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Modular Ship Design: Rapid Prototyping and Enhancing Efficiency through Design Modules

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ABSTRACT

In this paper, we introduce a modular approach to ship design, utilizing design modules to streamline the initial design phases. Ships are conceived as combinations of a primary 'ship module' and various 'design modules' tailored for specific spaces. These modules encompass predefined geometries, layouts, and equipment configurations. We introduce an optimization model that integrates decision variables for ship attributes and configuration variables for module selection. Through this framework, we aim to simplify design complexities, accelerate the production of detailed drawings, and foster innovation in ship design methodologies.

KEY WORDS

Modularity, Configure-to-order, Ship module, Design module, Modular ship.

INTRODUCTION

Modularity, as elucidated by Baldwin and Clark (2000), embodies a structured design framework wherein parameters and tasks intricately interconnect within modules, while retaining independence across them. These modules act as discrete units within a system, facilitating integration or separation through standardized interfaces, thereby offering manifold advantages across the lifecycle of modular ships.

In the realm of ship design, modularity emerges as a pivotal approach fostering innovation and efficiency. It enables designers to capitalize on previous designs and streamline representations within modules to effectively navigate the inherent complexities of maritime vessels (Papanikolaou, 2010). This simplification is paramount given the multitude of subsystems and diverse stakeholder requirements inherent in comprehensive ship designs. Moreover, principles underlying design building blocks (Andrews, 2011) and the packing approach (Van Oers, 2011), which employ independent design elements termed 'blocks' and 'objects', respectively, closely align with the concept of modularity.

Furthermore, modularity significantly influences ship production processes. By enabling parallel manufacturing and testing of modules, it reduces production timelines and enhances the efficiency of dry dock operations, a vital resource for shipyards. Additionally, standardized interfaces foster expanded outsourcing opportunities, further streamlining production processes.

In the operational phase, modularity facilitates concepts like 'evolutionary acquisition' and 'mission flexibility,' as delineated by Abbott et al. (2003). Unlike conventional ship acquisition processes, evolutionary acquisition defers investment decisions for modules until more information becomes available, aligning investment decisions with operational needs.

The SIMOSYS project from 2014 to 2018, spearheaded by Erikstad and Choi, proposed optimization models for the design of modular ships, leveraging modularity to navigate uncertainties in the operational phase, dubbing such ships as modular

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adaptable ships (MASs). However, in the design of MASs, complexity may arise in valuating flexibility due to their dynamic nature in responding to contextual changes. Addressing this challenge, Choi and Erikstad (2017) and Choi et al. (2017) present optimization models combining module configuration and valuation problems of MASs. Additionally, Choi et al. (2018) propose an optimization model for the design of the platform module of MASs, which serves as the basis accommodating various mission-related modules.

This paper is in alignment with the objectives set forth by the SIMOSYS project, placing a significant emphasis on enhancing module configuration and valuation methods while taking into account the layout, geometry, and scalability of modules. Scalability plays a pivotal role in augmenting the reusability of modules to effectively address the diverse requirements of stakeholders. As a result of addressing these optimization challenges, the overall design layout can be derived, facilitating a comprehensive solution to the design problem at hand.

DESIGN PROCESS OF MODULAR SHIPS

According to Ulrich (1995), modularity can be categorized into different types based on interface diversity and the presence of a main body. These types include sectional, bus, and slot modularity. Salvador et al. (2002) further elaborate on slot-type modularity, distinguishing between combinatorial modularity and component-swapping modularity. For the design of MASs, component-swapping modularity is often suitable, as the hull serves as the main body accommodating various module configurations. Unlike bus modularity, component-swapping modularity does not necessitate identical interfaces, making it a more versatile option. Figure 1 provides a visual representation of these four types of modularity.

