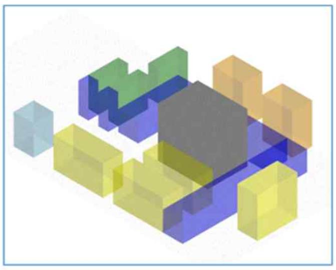
Preventing interference with equipment, developing a route within the installation space, and preventing collisions between pipes and obstacles were set as the constraints in the optimization problem. When the constraint was not satisfied, the design was removed to obtain a solution that satisfied the condition. The constraints applied to each node are given by Eq. (6):

$$b_i(x, y, z), e_j(c_j) \in A_E = A_1 - A_2 \tag{6}$$

In Eq. (6), b_i is an ith bulkhead in the engine room, and A_E is the area where equipment installation is feasible. Figure 13 shows A_1 and A_2, related to the equipment installation available area. These are the area subjected to equipment installation area where the equipment was installed.



A_1: **Equipment installation available area**



A_2: **Excluding equipment installation area**

Figure 13. Equipment installation available area

(2) Constraints by the expert system

The expert knowledge considered in Section 2.1 is examined as a constraint as well as an objective function in Section 2.2. A summary of the examination of the constraints on expert knowledge in equipment arrangement is shown in Figure 12.

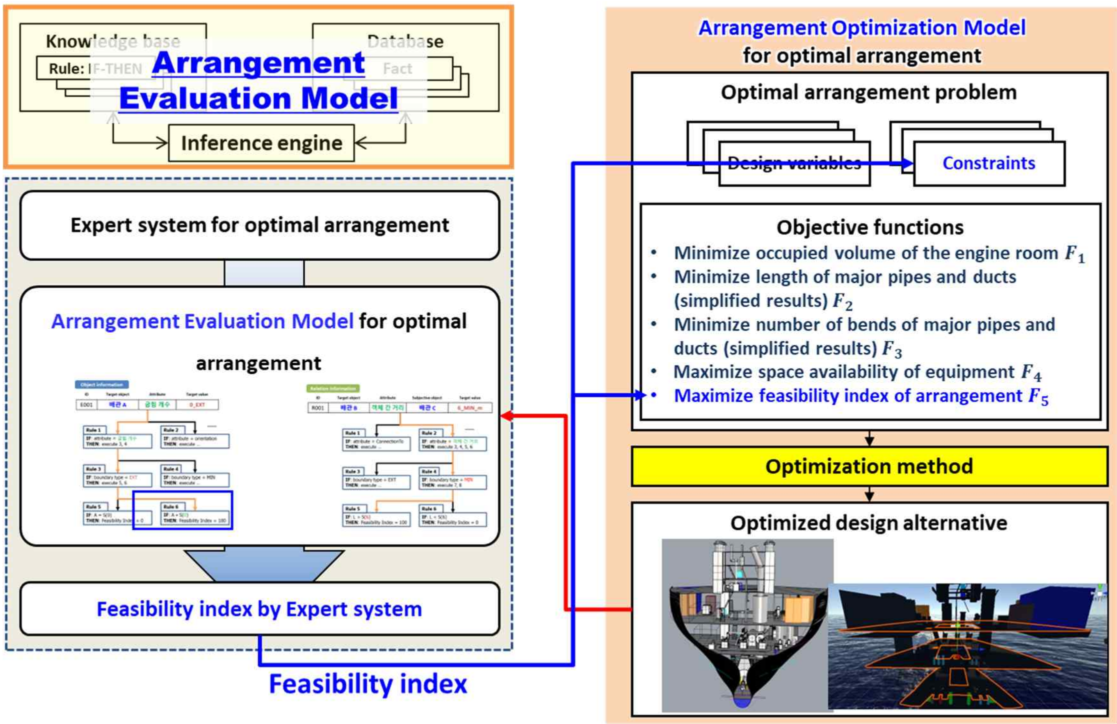


Figure 14. Constraints for equipment arrangement

AEM does not consider all expert knowledge as constraints, but rather calculates an optimal solution that must satisfy the knowledge whose priority is set as a constraint. In the optimization process of the equipment arrangement, solutions that do not satisfy the constraints are discarded. Examples of expert knowledge considered as constraints in the equipment arrangement process (the 1st stage) in this study are shown in Table 10 and Table 11.

Table 10. Examples of constraint expert knowledge (1)

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type
E001	Equipment	All	Clearance distance	0.9_MIN_m	IF Clearance distance ≥ 0.9 m THEN 100 ELSE 0	Constraint
E002	All	All	Whether exposed to passages	False	IF Whether exposed to passages = false THEN 100 ELSE 0	Constraint
E005	Equipment	Auxiliary Engine	Deck	1_EXT_0	IF Installation deck of auxiliary engine = 1 THEN 100 ELSE 0	Constraint
E006	Equipment	Boiler	Deck	2_EXT_0	IF Installation deck of boiler = 2 THEN 100 ELSE 0	Constraint

Table 11. Examples of constraint expert knowledge (2)

Relation ID	Target object	Property of target objec	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type

		t						
R002	Equipment	All	Distance From	Equipment	All	400_MIN_mm	IF Distance from all equipment to all equipment ＞ 400 mm THEN 100 ELSE 0	Constraint
R003	Equipment	All	Distance From	Equipment	Main Engine	5_MIN_m	IF Distance from all equipment to Main Engine ＞ 5 m THEN 100 ELSE 0	Constraint

2.2.5. Optimization method

Use an optimization technique to review various equipment arrangement designs and select the best arrangement design. In this study, three global optimization algorithms are reviewed for optimal equipment arrangement.

(1) Non-dominated Sorting Genetic Algorithm II (NSGA-II)

A genetic algorithm (GA) is an adaptive metaheuristic search algorithm based on the evolutionary ideas of natural selection and genetics. It is a suitable algorithm for finding a global optimum for complex optimization problems having several local optima. The optimization process of GA is shown in Figure 15.

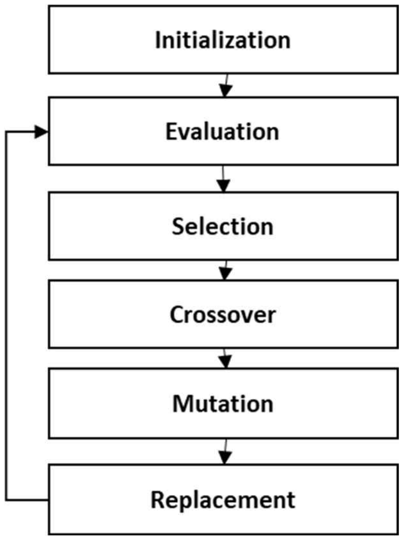


Figure 15. The process of GA

The optimum is found by repeating the evaluation, selection, crossover, mutation, and replacement. Among several GA algorithms, this study examines NSGA-II for optimization. Non-dominated Sorting Genetic Algorithm II (NSGA-II) is one of the variations of GA, and has the advantage of presenting a fast and wide-area solution by adopting a nondominated sorting method (Deb et al., 2002).

(2) Strength Pareto Evolutionary Algorithm (SPEA)

The Strength Pareto Evolutionary Algorithm (SPEA) (Zitzler et al., 1999) is an algorithm for finding or approximating the Pareto-optimal set for multiobjective optimization problems. SPEA combines non-dominate & scalar fitness value & tradeoff front clustering techniques. Also, the algorithm has strength in maintaining diverse populations. The optimization process of SPEA is shown in Figure 16.

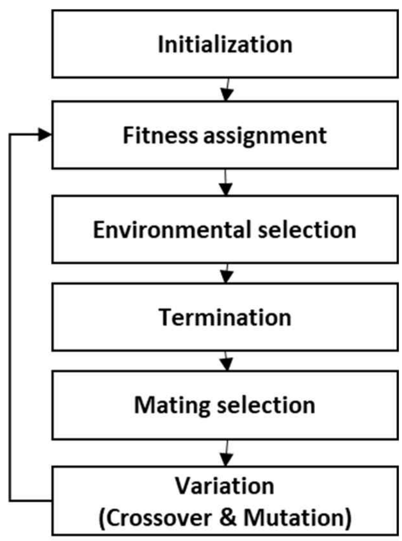


Figure 16. The process of SPEA

(3) Speed-constrained Multi-objective Particle Swarm Optimization (SMPSO)

Nebro et al. (2009) proposed Speed-constrained Multi-objective PSO (SMPSO) by developing Multi-objective Optimization Particle Swarm Optimization (MOPSO). Partical Swarm Optimization (PSO) algorithm is a bio-inspired metaheuristic algorithm mimicking the social behavior of bird flocking or fish schooling. The algorithm incorporates a velocity constriction procedure. The optimization process of SMPSO is shown in Figure 17.

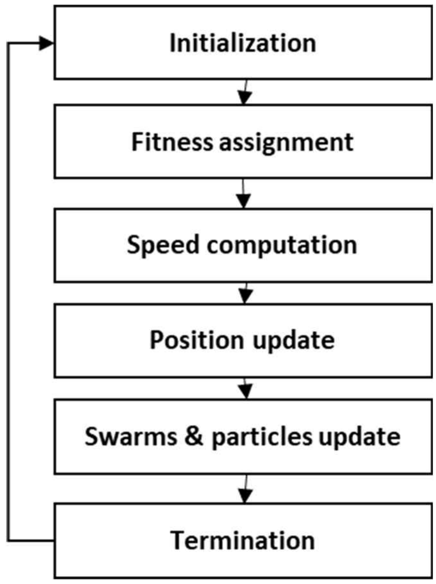


Figure 17. The process of SMPSO

(4) Selection of optimization method for an equipment arrangement problem

Among the three global optimization algorithms presented, the most suitable algorithm for the equipment arrangement problem is found. The equipment arrangement was performed for the optimization problem presented in this section, and the number of target equipment is 11, and the engine room, the space where the arrangement is performed, is 38.2 m wide, 60.0 m long, and 30.0 m high. The cases for NSGA-II and SPEA2 were optimized for 2,000 evaluations, while SMPSO was optimized for archive and swarm size by 100 and iterations with 20. Each parameter was set to find the best solution for a similar level of computation time. The Pareto optimal representation of the optimization result using SMPSO is shown in Figure 18.

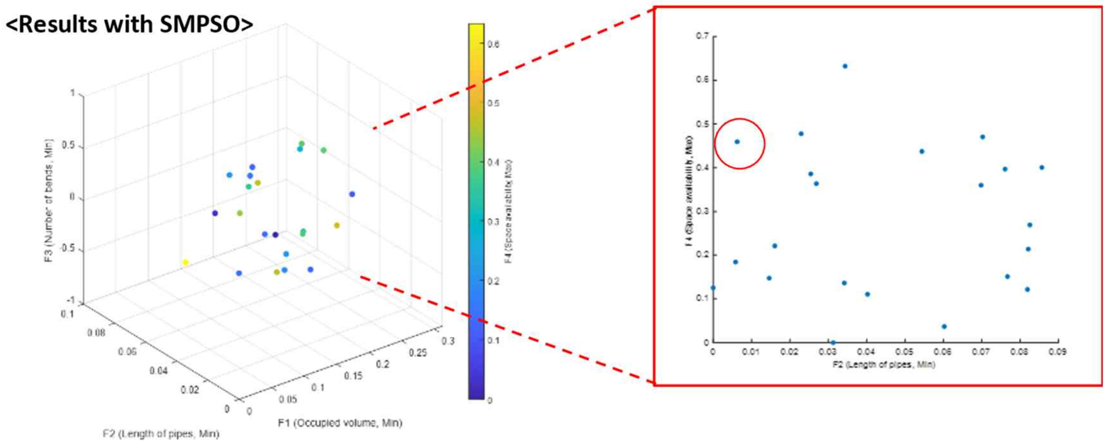


Figure 18. Pareto optimal of the case of SMPSO

Unlike SMPSO, the results using NSGA-II and SPEA2 converged to one solution, and the optimal solution for comparison was selected from the Pareto optimal set of SMPSO. The test case was selected, and compared the optimal solution based on F_2 and F_4, which are the most important and deviated from the Pareto optimal set. The results of the test case are shown in Figure 19 and Table 12.

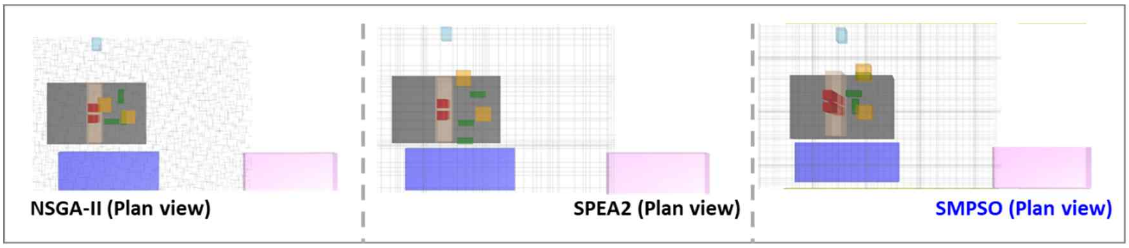


Figure 19. Optimization results by three global optimization algorithms (1)

Table 12. Comparison of global optimization algorithms in the test case

Case	Occupied volume of the engine room (F_1, Min) [m3]	Length of major pipes and ducts (F_2, Min) [m]	Number of bends of major pipes and ducts (F_3, Min)	Space availability of equipment (F_4, Max)	Feasibility index of arrangement (F_5, Max)	Computation time [sec]
NSGA-II	32,807	470	22	149	20,800	407
SPEA2	31,584	462	22	162	20,800	367
SMPSO	31,875	460	21	223	20,800	394

The optimization results showed that all three methods optimized F_1, F_2, and F_5. However, for F_3 and F_4, SMPSO gave the best results. As a result, SMPSO shows the most suitable results in the case. For the optimization cases, we performed optimal arrangement with longer evaluations and iterations. The cases for NSGA-II and SEPA2 were optimized for 10,000 evaluations, while SMPSO was optimized for archive and swarm size by 100 and iterations with 100. Each parameter was set to find the best solution for a similar level of computation time. Results are shown in Figure 17 and Table 12

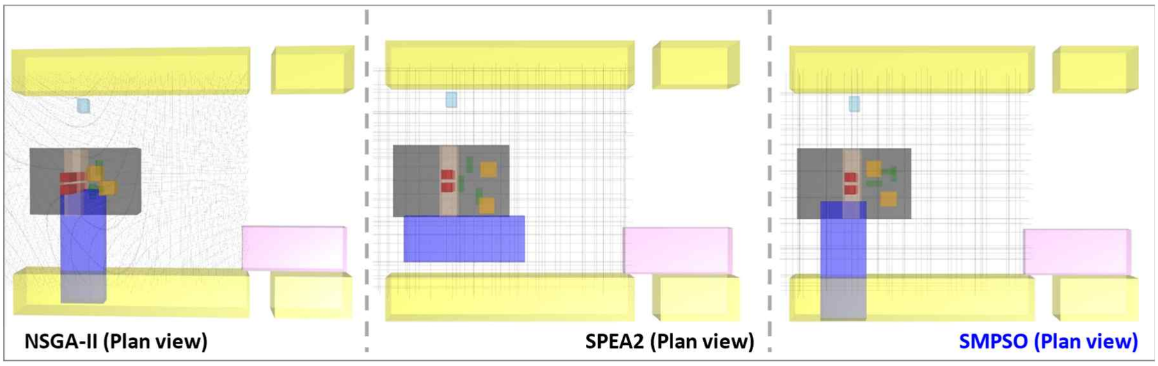


Figure 20. Optimization results by three global optimization algorithms (2)

Table 13. Comparison of global optimization algorithms in the test case (2)

Case	Occupied volume of the engine room	Length of major pipes and	Number of bends of major	Space availability of equipment (F_4, Max)	Feasibility index of arrangement (F_5, Max)	Computation time [hr]

	(F_1, Min) [m3]	ducts (F_2, Min) [m]	pipes and ducts (F_3, Min)			
NSGA-II	32,262	496	24	140	21,400	47.7
SPEA2	32,262	495	24	147	21,300	49.6
SMPSO	33,397	473	24	163	21,400	54.2

The optimization results for the test cases show that NSGA-II and SPEA2 algorithms perform better for F_1, but SMPSO performs best for other objective functions, especially F_2 and F_4. As a result of the cases that have been fully evaluated, SMPSO has found better solutions. In this study, we utilize the SMPSO algorithm to perform equipment arrangement during the first stage of arrangement.

2.3. Pipe Routing for Ship's Engine Room

In this paper, we propose an optimization model for pipe routing and present the optimization results. The optimization method, design variables, objective functions, and constraints considered in the pipe routing process are explained in this section.

2.3.1. Input information

For pipe routing, information of start and end points of pipes, positions of obstacles, positions of equipment, and specifications of pipes (diameter, material, etc.) is required. Information about the start and end points is required to perform route generation for the pipe based on that information. Information about obstacles is required to generate pipe routes that avoid them and to generate a grid that takes them into account. Equipment positions are used when performing pipe routing between equipment. Pipe specifications are required to perform non-conflicting routing of pipes by considering the diameter of the pipe.

2.3.2. Design variables

In this study, each pipe consisted of a series of nodes (pipe $p = \{n_1, n_2, \ldots, n_{Nnode}\}$). Each pipe had start and end points, and the nodes connected these at each grid interval. The pipe was composed of nodes connected continuously only along the x-, y-, and z-axes. Furthermore, each coordinate of the pipe nodes was set as a design variable. The ranges of the design variables and grid interval (grid space) were determined before the design. The dynamic grid (as explained in Section 2.3.6) was used to vary the grid interval. Therefore, the nodes constituting the pipe were composed of non-regular intervals.

Figure 21 shows an example of a pipe composed of nodes. For example, the pipe p_1 consists of five nodes (n_1, n_2, n_3, n_4, n_5).

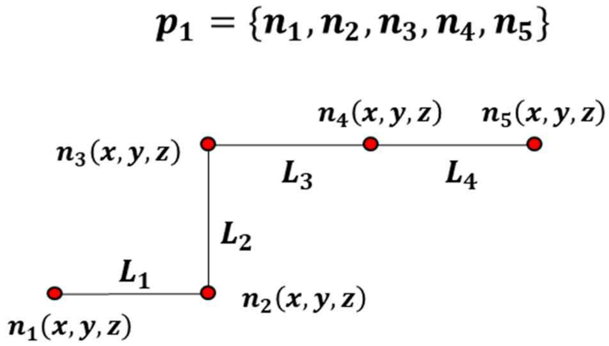


Figure 21. Components of the pipe

In this study, only 90 and 45-degree bends are considered using the introduced method, but it requires to be supplemented to represent various bend types in the future.

2.3.3. Objective functions

The minimization of the total length of the pipe route (f_1), number of bends (f_2), space factor (f_3), and feasibility index (f_4) are set as the objective functions. f_1 and f_2 are used as objective functions to minimize the piping costs in several previous studies (Park and Storch, 2002;Wang et al., 2018; Dong et al., 2022). f_3 is the objective function used for the efficiency of the design space, f_4 is used for the expert system for pipe routing proposed in this study. Each objective function is explained in detail in this section. Each objective function was normalized to a value between zero and one to consider its effect effectively. The five normalized objective functions are optimized by adding these, as shown in Eq. (7):

$$F = w_1F_1 + w_2F_2 + w_3F_3 + w_4F_4 + w_5F_5 \tag{7}$$

In Eq. (7), w_n is a weight factor that considers the value of each objective function and has a value between zero and one. The node with the minimized objective function and heuristic is selected by comparing the sum of the calculated objective functions and heuristic. A pipe route is generated by connecting each node.

(1) Total length of pipe routes

In this study, optimization was performed to minimize the total length of pipe routes and reduce the piping costs. The total length of the pipe routes (L_{total}; the first objective function (F_1)) is given by Eqs. (8) and (9):

$$F_1 = L_{total} = \sum_{j=1}^{N_{pipe}} L(p_j) \tag{8}$$

$$L(p_j) = \sum_{i=1}^{N_{node}} L(n_i, n_{i+1}) \tag{9}$$

In Eq. (8), $L(p_j)$ is the length of the jth pipe (p_j), and N_{pipe} is the total number of pipes. In Eq. (9), $L(p_j)$ is calculated as the sum of the distances between nodes constituting p_j. $L(n_i, n_{i+1})$ is the distance between the ith and $i+1$th nodes, and N_{node} is the total number of nodes constituting p_j. In the example shown in Figure 21, the total length of the pipe route L_{total} is $L_1 + L_2 + L_3 + L_4$.

(2) Total number of bends

To consider the pipe installation and maintenance, optimization is performed in a form that minimizes the total number of bends (N_{bend}; the second objective function (F_2)) for all the pipe routes. A bend is a bending between the pipe nodes. The total number of bends is calculated using Eq. (10):

$$F_2 = \sum_{j=1}^{N_{pipe}} N_{bend}(p_j) \tag{10}$$

In the example of Figure 21, because pipe p_1 has five nodes, the number of bends (N_{bend}) is two.

(3) Space availability of pipes

As in equipment arrangement, space availability is considered an objective function in pipe routing. Especially in pipe routing, space availability is much more important because of pipe support. Figure 22 shows the calculation of the space factor of pipes.

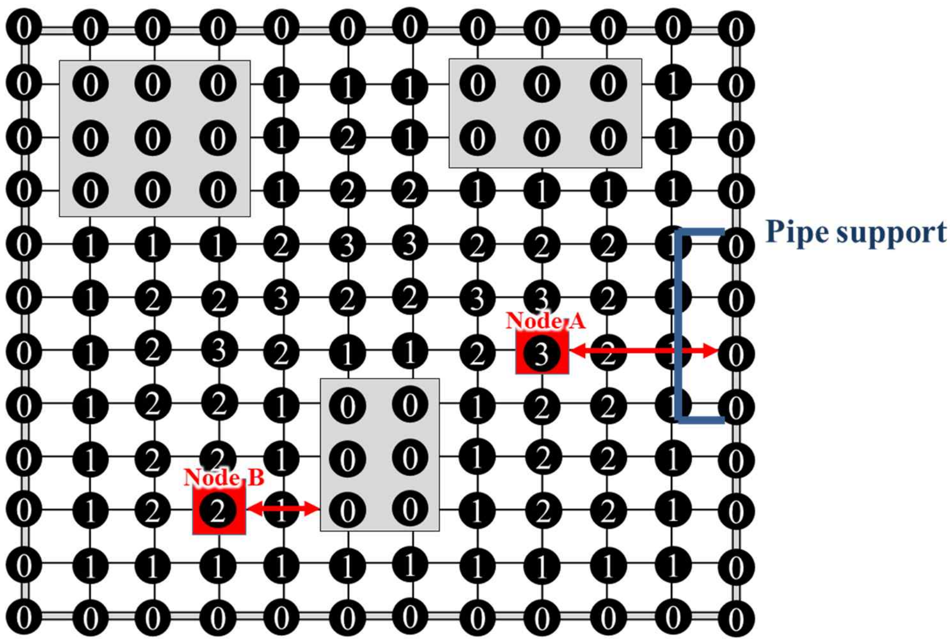


Figure 22. Space availability of pipes for pipe routing

As shown in Figure 22, since the pipe support is installed on the wall, the pipe nodes must be located close to the wall/equipment.

(4) Feasibility index of pipes

The feasibility index (the fourth objective function (F_4)) is the output of the expert system in Section 2.1 concerning how effectively it satisfies the expert knowledge. A higher feasibility index indicates that the design alternative is suitable for expert knowledge. This index was calculated using Eqs. (11) and (12):

$$F_4 = \sum_{j=1}^{N_{pipe}} F(p_j) \tag{11}$$

$$F(p_j) = \sum_{i=1}^{N_{node}} FI_i \cdot W_i \tag{12}$$

In Eq. (11), $F(p_j)$ is the feasibility index of the jth pipe (p_j). In Eq. (12), it is calculated as the sum of the products of the feasibility index of the ith node (FI_i) and its weight factor (W_i). The weight factor has a value between zero and one. It is set according to the importance of the expert knowledge intended by the user. As a result of Eq. (6), we can calculate the feasibility index and its sum for all nodes (i = 1 to N_{node}) constituting the pipe p_j. The calculated feasibility index is used for pipe routing for the ship's engine room through the process shown in Figure 23.

