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An Automated Method for Pipe Routing in Ship Unit Modules

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ABSTRACT

This study addresses challenges in ship arrangement design by proposing an automated pipe routing method in ship unit modules. Currently, designers rely on experience, lacking quantitative assessments and causing difficulties for non-experts. The proposed method incorporates expert knowledge and design rules into an expert system, evaluating expertise and adherence to rules. The system's evaluation result was used as the objective function of an optimization problem formulated for pipe routing in conjunction with metrics such as total pipe length, the number of bends, and space availability. Through validation by comparing actual unit module designs, it is demonstrated that the proposed method suggested improved pipe routing design while adhering to expert knowledge.

KEY WORDS

Ship Unit Module; Pipe Routing; Expert System; Arrangement Design; Optimization

INTRODUCTION

The equipment in the ship is installed by connecting a ship's unit modules, each individually manufactured. These unit modules consist of the equipment with similar functions and pipes connecting them. This is a frequently used method because it can reduce production and installation costs by considering the similarity of the equipment or piping systems that comprise the modules and performing the arrangement through modularization (Gunawan et al., 2021). However, when doing the design for these modules, designers must consider the locations of the installed equipment and pipes when they perform pipe routing. However, the current approach to pipe routing in unit modules relies heavily on the designers' experience and lacks quantitative assessments. Consequently, non-experts have difficulty understanding the characteristics of unit modules and performing pipe routing. Moreover, the design review of pipe routing is time-consuming and challenging due to intricate pipe patterns and the absence of quantitative evaluation. To address these issues, this study proposed a method that analyzes pipe patterns and automates pipe routing in unit modules while incorporating expert knowledge and design rules. For this, an expert system was developed to assess the expertise of pipe routing experts and their adherence to design rules. The result of evaluating the system, the feasibility index, was used as one of the objective functions of an optimization problem formulated for pipe routing in conjunction with metrics such as total pipe length, the number of bends, and space availability. An effective pathfinding algorithm was used to solve the optimization problem. The designs of actual unit modules were compared to the results obtained using the proposed method to validate its effectiveness. The comparative analysis with manual designs demonstrated that the proposed method finds better alternatives for pipe routing while adhering to expert knowledge.

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Related Works

Since automating pipe routing in ships has the benefit of reducing design and review costs, there have been several studies on automated pipe routing and optimal pipe routing to achieve better results. Kimura and Ikehira (2009) and Furuholmen et al. (2010) tried to optimize piping cost by using optimization algorithms such as genetic algorithm and ant colony algorithm to optimize pipe routing. Ando and Kimura (2011), Lee et al. (2019), and Gunawan et al. (2022) utilized pathfinding algorithms to perform automated pipe routing. Also, research has been done in the form of using a combination of pathfinding and optimization algorithms, such as the work of Dong and Bian (2020). More recently, research has been conducted on pipe routing using reinforcement learning (Shin et al., 2020; Y. Kim, Lee, Nam, & Han, 2023). In this study, one of the heuristic pathfinding algorithms was chosen to perform automated pipe routing for faster route finding. A summary of studies related to pipe routing and this study is in Table 1.

Table 1. A summary of related studies on pipe routing and this study

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

THEORETICAL BACKGROUND

The pipe routing target of this study, the ship unit module, refers to a set of equipment, piping, etc., that are typically grouped together within a particular system. Each piece of equipment and pipe that constitutes a module has input and output points, and they are complexly connected. Therefore, a detailed analysis of the characteristics of the connection relationship between equipment and pipes is required, and this study performs pipe routing of existing or new equipment based on the patterns already analyzed. The information analyzed includes the equipment's location, orientation, and bounding box information. Nozzle information was obtained by considering the pipes at the point of contact with the bounding box as the input/output point. We also utilized the pipes and equipment information, which includes pipe type, diameter, length, and coordinates.