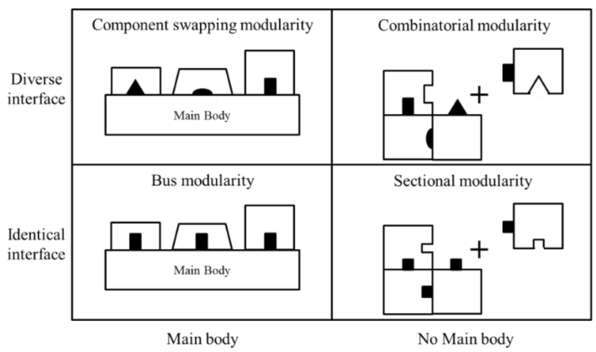

Figure 1: Four Types of Modularity Defined by Salvador et al. (2002).

The traditional ship design process follows a top-down approach, where designers refine options for a benchmark ship iteratively, ultimately reaching a finalized design. This aligns with a ‘build-to-order’ strategy, aiming to deliver customized products to each customer. Conversely, the module-based design process operates bottom-up. Here, design alternatives are generated by configuring predeveloped modules, indirectly determining design characteristics through module configuration. This facilitates the ‘configure-to-order (CTO)’ strategy, where multiple design projects utilize standard modules developed prior to confirmed orders, based on demand forecasts. Implementing the CTO process allows design teams to reduce development time and costs while enhancing design reliability with tested technologies. Additionally, rapid prototyping enhances customer communication, crucial for defining appropriate key performance indicators for design projects. Figure 2 depicts ship design projects employing the CTO process.

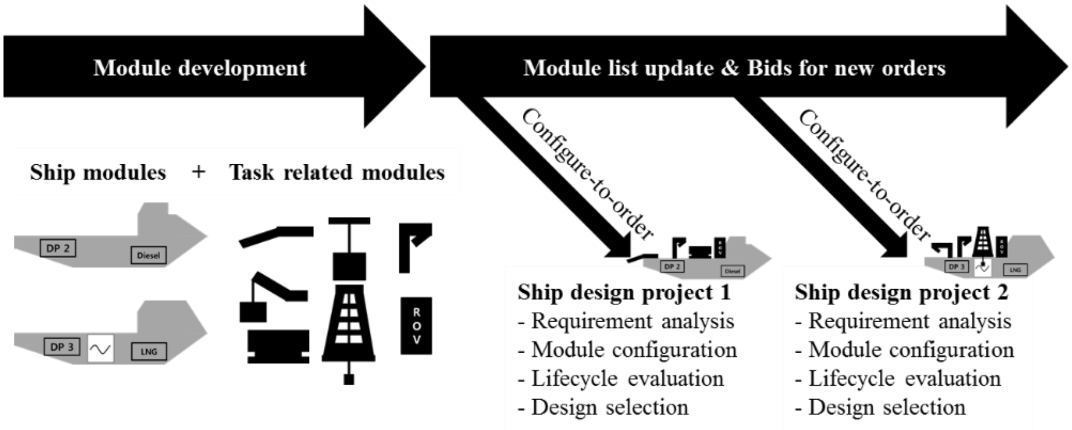

Figure 2: Ship Design Projects Based on the Configure-To-Order Strategy (Choi and Erikstad, 2017).

While Figure 2 offers valuable insight into the CTO process for modular ships, a deeper exploration is warranted to elucidate the intricate steps involved in obtaining detailed designs, such as general arrangements, through this method.

SHIP MODULES

Ship modules are the main body of modular ships in the component swapping modularity. In an optimization point of view, ship modules can be represented by decision variables and parameters, in which the decision variables indicate the attributes the value of which needs to be determined in the design problem, and the parameters indicate constant attributes the value of which are given. The choice of which design variables and constants to use to represent a ship module depends on the intended use of the ship module.

A ship module has its own properties but also spaces that are relatively high-level topology and geometry information acting as interfaces with other modules. Figure 3 describes an example of the ship module, in which the ship module has 7 spaces: steering gear room, main deck, store, stern deck, deck house, bow deck, and deck house up.