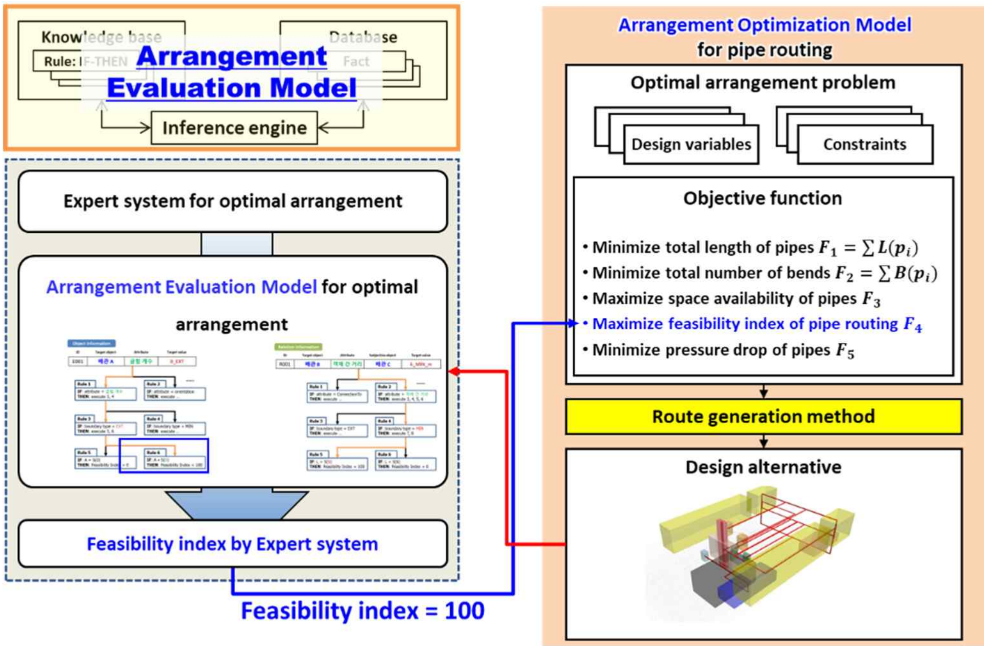


Figure 23. Using the objective function of the calculated feasibility index

By AEM introduced in Section 2.1, the design alternative is evaluated, and the feasibility index is calculated. The feasibility index is a value between 0 and 100, and is used as the 4th objective function among the five objective functions of the optimization process.

2.3.4. Constraints

In the pipe routing process, the proposed constraint is enforced in the form of excluding nodes that violate the constraint. If there is no pipe route that satisfies all the proposed constraints, repeat the 1st stage as shown in the process proposed in

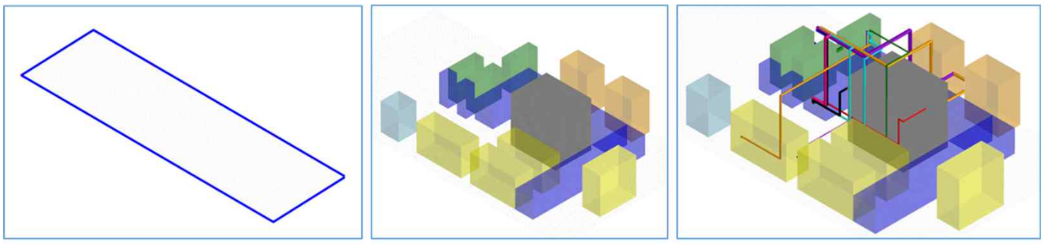
Figure 3.

(1) Pipe installation available area

The prevention of interference with equipment, development of a route within the installation space, and prevention of collisions between pipes and obstacles were set as the constraints in the optimization problem. When the constraint was not satisfied, the design was removed to obtain a solution that satisfied the condition. The constraints applied to each node are given by Eq. (13):

$$n_i(x, y, z) \in A = A_1 - A_2 - A_3 \tag{13}$$

In Eq. (13), n_i is an arbitrary node, and A is the area where pipe installation is feasible. Figure 24 shows A_1, A_2, and A_3 related to the pipe installation area. These are the area subjected to pipe installation, the area where the equipment was installed, and the area where the pipe was installed, respectively.



A_1: **Pipe installation area** A_2: **Excluding equipment installation area** A_3: **Excluding other pipe installation area**

Figure 24. Pipe installation available area

(2) Constraints by the expert system

The 2nd stage, the pipe routing process, also reviews constraint violations by the expert system. The expert knowledge considered in Section 2.1 is examined as a constraint as well as an objective function in Section 2.2. A summary of the examination of the constraints on expert knowledge in pipe routing is shown in Figure 25.

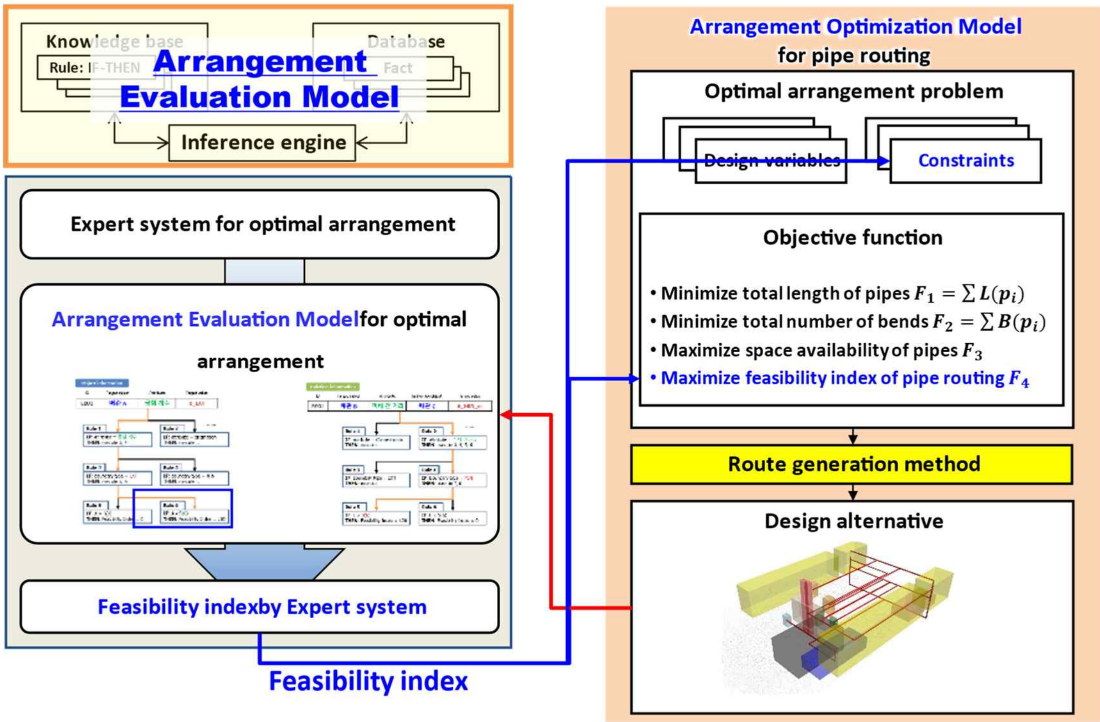


Figure 25. Constraints for pipe routing

AEM does not consider all expert knowledge as constraints but rather calculates an optimal solution that must satisfy the knowledge whose consideration type is set as a constraint. In the pipe routing process, solutions that do not satisfy the constraints are discarded. Examples of expert knowledge considered as constraints in the pipe routing process (the 2nd stage) in this study is in Table 14.

Table 14. Examples of constraint expert knowledge

Object ID	Target object	Property of target object	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type
R009	Pipe	All	Distance From	Equipment	Main engine	800_MIN_mm	IF Distance from all pipes to Main engine ≥ 800 mm Then 100 Else 0	Constraint

2.3.5. Route generation method

(1) Selection of route generation method

In this study, several route generation methods are compared, and among them, the most suitable method is selected for this study. In this process, the result of pipe routing with the total length of pipes (F_1) and total number of bends (F_2) set as objective functions. Pipe routing is performed in a design space with a width of 10 m, a length of 10 m, and a height of 10 m. The start point is (0, 0, 0), and the endpoint is (10, 10, 10) [m]. There is an obstacle blocking x = 5 m, y <= 6 m, and z <= 10 m inside the design space. For the computation of all cases, a PC with Intel Core i7-8700 CPU @ 3.20GHz, 32GB RAM is used.

The first case, Case 1, is the case of performing route generation using the A* algorithm. The result of Case 1 is shown in Figure 26.

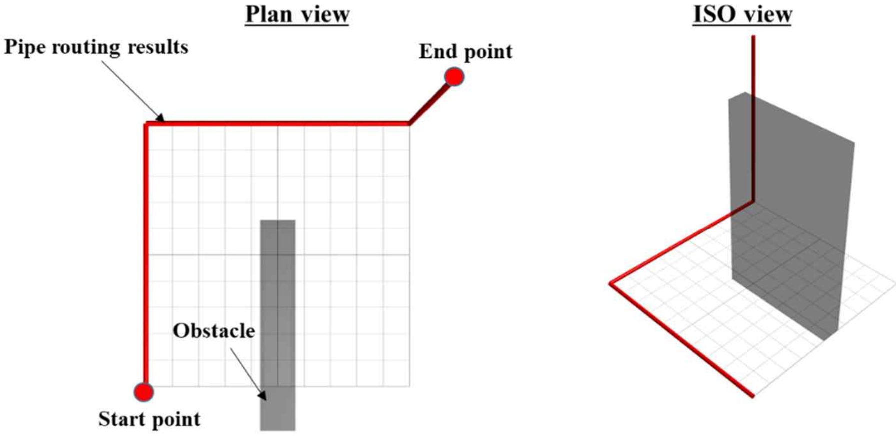


Figure 26. Results of route generation using A* algorithm

The pipe routing results for Case 1 are shown in Table 15.

Table 15. Results of Case 1

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Computation time [sec]
Case 1	30	2	0.128

Case 1 successfully generated an optimal pipe route avoiding an obstacle with fast computational speed. Case 2 uses the NSGA-II algorithm for pipe routing. Case 2 is the result of pipe routing for the minimum generation that can generate a route. For Case 2, the population size of 1,000 and generations of 10 are used. The figure shows the result of Case 2.

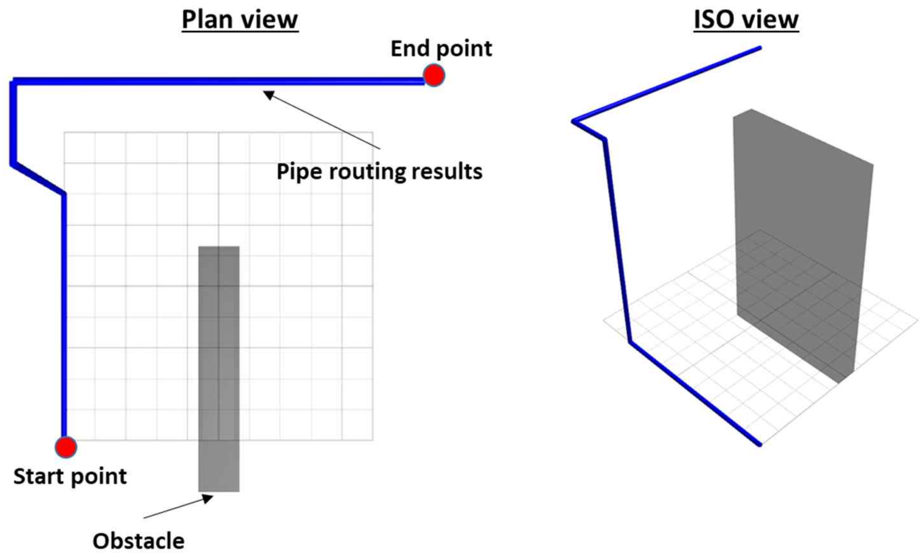


Figure 27. Results of route generation using NSGA-II algorithm (1)

The pipe routing results for Case 2 are shown in Table 16.

Table 16. Results of Case 2

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Computation time [sec]
Case 1	30	3	0.106

The shortest path was generated by minimizing F_1, but the number of bends (F_2)

was not optimized. Case 3 is the case of obtaining optimized pipe routing results by improving the optimization parameters in Case 2. Figure 28 is the result of Case 3.

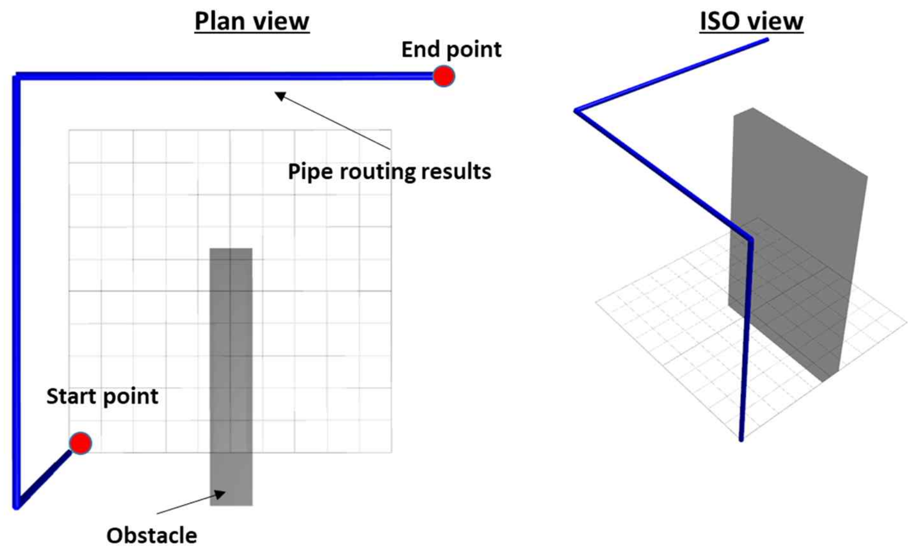


Figure 28. Results of route generation using NSGA-II algorithm (2)

The pipe routing results for Case 3 are shown in Table 17.

Table 17. Results of Case 3

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Computation time [sec]
Case 1	30	2	396.105

As a result of Case 3, the pipe routing with sufficient evaluation until an optimized route is performed. In Case 3, optimization required much time to formulate the problem and took too much time to calculate. As a result, pipe route generation using the optimization method requires a lot of evaluation before the optimized route is calculated. Pipe routing can be performed relatively fast using the route generation algorithm (A* algorithm). In this study, a pathfinding algorithm was selected for the route generation algorithm.

(2) Selection of pathfinding algorithm

A grid-based approach for optimal pipe routing was selected for this study (Furuholmen et al., 2010; Jiang et al., 2015; Lee et al., 2019; Dong and Bian, 2020; Kim et al., 2021). The design target area was divided into nodes by grids. We defined the properties of each node (such as obstacles and walls) where a pipe route could not be generated, including the start and end points of the pipe route. The pathfinding algorithm was used for pipe routing, and the least cost path (LCP) method was additionally used to generate a route that minimized the objective functions presented in Section 2.3. The LCP method is a method for pathfinding that minimizes the specified cost (objective function) rather than finding the shortest route in route search (Kang and Lee, 2017).

Among several pathfinding algorithms, an algorithm suitable for pipe routing in this study is selected. Including the A* algorithm reviewed in (1), the Dijkstra and JPS algorithms are reviewed as route generation methods for pipe routing. The

Dijkstra algorithm is one of the pathfinding methods. The optimal solution is calculated by searching for a local area and comparing the cost. Jump Point Search (JPS) algorithm uses a search strategy for speeding up optimal search by selectively expanding only certain nodes. It performs path finding using less memory by jumping to another node depending on the scenario (Harabor and Grastien, 2011; Min et al., 2020). Section 2.3.3, F_1, F_2, and F_3 are considered among the objective functions proposed in For selection of the pathfinding algorithm, the cost shown in Eq (15) is used. The pipe routing results using each pathfinding method are shown in Figure 29 and Table 18.

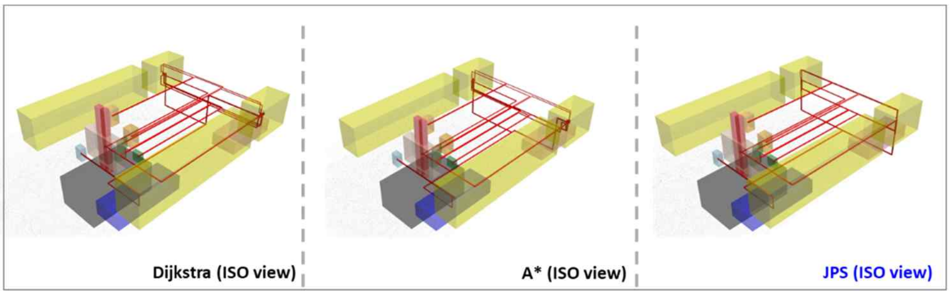


Figure 29. Comparison results of pathfinding methods (1)

Table 18. Comparison results of pathfinding methods (2)

Case	Total length of pipes (F1,	Total number of bends (F2, Min)	Space availability of pipes (F3, Min)	Feasibility index of pipes (F4, Max)	Computation time [sec]

	Min) [m]				
Dijkstra	1,781	29	4,961	914	30.8
A*	1,777	29	4,946	914	13.9
JPS	1,773	27	5,010	916	10.5

In Table 18, the pipe routing result using the Dijkstra algorithm takes too much computation time and does not produce the best results. Because of many obstacles, the JPS algorithm takes resources to determine a jump. However, compared to other algorithms, the JPS algorithm has better performance and fast computational speed.

For the JPS algorithm, Too many resources are used to determine horizontal/vertical orientation, even though very few jumps are involved. In this study, we tried simple improvements to the jump loop to speed up the computation when no jumps are involved.

2.3.6. Grid configuration for pipe routing

(1) Design area for pipe routing

If pipe routing is performed by selecting all engine room areas as candidates, too many candidate nodes are examined with much computation time. In this study, we try to limit the design area for pipe routing to perform the arrangement design within the realistic time available. The design area for pipe routing is shown in Figure 30.

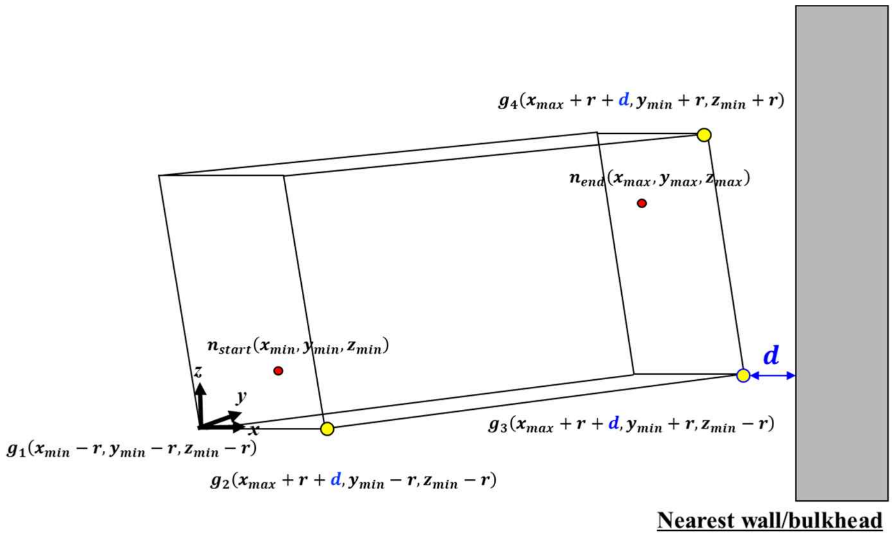


Figure 30. Design area for pipe routing

In Figure 30, for a start point n_{start} and an end point n_{end}, compare the respective coordinates of the two points to define the minimum ($x_{\min}$, $y_{\min}$, $z_{\min}$) and maximum ($x_{\max}$, $y_{\max}$, $z_{\max}$) values of each x, y, z coordinate of the pipeline's start and end points. Then margin r is added to x, y, and z to the 8 points (g_1, g_2, …, g_8) to define the design space. To properly account for space availability, the design space extends to the nearest wall or the bulkhead. The distance to the wall is defined as d, and the maximum value for the x-coordinate of the pipe routing available area is applied as x_{max} $+r+d$. Finally, the coordinates of the 8 points of the design area in Figure 30 are as follows.

$$g_1 = (x_{\min} - r, y_{\min} - r, z_{\min} - r)$$

$$g_2 = (x_{\max} + r + d, y_{\min} - r, z_{\min} - r)$$

$$g_3 = (x_{\min} - r, y_{\min} + r, z_{\min} - r)$$

$$g_4 = (x_{\max} + r + d, y_{\min} + r, z_{\min} - r)$$

$$g_5 = (x_{\min} - r, y_{\min} - r, z_{\min} + r)$$

$$g_6 = (x_{\max} + r + d, y_{\min} - r, z_{\min} + r)$$

$$g_7 = (x_{\min} - r, y_{\min} + r, z_{\min} + r)$$

$$g_8 = (x_{\max} + r + d, y_{\min} + r, z_{\min} + r)$$

After defining the size of the design area, the area is divided into nodes with a maximum grid space. By default, pipe routing is performed according to a maximum grid space, but it can also be reconfigured to a changed grid space by the dynamic grid method introduced in Section 2.3.6 (2). The design target space of this study, the engine room, has dimensions of 60.0 m x 38.3 m x 30.0 m and is composed of gird (voxels) with a minimum size of 10 mm x 10 mm x 10 mm. In total, the design target space was composed of 6000 x 3830 x 3000 $\approx$ 6.9×10^{10} grids.

(2) Dynamic grid method used for pipe routing

Several attempts have been undertaken to reduce the computation time of grid-based pathfinding methods. Kim et al. (2013) proposed a nonuniformly divided cell to reduce the number of calculations. They constructed graphs through vertex branching and placed grids by considering obstacles or walls. In this study, we used the dynamic grid method in which the grid varies according to the location of the obstacles or the arrangement of the other pipes. This method can reduce computational time by focusing the computational effort on regions with obstacles and other pipes. In this method, the calculation time and accuracy are determined according to the grid space (grid interval). The calculation time is short if the grid space is large. If the grid space is small, the calculation time increases. However, the accuracy of the results also increases. The grid space varies depending on the surrounding environment. The proposed dynamic grid method has certain similarities with the JPS algorithm. However, it can reduce the consumption of computation time and memory by recycling the grid for routing multiple pipes and the next design stage (for example, arrangement of equipment). The pipe routing process using a dynamic grid is shown in Figure 31.

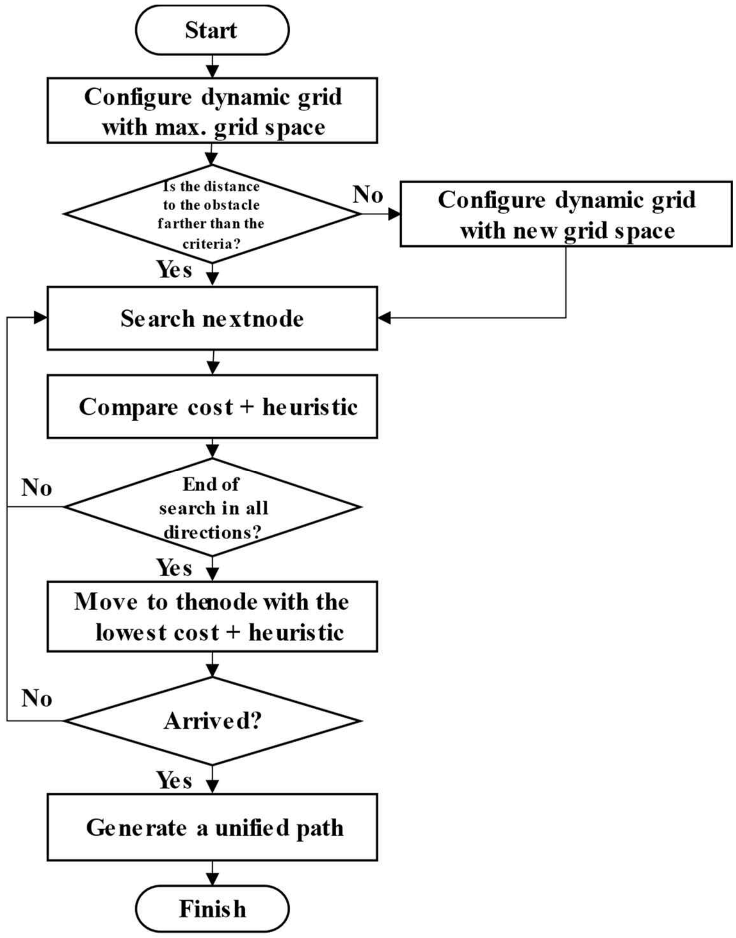


Figure 31. Process of pipe routing using a dynamic grid

First, a dynamic grid with maximum grid space is configured. In this study, the grid space can be modified 1-20 times the minimum grid space depending on the distance between the node and the obstacle. After that, it checks if the distance to the obstacle is farther than the criteria. When the distance between the node and the obstacle is over ten times the minimum grid space, a dynamic grid is used to adjust the grid space. Figure 32 shows examples of a uniform grid (a) and dynamic grid (b) adjusted according to the presence or absence of obstacles.