Expert System for Pipe Routing in Ship Unit Modules

Many parts of pipe routing design are based on the data of previous ships or the know-how of experts. In order to apply the data of previous ships or the know-how of experts, this study uses an expert system to evaluate the results of pipe routing design and utilize them as objective functions or constraints (Kendal & Creen, 2007; Kim et al., 2015; Kim and Roh, 2016; Kim et al., 2017; Jung et al., 2018). The expert system utilized in this study consists of an Arrangement Template Model and an Arrangement Evaluation Model. They are described in the following sub-sections.

Arrangement Template Model

An Arrangement Template Model is a data structure for storing information about an arrangement target. The main value of the information of each "Node" that constitutes the "Pipe" that is most utilized in this study is stored in the "Pipe." For example, the "Max. Serial straight nodes" property value (maximum intuition length) is utilized in the Arrangement Evaluation Model by selecting the largest value among the "Serial straight nodes" values for each "Node."

Arrangement Evaluation Model

An Arrangement Evaluation Model consists of an ID, a target object, an attribute, and a target value (K. S. Kim et al., 2015). A target object and a subjective object are the objects that specify information. An attribute means the attribute of the object, such as the distance between objects whether they are connected. A target value is a value that the attribute should have. Object information refers to expert knowledge about the requirements related to the properties of a particular object, and relationship information refers to expert knowledge about the relationships between objects.
The American Bureau of Shipping (ABS) recommended arranging items that need to be precise, frequently used, or used for emergency purposes at a height of 860 to 1,350 mm from the floor (American Bureau of Shipping, 2018) as shown in Figure 1.

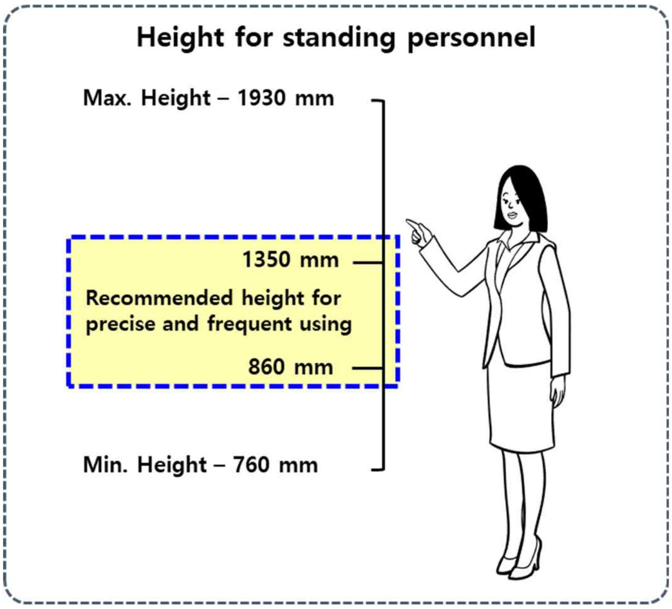

Figure 1: Recommended height for standing personnel

Expert knowledge can be expressed in the IF/THEN rule and used in the Arrangement Evaluation Model (rule-based expert system). If the corresponding expert knowledge is not essential, a continuous feasibility index can be calculated. An example of this categorized expert knowledge is shown in Table 2.

Table 2: Examples of expert knowledge in the Arrangement Evaluation Model

ID	Target object	Attribute	Target value	Knowledge expression	Priority
A001	All nodes	Node z coordinate	860_MIN_mm	IF node z coordinate ≥ 860 mm THEN 100 ELSE 0	3
A002	All nodes	Node z coordinate	1350_MAX_mm	IF Node z coordinate < 1350 mm THEN 100 ELSE 0	3

In Table 1, ID refers to the ID that classifies the relevant expert knowledge. The target object refers to the target to which the expert knowledge is applied. Attribute refers to the property of an object to which expert knowledge is applied. Target value refers to the value that an attribute must achieve to satisfy expert knowledge. Knowledge expression is content expressing the relevant expert knowledge using IF/THEN rules. If expert knowledge is satisfied, a feasibility index of 100 is obtained; otherwise, a feasibility index of 0 is obtained. The total feasibility index is used as the third objective function. Priority refers to the level of priority of that expert's knowledge. This is determined through interviews with experts and is an integer between 0 and 3. 0 is the most essential expert knowledge that must be satisfied, and 3 is the least important.