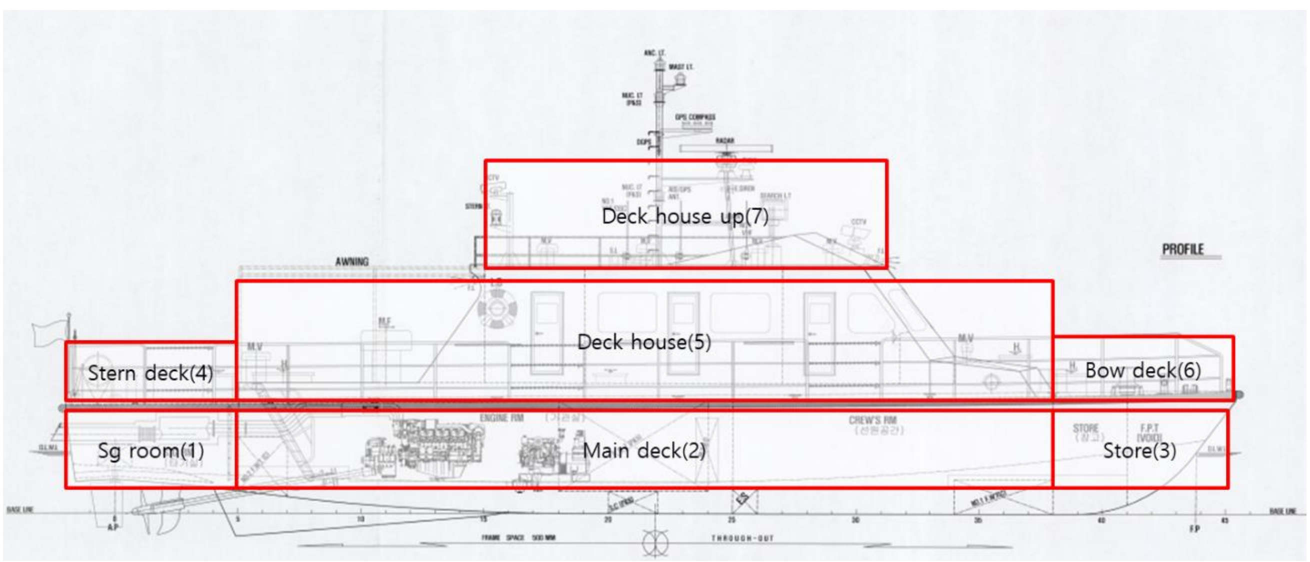

Figure 3: An Example of a Ship Module.

DESIGN MODULES

Because spaces in a ship module have only their boundary shape, the spaces need to be divided into more smaller subspaces. This is a highly complex problem that requires simultaneous consideration of geometry and topology. As the complexity of the problem increases from an optimization perspective, finding good solutions becomes increasingly challenging. Therefore, this study introduces the concept of design modules to reduce the complexity of the problem.

The design modules are predeveloped partial designs which comprise subspaces. Each subspace has its geometry information and could have a set of equipment and its lower-level subspaces. Figure 4 describes examples of design modules of main deck and Figure 5 presents the schematic diagram that illustrates the relations between ship module, space, design module, subspace.