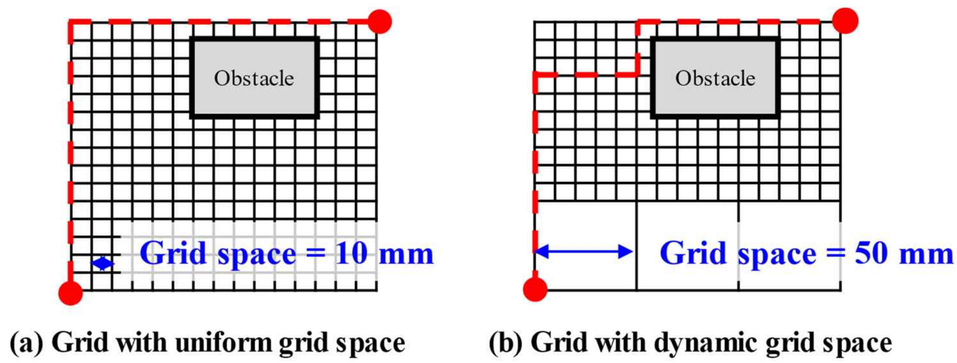


Figure 32. Example of grid space adjustment of the dynamic grid (1)

In Figure 32 (b), a wider grid space is applied to the grid at a long distance from the obstacle. The computation time can be reduced with a wider grid space when applying the pathfinding algorithm. A more detailed illustration of determining grid spacing is shown in Figure 33.

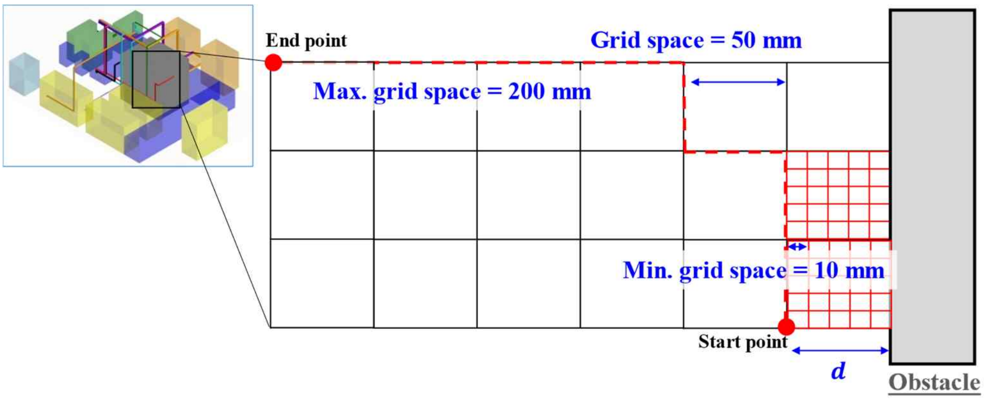


Figure 33. Example of grid space adjustment of the dynamic grid (2)

In Figure 33, *d* is the distance to the nearest obstacle or bulkhead. A three-dimensional grid (with a maximum space of 200 mm) is created in a defined area. If *d* ≦ *grid space*, smaller grid spaces are created for considering the distance to the nearest obstacle/ bulkhead. In this study, the maximum grid space is 200 mm, and the minimum grid space is 10 mm.

After configuring the dynamic grid, the next node that can be reached from the current location is identified. Then, the sum of the costs and heuristics of the searched nodes are calculated and compared. Then, we proceed to the best node. This process is repeated until the pipe arrives at the end point. Upon arrival at the end point, the calculated route with the adjusted grid space is connected to the route in the minimum grid space by correcting the coordinate system to match the minimum grid space to generate a unified path. A comparison was performed on the example problem proposed by Kim et al. (2023) to validate the pipe routing method proposed in this section.

Kim et al. (2023) presented an example of four pipes connecting 14 equipment. This study performed pipe routing for the same example proposed by Kim et al. (2023). For the objective functions, total pipe length (F_1) and total number of bends (F_2) are used. The results of an example by Kim et al. (2023) are shown in Figure 34 and Table 20.

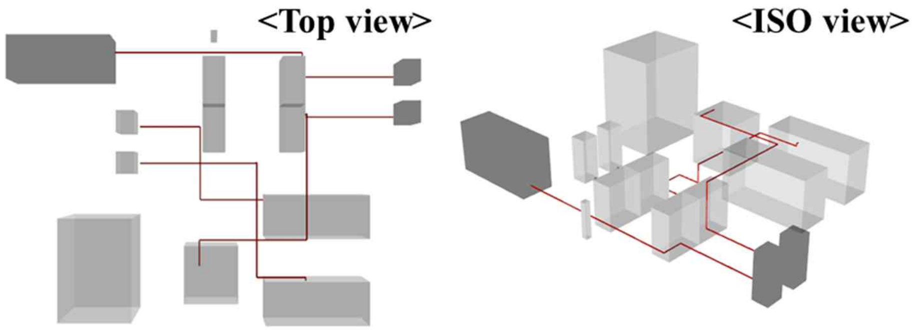


Figure 34. The result of an example in Kim et al. (2023) (1)

Table 19 The result of an example in Kim et al. (2023) (2)

Case	Method	Total pipe length (F_1, Min) [m]	Total number of bends (F_2, Min)	Computation time [sec]
Case 1 (Kim et al. (2023))	A*	47.34	25	39240.72
Case 2 (Kim et al. (2023))	JPS	47.34	20	107.68

Case 3 (Kim et al. (2023))	Reinforcement Learning	47.34	18	6.7
Case 4 (Proposed method)	JPS	47.34	18	6.8

As a result of pipe routing for the example, although the two methods were not tested in the same environment, the pipe routing method proposed in this study (Case 4) is much faster than the existing method (Case 2) that utilizes the JPS algorithm (Min et al., 2020) and takes a similar amount of time as the method that utilizes reinforcement learning (Case 3), which takes time to learn. This confirms that the method proposed in this study can perform pipe routing in a relatively short computation time compared to existing pipe routing methods.

Since the conditions for pipe routing in each stage are different, it may fail to generate a pipe route using a narrower grid space in the 2nd stage.

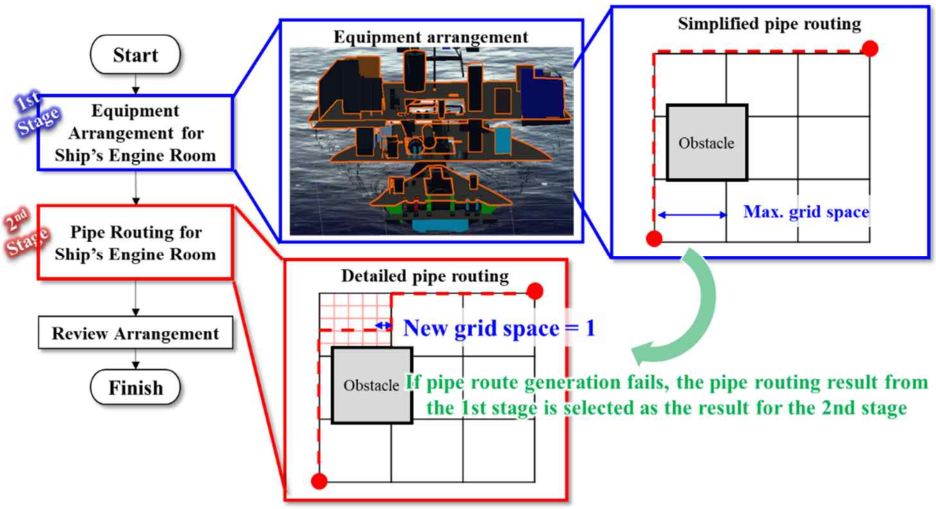


Figure 35. Pipe routing method when 2nd stage pipe routing fails

In this case, pipe routing in the 2nd stage can be guaranteed by selecting pipe routing results generated in the 1st stage, as shown in Figure 35.

3. Verification

In order to perform the verification of the methods proposed in this study, four verification cases were performed. The verification cases were for sensitivity analysis, analysis of objective functions in the 1st stage, and equipment arrangement using pipe routing, as shown in Table 20.

Table 20 Verification cases

Verifications	Tests		Method
Sensitivity analysis	Sensitivity analysis	Design of experiment using full factorial method	Comparison of parameter effects
Analysis of objective functions in the 1st stage	Relationship analysis	.	Relationship analysis between objective functions
Equipment arrangement using pipe routing	Optimal equipment arrangement	Simple arrangement cases	Comparison of equipment arrangements with and without pipe routing

In the first verification case, a sensitivity analysis was performed to compare the parameter effects of each design variable on the objective function. The data collected for this purpose utilized the design of experiment using the full factorial method. In the second verification case, the relationship analysis between each objective function of the 1st stage was performed. In this process, we performed an arrangement of two objective functions and analyzed the result. In the third verification case, we verified that the optimal equipment arrangement with pipe routing proposed in this study works effectively. In this case, a comparison of equipment arrangements with and without pipe routing was performed.

3.1. Sensitivity Analysis for the 1st stage

It is necessary to accumulate data for sensitivity analysis for an equipment arrangement problem (1st stage). In this study, the design of experiment (DOE) was used to select the data to be used for sensitivity analysis. There are various DOE patterns, and in this study, sensitivity analysis was performed with the full factorial design.

Optimization was performed using the design variables, objective function, and constraints suggested in Section 2.2. The ranges of the design variables used were as follows:

$-15.0\text{ m} < \Delta Zc_1, \Delta Zc_2, \Delta Zc_3 < 15.0\text{ m}$

$0.0\text{ m} < x_{ej} < 16.0\text{ m}$

$0.0\text{ m} < y_{ej} < 30.0\text{ m}$

$0 < z_{ej} < 2$ (Number of the deck)

$0 < o_{ej} < 1$ [90 degrees]

ΔZ_{ci} means the height change of deck c_i. x_{ej} is the x-coordinate of equipment e_j, y_{ej} is the y-coordinate of equipment e_j, z_{ej} is the z-coordinate of equipment e_j. o_{ej} is the orientation of equipment e_j expressed in units of 90 degrees. In this study, we performed full factorial design, dividing all design variables into three levels (two levels for o_{ej}) and performing a sensitivity analysis on 1,458 results of the 1st stage. The peak-to-peak values of each design variable for the first objective function (F_1) were as Figure 36.

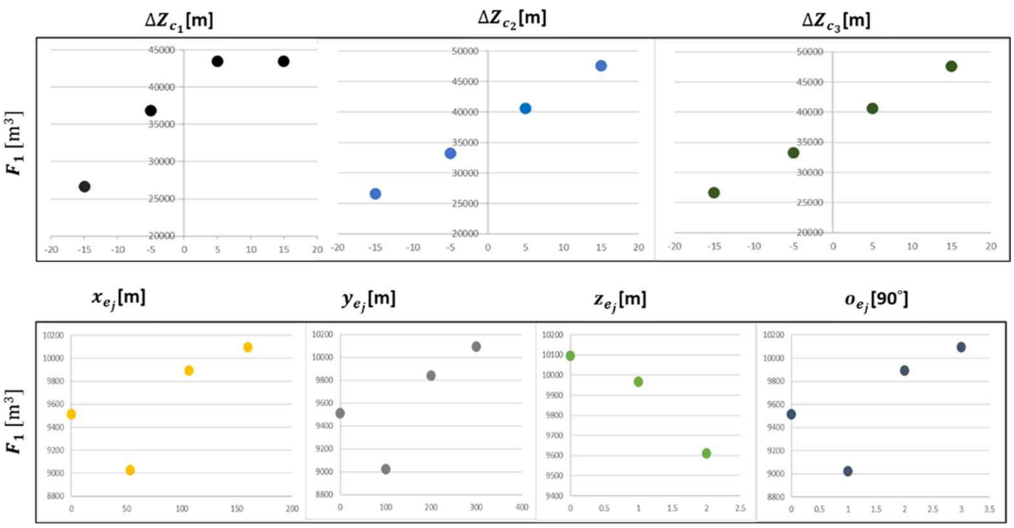


Figure 36. Results of sensitivity analysis (Peak-to-peak values)

The results of sensitivity analysis for the first objective function were as Figure 37.

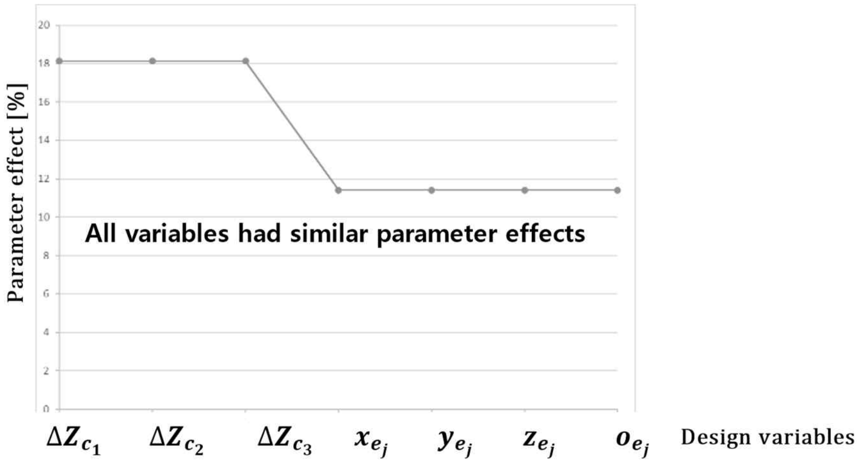


Figure 37. Results of sensitivity analysis (F_1)

The parameter effect was calculated how much the peak-to-peak value affects the objective function. All variables had similar parameter effects except for the 6th design variable (z_{ej}). For all objective functions, this was summarized as following Figure 38.

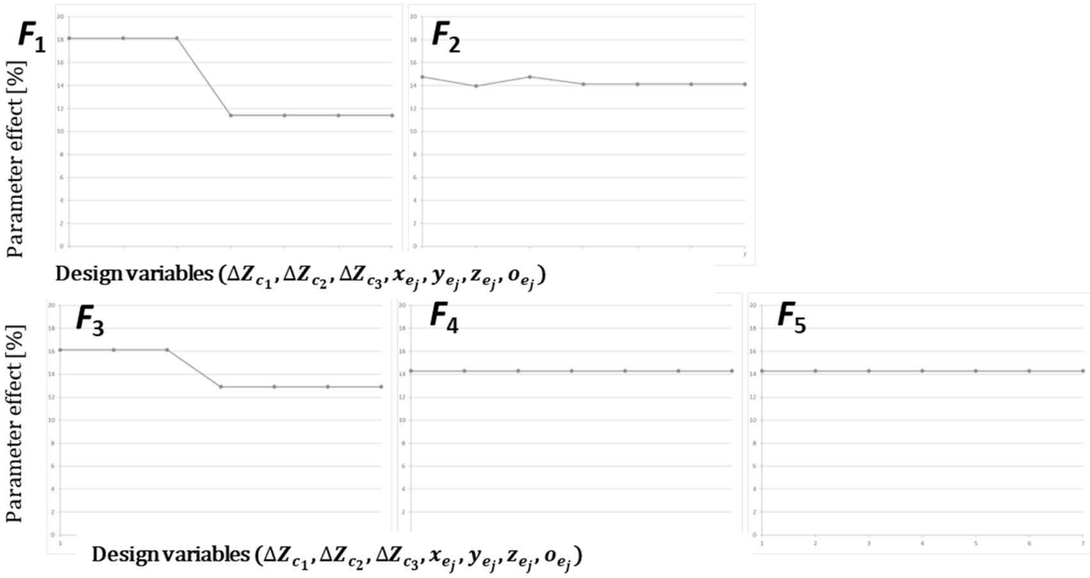


Figure 38. Results of sensitivity analysis (All objective functions)

For F_3, the height of the two decks where most of the equipment is located had a greater effect. For F_4 and F_5, all design variables contribute uniformly to the objective function. As a result of performing analysis on all five objective functions, it was confirmed that all the selected design variables had a similar effect on each objective function.

3.2. Analysis of objective functions in the 1st stage

In this section, we analyze the relationship between the objective functions in the 1st stage, proposed in Section 2.2. The relationship between the two objective functions was verified by repeating the optimization problem in which two or three objective functions were selected as objective functions.

The first case is the relation analysis between minimize length of major pipes and ducts (simplified results) F_2 and Minimize number of bends of major pipes and ducts (simplified results) F_3 as shown in Figure 39.

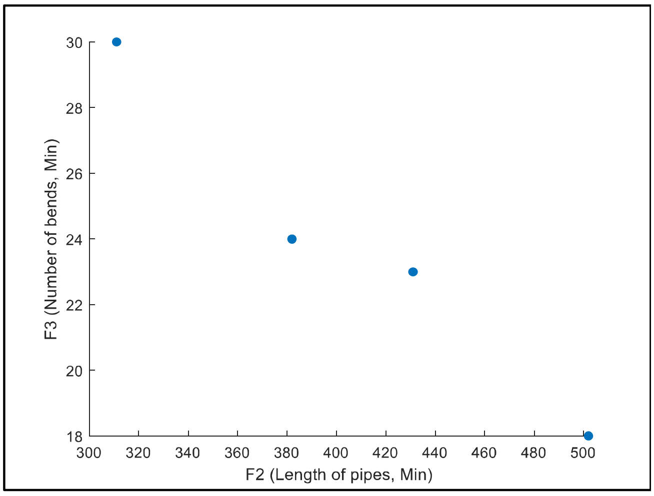


Figure 39. Relation analysis between F_2 and F_3

F_2 (Pipe length) and F_3 (Number of bends) were inversely proportional. Increasing the length of pipes and ducts connecting equipment could reduce the number of bends. They are the most conventional and core objective functions, and they have a clear negative correlation in this study. The second case is the relation analysis between F_1 and F_2 as shown in Figure 40.

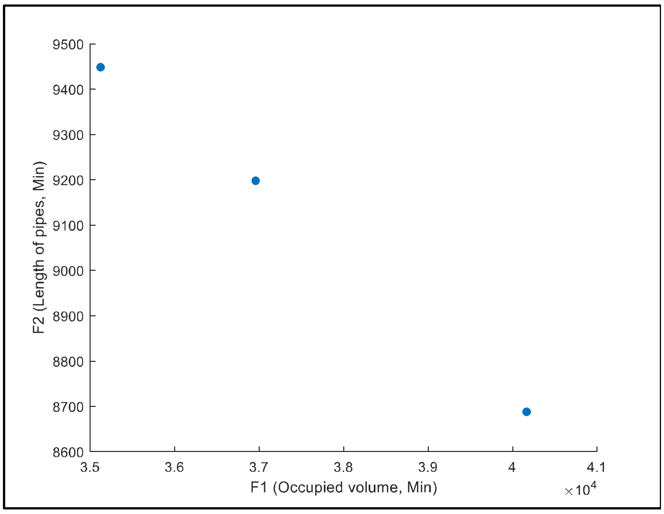


Figure 40. Relation analysis between F_1 and F_2

F_1 (Occupied volume) was proportional to F_2 (Pipe length) in the range where F_1 was large but inversely proportional. However, when the distance between equipment gets closer than a certain level, problems like the example below can be encountered. If the equipment was densely arranged, pipe routes became longer, as shown in Figure 41.

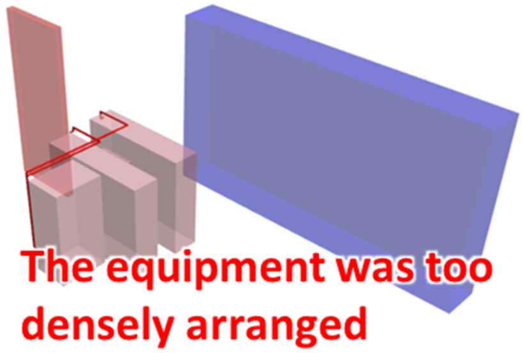


Figure 41. An example of densely arranged equipment

Figure 41 is an example that can show that when equipment is arranged too densely without considering pipe routing, the length of pipes increases. In situations like this example, F_1 and F_2 were not simply proportional, so optimization of the two objective functions is required to minimize both functions. The next case is the relation analysis between F_2 (Pipe length) and F_4 (Space availability). The result is shown in the following Figure 42.

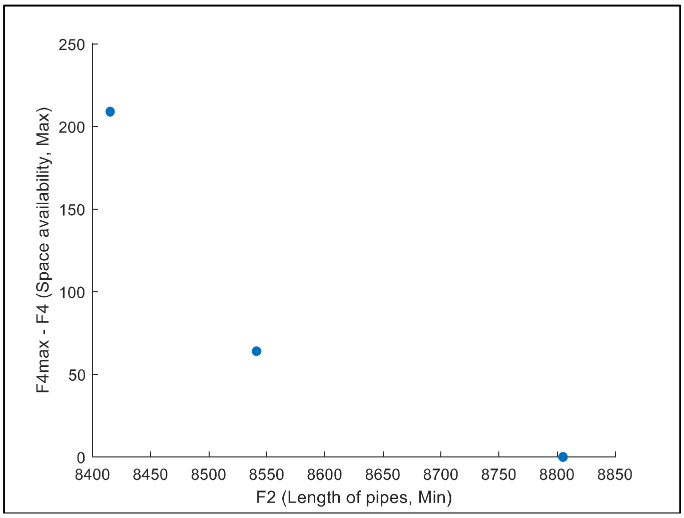


Figure 42. Relation analysis between F_2 and F_4

In Figure 42, F_2 (Pipe length) and F_4 (Space availability) were proportional to each other. Even in the verification example, they were proportional to each other, but if there was a bulkhead around the pipe path, the path became different. An example of an exception is shown in Figure 43.

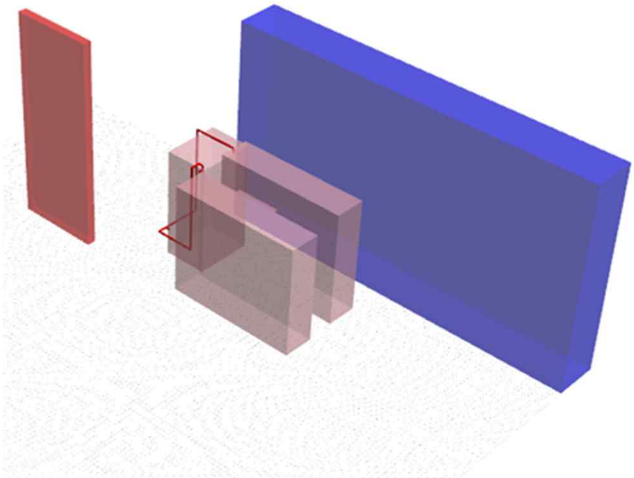


Figure 43. An example of an exception with a bulkhead around the pipe route

Figure 43 shows an exceptional case where the two objective functions may not be proportional to each other if the pipe routing is performed very inefficiently. It is also possible to have different results depending on the height of the deck, which is determined in the 1st stage. The next case is the relation analysis between F_1 (Occupied volume) and F_4 (Space availability). The result is shown in the following Figure 44.

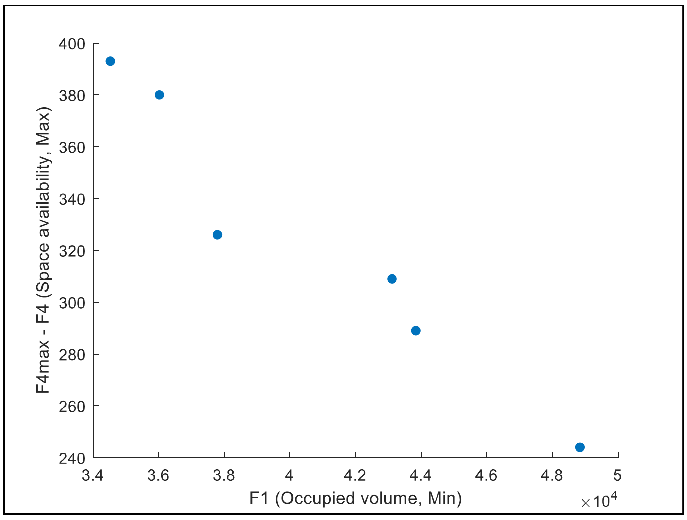


Figure 44. Relation analysis between F_1 and F_4

In Figure 44, F_1 (Occupied volume) was inversely proportional to F_4 (Space availability). However, while a typical inverse proportionality graph should be expected, the optimization problem in this study involves discrete design variables and objective functions, resulting in the Pareto set shown in Figure 44.