Pipe Routing for Ship Unit Modules

Design Variables

For design variables, we set the positions of nodes constituting each pipe as design variables. For objective functions in pipe routing, we calculate values based on the information of each node constituting the pipe p_i. Figure 2 shows an example of a pipe with nodes. For example, the pipe p_1 in Figure 2 consists of four nodes (n_1, n_2, n_3, n_4).

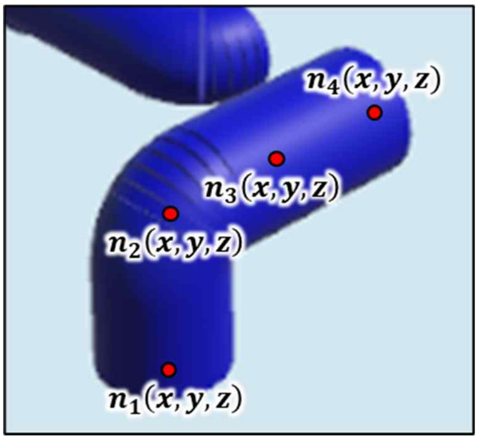

Figure 2: An example of nodes of the pipe p_1

Objective Functions

The 1st objective function $F_1 = L(p_i)$ is calculated as the sum of the distances between nodes constituting p_i. In Figure 2, the sum of the length between nodes (n_1, n_2, n_3, n_4) is $L(p_1)$. In the 2nd objective function, the total number of bends F_2 is calculated by the number of bends in pipe $B(p_i)$. In Figure 2, the number of bends $B(p_1) = 1$ can be calculated from the information of nodes (n_1, n_2, n_3, n_4). To consider the workability and cost of pipe installation and maintenance, The smaller the total length of pipes (F_1) and the number of bends (F_2), the better the pipe routing. F_1 and F_2 were commonly utilized as objective functions for pipe routing in various related works, including Furuholmen et al. (2010), Ando and Kimura (2011), and Lee et al. (2019). For the 3rd objective function, the space availability of pipes F_3 is used. It is a value of how efficiently the pipe is utilizing the space. In this study, space availability is a measurement of how efficiently the piping is arranged in a given design space. When piping is co-located with other equipment, the arrangement of supports and space availability should be considered. While there are previous studies that have considered space availability, this study used the space availability metric of the study of Lee et al. (2019). They calculated the distance from the wall or obstacle to where the piping is installed and used this as an indicator of space availability. The lower this value is, the closer the piping is located to the wall and the better the space is utilized. Minimizing this value was defined as the 3rd objective function F_3. As the final objective function F_4, we used the sum of the feasibility index, the output of the Arrangement Evaluation Model.

Constraints

For constraints, we check pipe routing to prevent collisions with obstacles and deviations from the pipe installation area.

Pipe Routing Method

For generating routes for pipes, the Jump Point Search (Harabor & Grastien, 2011; Min, Ruy, & Park, 2020) algorithm is used. To improve the computational speed of pipe routing, we utilized a grid with a dynamic size. By defining a grid that changes dynamically according to the complexity around the grid space, it is designed to use a grid of a different size depending on the situation (Ha, Roh, Kim, & Kim, 2023). Let d be the distance from where the node is located to the closest obstacle, and if $d \leqq$ *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.

APPLICATIONS

In this study, pipe routing was performed using the proposed method for a ship's on-deck unit modules. A comparison of the objective function with the results of a manual design is shown in the following figures and tables. In this study, manual design refers to pipe routing results that are designed by experts according to design rules and manuals. Figure 3 and Table 3 show the pipe routing results for the first module.