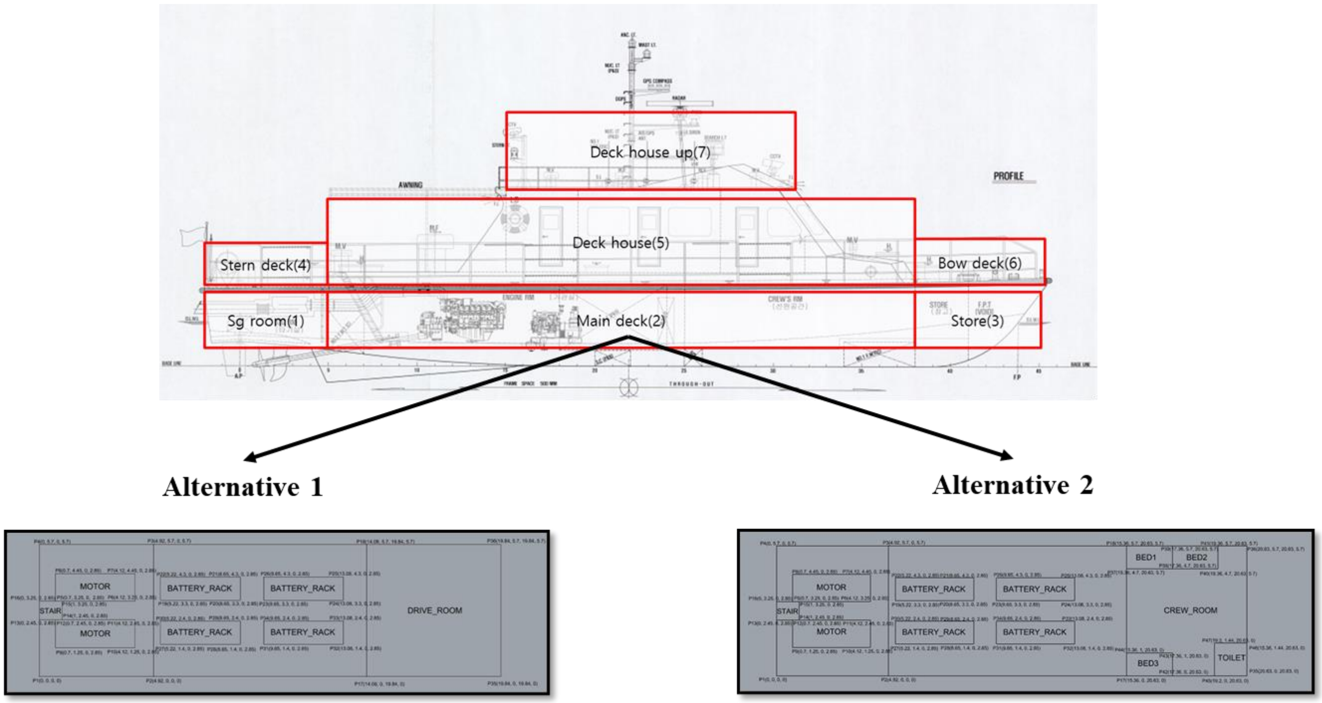

Figure 4: Two Design Module Alternatives of the Main Deck Space.

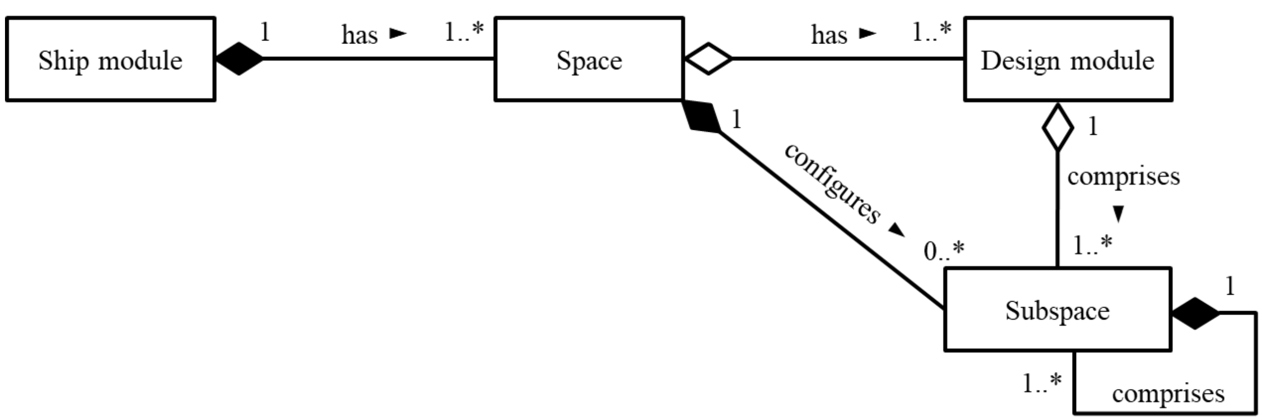

Figure 5: Schematic Diagram Between Ship Module, Space, Design Module, and Subspace.