As results for analyses of all objective functions, when equipment is densely arranged, F_2 (Pipe length) and F_4 (Space availability) tend to decrease, but when the equipment is densely arranged beyond a certain level, the opposite tendency is shown to secure the space required for equipment maintenance. Space availability also tends to increase as F_2 (Pipe length) increases. Also, Equipment arrangement should be performed without excessively increasing F_2 (Pipe length) due to equipment being overcrowded. The combinations for all objective functions are shown in Figure 45 and Figure 46.

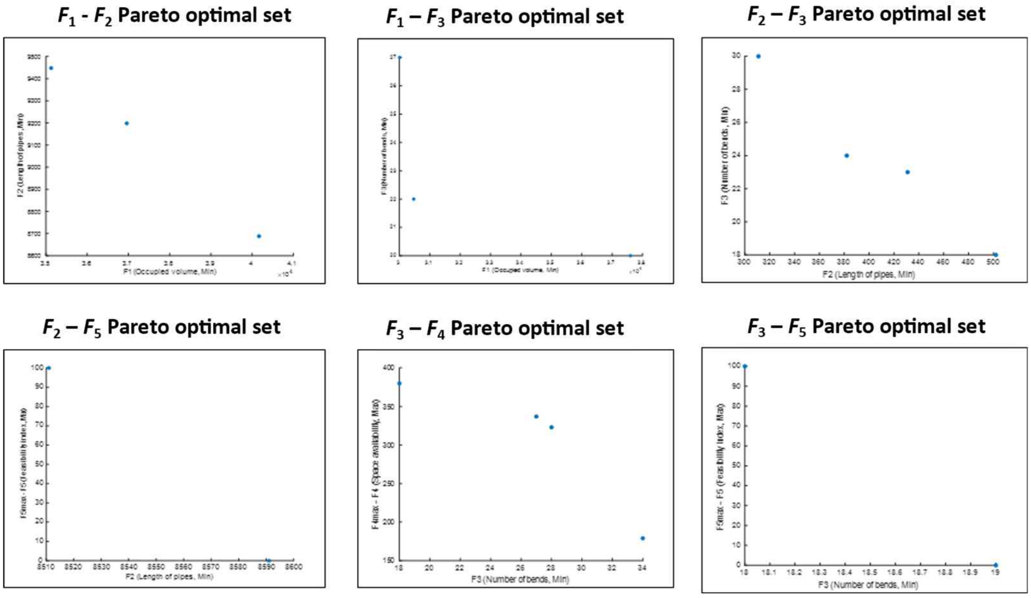


Figure 45. The combinations for all objective functions (1)

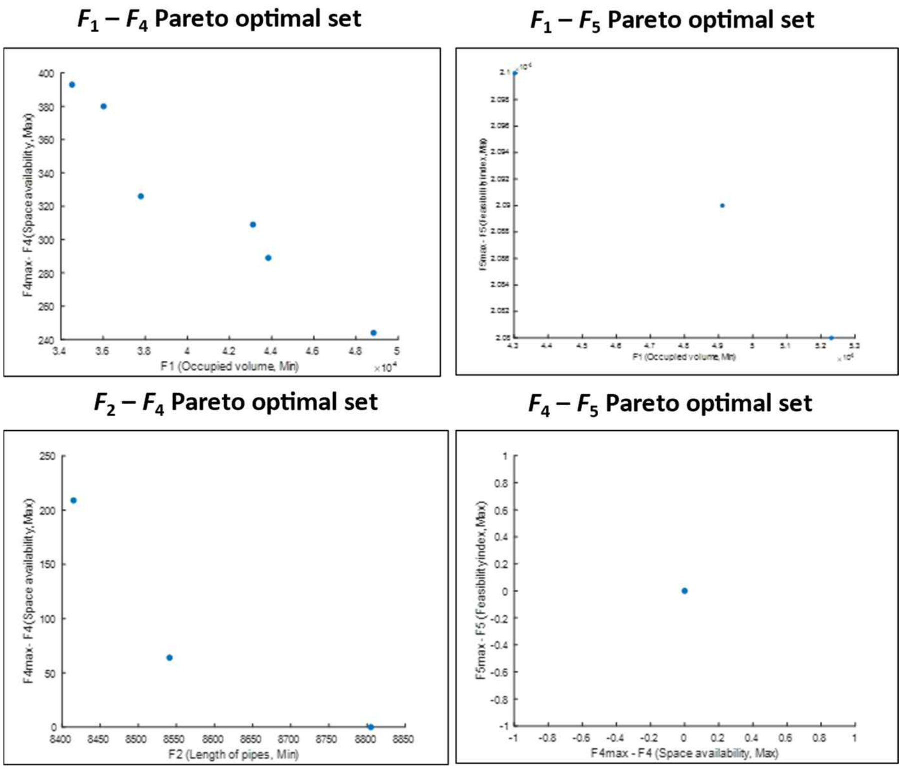


Figure 46. The combinations for all objective functions (2)

In Figure 45 and Figure 46, although the number of solutions is small, a tendency has been identified for each objective function. However, for F_5, the number of Pareto optimal sets is small because most solutions satisfy the expert knowledge to a similar level. The analysis of the three objective functions is shown below. The Pareto optimal set for the proposed optimization problem has been constructed. For better understanding, the three-dimensional Pareto optimal set is visualized in two views, as shown in Figure 47.

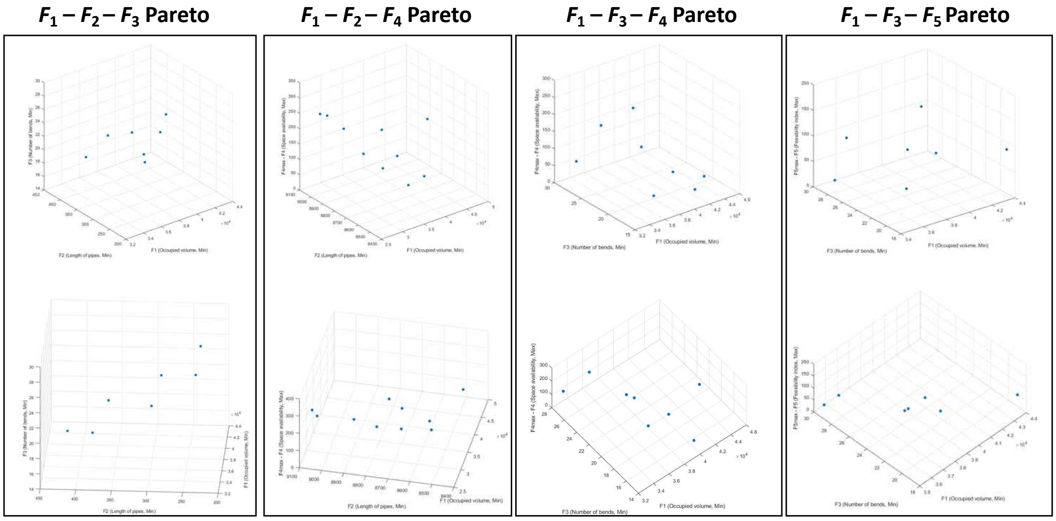


Figure 47. The combinations for all objective functions (3)

Figure 47 confirms that each Pareto set was successfully generated. The number of solutions that constitute the Pareto set for each case is not large, so it does not exactly create a Pareto surface, but the relation between the objective functions identified in the second dimension has been confirmed in the third dimension. The combinations for all objective functions are shown in Figure 48 and Figure 49.

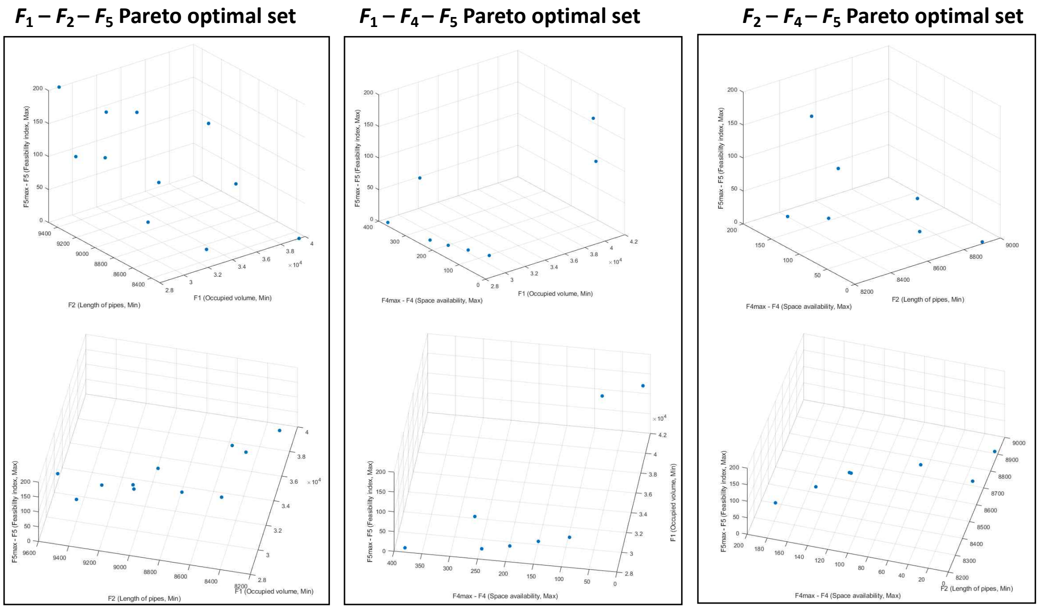


Figure 48. The combinations for all objective functions (4)

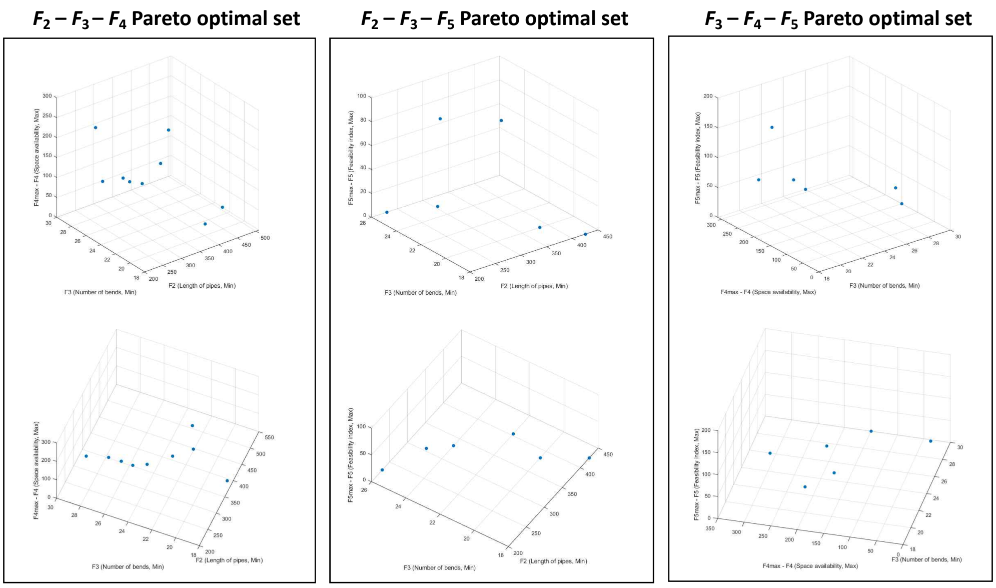
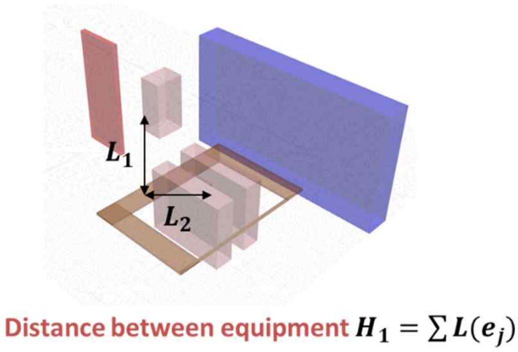


Figure 49. The combinations for all objective functions (5)

The relationship analysis for three objective functions shows the same results as for two objective functions. The objective functions that require minimization have an inverse relationship with each other and the opposite relationship with the objective function that requires maximization. Through the verification performed in this section, it is confirmed that the optimal solution corresponding to the Pareto optimal set can be obtained by selecting two or three of the objective functions proposed in this study. This proves that optimization can be successfully performed even for applications that utilize all five proposed objective functions.

3.3. Equipment arrangement using pipe routing

Section 3.3 verifies the difference between considering and not considering pipe routing in the equipment arrangement stage (1st stage). Existing studies did not perform actual pipe routing when performing equipment arrangement but performed equipment arrangement considering only the distance between equipment (Gunawan et al., 2021; Wang and Chen, 2021). In this study, in order to reduce errors and redesign efforts in the pipe routing stage, a simplified pipe routing is performed in the 1st stage, and an optimal arrangement is performed considering the total length of pipes as an objective function, as shown in Figure 50.



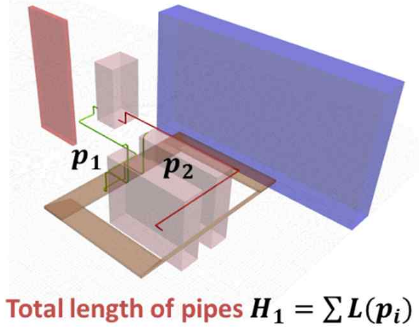
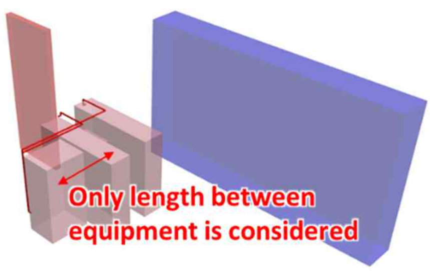


Figure 50. Comparison of the objective function of the length of pipes

In Figure 50, Case A show the pipe length is calculated using only the vertical/horizontal distance between equipment centers. In Case B, the pipe length is calculated by actual pipe routing between equipment. The optimal arrangement results for the verification cases are shown in Figure 51 and Table 21.



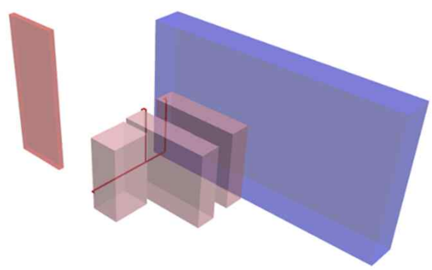


Figure 51. Results of verification considering pipe routing in the 1st stage (1)

Table 21 Results of verification considering pipe routing in the 1st stage (2)

Case	Using pipe routing	Total pipe length (F_1, Min) [m]	Space availability (F_2, Max)	Feasibility index (F_3, Max)	Computation time [sec]
Case A	X	11.9	51	760	56
Case B	O	9.7	52	760	245

In Figure 51 and Table 21, because Case A only considered the distance between the machines, it did not generate a proper pipe route, and a detour was created. Since Case B used an objective function that considers the actual pipe routing, the total pipe length (F_1) is much smaller. Therefore, if pipe routing is not considered at the stage of equipment arrangement, the pipe routing may not be performed properly or efficiently.

4. Applications

The target ship of the optimal arrangement is 320K VLCC (Very Large Crude-oil Carrier). In applications, optimal arrangements for three decks, 11 equipment, and 16 pipes in the engine room of 320K VLCC were performed. The principal dimensions of the target ship are as shown in the table below.

Table 22. Principal dimensions of the target ship

Principal dimensions	Value
LOA (Length overall)	332.0 m
LBP (Length between perpendiculars)	320.0 m
B (Breadth)	60.0 m
D (Depth)	30.5 m
Td / Ts (Design draft/Scantling draft)	21.0 / 22.5 m
Deadweight	320,000 ton

4.1. Overview of SyDLab Equipment/Pipe Arrangement Program

SyDLab Equipment/Pipe Arrangement Program based on the theoretical background. The program supports equipment arrangement and pipe routing. It is an in-house program written in C# (.Net), and Unity. It has components of Menu, 3D View, Simplifed View, Expert System View, Report View, etc. The program was developed as shown in Figure 52.

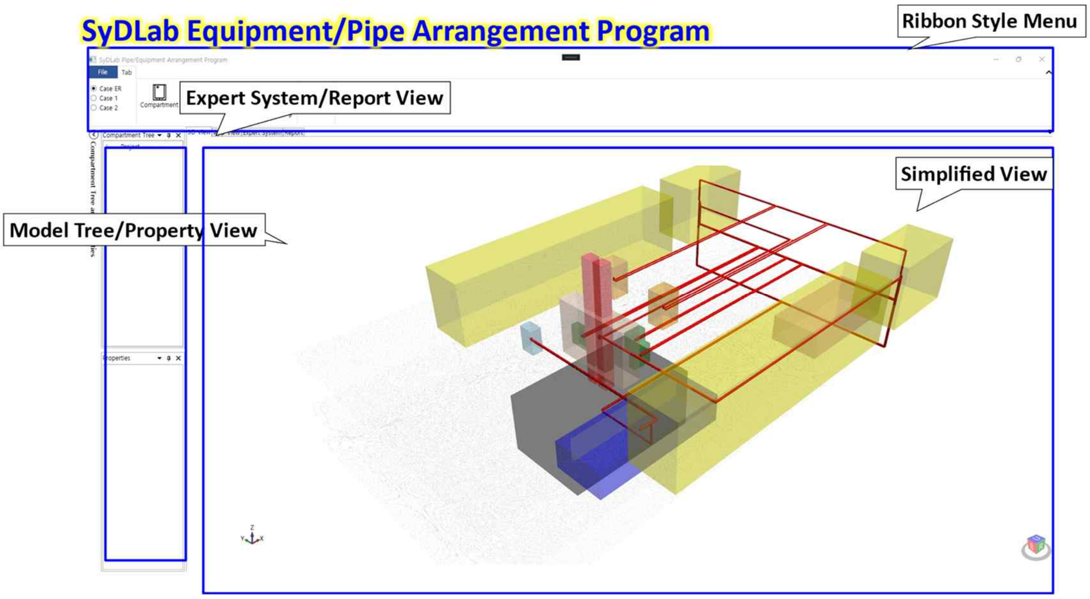


Figure 52. SyDLab Equipment/Pipe Arrangement Program (Simplified View)

In Figure 52, the Ribbon Style Menu at the top allows the designer to select the model and design stage for the arrangement. The equipment arrangement of the first stage and the pipe routing of the second stage can be performed separately or at the same time. In the Model Tree/Property View, you can understand the relation information and property information of the arranged objects. Simplified View visualizes the arrangement results in a simplified form so that designers can easily understand the arrangement results. An illustration of the 3D view is shown in Figure 53.

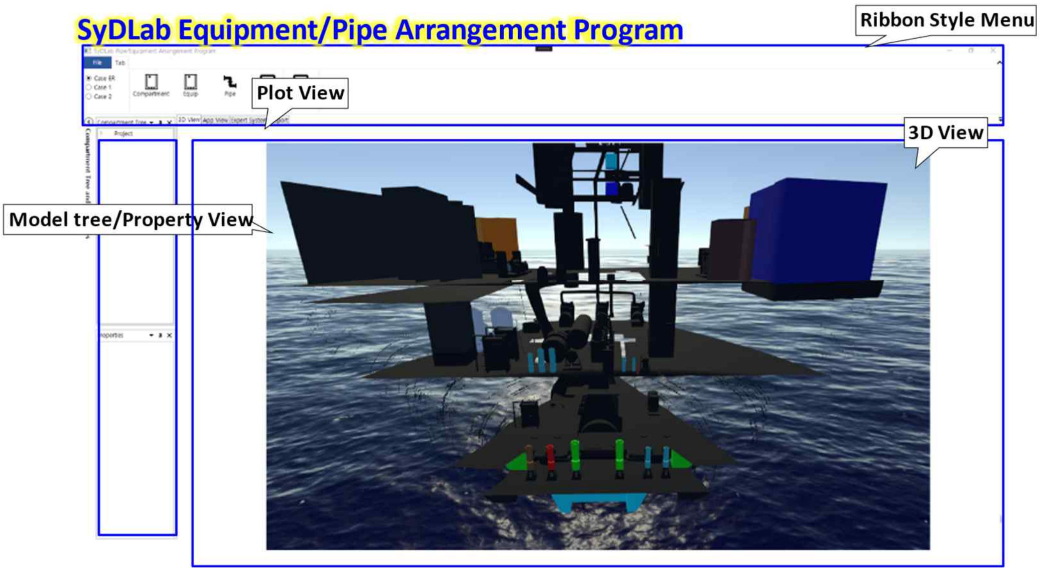


Figure 53. SyDLab Equipment/Pipe Arrangement Program (3D View)

In Figure 53, 3D View shows the results of visualizing a 3D model of the actual ship's engine room. Each equipment and pipe is represented with simplified shapes to clearly show the connections between them and help designers easily recognize them.

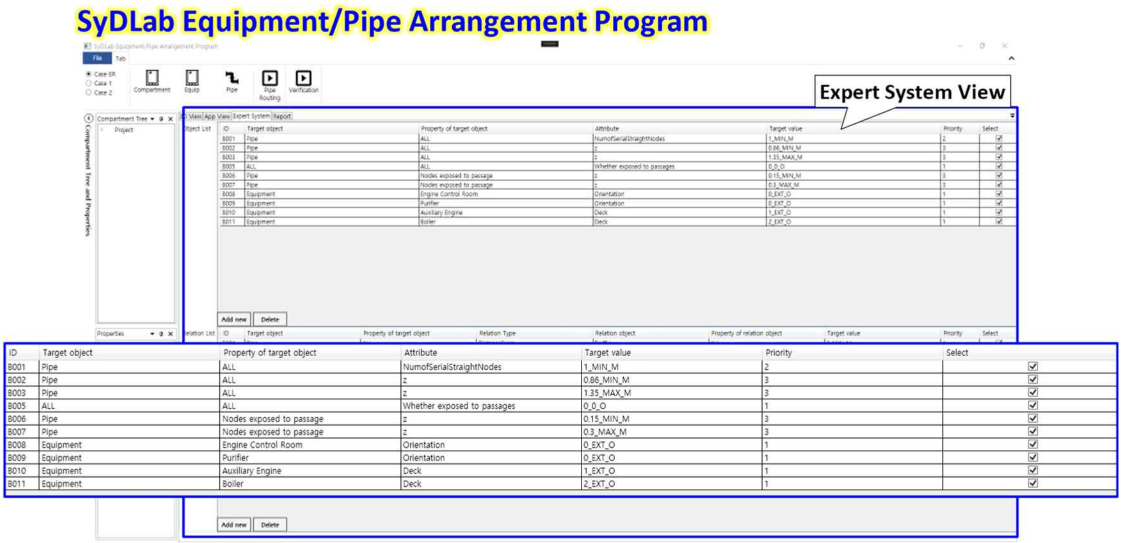


Figure 54. SyDLab Equipment/Pipe Arrangement Program (Expert System View)

Figure 54 shows the Expert System View of the program. In Expert System View, you can view, add, and modify the expert knowledge applied to the current arrangement target. The designer can add, delete, or modify the entered expert knowledge in the form shown in Figure 55.

