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A submarine arrangement design program based on the expert system and the multistage optimization

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ABSTRACT

The arrangement design of a submarine depends on the data of the parent ships and the knowledge of experts. Some delay in design can occur when data or experts are absent. An arrangement design problem of a submarine can also be difficult to solve due to the number of compartments and equipment placed in the limited space, as well as the numerous potential alternatives for the arrangement design. Thus, a compelling need arises to accumulate data regarding the parent ships, the knowledge of experts, and design rules as a systematic structure, increasing the demand for optimization of the arrangement design. In this study, we proposed an arrangement method of the submarine compartments and equipment based on an expert system and a multistage optimization. For this task, we used a template model for the arrangement design of a submarine proposed by the authors in the previous study to store the arrangement data. We also improved and used an expert system that can systematically computerize the knowledge of experts, previously developed by the authors. Then, we proposed an optimization method that can yield a better arrangement design after formulating a submarine arrangement problem as an optimization problem, solving it with the use of an efficient optimization algorithm. To evaluate the applicability of the proposed method, we developed a prototype program consisting of an arrangement template model, an expert system module, and an optimization module. Finally, we applied the developed program to a problem with regard to the arrangement design of a small submarine. The results showed that the developed program can be used as a new tool for the arrangement design of a submarine.

1. Introduction

1.1. Research background

Designers have performed the arrangement design of a ship by referring to previous ships as examples, modifying certain parts as needed. In the case of the arrangement design of a submarine, however, limited data is available about previous submarine designs. Thus, the role of experts is extremely important in the stage of the arrangement design of a submarine, being dependent on the limited data regarding parent ships and the knowledge of experts. Some delay in design can occur when data or experts are absent. Thus, an expert system can represent one of the alternative solutions to such problems. An expert system involves systematically computerizing the knowledge of experts. Arrangement design experts have difficulty calculating complicated, quantitative values (e.g., material flows and space efficiency), but they can take account of many things (e.g., the efficiency, manufacturability, and maintenance aspects of the submarine) by relying on their knowledge. If well developed and applied in the stage of the arrangement design, an expert system can be used to evaluate the feasibility of an arrangement design alternative, rather than relying solely on experts for each design instance. Thus, the authors of this study had previously developed an expert system (that could systematically computerize the knowledge of experts in the stage of the arrangement design of a submarine), further improved for use in this study.

In general, such design efforts place a number of compartments and equipment in a limited space (called a pressure hull), with many potential alternatives for its arrangement design. Finding the best arrangement for a submarine requires finding an optimal arrangement among many alternatives by considering specific criteria (e.g., the feasibility of the arrangement, the operational performance of the submarine, and the convenience of the crew). While difficult, this problem can be effectively solved within the allowable time if using an optimization technique. Thus, we

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mathematically formulated an optimization problem in this study for finding an optimal arrangement based on the evaluation results for design alternatives obtained from the expert system. As formulating an optimization problem with all the variables to be used in the arrangement design presents difficult challenges, we divided the optimization process in this study into three steps, then formulated a multistage optimization problem to consider and solve all these steps.

In other words, in order to solve the difficult problems regarding the arrangement design of a submarine (including the problem of delay in design due to missing data or the absence of experts), we proposed in this study a submarine arrangement design method based on the expert system and the multistage optimization, and we developed a prototype program for the proposed method.