Let's delve deeper into these alternatives. Figures 6 and 7 depict alternative 1 and 2, respectively, of the main deck space. A notable distinction between these alternatives lies in the presence or absence of the drive room and accommodation space. The selection of each module can vary depending on the specific accommodation requirements for the main deck space.

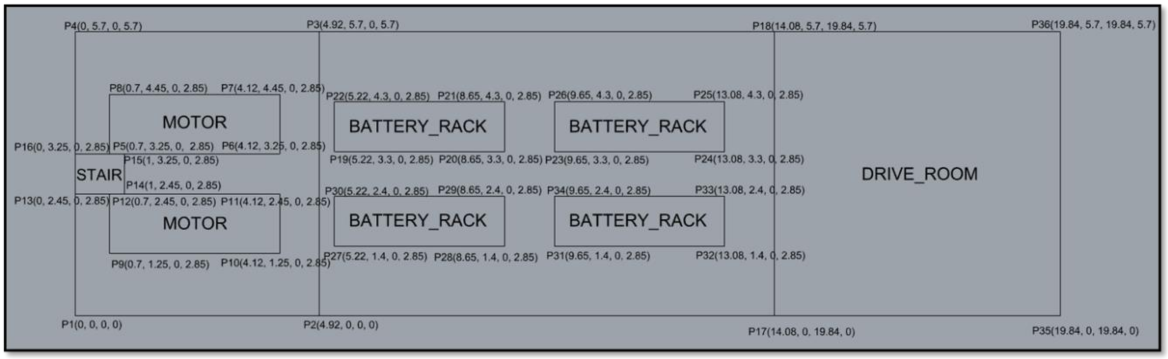

Figure 6: Design Module Alternative 1 of the Main Deck Space.

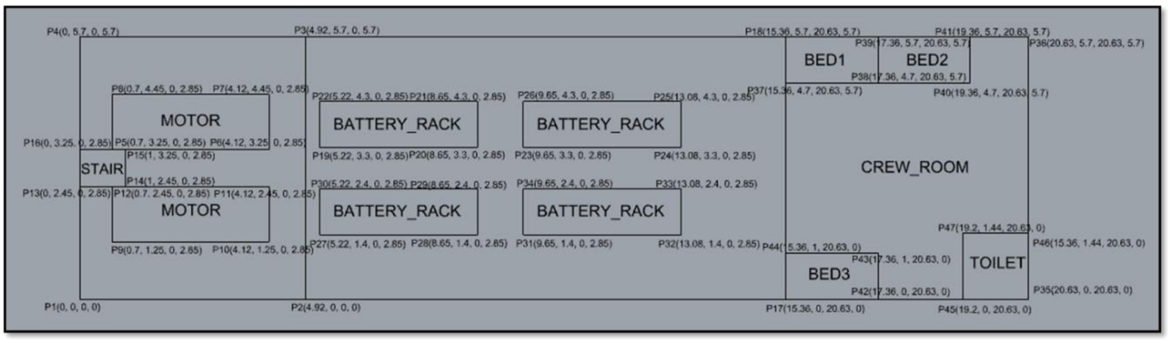

Figure 7: Design Module Alternative 2 of the Main Deck Space.

Because the design modules are predeveloped designs, the scale of the design modules needs to be adjusted to fit to the space where the design modules are assigned. Design modules are developed with scalability in mind to compensate for differences in basic form and allocated space size. The vertices of the detailed compartments constituting the design module are comprised of four pairs of values (x, y, a, b), where each value sequentially represents the x-coordinate, y-coordinate, x-scale factor, and y-scale factor. Here, the x and y coordinates denote the coordinates in the basic form, while the scale factors a and b are used to define the scalability of the design module, determining the new coordinates of the vertices through Equations 1 and 2.