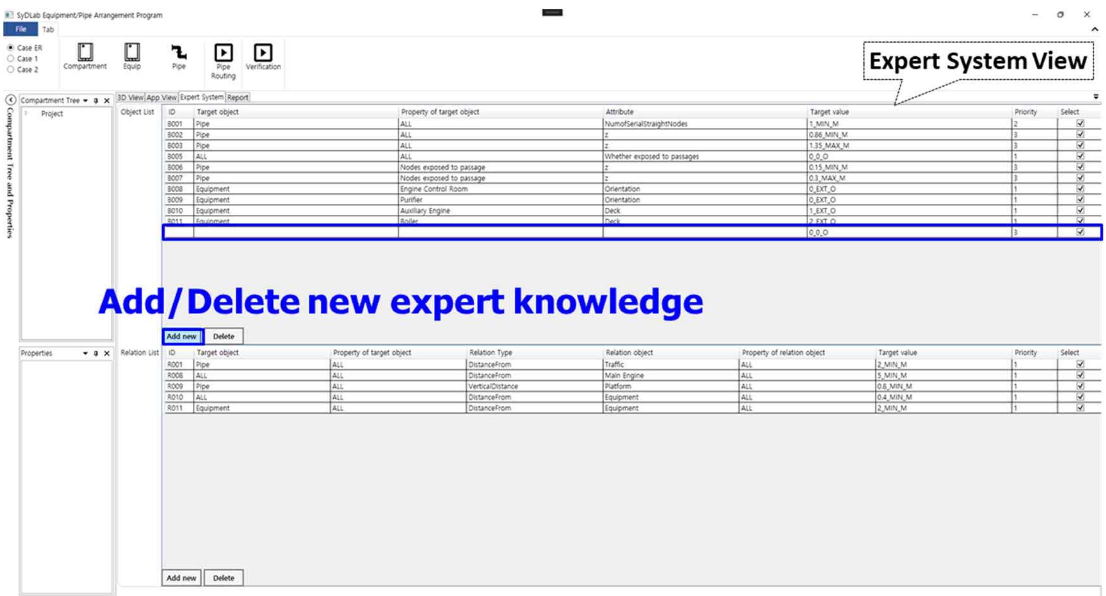


Figure 55. Add/delete new expert knowledge in Expert System View

The expert knowledge is represented by the AEM introduced in Section 2.1, and the expert knowledge applied to the applications in this study can be found in Section C of the APPENDICES. Report View visualizes the report for objective functions, constraint, and lightweight distribution and allows the user to review it. Figure 56 shows the graph for constraint in Report View.

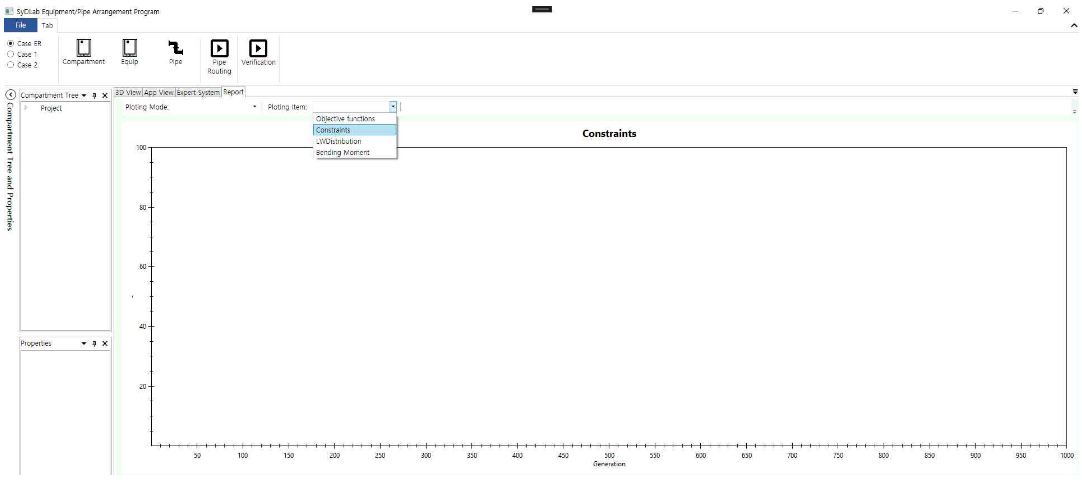


Figure 56. SyDLab Equipment/Pipe Arrangement Program (Report View - Constraints)

Figure 57 shows the screen where the designer can review the lightweight distribution in Report View.

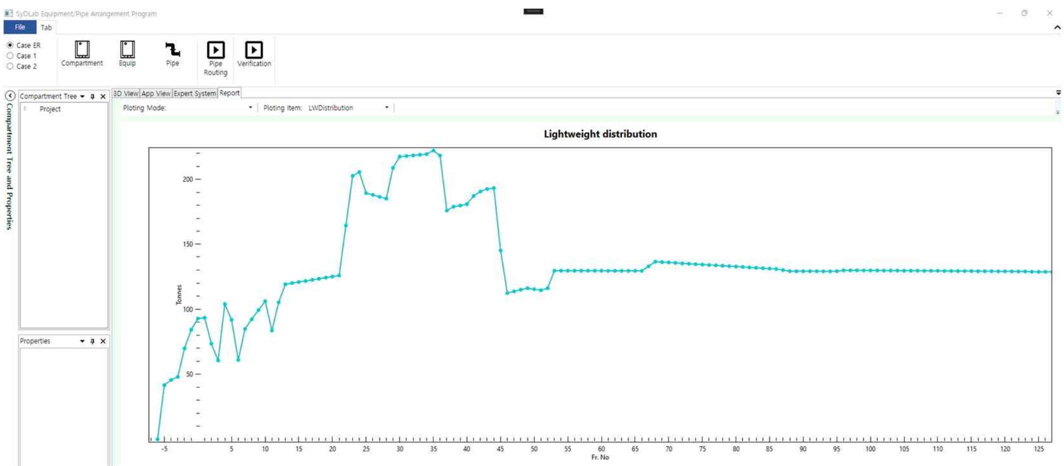


Figure 57. SyDLab Equipment/Pipe Arrangement Program (Report View –

Lightweight distribution)

Using Report View, a designer can review the lightweight distribution that has changed from the manual design. However, the equipment arrangement for the engine room in this study does not significantly change the weight distribution over the length of the ship.

4.2. Equipment Arrangement in Engine Room for 320K VLCC (1st stage)

In the 1st stage, the location of the deck in the engine room and the optimal arrangement of the equipment in terms of location and installation orientation is performed.

4.2.1. Input information

The design of the engine room of an existing ship is presented as a manual design, designed through expert interviews and previous data. The arrangement of decks and major equipment in the engine room of a 320K VLCC is shown in the following Figure 58.

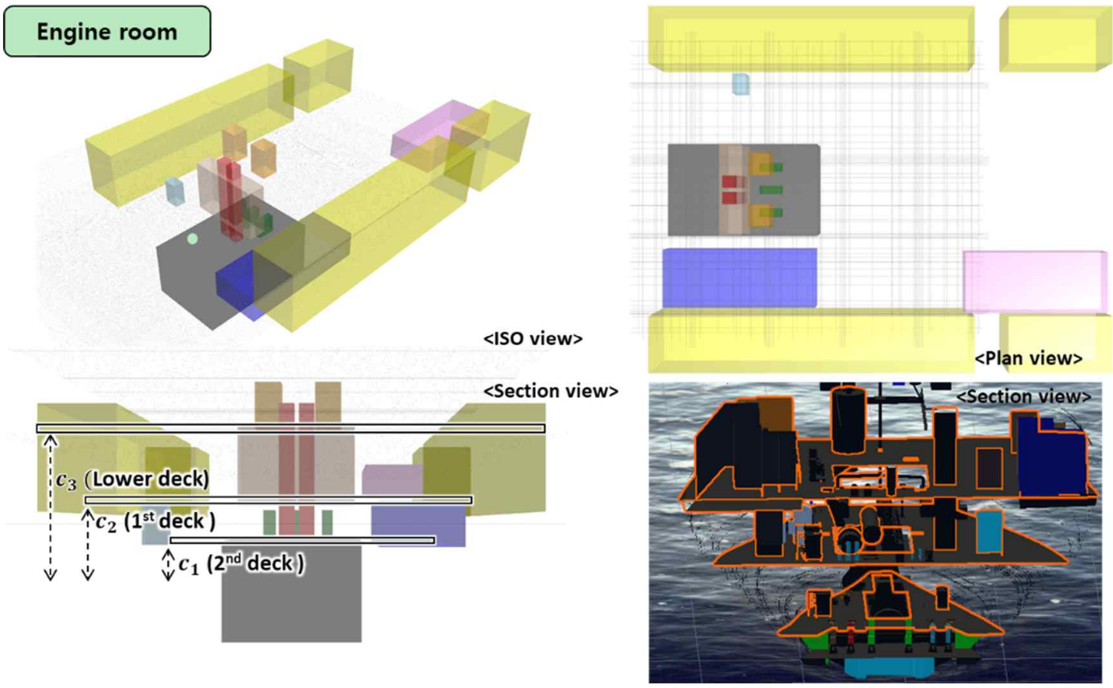


Figure 58. Decks and equipment arrangement of the manual design

In the engine room, the arrangement targets are three decks, 12 major equipment, and the pipes connecting the equipment. The result of calculating the objective function proposed in Section 2.2 for manual design is shown in Table 23 and Table 24.

Table 23. Deck heights of the manual design

	Manual design
Lower deck [m]	183.0

1st deck [m]	119.0
2nd deck [m]	60.0

Table 24. Comparison of global optimization algorithms in the test case

Objective function			Manual design
Economics	F_2 (Min)	Length of pipes and ducts [m]	910
	F_3 (Min)	Number of bends	27
Space availability	F_1 (Min)	Occupied volume [m^3]	54,416
	F_4 (Max)	Space availability of equipment	78.75
Expert system	F_5 (Max)	Feasibility index	16,581

The optimal arrangement is performed for the design variables and objective functions introduced in Section 2.2. The engine room, the space where the arrangement is performed, is 38.2 m wide, 60.0 m long, and 30.0 m high. The ranges of the design variables used are as follows:

$-15.0 \text{ m} < \Delta Zc_1, \Delta Zc_2, \Delta Zc_3 < 15.0 \text{ m}$

$0.0 \text{ m} < x_{ej} < 60.0 \text{ m}$

$0.0 \text{ m} < y_{ej} < 38.2 \text{ m}$

$0 < z_{ej} < 2$ (deck)

$0 < o_{ej} < 3$ [90 degrees]

ΔZ_{ci} means the height change of deck c_i. x_{ej} is the x-coordinate of equipment e_j, y_{ej} is the y-coordinate of equipment e_j, z_{ej} is the z-coordinate of equipment e_j. o_{ej} is the orientation of equipment e_j expressed in units of 90 degrees. The equipment arrangement problem is a multi-objective optimization problem. Since it is not practical to show all the optimization results for the five objective functions, we present the results for representative cases, as shown in Table 25.

Table 25. Categorized objective functions for economics, space availability, and expert systems

Objective function		
Economics (F_E)	F_2 (Min)	Length of pipes and ducts
	F_3 (Min)	Number of bends
Space availability (F_S)	F_1 (Min)	Occupied volume
	F_4 (Max)	Space availability of equipment
Expert system	F_5 (Max)	Feasibility index

To present representative cases, we have divided the objective functions into three categories. F_2 and F_3 are objective functions related to economics, F_1 and F_4 are objective functions related to space availability. Finally, F_5 is an objective function related to expert systems. We normalized the proposed objective functions to values between 0 and 1.

The solutions of the optimization results using the proposed objective functions are shown in Figure 59.

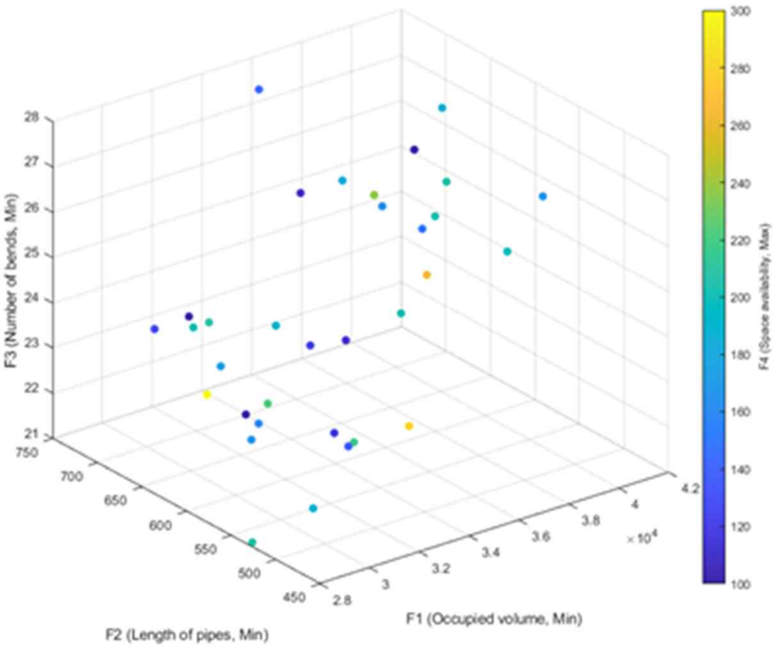


Figure 59. Pareto optimal of the 1st stage

Figure 59 shows the Pareto optimal obtained using the multi-objective optimization method for F_1, F_2, F_3, and F_4. The figure was plotted except for F_5, where the difference between the Pareto optimal was insignificant. Figure 60 shows Pareto fronts which were represented by a combination of two objective functions chosen from F_1, F_2, F_3, and F_4.

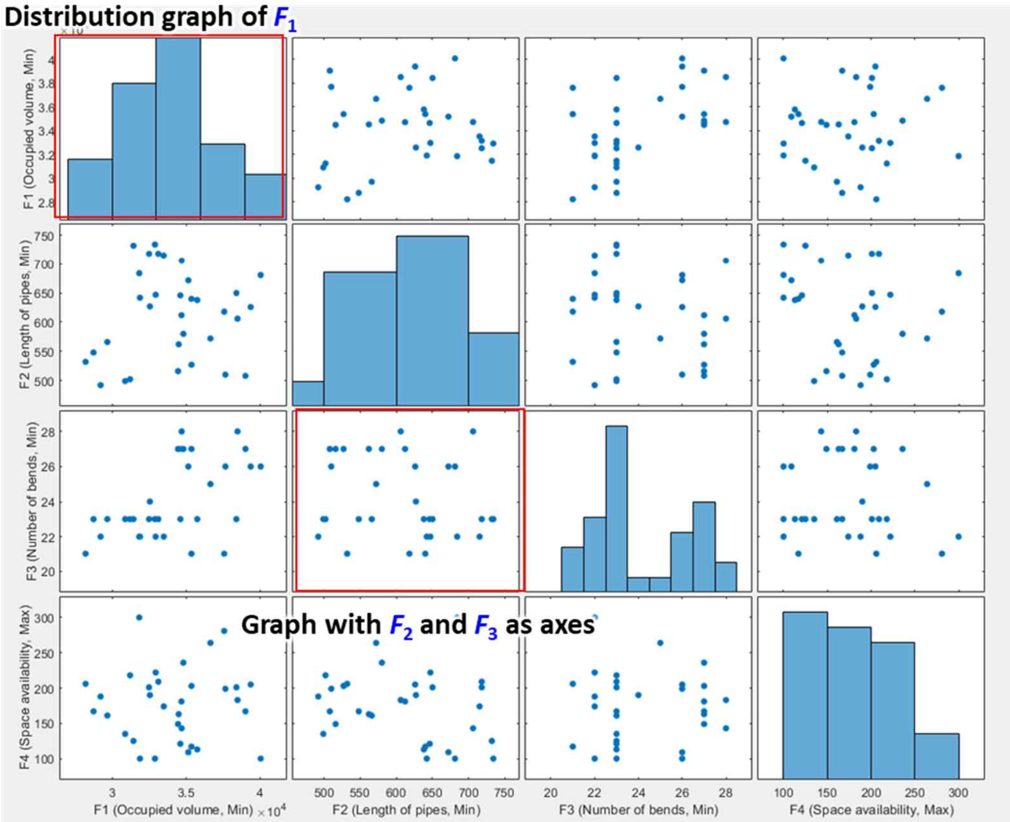


Figure 60. Preto fronts with combinations of two objective functions

In Figure 60, the Pareto optimal set for the five objective functions is visualized in two dimensions, therefore the Pareto lines are not clearly visualized. The best optimal solution with F_1, F_2, and F_4 were selected, as shown in Figure 61, Figure 62, and Figure 63.

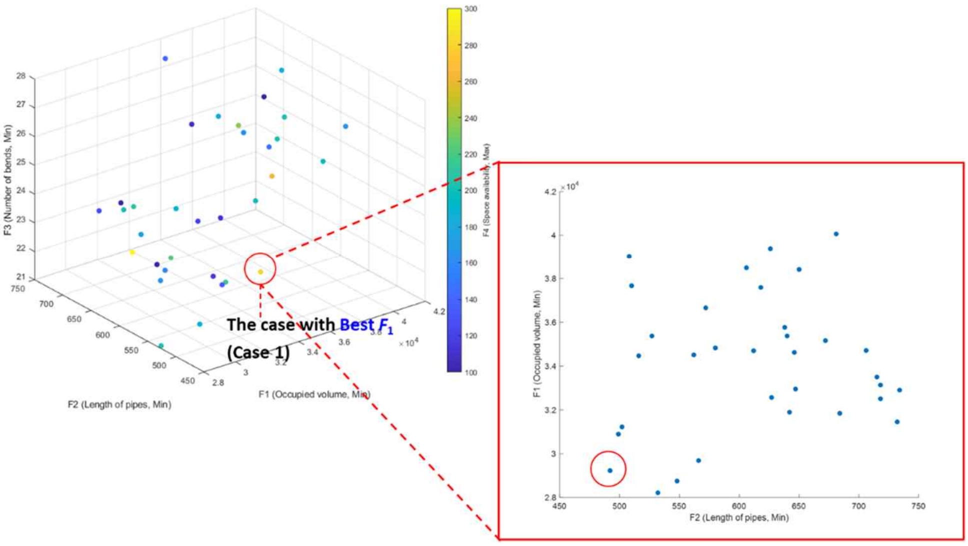


Figure 61. Selection of the case with Best F_1 (Case 1)

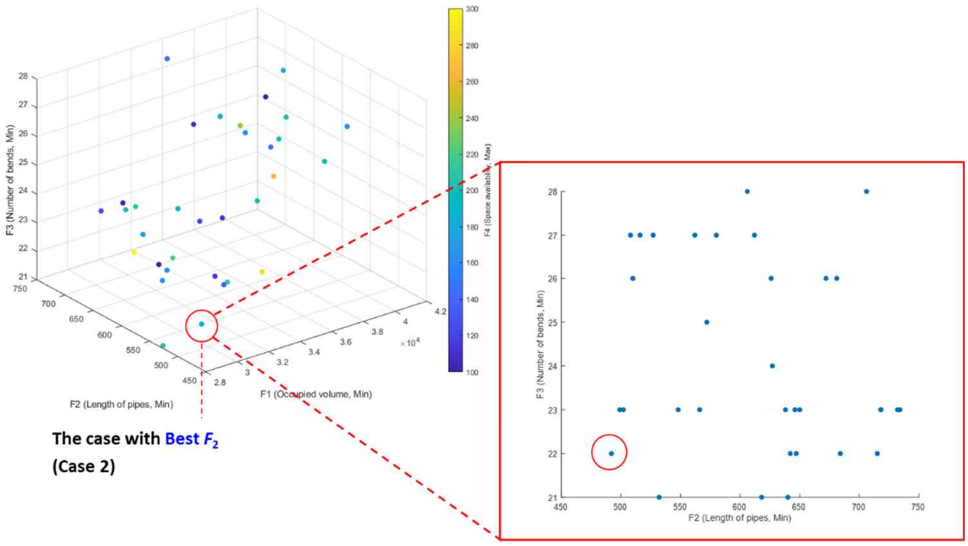


Figure 62. Selection of the case with Best F_2 (Case 2)

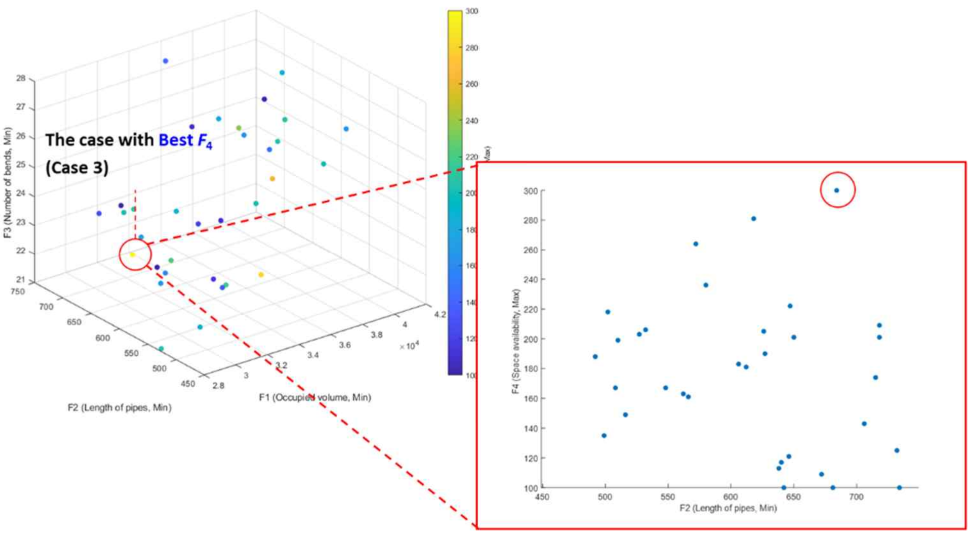


Figure 63. Selection of the case with Best F_4 (Case 3)

In solutions, the solutions represented by the red circles were the optimal fronts.

Case 1 was the most economical case with the most optimized value of F_1 and F_4. Case 2 is the most space-available case with the best F_2. Case 3 is the balanced case where both objective functions are properly considered. We present the results of each optimal front case in this section.

4.2.2. Case 1 results for the 1st stage

Case 1 is the best case for an objective function related to economics. The result of the arrangement of the decks for Case 1 is shown in Figure 64 and Table 26.

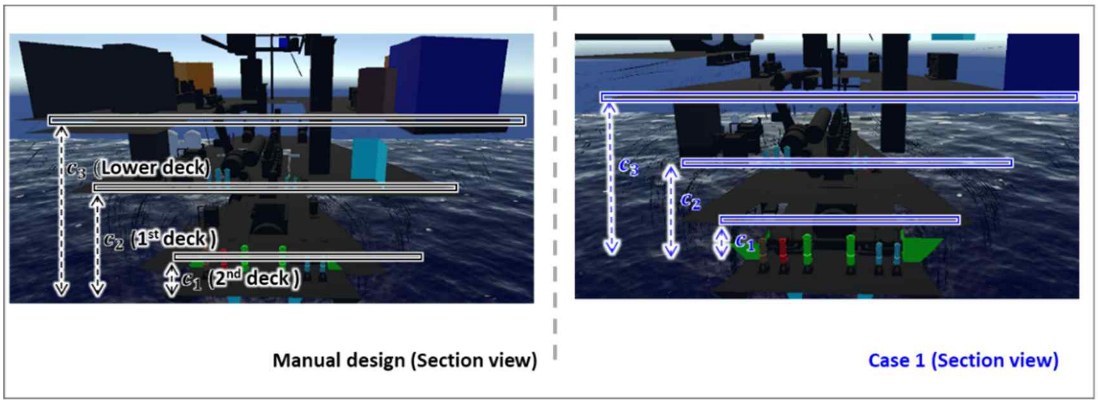


Figure 64. The result of the arrangement of decks for Case 1

Table 26. Deck heights of Case 1

	Manual design	Optimal design results (Case 1)
Lower deck [m]	183.0	186.0
1st deck [m]	119.0	132.0
2nd deck [m]	60.0	69.0

In Figure 64 and Table 26, the height all three were increased. The spacing between the 1st deck, where most of the equipment is installed, and the other decks has been reduced. This is a result of optimization to reduce the occupied volume of equipment and reduce the length of pipes. The results of the equipment arrangement for Case 1 are shown in Figure 65 and Table 27.