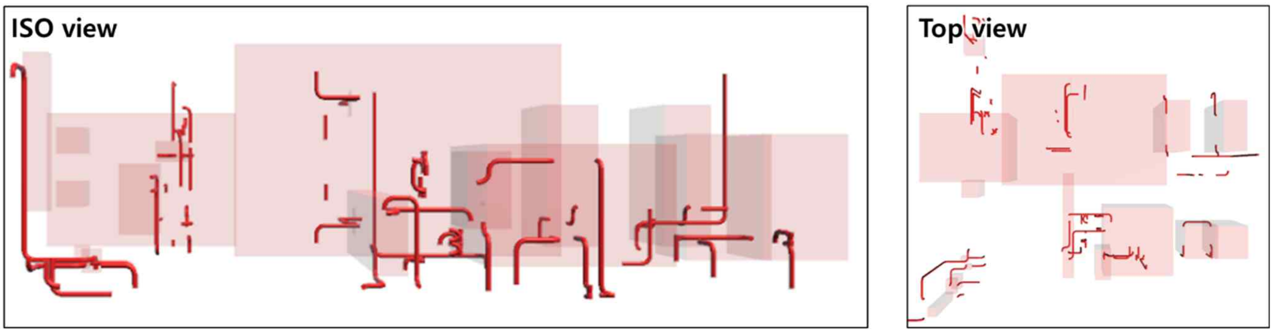

Figure 3: The result of pipe routing for Module 1

Table 3: The objective functions of pipe routing for Module 1

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Avg. space availability of pipes (F_3, Max)	Feasibility index of pipes (F_4, Max)	Calc. time [Sec]
Module 1 (Manual)	74.87 (100%)	183 (100%)	8,166.5 (100%)	483 (100%)	-
Module 1 (Proposed)	**58.50 (78.1%)**	**112 (61.2%)**	**10,274.4 (125.8%)**	**483 (100%)**	**64.21**

For Module 1, the total length of pipes (F_1) was reduced by 21.9%, and the total number of bends (F_2) was reduced by 38.8%. The space availability of pipes (F_3) improved by 25.8%, and the routing results satisfied all expert knowledge (F_4). The pipe routing results for Module 2 are shown in Figure 4 and Table 4.

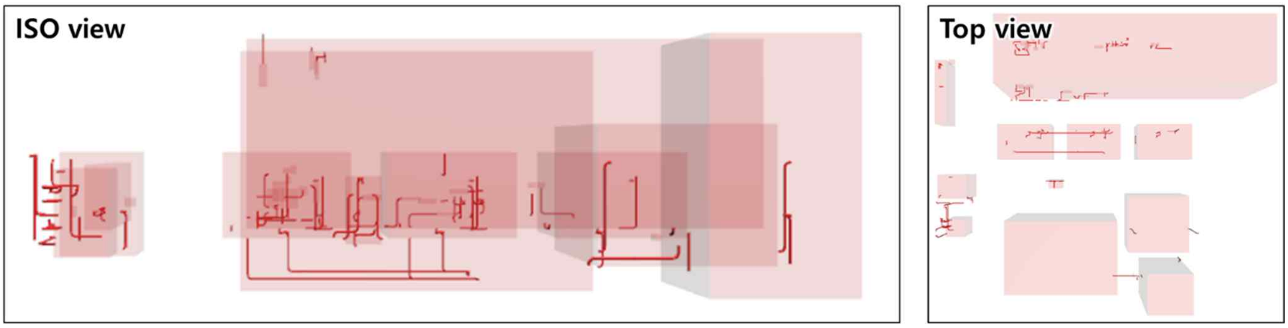

Figure 4: The result of pipe routing for Module 2

Table 4: The objective functions of pipe routing for Module 2

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Avg. space availability of pipes (F_3, Max)	Feasibility index of pipes (F_4, Max)	Calc. time [Sec]
Module 2 (Manual)	111.89 (100%)	204 (100%)	8,255 (100%)	952 (100%)	-
Module 2 (Proposed)	**97.20 (86.9%)**	**185 (90.7%)**	**10,022.6 (121.4%)**	**952 (100%)**	**89.7**

For Module 2, the total length of pipes (F_1) was reduced by 13.1%, and the total number of bends (F_2) was reduced by 9.3%. Space availability of pipes (F_3) improved by 21.4%, and the routing results satisfied all expert knowledge (F_4). The pipe routing results for all on-deck modules are shown in Figure 5 and Table 5.