$$\text{New } x = x + (\text{length of space along x-axis} / \text{length of ship module along x-axis} - 1) * a \quad [1]$$

$$\text{New } y = y + (\text{length of space along y-axis} / \text{length of ship module along y-axis} - 1) * b \quad [2]$$

Let's examine a more detailed example. In Figure 5, the design module includes spaces for a galley, toilet, and meeting room. The galley's shape can expand or contract based on the length of the allocated space along the y-axis, causing P6 and P7 to move vertically. However, its dimensions along the x-axis remain constant regardless of the allocated space's length in that direction. Conversely, alterations in the allocated space's dimensions along both the x and y axes do not affect the shape of the toilet. However, adjustments in both the x and y axes of the allocated space impact the configuration of the meeting room. Specifically, changes along the x-axis cause P8 and P9 to shift horizontally, while variations along the y-axis prompt vertical movements of P6 and P9. Notably, P2, P3, and P5 remain unaffected by adjustments in the dimensions along both axes of the allocated space.

Figure 8 illustrates the geometric alterations observed in the toilet. The x-scale factor and y-scale factor values for the toilet's vertices are set to 0, signifying that vertex coordinates remain constant regardless of the design module's allocation to different spatial configurations. Determining the scale factor values allows design module creators to accurately convey their design intentions.

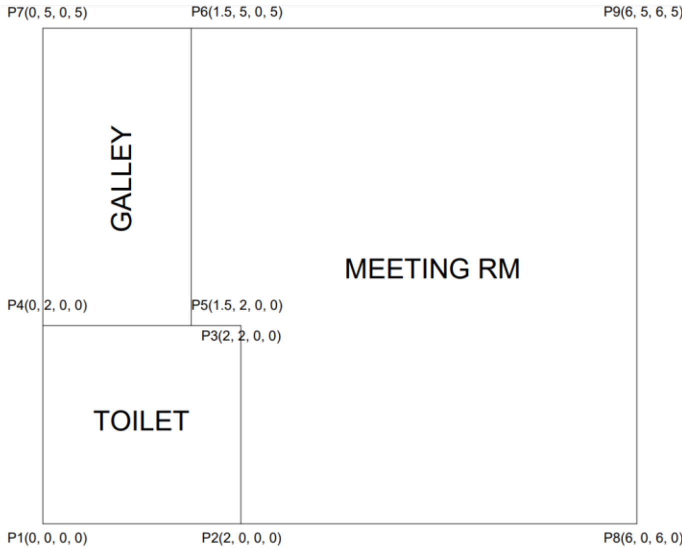

Figure 8: An Example of a Design Module That Comprises a Galley, Toilet, and Meeting Room.

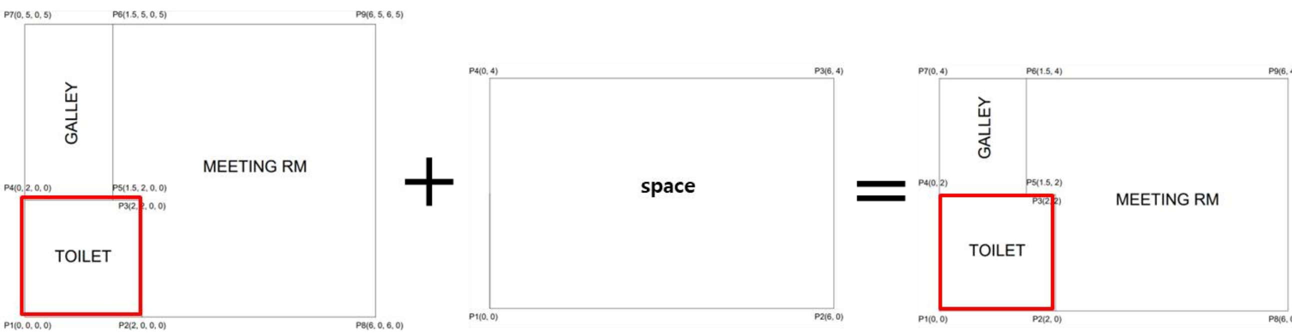

Figure 9: Geometry Changes When the Design Module Is Combined with a Space.