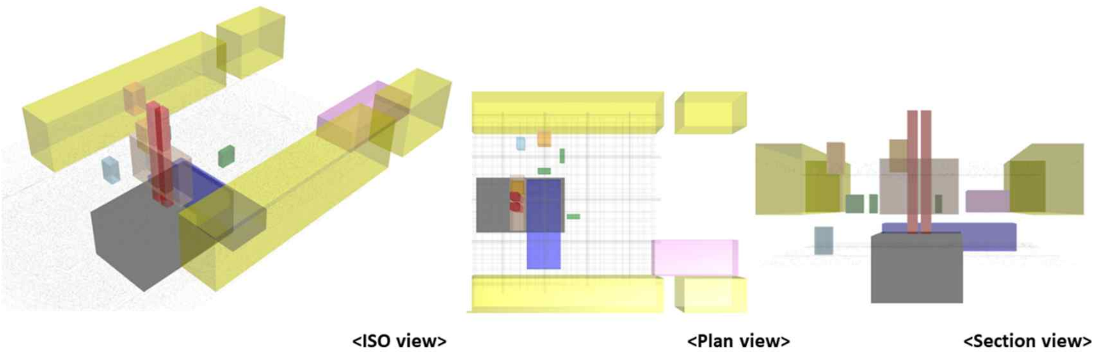


Figure 65. The result of the arrangement of equipment for Case 1

Table 27. Results of Case 1

Objective function			Manual design results	Optimal design results (Case 1)
Economics	F_2 (Min)	Length of pipes and ducts	910	608 (-33.2%)
	F_3 (Min)	Number of bends	27	23 (-14.8%)
Space availability	F_1 (Min)	Occupied volume	54,416	40,547 (-25.5%)
	F_4 (Max)	Space availability of equipment	78.75	215 (+173.0%)
Expert system	F_5 (Max)	Feasibility index	16,581	20,800 (+25.4%)

As a result of the optimal arrangement for Case 1, all objective functions were improved, especially objective functions related to economics. F_2 was improved by 33.2% compared to manual design results, and F_3 was improved by 14.8% compared to manual design results. F_1 and F_4 related to space availability improved by 25.5% and 173.0%, compared to manual design, and the feasibility index for expert knowledge (F_5) improved by 25.4%.

4.2.3. Case 2 results for the 1st stage

Case 2 considers objective functions related to space availability. The result of the arrangement of the decks for Case 2 is shown in Figure 66 and Table 28.

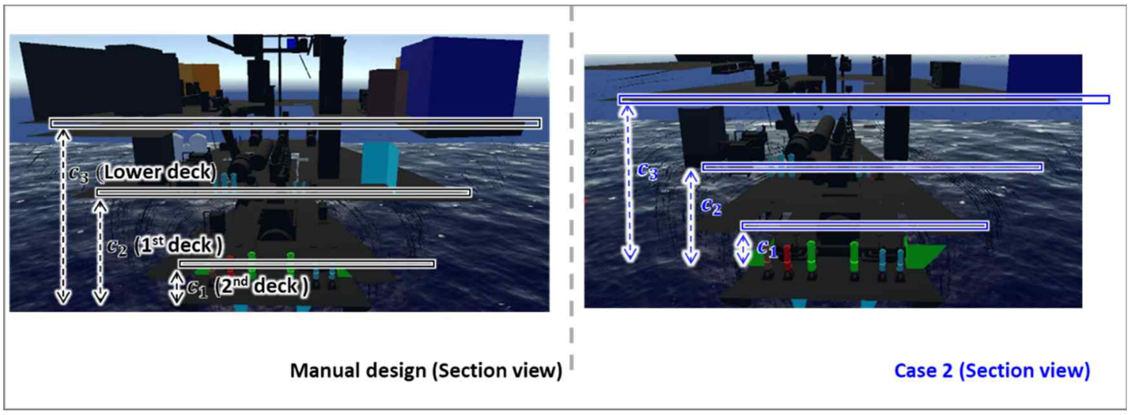


Figure 66. The result of the arrangement of decks for Case 2

Table 28. Deck heights of Case 2

	Manual design	Optimal design results (Case 2)
Lower deck [m]	183.0	178.0
1st deck [m]	119.0	122.0
2nd deck [m]	60.0	69.0

As result of the arrangement of decks for Case 2, the height of the lower deck was decreased, and the heights of 1st deck and 2nd deck were increased. As in Case 1, the optimization is performed in the direction of closing the other two decks to the 1st deck. The results of the equipment arrangement for Case 2 are shown in Figure 67 and Table 29.

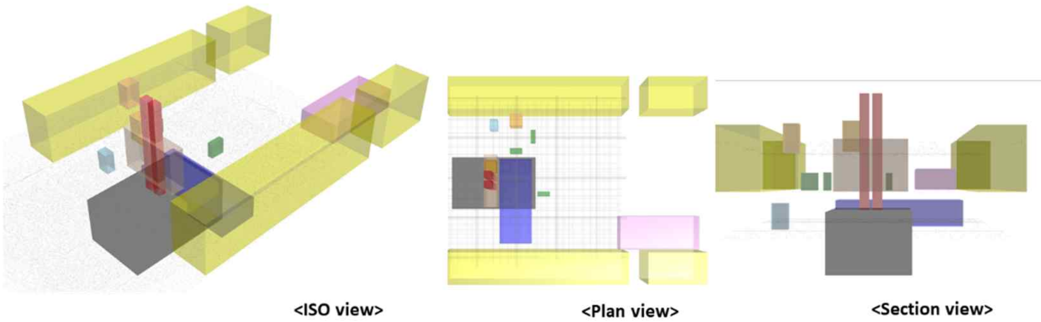


Figure 67. The result of the arrangement of equipment for Case 2

Table 29. Results of Case 2

Objective function			Manual design results	Optimal design results (Case 2)
Economics	F_2 (Min)	Length of pipes and ducts	910	632 (-30.5%)
	F_3 (Min)	Number of bends	27	23 (-14.8%)
Space availability	F_1 (Min)	Occupied volume	54,416	33,221 (-38.9%)
	F_4 (Max)	Space availability of equipment	78.75	308 (+291.1%)
Expert system	F_5 (Max)	Feasibility index	16,581	20,900 (+26.0%)

In Table 29, as a result of the optimal arrangement, all objective functions were improved, especially objective functions related to space availability. F_1 was improved by 38.9% compared to manual design results, and F_4 was improved by 291.1% compared to manual design results. F_5 also improved by 26.0%. Compared to Case 1, where the objective functions related to Economics were better improved, those objective functions were improved less, but other objective functions were improved more.

4.2.4. Case 3 results for the 1st stage

Case 3 is the case where all objective functions are considered in balance. The result of the arrangement of the decks for Case 3 is shown in Figure 68 and Table 30.

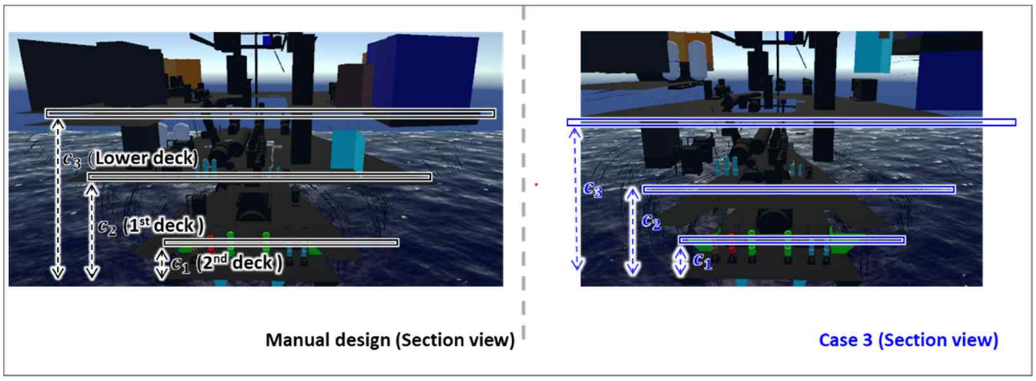


Figure 68. The result of the arrangement of decks for Case 3

Table 30. Deck heights of Case 3

	Manual design	Optimal design results (Case 3)
Lower deck [m]	183.0	181.0
1st deck [m]	119.0	120.0
2nd deck [m]	60.0	64.0

As a result of the arrangement for Case 3, the height of the lower deck and 1st deck decreased. The results of the equipment arrangement for Case 3 are shown in Figure 69 and Table 31.

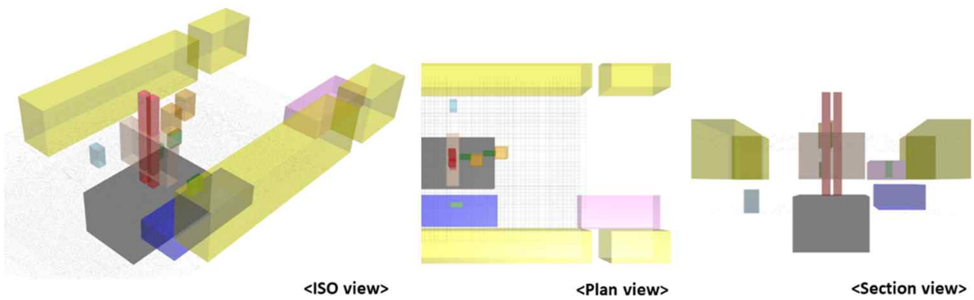


Figure 69. The result of the arrangement of equipment for Case 3

Table 31. Results of Case 3

Objective function			Manual design	Optimal design results (Case 3)
Economics	F_2	Length of pipes and	910	636 (-30.1%)

	(Min)	ducts		
	F_3 (Min)	Number of bends	27	21 (-22.2%)
Space availability	F_1 (Min)	Occupied volume	54,416	33,644 (-38.2%)
	F_4 (Max)	Space availability of equipment	78.75	144 (+82.9%)
Expert system	F_5 (Max)	Feasibility index	16,581	20,800 (+25.4%)

As a result of the arrangement for Case 3, there were balanced improvements to all objective functions. F_2 improved by 30.1%, and F_3 improved by 22.2% compared to manual design results. F_1 improved by 38.2%, and F_4 improved by 82.9%. F_5, an objective function related to expert systems, also improved by 25.4% compared to manual design results.

4.2.5. Summary of the 1st stage results

Table 32 summarizes the results of the optimal arrangement performed for the 1st stage.

Table 32. Summary of the 1st stage results

Objective function	Manual design	Best F_1 (Case 1)	Best F_2 (Case 2)	Best F_4 (Case 3)

Economics	F_2 (Min)	Length of pipes and ducts [m]	910	532 (-41.5%)	492 (-45.9%)	632 (-30.5%)
	F_3 (Min)	Number of bends	27	21 (-22.2%)	22 (-18.5%)	23 (-14.8%)
Space availability	F_1 (Min)	Occupied volume [m3]	54,416	28,214 (-48.1%)	29,228 (-46.3%)	33,221 (-38.9%)
	F_4 (Max)	Space availability of equipment	78.75	206 (+161.6%)	188 (+138.7%)	308 (+291.1%)
Expert system	F_5 (Max)	Feasibility index	16,581	20,800 (+25.4%)	20,900 (+26.0%)	20,900 (+26.0%)
Improvement rate (Average)				59.8%	55.1%	80.3%

In Case 1, the objective function related to economics was improved. Compared to the manual design, the objective functions in Case 1 improved by an average of 59.8%. In Case 2, the objective functions related to space availability were improved the most, and in particular, the space availability of equipment was improved the most. Also, the feasibility index showed the best results among the cases. Compared to the manual design, the objective functions in Case 2 improved by an average of 55.1%. Finally, in Case 3, all objective functions were improved evenly. Compared to the manual design, the objective functions in Case 3 improved by an average of 80.3%. The optimization results for the 1st stage showed that the objective function could be significantly improved in all cases. The manual design being compared is a reconstruction based on expert knowledge and drawings that closely approximates the design used on the actual ship. There is some expert knowledge that cannot be expressed, and the manual design sacrifices objective functions for ease of production. Since we only arranged 11 major equipment, we could not evaluate other equipment. We hope to compensate for this in future research.

Overall, among the optimal solutions, we chose Case 3 with the largest improvement in F_4 and average objective functions to perform the 2nd stage, pipe routing.

4.3. Pipe Routing Design in Engine Room for 320K VLCC (2nd stage)

In the 2nd stage of the arrangement, pipe routing design is performed based on the results of equipment arrangement in Case 3 of Section 4.2. The result of formulating the problem of the 2nd stage proposed in Section 2.3 is as follows.

In the 2nd stage, each coordinate of the pipe nodes n_j (x, y, z) was set as a design variable. For the pipe routing, we performed the larger diameter pipes first. For objective functions, minimize total length of pipes (F_1), minimize total number of bends (F_2), maximize space availability of pipes (F_3), and maximize feasibility index of pipes (F_4) were set. For constraints, collision with obstacles in the equipment installation area (pipe Installation available area) was checked. For the route generation method, JPS algorithm was used.

As in the first stage, three pipe routing design cases were proposed by combining the objective functions proposed in Section 2.3. Case 1 considered the objective function related to economics, and Case 2 considered the objective function related to spatial availability. In Case 3, all objective functions were considered balanced, and the feasibility index of expert knowledge was considered in all cases. After normalizing the value of each objective function between 0 and 1, it is calculated by Eq. (14)

$$F = w_1F_1 + w_2F_2 + w_3F_3 + w_4F_4 \tag{14}$$

In Eq. (14), w_n are weights between 0 and 1 for each objective function. The optimal solution was derived by assigning weight factors to each objective function. The case study in this section was applied to examine the effect of weight factors for each objective function.

This study presents an initial design to be used as a standard for pipe routing results. This is pipe routing results considering only the basic objective functions. Among the objective functions proposed in Section 2.3, only F_1 and F_2 were considered, and pipe routing was performed for 16 major pipelines. The results are shown in Figure 70 and Table 33.

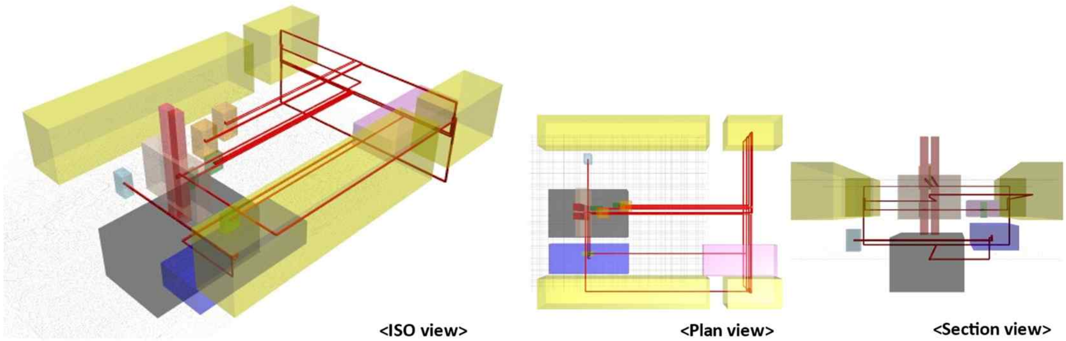


Figure 70. Results of initial design results (1)

Table 33. Results of initial design results (2)

Objective function			Economics (Case 1)	Initial design results
Economics	F_1 (Min)	Length of pipes and ducts [m]	0.25	1,775
	F_2 (Min)	Number of bends	0.25	31
Space availability	F_3 (Max)	Space availability of pipes	0	768
Expert system	F_4 (Max)	Feasibility index	0.5	4,989

In Figure 70 and Table 33, pipe routing was performed to optimize F_1 and F_2, which were considered as objective functions. However, F_3 and F_5, which were not considered as objective functions, were not optimized. In Section 4.3, the pipe routing results are compared against the initial design.

4.3.1. Case 1 results for the 2nd stage

Case 1 is the result of performing pipe routing considering the length of pipes and ducts (F_1), and number of bends (F_2) related to economics as the objective functions. The results are shown in Figure 71 and Table 34.

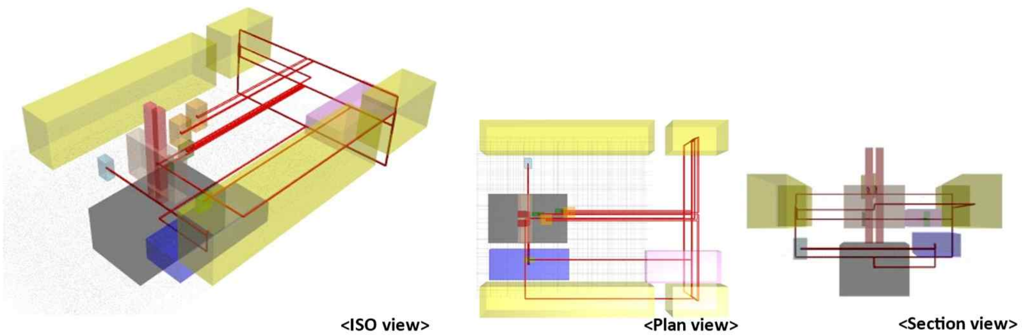


Figure 71. Results of Case 1 in the 2nd stage (1)

Table 34. Results of Case 1 in the 2nd stage (2)

Objective function			Economics (Case 1)	Initial design	Optimal design results
Economics	F_1 (Min)	Length of pipes and ducts [m]	0.25	1,775	1,773 (-0.1%)
	F_2 (Min)	Number of bends	0.25	31	31 (+0.0%)

Space availability	F_3 (Max)	Space availability of pipes	0	768	915.0 (+19.1%)
Expert system	F_4 (Max)	Feasibility index	0.5	4,989	5021.5 (+0.7%)

As a result of pipe routing for Case 1, F_1, F_2, and F_5 considered in Case 1 did not achieve better results compared to the initial design. Compared to the initial design, F_1, F_2, and F_5 are 2.7%, 7.4%, and 0.8% worse, respectively. In Case 1, space availability was not considered, so pipe routing was performed at the height where pipe support is difficult to install. The following Figure 72.

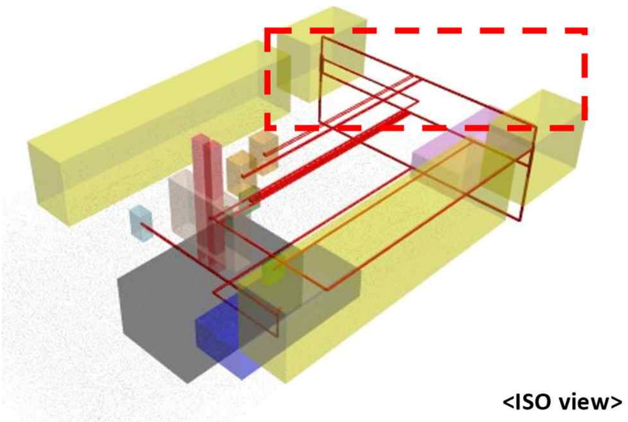


Figure 72. Problematic pipe routing at a height where pipe support is difficult to install

The red rectangle in Figure 72 was the result of performing pipe routing at a height where it was difficult to install pipe supports because space availability was not considered.

4.3.2. Case 2 results for the 2nd stage

Case 2 is the result of performing pipe routing considering an objective function related to space availability. The results are shown in Figure 73 and Table 35.

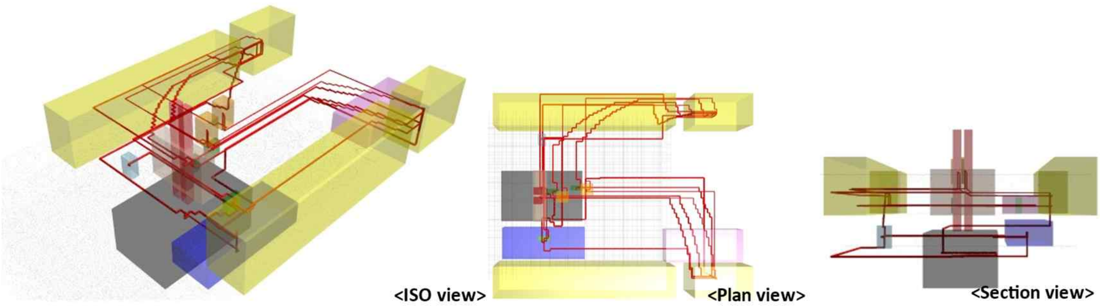


Figure 73. Results of Case 2 in the 2nd stage (1)

Table 35. Results of Case 2 in the 2nd stage (2)

Objective function			Space availability (Case 2)	Initial design	Optimal design results
Economics	F_1 (Min)	Length of pipes and ducts [m]	0	1,775	1,975 (+11.3%)

	F_2 (Min)	Number of bends	0	31	275 (+787.1%)
Space availability	F_3 (Max)	Space availability of pipes	0.25	768	840.0 (+9.4%)
Expert system	F_4 (Max)	Feasibility index	0.5	4,989	4,300.8 (-13.8%)

The pipe routing for Case 2 resulted in a lot of bends, and the length of the pipes was not taken into account at all. Compared to the initial design, F_3 did not improve, F_1 increased by 4.0%, and F_2 increased by 311.1%.

4.3.3. Case 3 results for the 2nd stage

Case 3 is the result of pipe routing considering all the proposed objective functions in a balanced case. The results are shown in Figure 74 and Table 36.

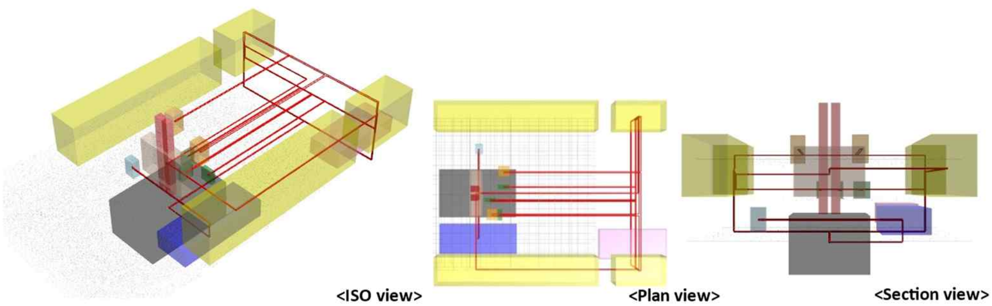


Figure 74 Results of Case 3 in the 2nd stage (1)

Table 36. Results of Case 3 in the 2nd stage (2)

Objective function			Balance (Case 3)	Initial design	Optimal design results
Economics	F_1 (Min)	Length of pipes and ducts [m]	0.2	1,775	1,775 (+0.0%)
	F_2 (Min)	Number of bends	0.2	31	29 (-6.5%)
Space availability	F_3 (Max)	Space availability of pipes	0.2	768	911.3 (+18.6%)
Expert system	F_4 (Max)	Feasibility index	0.2	4,989	5,002.1 (+0.26%)

As a result of pipe routing for Case 3, each objective function improved by 5.1% for F_5 and 0.2% for F_3 compared to the initial design. All five objective functions are optimized well.

4.3.4. Summary of the 2nd stage results

A summary of the results for all cases is shown in Table 37.

Table 37. Summary of pipe routing results for 2nd stage

Objective function			Initial design	Economics (Case 1)	Space availability (Case 2)	Balance (Case 3)
Economics	F_1 (Min)	Length of pipes and ducts [m]	1,775	1,773 (-0.1%)	1,975 (+11.3%)	1,775 (+0.0%)
	F_2 (Min)	Number of bends	31	31 (+0.0%)	275 (+787.1%)	29 (-6.5%)
Space availability	F_3 (Max)	Space availability of pipes	768	915.0 (+19.1%)	840.0 (+9.4%)	911.3 (+18.6%)
Expert system	F_4 (Max)	Feasibility index	4,989	5021.5 (+0.7%)	4,300.8 (-13.8%)	5,002.1 (+0.26%)
Improvement rate (Average)				4.0%	-160.6%	5.1%

In Case 1, the objective function related to economics was improved. Compared to the initial design, objective functions in Case 1 improved by an average of 4.0%. In Case 2, many bends occurred because the bends were not considered, which would cause serious pressure drops and increase costs. In Case 3, all objective functions were improved evenly. Compared to the initial design, objective functions in Case 3 improved by an average of 5.1%. This confirms that a pipe routing design that utilizes the objective functions proposed in this study evenly can generate pipe routes that fit the designer's intention.

5. Conclusions and future works

5.1. Summary

This study focused on the optimal arrangement of equipment and pipes in a ship's engine room. For the arrangement, an expert system was applied to apply expert knowledge and know-how. In addition, a two-stage optimization method was proposed to perform equipment arrangement and pipe routing effectively. The proposed method was applied to the engine room arrangement of a 320K VLCC through the developed program, and the results were compared/analyzed with the manual design.

Firstly, the expert system for the ship's engine room arrangement was introduced to develop the arrangement process. The data required for the arrangement was stored in the ATM by the expert system and evaluated by AEM. In this process, we improved AEM to adapt it to the arrangement of this study. The feasibility index calculated by the expert system was utilized as an objective function in the equipment arrangement and pipe routing process.