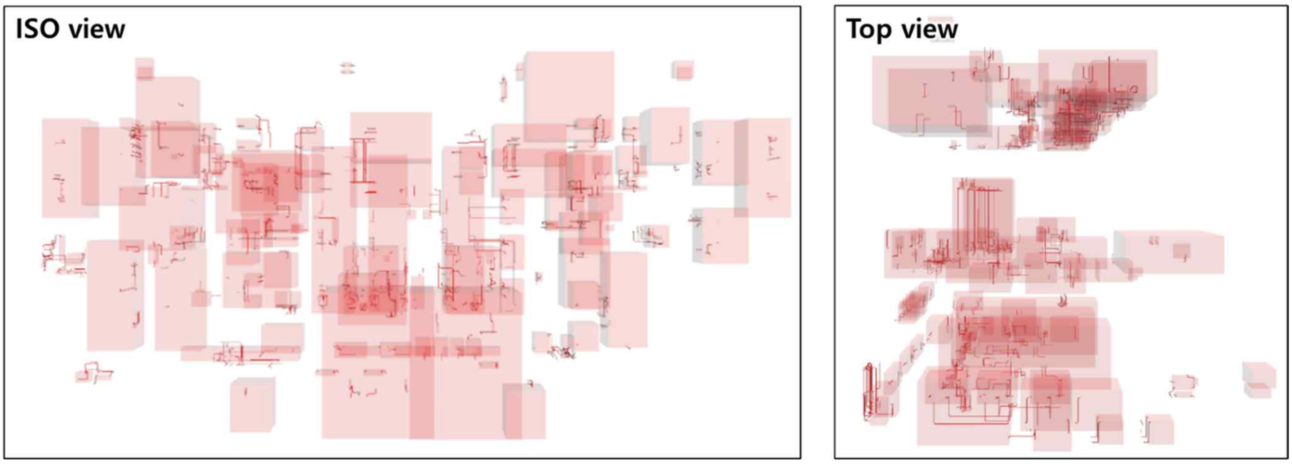

Figure 5: The result of pipe routing for all on-deck modules

Table 5: The objective functions of pipe routing for all on-deck modules

Case	Total length of pipes (F_1, Min) [m]	Total number of bends (F_2, Min)	Avg. space availability of pipes (F_3, Max)	Feasibility index of pipes (F_4, Max)
All on-deck modules (Manual)	4,887 (100%)	1,439 (100%)	10,640.2 (100%)	15,006 (100%)
All on-deck modules (Manual)	4,843 (99.1%)	1,236 (85.9%)	11,778.2 (110.7%)	15,006 (100%)

After performing pipe routing, we can see that all the objective functions improved compared to the original results of the manual design. F_1 improved by 0.9%, F_2 by 14.1%, and F_3 by 10.7%, and the feasibility index for expert knowledge was the same as the manual design given by the expert. The routing results satisfied every expert knowledge.

CONCLUSIONS

This study performs successful pipe routing by utilizing the given information about the unit modules of a ship and the interrelations between pipes. The pipe routing results obtained in this study show a significant improvement over manual designs, achieving a reduction of up to 21.9% in the total length of pipes (F_1) and up to 38.8% in the number of bends (F_2). Space availability in the piping was improved by up to 25.8%, and the feasibility index for expert knowledge was evaluated, and all expert knowledge was satisfied. Leveraging the method proposed in this research, we developed a prototype for an automated program dedicated to the pipe routing of ship unit modules.

The accurate start and end points of the pipes are defined based on the connection information of the pipes, ensuring precision in the pipe routing process. Since the pipe routing in this study is targeted at the initial design stage, there is a limitation that prior research is needed to extract the information required for pipe routing from P&IDs at this stage. Additionally, we will include a review of potential improvements in pipe routing to meet the requirements of additional expert knowledge in this field.

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REFERENCES

American Bureau of Shipping. (2018). Guidance Notes on the Application of Ergonomics to Marine Systems.