MATHEMATICAL MODEL FOR MODULAR SHIP DESIGN USING DESIGN MODULES

In this section, we introduce an optimization model tailored specifically for addressing design challenges inherent in modularity through the utilization of design modules. It is important to note that our approach assumes a static design problem, wherein dynamic changes occurring during the operational phase are not explicitly accounted for.

Sets:

$\boldsymbol{S}$	Set of spaces, indexed by s
$\boldsymbol{M}_s$	Set of design modules of space s, indexed by m
$\boldsymbol{P}$	Set of capabilities, indexed by p
$\boldsymbol{P}^{MAX}$	Subset of capabilities that need to be maximized, indexed by p
$\boldsymbol{P}^{MIN}$	Subset of capabilities that need to be minimized, indexed by p
$\boldsymbol{P}^{GOAL}$	Subset of capabilities that have a goal value, indexed by p
$\mathbf{x}$	Set of ship variables, indexed by x_i
$\mathbf{y}$	Set of module selection variables, indexed by y_{sm}

Parameters:

R_p^{MIN}	Minimum requirement of capability p
R_p^{MAX}	Maximum requirement of capability p
L_i^X	Lower boundary of basic variable x_i
U_i^X	Upper boundary of basic variable x_i
W_p	Weight of capability p
W_p^-	Weight of negative deviation of capability p
W_p^+	Weight of positive deviation of capability p

Variables:

x_i	i-th ship variable
y_{sm}	1 if design module m is selected for space s, 0 otherwise

Model:

$$\text{Min} \quad \sum_{p\in \boldsymbol{P^{MIN}}} W_p f_p(\mathbf{x},\mathbf{y}) - \sum_{p\in \boldsymbol{P^{MAX}}} W_p f_p(\mathbf{x},\mathbf{y}) + \sum_{p\in \boldsymbol{P^{GOAL}}} W_p^- d_p^- + W_p^+ d_p^+ \qquad [3]$$

$$\text{s.t.} \quad \sum_{m\in M_s} y_{sm} = 1 \qquad s \in \boldsymbol{S} \qquad [4]$$

$$f_p(\mathbf{x},\mathbf{y}) + d_p^- - d_p^+ = G_p \qquad p \in \boldsymbol{P}^{GOAL} \qquad [5]$$

$$d_p^-, d_p^+ \geq 0 \qquad p \in \boldsymbol{P}^{GOAL} \qquad [6]$$

$$R_p^{MIN} \leq f_p(\mathbf{x},\mathbf{y}) \qquad p \in \boldsymbol{P}^{MIN} \qquad [7]$$

$$f_p(\mathbf{x},\mathbf{y}) \leq R_p^{MAX} \qquad p \in \boldsymbol{P}^{MAX} \qquad [8]$$

$$\left.\begin{array}{ll} x_i \in \{0, 1\} & \text{if } x_i \text{ is a binary variable,} \\ L_i^X \leq x_i \leq U_i^X & \text{otherwise,} \end{array}\right. \qquad i \in \{1, \dots, |\mathbf{x}|\} \qquad [9]$$

$$y_{sm} \in \{0, 1\}. \qquad s \in \boldsymbol{S}, \mathrm{m} \in \boldsymbol{M}_s \qquad [10]$$

Equation [3] serves as the objective function, encompassing the overarching goals of the design process. It balances the minimization and maximization of various capabilities essential for the ship's performance while ensuring convergence towards a desirable outcome. Equation [4] guarantees the integrity of the design by stipulating that only one design module can be selected for each space, preventing redundancies or conflicting configurations. Equation [5] establishes a connection between the desired goals for specific capabilities and their actual achievement, employing negative and positive deviation variables to quantify the extent of any discrepancies. Equation [6] enforces the non-negativity constraint on the deviation variables, ensuring that any deviations from the desired goals are expressed as positive values, reflecting a proactive approach to addressing deficiencies. Equations [7] and [8] set the boundaries for the minimum and maximum requirements of each capability, respectively, ensuring that the design satisfies essential performance thresholds while avoiding over-specification. Equations [9] and [10] define the feasible ranges for the ship and module selection variables, allowing for binary decisions regarding the inclusion or exclusion of specific design elements within the overall configuration.