In two-stage optimization, the first stage performed the optimal arrangement of the height of the deck in the engine room and the location and orientation of the equipment. The objective functions were the occupied volume of the engine room, the length and the number of bends in pipes and bends, the space availability of the equipment, and the feasibility index of the equipment. The area in which the equipment can be installed was set as a constraint. For equipment arrangement, several global optimization methods were applied, and the most suitable method for this study was selected.

The second stage optimizes the routing of the pipes and ducts connecting the arranged equipment. This process determined the coordinates of the nodes that compose the pipe routing, and the objective function calculated the total length of pipes and the total number of bends, the space availability of pipes, and the feasibility for expert knowledge. The constraints were installation availability, taking into account the arrangement of the equipment and existing pipes and ducts. For the route generation method, both optimization and pathfinding algorithms are examined, and the JPS algorithm was selected for pipe routing. In addition, a dynamic grid method was used to improve the computation time for pipe routing.

In the verification section, several verification examples were provided for verifying variables and objective functions of the optimization problem. The test examples and methods are summarized in Table 38.

Table 38 Verification cases

Verifications	Tests		Method
Sensitivity analysis	Sensitivity analysis	Design of experiment using the Taguchi method	Comparison of parameter effects
Analysis of objective functions in the 1st stage	Relationship analysis	.	Relationship analysis between objective functions

Equipment arrangement using pipe routing	Optimal equipment arrangement	Simple arrangement cases	Comparison of equipment arrangements with and without pipe routing

Finally, to verify the effectiveness of the proposed method, the optimal layout of the engine room of a 320,000-ton deadweight very large crude carrier (VLCC) was performed. The results verified that the proposed method could derive the optimal arrangement for the decks, equipment, and pipes of the ship's engine room.

5.2. Contributions (Originality)

This study has several contributions distinguished from the other works.

5.2.1. Theoretical contributions

In this study, an expert system was used to evaluate the feasibility index of expert knowledge of design alternatives for equipment arrangement and pipe routing. In this process, we proposed an Arrangement Evaluation Model that adds properties of the object to be suitable equipment and pipes. The improved expert system was utilized to represent and evaluate the expert knowledge related to equipment arrangement and pipe routing and the optimal arrangement method of equipment and pipes inside the engine room, considering the expert knowledge was proposed.

5.2.2. Contributions for application

This study proposed several methods for equipment arrangement to improve the accuracy of equipment arrangement. In the optimization process, this study proposed an optimal equipment arrangement method that considers space availability and expert knowledge as objective functions. In addition, this study proposed a method that can derive a more accurate optimal arrangement by considering the equipment and piping arrangement of the ship together to perform equipment arrangement inside the engine room and propose an improved equipment arrangement.

In the piping arrangement stage, we proposed a method to perform optimal pipe routing considering the economics and space availability of design alternatives.

5.2.3. Other contributions

The proposed equipment arrangement and pipe routing for ship's engine room were all developed as the program in C# programing language and Unity. The program helps designers review the situation with the equipment arrangement, pipe routing, and expert system.

5.3. Future works

Future research will focus on the validation and improvement of the suggested methods. The computation time required for the pipe arrangement process will be improved. Then, the optimization of the feasibility index will be improved by utilizing a hybrid method or by improving the heuristic function of the route generation algorithm. The hybrid method is a method that combines an optimization method and a route generation method for pipe routing to optimize objective functions globally. The proposed route generation method is focused on providing fast results in the pipe routing stage because it only presents one route at a time. However, it is not suitable for calculating and optimizing various properties of the pipe, such as stress calculation and pressure drop. The hybrid method is expected to be able to perform pipe routing with these shortcomings. One of the other possible improvements is the enhancement of the heuristic function, which is expected to take into account future expert knowledge in route selection. Also, the pressure drop and flow rate for the branch pipe routing will be calculated, and the optimal pipe routing method considering this will be studied. Moreover, system and equipment modules often make equipment arrangements and pipe routing in the actual arrangement design process. By dividing the process of pipe routing into a pattern constituting an equipment module and a general line, the arrangement process considering the characteristics of the actual design will be performed. Various bending angles of pipes should also be considered. In this study, only pipe routing in the length-breadth-depth direction of the ship was performed, but some pipes in the actual ship may have diagonal routes, which should be considered. Finally, additional expert knowledge will be secured through collaboration with each shipyard, and arrangement results will be verified.

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APPENDICES

A. Pressure drop of pipes

In this section, a review of the selection of pressure drop of pipes as the objective function is performed. For the verification case, the objective functions and constraints proposed in Section 2.3 were used for pipe routing. For the route generation method, the A* algorithm was used. The verification case is shown in Figure 75, where pipe routing was performed for two pipes connecting equipment A and equipment B.

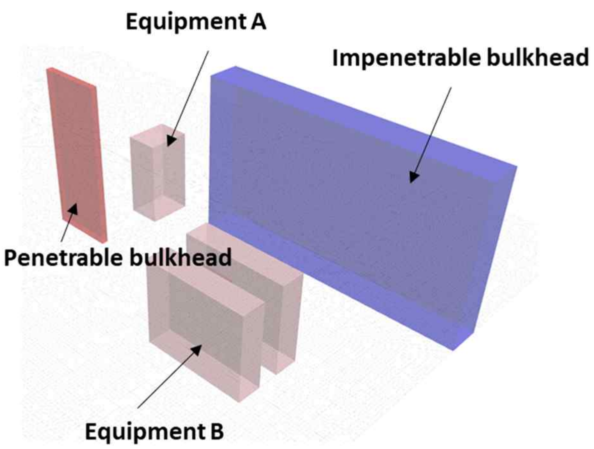

Figure 75. Verification case for pipe routing considering pressure drop of fluids

The results are shown in Figure 76 and Table 39. Case C is the verification case without considering the pressure drop of fluids in pipes, and Case D is the verification case considering the pressure drop of pipes.

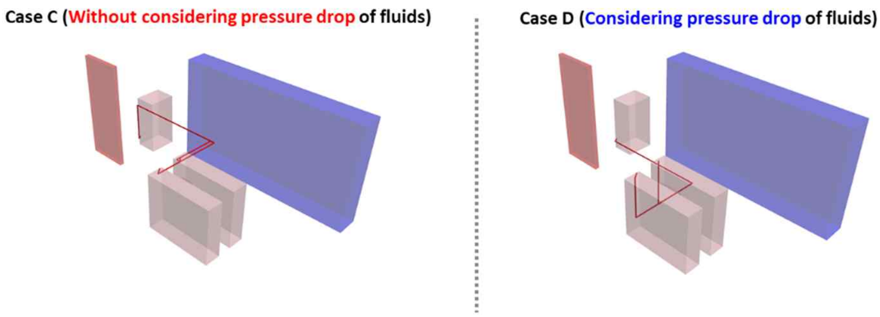

Figure 76. Results of verification cases for pipe routing considering pressure drop of fluids (1)

Table 39 Results of verification cases for pipe routing considering pressure drop of fluids (2)

Case	Considering pressure drop	Total pipe length (F_1, Min) [m]	Total number of bends (F_2, Min)	Space availability (F_3, Max)	Feasibility index (F_4, Max)	Pressure drop of pipes [Pa]	Computation time [sec]
Case C	X	18.9	5	9.6	388	592	4.2
Case D	O	18.9	4	2.8	329.5	445	6.2

In Figure 76 and Table 39, pipe routing with less bending and pressure drop could be proposed, although Case D takes more computation time than Case C. According to the verification cases, considering pressure drops of pipes as the objective function decreases the space availability and feasibility index but reduces the total number of bends. However, this objective function is redundant with F_1 and F_2, and it has a negative impact on the computation time, as shown in Table 39. Therefore, pressure drop was not selected as the objective function in this study.

B. Additional verification

In this section, the following verification cases are defined to verify the effectiveness of the objective functions of the proposed method described in the previous section. Table 40 summarizes the objective functions considered for each verification case.

Table 40. Cases for the verification of the proposed method

Cases	Total length of pipe route (f1)	Total number of bends (f2)	Avg. space factor (f3)	Avg. feasibility index (f4)	Dynamic grid
Case A-1	O	O	X	X	X
Case A-2	O	O	O	X	X
Case B-1	O	O	X	X	X
Case B-2	O	O	X	O	X
Case C-1	O	O	O	X	X
Case C-2	O	O	O	X	O

Cases A-1 and A-2 verified the design differences when the space factor was considered for simple pipe routing. Cases B-1 and B-2 verified whether a path maximizing the feasibility index can be generated effectively when expert knowledge of the *z*-coordinate of the nodes constituting the pipe exists. The unit of the coordinates in all the cases was meter.

B.1. Verification cases for the space factor

Cases A-1 and A-2 are examples of pipe routing that connect two equipment, with the start point (1.0, 1.0, 2.0) and end point (6.0, 1.0, 2.0). There is an impenetrable wall at $x \leq 0$ m. The results of the pipe routing are shown in Figure 77.

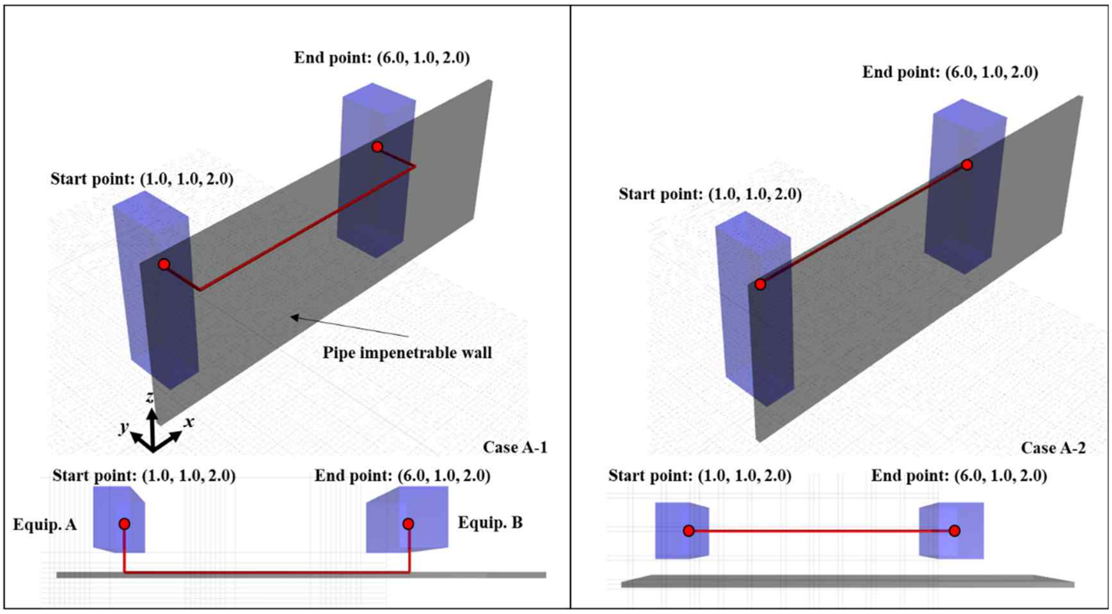

Figure 77. Results of Cases A-1 and A-2 (1)

The results of pipe routing for Case A are shown in Table 41.

Table 41. Results of Cases A-1 and A-2 (2)

Cases	Considering space avg. space factor (f3)	Minimum distance to the wall [m]	Total length of pipe route [m]
Case A-1	X	0.5	5.0
Case A-2	O	0	6.0

In Case A-1, because only the total length of the pipe route and total number of bends were set as objective functions, the pipe route was designed as a straight line that minimized the pipe length and bends regardless of the wall. Thus, the minimum distance to the wall in Case A-1 was 0.5 m, and the total length of the pipe route was 5.0 m. In contrast, in Case A-2, which additionally set the space factor as the objective function, the designed route was attached to the wall to increase the space availability. Therefore, the total length of the pipe route was 6.0 m, which is longer than Case A-1. However, the minimum distance to the wall was 0 m. As shown in the results of Case A, setting the space factor as the objective function can increase space availability and allow for design considerations such as reducing the distance from the wall to install pipe supports.

B.2. Verification cases for the expert system

Cases B-1 and B-2 are examples of pipe routing that connect two equipment with the start point (1.0, 1.0, 1.4) and end point (6.0, 1.0, 1.4). The expert knowledge applied to Case B is presented in Table 42.

Table 42. Expert knowledge of Case B

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression
A001	Node	All	Node z-coordinate	1350_MAX_mm	IF Node z-coordinate ≥ 1350 mm THEN 100 ELSE 0

The results of pipe routing for Case B are shown in Figure 78.

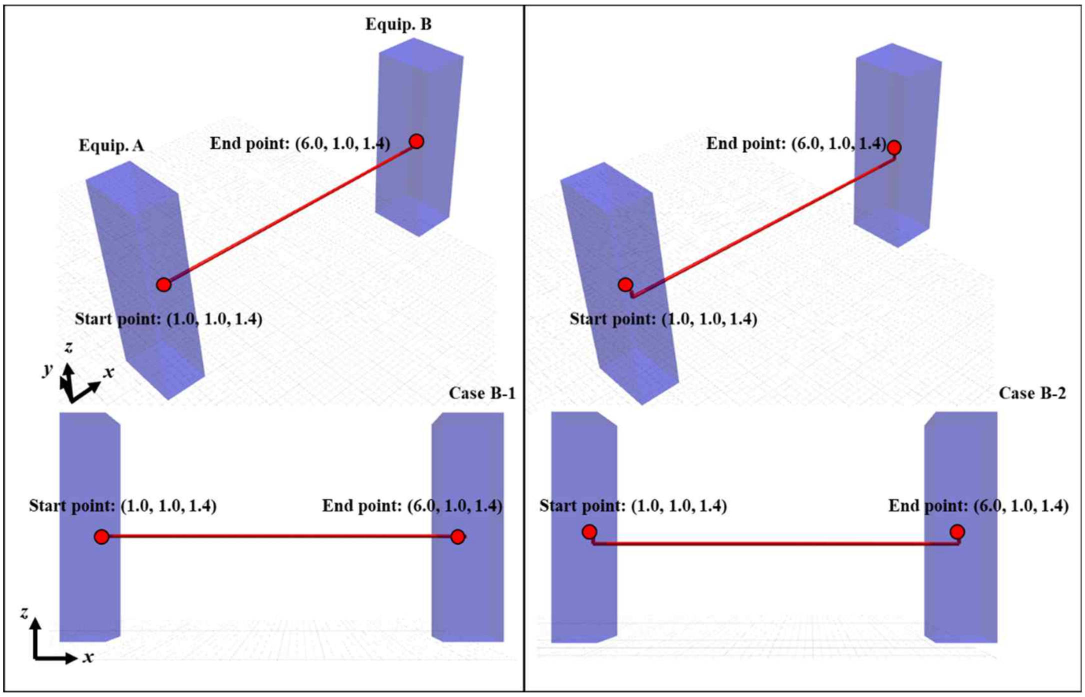

Figure 78. Results of Cases B-1 and B-2 (1)

The results of pipe routing for Case B are shown in Table 43.

Table 43. Results of Cases B-1 and B-2 (2)

Cases	Considering space avg. feasibility index (f4)	The number of nodes satisfying expert knowledge	Total length of pipe route [m]
Case B-1	X	0	5.0
Case B-2	O	20	5.1

In Case B-1, because the total length of the pipe route and total number of bends were set as the objective functions, the pipe route was designed as a straight line connecting the start and end points without considering expert knowledge. As a result, a pipe route with a total length of 5.0 m was generated. In contrast, in Case B-2, where the feasibility index for expert knowledge was also set as the objective function, a pipe route was designed by constructing nodes with *z*-coordinates suitable for expert knowledge. Therefore, the total length of the pipe route was 5.1 m, which was longer than the route of Case B-1. However, the number of nodes satisfying expert knowledge was 20, thereby maximizing the average feasibility index.

For additional verification, for the 1st stage in Section 4.2, we verified that the 1st stage arrangement results change significantly with and without the use of the objective function F_5 (Feasibility index). The expert knowledge in Table 44 is the expert knowledge that restricts the arrangement direction of the purifier to 0 degrees (stern direction) for the connection with other equipment.

Table 44. Expert knowledge of equipment arrangement (Object information)

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type
E004	Equipment	Purifier	Orientation	0_EXT_0	IF Orientation = 0 THEN 100	3

					ELSE 0	

Figure 79 and Table 45 are the results of the 1st stage with and without F_5 as the objective function.

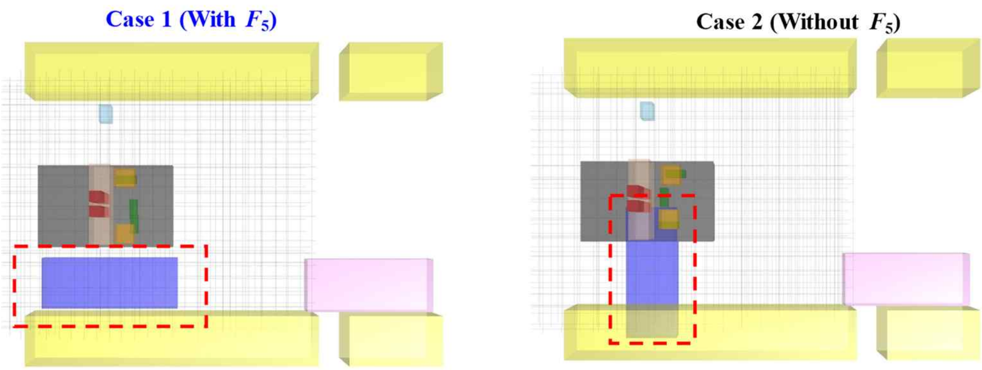

Figure 79. Arrangement results of the 1st stage with/without F_5

Table 45. Results of the 1st stage with/without F_5

Case	Occupied volume of the engine room (F_1, Min) [m]	Total pipe length (F_2, Min) [m]	Number of bends (F_3, Max)	Space availability of equipment (F_4, Max)	Feasibility index of arrangement (F_5, Max)
Case 1 (With F_5)	32,011.6	9,268.0	46	181.0	20,800

Case 2 (Without F_5)	35,876.4	8,968.0	46	271.0	-

If the objective function F_5 (Feasibility index) is not used, the arrangement direction of the equipment did not satisfy the expert knowledge to reduce the length of the pipes (F_2) and increase the space availability (F_4). In these cases, we verified that the optimization problem with the feasibility index for expert knowledge as the objective function works well.

B.3. Verification cases for the dynamic grid

Case C verified whether good results could be obtained with a low computational cost when pipe routing is performed using the dynamic grid proposed in Section 3.5. Cases C-1 and C-2 are examples of pipe routing that connect the start point (0.0, 0.0, 0.0) and end point (1.5, 1.5, 1.5). The minimum grid space in both cases was 0.1 m. Cases C-1 and C-2 set the maximum grid space to 0.1 m and 0.5 m, respectively. The maximum grid space was limited to 0.5 m. There was an obstacle with a length of 0.6 m, width of 0.4 m, and height of 1.5 m. The results of the pipe routing are shown in Figure 80.

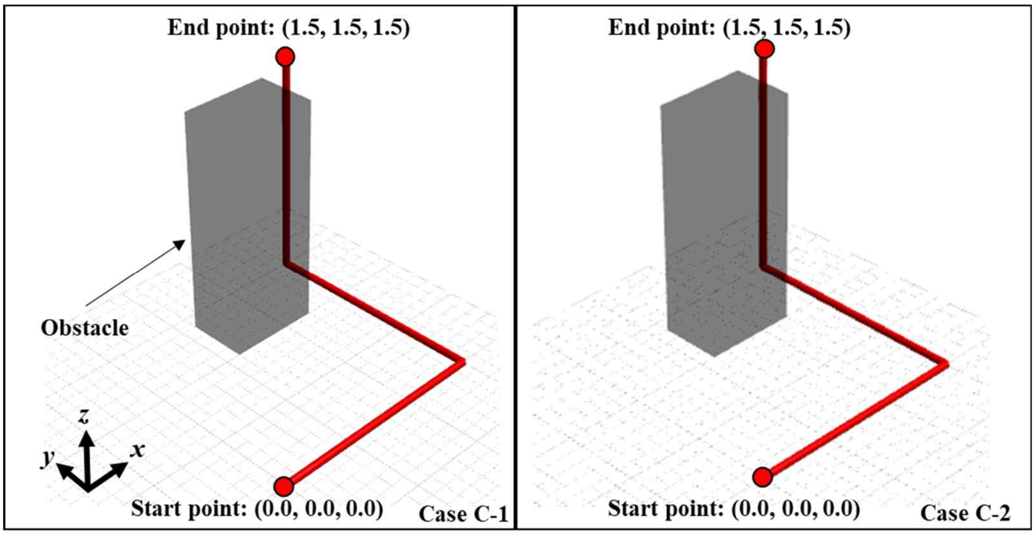

Figure 80. Results of Cases C-1 and C-2 (1)

The results of pipe routing for Case C are shown in Table 46.

Table 46. Results of Cases C-1 and C-2 (2)

Cases	Total length of pipe route (f1) [m]	Total number of bends (f2)	Avg. space factor (f3)	Min. grid space [m]	Max. grid space [m]	Calculation time [ms]
Case C-1	4.5	2	0	0.1	0.1	409
Case C-2	4.5	2	0	0.1	0.5	120

Cases C-1 and C-2 were verification cases in which only the maximum grid space was calculated. In Case C-2, a dynamic grid was applied, and the grid space was set to vary from 0.1 m to 0.5 m. Although the same pipe routing result was obtained, the calculation time was reduced by approximately 70.7% to 120 ms. These verification cases established that the calculation time could be reduced using the dynamic grid method proposed in this study.

C. Expert knowledge for applications

In this section, we categorize and introduce the expert knowledge utilized in the applications of this study. All expert knowledge is organized by the IF-THEN rule and the form defined in Section 2.1. In Section C.1, a list of expert knowledge on equipment arrangement is introduced. In Section C.2, a list of expert knowledge on pipe routing is introduced. Each expert knowledge is categorized into object information and relation information.

C.1. A list of expert knowledge for equipment arrangement

A list of expert knowledge for equipment arrangement is shown in Table 47.

Table 47. A list of expert knowledge for equipment arrangement (Object information)

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type
E001	Equipment	2	Clearance distance	0.9_MIN_m	IF Clearance distance ≥ 2 m THEN 100 ELSE 0	Constraint

E002	All	All	Whether exposed to passages	False	IF Whether exposed to passages = false THEN 100 ELSE 0	1
E003	Equipmen t	Engine Control Room	Orientatio n	0_EXT_0	IF Orientatio n = 0 THEN 100 ELSE 0	3
E004	Equipmen t	Purifier	Orientatio n	0_EXT_0	IF Orientatio n = 0 THEN 100 ELSE 0	3
E005	Equipmen t	Auxiliar y Engine	Deck	1_EXT_0	IF Deck = 1 THEN 100 ELSE 0	2
E006	Equipmen t	Boiler	Deck	2_EXT_0	IF Deck = 2 THEN 100 ELSE 0	2

In Table 32, E001 is the information that a clearance distance of at least 2 meters must be secured around the equipment for maintenance and installation of the equipment. In particular, this information is essential, so we set the Consideration type as a constraint to ensure that we always find a solution that satisfies this knowledge. E002 is the information that no other equipment should be installed at the point where the passage is installed (or planned). E003 and E004 are expert knowledge about the orientation of the equipment being installed, and each equipment or space should be arranged in a certain direction. E005 and E006 are expert knowledge about the deck on which the specific equipment is being installed, and each equipment must be arranged on the designated deck. Table 48 shows the relation information related to equipment.

Table 48. A list of expert knowledge for equipment arrangement (Relation information)

Object ID	Target object	Property of target object	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type
R001	Equipment	All	Distance From	Traffic	All	5_MIN_m	IF Distance from all equipment to Traffic ≤ 5 m THEN 100 ELSE 0	1
R002	Equipment	All	Distance From	Equipment	All	400_MIN_mm	IF Distance from all equipment to all equipment > 400	Constraint

							mm THEN 100 ELSE 0	
R003	Equipment	All	Distance From	Equipment	Main Engine	5_MIN_m	IF Distance from all equipment to Main Engine ＞ 5 m THEN 100 ELSE 0	Constraint

In Table 48, R001 is the information that each device and traffic must be at least 5 meters apart. R002 is the information that all equipment must be at least 400 mm apart from each other. R003 is the information that all equipment and the main engine must be at least 5 meters apart. Since R002 and R003 are essential for the maintenance of the equipment, we set the Consideration type as a constraint to always find a satisfactory solution.