1.2. Related works

As mentioned earlier, most of the equipment in a submarine (being a special kind of ship) must be placed in a limited space. Thus, the arrangement design of a submarine requires greater efforts compared to the arrangement design of a conventional ship, due to the severe space limitations of the former. Many studies on the arrangement design for ships have been conducted, but there have been precious few publicly-available studies on the arrangement design for submarines, as most submarines have been made for military purposes and thus are kept secret. Most that are available focused on an expert system or the optimization for the arrangement design of a ship, but not both. A summary of past studies related to arrangement design in the field of naval architecture and ocean engineering appears below. Byun [1] proposed an expert system based on knowledge bases for supporting initial ship design (e.g., compartment design at the initial design stage), constructing knowledge bases for determining the arrangement of the compartments and the principal dimensions of an oil tanker to obtain the maximum volume of cargo oil (as per the ship owner's requirements and the pertinent international regulations). Shin et al. [2] proposed an expert system for the layout design of the machinery in a ship, devising rules for the layout design of the machinery from the relation between the equipment to the ship owner's requirements, the insights of the designer, etc. When evaluating the rules for design alternatives, these designers also considered fuzzy rules. Finally, these designers developed a new algorithm for the layout design of machinery using the expert system. Lee et al. [3,4] proposed a method for the arrangement design of the facilities on the multi-decks of a naval ship by considering that such ships have inner walls and passages, proposing an improved genetic algorithm that represented the layout of the facilities in a four-segmented chromosome. All the relationships between the facilities and passages were represented through an adjacency graph (i.e., they found an optimal layout for the facilities on the decks by using the optimization technique. Helvacioglu and Insel [5] proposed a multistage expert system for the arrangement design of a container ship (i.e., compartment arrangement), dividing a container ship into several large blocks called function groups, then initially arranging them to determine the compartment arrangement. By considering more detailed data, these designers derived the final arrangement of the ship's compartments, using heuristic knowledge and rules for the container ship in their expert system. Chung et al. [6] proposed a submarine arrangement design method based on an expert system and an optimization technique, using a rule-based expert system in their method. These designers selected partitions dividing the pressure hull into compartments, and the sequence of the compartments, as design variables for optimization. The evaluation values for the alternatives obtained from their expert system were used as an objective function for optimization (i.e., if a certain alternative violated a rule, a penalty would be added to the value of the objective function of that alternative). Yang et al. [7] proposed a knowledge-based engineering methodology for ship structural design. To design structural members (e.g., L bars, T bars, brackets, etc.), these designers defined several parametric models and parameters (e.g., web thickness, ribbon width, etc.). Gathering various knowledge from rules or experts to design the structural members, these designers developed a products design knowledge base containing such knowledge. Following their study, Cui et al. [8] suggested a knowledge-based engineering method for ship structural design, including optimization. A products design knowledge base in their study was similar with the former study; however, their study adopted an optimization process, after selecting parameters used to design structural members. To reduce structural weight without strength failure, the parameters were optimized using GA. Then, these designers applied the proposed method to design a midship. Shin [9] proposed a method for the arrangement design of a naval ship by considering its survivability at the initial design stage. Shin used the SLP (systematic layout planning) method for analyzing the relation between the equipment in the naval ship, then proposed an arrangement method for generating alternatives and evaluating them. The SLP method differs from an expert system in that the method decides the arrangement by using the relation matrix between the equipment; however, as such equipment would be made by an expert, the SLP method remains somewhat similar to an expert system. We proposed an expert system based on an arrangement evaluation model (AEM) for the arrangement design of a submarine from a previous study [10], with the AEM proposed as an expansion of a rule-based expert system. In addition, we proposed an arrangement template model (ATM) for the submarine to store the arrangement data of the submarine. However, we chose not to integrate the expert system with an optimization technique for arrangement design.

The field of architecture also produces research on expert systems. Park [11] proposed a framework for representing the knowledge of experts by using the space requirements (area, position, etc.) and the relation between the spaces (adjacency, level difference, etc.). Then, Park manually evaluated the given arrangement for a building using the proposed framework.

As with the above, most relevant research thus far has focused on the expert system or the optimization technique for the arrangement design (i.e., in most studies, the designers independently performed the expert system and the optimization process, without any integration between them). Moreover, a three-dimensional submarine arrangement design method based on an expert system and an optimization technique has not yet been studied. Thus, by expanding on the previous study [10], we used an arrangement evaluation model (AEM) in this study that could systematically convey the knowledge of experts for the arrangement design of a submarine to evaluate the feasibility of the alternatives for the arrangement design. We mathematically formulated multistage optimization problems based on the evaluation values from our expert system (AEM) for the efficient performance of optimization. In addition, we used a data structure for the arrangement design of a submarine (arrangement template model; ATM) for storing all the data for the arrangement design and to effectively interface the data between the expert system module and the optimization module. In this study, we seamlessly integrated the expert system and the optimization process, incorporating the expert system to optimization problems as one of the objective functions. Using this method, we linked the expert system (including the knowledge of experts) with (but separate from) the optimization process; thus, the developed program based on the method did not need to be recompiled or rebuilt, even when the knowledge of experts changed or updated. However, when