CONCLUSIONS

The modular approach presented in this paper offers several notable advantages in ship design methodologies. By employing design modules and optimization models, the design process is streamlined, leading to enhanced efficiency and innovation. Here, we discuss the implications and potential future directions stemming from this research.

Firstly, the use of modular design significantly simplifies the initial design phases. Instead of starting from scratch for each new ship design, designers can leverage predeveloped design modules, saving time and resources. This streamlined process accelerates the production of detailed drawings and prototypes, facilitating rapid prototyping and iteration cycles.

Secondly, the optimization model introduced in this paper enables optimal selection and configuration of design modules based on specific ship requirements. By considering both ship attributes and module configurations simultaneously, the model ensures that design decisions are made with the overarching goals of the ship's performance in mind.

Furthermore, the scalability of design modules enhances their reusability across different ship designs and types. This scalability not only improves design efficiency but also fosters innovation by allowing designers to experiment with different configurations and arrangements to meet diverse stakeholder needs.

However, it is important to acknowledge the limitations of the proposed approach, particularly in the context of 3D design. While the optimization model and design modules offer significant benefits in 2D design spaces, translating these concepts into three-dimensional environments poses challenges. Future studies could explore methodologies for extending the modular approach to 3D design, addressing issues such as spatial constraints, interface complexities, and computational requirements.

In conclusion, the modular ship design framework presented in this paper offers a promising pathway towards more efficient and innovative ship design methodologies. By simplifying design complexities, accelerating prototyping processes, and fostering innovation, this approach holds the potential to revolutionize the way ships are conceptualized and developed. Future research could focus on further refining optimization models, expanding the range of design modules, and addressing the challenges of 3D design integration.

CONTRIBUTION STATEMENT

Minjoo Choi: Conceptualization; data curation; methodology; software; writing – original draft; writing – review and editing; supervision; project administration; funding acquisition. **Jaekyeong Lee**: Data curation; methodology; validation; software; visualization.

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REFERENCES

Abbott, J., Devries, R., Schoenster, W., Vasilakos, J., Firebaugh, M., Malchiodi, A., & Goddard, C. (2003). The impact of evolutionary acquisition on naval ship design. Transactions Society of Naval Architects and Marine Engineers (SNAME), 111, 259-286.

Andrews, D. J. (2011). Marine requirements elucidation and the nature of preliminary ship design. Transactions Royal Institution of Naval Architects (RINA), Vol 153, Part A1, International Journal Maritime Engineering (IJME), Jan-Mar 2011.

Baldwin, C. Y., & Clark, K. B. (2000). Design rules: The power of modularity (Vol. 1). Cambridge: MIT press.

Choi, M., & Erikstad, S. O. (2017). A module configuration and valuation model for operational flexibility in ship design using contract scenarios. Ships and Offshore Structures, 12(8), 1127-1135.

Choi, M., Rehn, C. F., & Erikstad, S. O. (2018). A hybrid method for a module configuration problem in modular adaptable ship design. Ships and Offshore Structures, 13(4), 343-351.

Choi, M., Erikstad, S. O., & Chung, H. (2018). Operation platform design for modular adaptable ships: Towards the configure-to-order strategy. Ocean Engineering, 163, 85-93.

Papanikolaou, A. (2010). Holistic ship design optimization. Computer-Aided Design, 42(11), 1028-1044.

Salvador, F., Forza, C., & Rungtusanatham, M. (2002). Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions. Journal of Operations Management, 20(5), 549-575.

Van Oers, B. J. (2011). A packing approach for the early stage design of service vessels. PhD Thesis, TU Delft.