C.2. A list of expert knowledge on pipe routing

A list of expert knowledge on equipment arrangement is shown in Table 47.

Table 49. A list of expert knowledge for pipe routing (Object information)

Object ID	Target object	Property of target object	Attribute	Target value	Knowledge expression	Consideration type
B001	Pipe	All	Minimum straight pipe length	1_MIN_m	IF Minimum straight pipe length ≥ 1 m Then 100 Else 0	2
B002	Pipe	All	Bending angle	90_MIN_deg	IF Bending angle ≥ 90 deg Then 100 Else 0	3
B003	Node	All	Whether exposed to passages	False	IF Whether exposed to passages = false Then 100 Else 0	1
B004	Node	Exposed to passage	Node z coordinate	150_MIN_mm	IF Node z coordinate ≥ 150 mm Then 100 Else 0	2
B005	Node	Exposed to passage	Node z coordinate	300_MAX_mm	IF Node z coordinate ≤ 300 mm Then 100 Else 0	2
B006	Duct	All	Height	4,500_MAX_mm	IF Height of all ducts ≤	1

					4,500 mm Then 100 Else 0	
B007	Duct	All	Height	2,100_MIN_mm	IF Height of all ducts ≥ 2,100 mm Then 100 Else 0	1

In Table 49, B001 is the knowledge that the minimum straight length of a pipe should be at least one meter for production convenience. B002 is also the knowledge to limit the bend angle of a pipe for production convenience. B003 is the knowledge to ensure that the pipe does not collide with the passage. B004 and B005 are knowledge that if a pipe is going to pass through a passage, the node z coordinate of the pipe should be limited. B006 and B007 are knowledge about the installation location of the duct. Considering the installation of the support of the duct, the duct should be arranged at the appropriate height. The following table shows the relation information related to pipe routing.

Table 50. A list of expert knowledge for pipe routing (Relation information)

Object ID	Target object	Property of target object	Attribute	Target value	Subjective object	Property of subjective object	Knowledge expression	Consideration type

R0 04	Pip e	All	Distance From	Traffic	All	5_MIN_m	IF Distance from all pipes to Traffic ≤ 5 m Then 100 Else 0	1
R0 05	Pip e	All	Vertical Distance From	Platfor m	All	2 MIN_m	IF Vertical distance from all pipes to platform ≤ 2 m Then 100 Else 0	1
R0 06	Pip e	All	Distance From	Equip ment	All	400_MIN _mm	IF Distance from all pipes to all equipme nt ＞ 400 mm Then 100 Else 0	1
R0 07	Duc t	All	Distance From	Pipe	All	50_MIN_ mm	IF Distance from all ducts to all pipes ≥ 50 mm Then 100 Else 0	1
R0 08	Stru ctur e	All	Distance From	Pipe	All	50_MIN_ mm	IF Distance from all structure s to all pipes ≥ 50 mm Then 100	1

							Else 0	
R0 09	Pip e	All	Distance From	Equip ment	Main engine	800_MIN _mm	IF Distance from all pipes to Main engine ≥ 800 mm Then 100 Else 0	Constrai nt
R0 10	Pip e	All	Vertical Distance From	Struct ure	D/B	150_MIN _mm	IF Vertical distance from all pipes to D/B ≥ 150 mm Then 100 Else 0	1
R0 11	Duc t	All	Vertical Distance From	Deck	Upper	3,300_M AX_mm	IF Horizont al distance from all ducts to the upper deck ≤ 3,300 mm Then 100 Else 0	1

In the table, R004 and R005 are expert knowledge about the location of piping routed near structures such as traffic and platforms. R006 is expert knowledge regarding the minimum distance between each equipment and pipe routing required for maintenance. R007 and R008 are expert knowledge to ensure the minimum distance required for the installation and welding of pipes. For the calculation of the minimum distance, the method shown in Figure 81 was used.

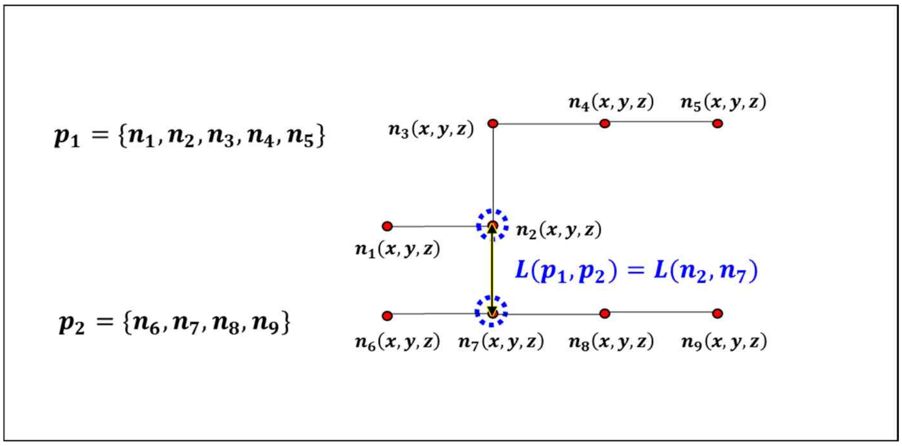

Figure 81. Calculation of the minimum distance between pipes/ducts

In Figure 81, The distance between pipes p_1 and p_2 ($L(p_1, p_2)$) was determined by the distance between the closest nodes between them n_2 and n_7. If the distance between two points is not the minimum distance, AEM calculates the distance between the points and a straight line and utilizes that. R009 is an expert knowledge to free up space for maintenance of the main engine. R010 is the distance of pipes from the bottom for safety. R011 is the height limit for the installation of pipes. The expert knowledge proposed in this study is a selection of generally applicable expert knowledge, and it is necessary to collect and apply additional expert knowledge that apply differently to each pipe.

D. Arrangement design analysis with the weight-based optimization method

The equipment arrangement problem is a multi-objective optimization problem. Since it is not practical to show all the optimization results for the five objective functions, In this section, we will analyze the effect of each objective function on the optimal solution using a weight-based optimization method. The results for representative cases are presented as shown in Table 51.

Table 51. Cases for weight-based optimization

Objective function			Economics (Case D-1)	Space availability (Case D-2)	Balance (Case D-3)
Economics	F_2 (Min)	Length of pipes and ducts	0.25	0	0.2
	F_3 (Min)	Number of bends	0.25	0	0.2
Space availability	F_1 (Min)	Occupied volume	0	0.25	0.2
	F_4 (Max)	Space availability of equipment	0	0.25	0.2
Expert system	F_5 (Max)	Feasibility index	0.5	0.5	0.2

To present representative cases, we have divided the objective functions into three categories. F_2 and F_3 are objective functions related to economics, F_1 and F_4 are objective functions related to space availability. Finally, F_5 is an objective function related to expert systems.

D.1. Case D-1 results for the 1st stage

Case D-1 considers objective functions related to economics. The result of the arrangement of the decks for Case D-1 is shown in Figure 82 and Table 52.

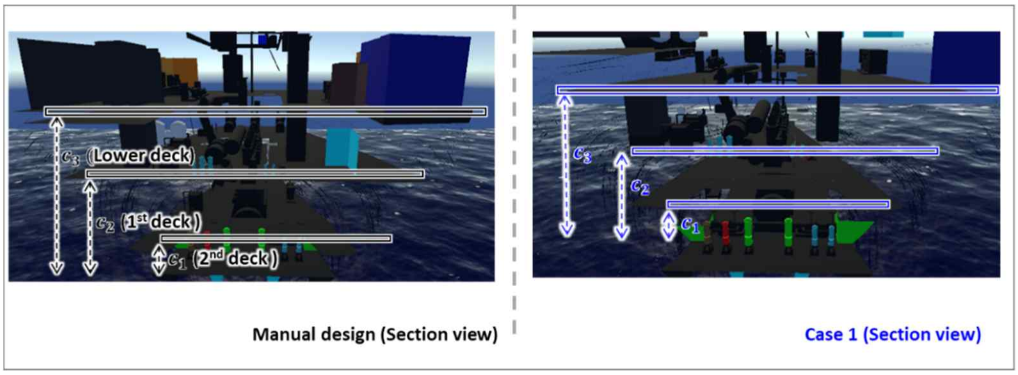

Figure 82. The result of the arrangement of decks for Case D-1

Table 52. Deck heights of Case D-1

	Manual design	Economics (Case D-1)
Lower deck [m]	183.0	191.0
1st deck [m]	119.0	114.0
2nd deck [m]	60.0	70.0

In Figure 83 and Table 53, the height of the lower deck and 2nd deck were increased. The results of the equipment arrangement for Case D-1 are shown in Figure 83 and Table 53.

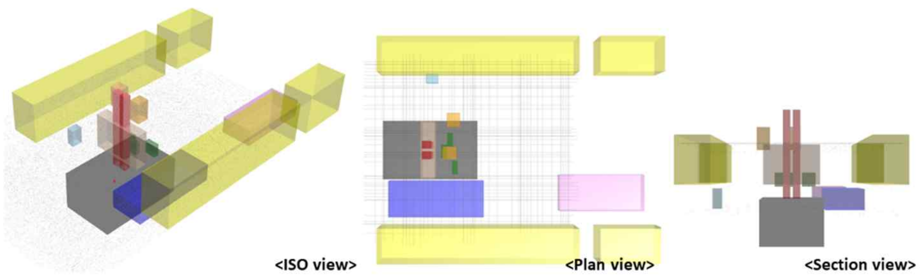

Figure 83. The result of the arrangement of equipment for Case D-1

Table 53. Results of Case D-1

Objective function			Economics (Case D-1)	Manual design results	Optimal design results
Economics	F_2 (Min)	Length of pipes and ducts	0.25	910	461 (-49.3%)

	F_3 (Min)	Number of bends	0.25	27	21 (-22.2%)
Space availability	F_1 (Min)	Occupied volume	0	54,416	33,833 (-37.8%)
	F_4 (Max)	Space availability of equipment	0	78.75	159 (+101.9%)
Expert system	F_5 (Max)	Feasibility index	0.5	16,581	20,800 (+25.4%)

As a result of the optimal arrangement for Case D-1, all objective functions were improved, especially objective functions related to economics. F_2 was improved by 49.3% compared to manual design results, and F_3 was improved by 22.2% compared to manual design results. F_5 also improved by 25.4%.

D.2. Case D-2 results for the 1st stage

Case D-2 considers objective functions related to space availability. The result of the arrangement of the decks for Case D-2 is shown in Figure 84 and Table 54.

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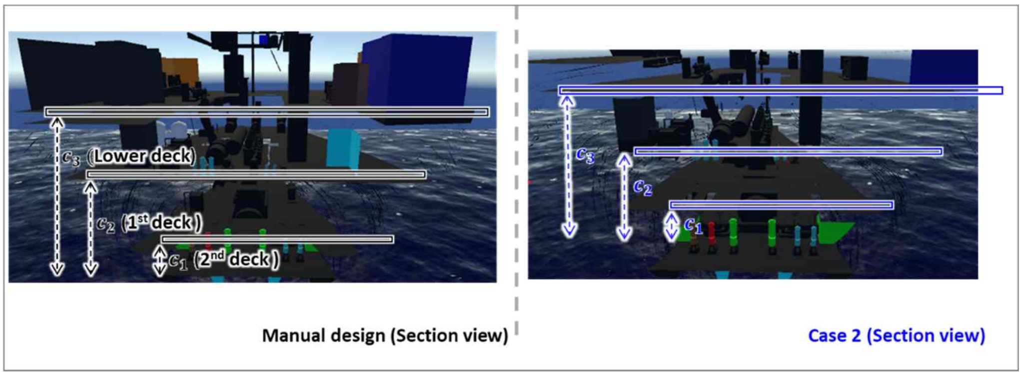

Figure 84. The result of the arrangement of decks for Case D-2

Table 54. Deck heights of Case D-2

	Manual design	Space availability (Case D-2)
Lower deck [m]	183.0	197.0
1st deck [m]	119.0	119.0
2nd deck [m]	60.0	74.0

As a result of the arrangement of decks for Case D-2, the height of the lower deck and 1st deck were decreased. The results of the equipment arrangement for Case D-2 are shown in Figure 85 and Table 55.

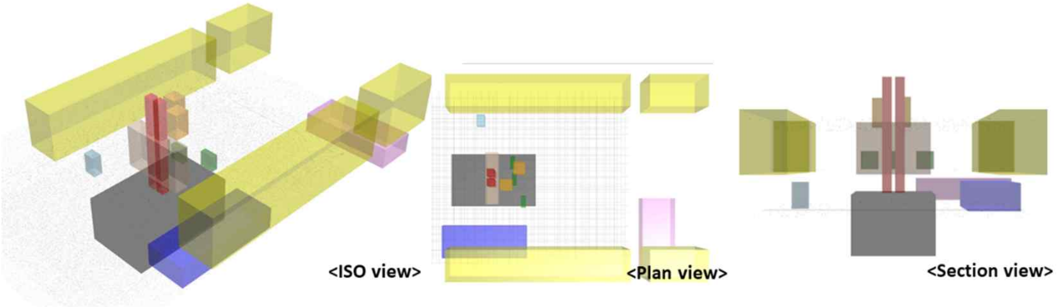

Figure 85. The result of the arrangement of equipment for Case D-2

Table 55. Results of Case D-2

Objective function			Economics (Case 1)	Manual design results	Optimal design results
Economics	F_2 (Min)	Length of pipes and ducts	0	910	468 (-48.5%)
	F_3 (Min)	Number of bends	0	27	21 (-22.2%)
Space availability	F_1 (Min)	Occupied volume	0.25	54,416	30,023 (-44.8%)
	F_4 (Max)	Space availability of equipment	0.25	78.75	177 (+124.7%)
Expert system	F_5 (Max)	Feasibility index	0.5	16,581	20,900 (+26.0%)

In Table 55, as a result of the optimal arrangement, all objective functions were improved, especially objective functions related to space availability. F_1 was improved by 44.8% compared to manual design results, and F_4 was improved by

124.7% compared to manual design results. F_5 also improved by 26.0%.

D.3. Case D-3 results for the 1st stage

Case D-3 is the case where all objective functions are considered in balance. The result of the arrangement of the decks for Case D-3 is shown in Figure 86 and Table 56.

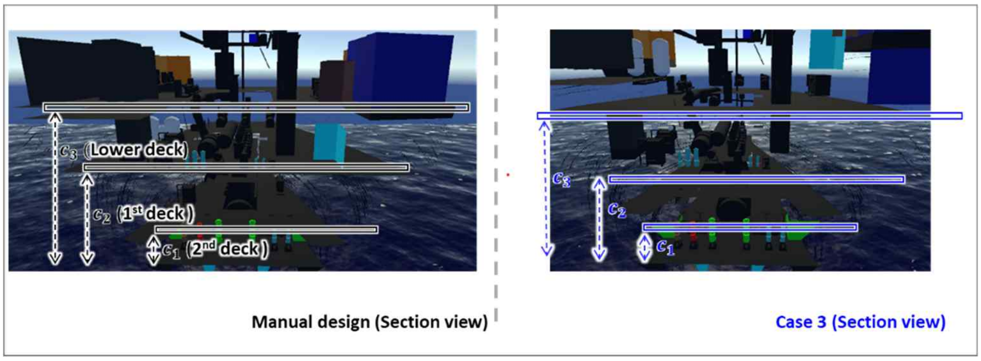

Figure 86

. The result of the arrangement of decks for Case D-3

Table 56. Deck heights of Case D-3

	Manual design	Balance (Case D-3)
Lower deck [m]	183.0	174

1st deck [m]	119.0	108
2nd deck [m]	60.0	61.0

As a result of the arrangement for Case D-3, the height of the lower deck and 1st deck decreased. The results of the equipment arrangement for Case D-3 are shown in Figure 87 and Table 57.

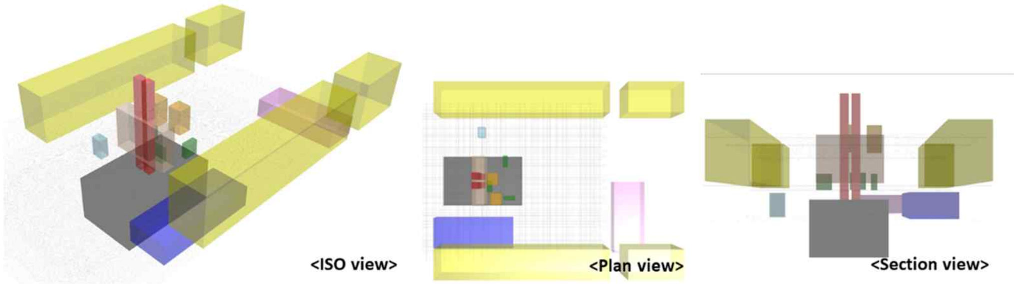

Figure 87. The result of the arrangement of equipment for Case D-3

Table 57. Results of Case D-3

Objective function			Balance (Case D-3)	Manual design results	Optimal design results
Economics	F_2 (Min)	Length of pipes and ducts	0.2	910	468 (-48.5%)
	F_3 (Min)	Number of bends	0.2	27	21 (-22.2%)
Space	F_1	Occupied volume	0.2	54,416	30,023 (-

availability	(Min)				44.8%)
	F_4 (Max)	Space availability of equipment	0.2	78.75	177 (+124.7%)
Expert system	F_5 (Max)	Feasibility index	0.2	16,581	20,900 (+26.0%)

As a result of the arrangement for Case D-3, there were balanced improvements to all objective functions. F_2 improved by 48.5%, and F_3 improved by 22.2% compared to manual design results. F_1 improved by 44.8%, and F_4 improved by 124.7%. F_5, an objective function related to expert systems, also improved by 26.0% compared to manual design results.

D.4. Summary of Section D

Table 58 summarizes the results of the optimal arrangement performed for the 1st stage.

Table 58. Summary of the 1st stage results

Objective function	Manual design	Economics (Case D-1)	Space availability (Case D-2)	Balance (Case D-3)

Economics	F_2 (Min)	Length of pipes and ducts [m]	910	461 (-49.3%)	468 (-48.5%)	450 (-50.5%)
	F_3 (Min)	Number of bends	27	21 (-22.2%)	21 (-22.2%)	21 (-22.2%)
Space availability	F_1 (Min)	Occupied volume [m^3]	54,416	33,833 (-37.8%)	30,023 (-44.8%)	31,021 (-42.9%)
	F_4 (Max)	Space availability of equipment	78.75	159 (+101.9%)	177 (+124.7%)	173 (+119.7%)
Expert system	F_5 (Max)	Feasibility index	16,581	20,800 (+25.4%)	20,900 (+26.0%)	20,800 (+25.4%)
Improvement rate (Average)				47.3%	53.2%	52.1%

In Case D-1, the objective function related to economics was improved. In Case D-2, the objective functions related to space availability were improved the most, and in particular, the space availability of equipment was improved the most. Also, the feasibility index showed the best results among the cases. Finally, in Case D-3, all objective functions were improved evenly. The optimization results for the 1st stage showed that the objective function could be significantly improved in all cases, and we were able to present an arrangement design that successfully applied expert knowledge by applying an expert system.

국문 초록

선박의 기관실 배치 자동화를 위한 장비 및 배관 최적 배치 방법

선박 기관실의 배치 설계는 기관실에 배치된 장비와 배관의 간섭, 설계 규칙 및 실적선 데이터, 전문가 지식 등의 다양한 요소들을 고려해 수행되어야 한다. 복잡하고 관습적인 영역이 많은 선박의 배치 설계 과정은 과거 선박 데이터와 전문가의 설계 경험이나 노하우에 의존하고 있다. 이러한 특징 때문에, 선박의 배치 설계는 기존 선박의 설계와 전문가에 의존하는 경직된 설계가 주로 이뤄진다. 본 연구에서는 전문가가 다양한 배치 설계를 시도하고, 최적화된 배치 설계를 제안할 수 있는 배치 설계 방법을 제안하고자 한다. 이를 위해 기존의 선박 배치 설계 방법을 보완하고 전문가 지식을 체계화할 수 있는 전문가 시스템을 구성하고, 이를 최적화 기법과 연계한 배치 설계 방법을 제안하였다.

전문가들의 전문가 지식을 구체화하고 이를 체계적으로 전산화하기 위해 배치 템플릿 모델 (Arrangement Template Model)을 구성해 자료 구조를 표현했으며, 배치 평가 모델 (Arrangement Evaluation Model)을 통해 전문가 지식을 평가했다. 배치 평가 모델을 통해 평가된 배관 라우팅 결과는 배관 라우팅 최적화 문제의 목적 함수로 활용했다. 배관 라우팅 및 장비 배치 안에 대한 여러 대안을 짧은 시간 내에 검토하고 최적화된 설계 안을 도출하기 위해 최적화 기법을 전문가 시스템과 연계하고 이를 이용한 최적화 문제를 정식화하였다.

본 연구에서는 기관실에 대한 최적 배치 설계를 효과적으로 수행하기 위해, 2 단계로 이뤄진 다단계 최적화 방법을 제안하였다. 1 단계에서는 기관실 내 갑판의 위치와 장비의 위치와 설치 방향에 대한 최적 배치를 수행했다. 1 단계 최적 배치 설계에서는 기관실에 배치되는 장비들이 차지하는 공간 최소화, 배관 및 덕트의 길이와 굽힘 최소화, 공간 가용성 최대화, 전문가 지식의 적합성 최대화를 목적 함수로 설정했다. 특히, 선박의 배관 배치 설계 결과를 장비 배치에 반영하기 위해,

선박의 장비 배치 단계에서 배관 배치를 함께 고려할 수 있는 최적 장비 배치 방법을 제안했다. 또한, 배치 설계에 대한 전문가의 지식과 경험을 효과적으로 활용하기 위해 전문가 시스템을 활용해 전문가 지식의 적합성을 계산했다. 제약 조건으로는 장비의 설치 가능 여부와 전문가 지식의 일부를 검토했다. 최적화 알고리즘으로는 다양한 전역 최적화 방법을 비교·분석하고, 가장 적합한 알고리즘을 선택해 최적 배치를 수행했다.

기관실의 배치 설계 2 단계에서는 1 단계에서 배치된 장비들을 연결하는 배관 및 덕트의 배치 최적화를 수행했다. 2 단계에서는 기관실의 배관 및 덕트의 길이와 굽힘 최소화, 공간 가용성 최대화, 전문가 지식의 적합성 최대화를 목적 함수로 설정했다. 마찬가지로 배관 배치에 대한 전문가의 지식과 경험을 효과적으로 활용하기 위해 전문가 시스템을 활용했다. 제약 조건으로는 배관의 설치 가능 여부와 전문가 지식의 일부가 검토됐다. 경로 생성 알고리즘으로 다양한 경로 생성 알고리즘을 검토했으며, 본 연구의 예제에서 더 나은 결과를 보인 JPS

(Jump Point Search) 알고리즘을 활용해 최적 배관 배치를 수행했다. 본 연구에서 제안한 선박 기관실의 장비 및 배관 최적 배치 방법을 활용해 초기 배치 설계를 위한 프로그램을 개발했다. 개발된 프로그램을 통해 재화 중량 320,000 톤 대형 원유 운반선 (VLCC)의 기관실의 최적 배치를 수행해 제안한 방법의 효용성을 확인했다.

향후에는 주요 장비만을 고려한 본 연구의 한계점을 보완하고자, 고려된 주요 장비 외의 장비들에 대한 배치 설계를 추가로 수행하고자 한다. 배관 배치 과정에서도 다양한 최적화 방법과 경로 탐색 방법의 검토를 통해 배관 배치 과정에 소요되는 계산 시간을 개선하고 검토하지 못했던 목적 함수를 최적화하는 방법을 연구하고자 한다. 또한, 다양한 굽힘 각도를 고려한 배관 배치 방법을 연구하고, 각 배관의 특징 (유량, 분기 배관등) 등을 고려한 다양한 전문가 지식을 추가로 확보하고, 배치 결과에 대한 검증작업을 수행해 완성도 있는 배치 설계 방법을 제안하고자 한다.

Keywords: 기관실 배치, 최적 배치, 배관 배치, 전문가 시스템, 최적화 기법,

경로 탐색 알고리즘

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