Ando, Y., & Kimura, H. (2011). An Automatic Piping Algorithm Including Elbows and Bends. *Proceedings of the International Conference on Computer Applications in Shipbuilding*, 3, 153–158.

Furuholmen, M., Glette, K., Hovin, M., & Torresen, J. (2010). Evolutionary Approaches to the Three-dimensional Multi-pipe Routing Problem: A Comparative Study Using Direct Encodings (pp. 71–82). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-12139-5_7

Gunawan, G., Utomo, A.S.A., Hamada, K., Ouchi, K., Yamamoto, H., & Sueshige, Y. (2021). Optimization of Module Arrangement in Ship Engine Room. *Journal of Ship Production and Design*, 37(01), 54–66. https://doi.org/10.5957/jspd.12190066

Ha, J., Roh, M.I., Kim, K.S., & Kim, J.H. (2023). Method for Pipe Routing Using the Expert System and the Heuristic Pathfinding Algorithm in Shipbuilding. *International Journal of Naval Architecture and Ocean Engineering*, 15, 100533. https://doi.org/10.1016/J.IJNAOE.2023.100533

Harabor, D., & Grastien, A. (2011). Online Graph Pruning for Pathfinding On Grid Maps. *Proceedings of the AAAI Conference on Artificial Intelligence*, 25(1), 1114–1119. https://doi.org/10.1609/AAAI.V25I1.7994

Jung, S. K., Roh, M. Il, & Kim, K. S. (2018). Arrangement Method of a Naval Surface Ship Considering Stability, Operability, and Survivability. *Ocean Engineering*, 152, 316–333. https://doi.org/10.1016/J.OCEANENG.2018.01.058

Kendal, S. ., & Creen, M. (2007). *An Introduction to Knowledge Engineering*. London: Spring.

Kim, K.S., & Roh, M.I. (2016). A Submarine Arrangement Design Program Based on the Expert System and the Multistage Optimization. *Advances in Engineering Software*, 98, 97–111. https://doi.org/10.1016/J.ADVENGSOFT.2016.04.008

Kim, K.S., Roh, M.I., & Ha, S. (2015). Expert System based on the Arrangement Evaluation Model for the Arrangement Design of a Submarine. *Expert Systems with Applications*, 42(22), 8731–8744. https://doi.org/10.1016/J.ESWA.2015.07.026

Kim, S.K., Roh, M.I., & Kim, K.S. (2017). Evaluation of Feasibility Index in the Arrangement Design of an Offshore Topside Based on the Automatic Transformation of Experts' Knowledge and the Fuzzy Logic. *Ocean Engineering*, 130, 284–299. https://doi.org/10.1016/J.OCEANENG.2016.11.057

Kim, Y., Lee, K., Nam, B., & Han, Y. (2023). Application of Reinforcement Learning Based on Curriculum Learning for the Pipe Auto-routing of Ships. *Journal of Computational Design and Engineering*, 10(1), 318–328. https://doi.org/10.1093/JCDE/QWAD001

Kimura, H., & Ikehira, S. (2009). Automatic Design for Pipe Arrangement Considering Valve. *Proceedings of the International Conference on Computer Applications in Shipbuilding*, Shanghai, China.

Lee, J. B., Roh, M.I., & Oh, M.J. (2019). Pipe Routing of Offshore Structure Considering Space Availability. *Korean Journal of Computational Design and Engineering*, *24*(3), 280–288. https://doi.org/10.7315/cde.2019.280

Min, J.G., Ruy, W.S., & Park, C. S. (2020). Faster Pipe Auto-routing Using Improved Jump Point Search. *International Journal of Naval Architecture and Ocean Engineering*, *12*, 596–604. https://doi.org/10.1016/J.IJNAOE.2020.07.004

Shin, D., Park, B., Lim, C., Oh, S., Kim, G., & Shin, S. (2020). Pipe Routing using Reinforcement Learning on Initial Design Stage. *Journal of the Society of Naval Architects of Korea*, *57*(4), 191–197. https://doi.org/10.3744/SNAK.2020.57.4.191