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3D Parametric Modeling for Ship Concept Design: A Flexible Approach to General Arrangement Plan

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Abstract. The concept design phase of a ship is a critical stage that lays the foundation for successful project development, as it establishes the primary framework for the vessel's operational and technical characteristics. This phase requires the evaluation of multiple design alternatives to achieve an optimal balance between performance and feasibility while addressing the complex requirements of stakeholders. Traditionally, general arrangement plans have been developed using 2D CAD tools, where spatial organization decisions are primarily driven by experience and specific owner requests. However, this conventional approach presents significant limitations, particularly when modifications are needed. Since adjustments often require extensive manual rework, the process becomes inefficient and less adaptable to evolving design constraints. Additionally, ensuring consistency across multiple design iterations can be challenging, increasing the risk of errors and delays. To overcome these limitations, this study introduces an innovative methodology for ship concept design, leveraging 3D parametric modeling as a key enabler for enhanced flexibility and efficiency. Unlike traditional methods, this approach facilitates the rapid generation and assessment of alternative solutions, particularly through the development of parametric general arrangement plans. These plans allow for the swift modification of design parameters, such as layout dimensions, volumetric capacities, and functional configurations, while maintaining overall consistency within the model. The effectiveness of the proposed methodology is demonstrated through a case study involving the design of a passenger transport vessel. By integrating advanced parametric modeling techniques, the design process becomes more dynamic and responsive, enabling the exploration of multiple spatial configurations with ease. This enhanced adaptability not only streamlines the overall workflow but also allows designers to quickly address changes in requirements or constraints posed by shipowners, ultimately leading to a more efficient and iterative design process.

Keywords. 3D Parametric Modeling, Ship Concept Design, General Arrangement Plan, Grasshopper

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1. Introduction

The conceptual design phase represents a foundational step in ship development, wherein the vessel's primary characteristics, both operational and technical, are initially defined. During this stage, designers must explore a vast and often complex solution space to identify configurations that not only satisfy diverse stakeholder needs but also conform to performance, regulatory, and safety constraints [1, 2]. This exploratory process requires the generation and evaluation of multiple alternatives, highlighting the importance of flexibility, efficiency, and responsiveness in early-stage design [3, 4]. These activities are based on methods such as concurrent and system engineering [5, 6].

Historically, general arrangement (GA) plans have been developed through two-dimensional CAD systems, supported by expert knowledge and manual drafting. While such practices have formed the backbone of conventional naval design, they present significant challenges in terms of scalability, adaptability, and iterative development. Notably, the lack of parametric structure constrains the ability to accommodate changes efficiently, often necessitating time-consuming manual updates and comprehensive consistency checks across various design versions [7, 8]. These limitations hinder rapid decision-making and increase the risk of design inconsistencies.

The increasing integration of computational tools has led to the evolution of parametric design methods, originating in fields such as architecture and industrial product design [9]. In naval architecture, parametric modeling has become widely adopted in the development of ship hull forms, enabling designers to manipulate geometry through a limited set of control variables while maintaining geometric continuity and physical feasibility. Techniques such as B-splines, NURBS, and Free Form Deformation (FFD) are now routinely used for hull surface generation and hydrodynamic optimization [3, 10].

Recent advancements have also introduced data-driven approaches to hull design. Generative models like ShipHullGAN utilize deep convolutional networks to learn and reproduce a broad range of hull geometries, supporting the automated generation of feasible shapes under design constraints [10]. Such tools offer a shift from manual parameterization toward latent-space design exploration, enhancing both creativity and engineering control. These methods are increasingly coupled with statistical reduction techniques such as Principal Component Analysis (PCA) and Proper Orthogonal Decomposition (POD), which further support efficient search and optimization in high-dimensional design spaces [11, 12].

In contrast, the application of parametric methodologies to internal spatial configurations, particularly GA modeling, remains less mature. Traditional layout planning is typically informed by historical arrangements and constrained by rigid, 2D drafting conventions. As a result, the design process is often linear and fragmented, complicating updates in response to shifting requirements or feedback. To address this gap, recent research has introduced rule-based and constraint-driven frameworks for parametric GA generation. These approaches automate space allocation by enforcing adjacency rules and functional zoning logic [4, 2], thereby supporting fast iteration and compliance checking.

Advanced modeling environments like Rhinoceros and Grasshopper now enable the creation of fully parameterized 3D GA models, in which each compartment or structural element can be adjusted through editable variables. This capacity for rapid iteration is further enhanced by intelligent evaluation systems, including AI-based classifiers capable of assessing layout quality and regulatory compliance in real time [13].

Additionally, object-packing algorithms and multi-objective optimization techniques have been integrated into early design frameworks such as the TU Delft Ship Synthesis Model, improving the generation of feasible GA configurations while considering operability and safety [8, 14].

Despite these developments, current design workflows remain largely decoupled, treating hull form generation and GA planning as separate processes. This separation leads to inefficiencies and a lack of coherence when modifications in one domain necessitate corresponding adjustments in the other. The transition toward Ship Design 4.0, driven by digitalization, automation, and data-centric integration, demands more unified approaches that embed parametric logic across both external and internal aspects of ship architecture [15].

In response to these challenges, this study proposes a methodology for early-stage ship design that leverages 3D parametric modeling for general arrangements, tightly integrated with hull form definition. The method is applied to a case study involving a passenger vessel, wherein multiple spatial configurations are generated and evaluated rapidly. By embedding parametric intelligence in both volumetric and layout components, the proposed approach enhances design consistency, improves responsiveness to constraints, and supports informed decision-making throughout the conceptual phase.

2. Methodology

This study proposes a parametric modeling approach to support early-stage spatial design in passenger vessels, with particular focus on the main deck layout. The methodology was implemented using Grasshopper, a node-based algorithmic modeling environment integrated within Rhinoceros 3D. This tool is widely used in architecture and increasingly adopted in engineering disciplines for its capacity to manage complex geometries through programmable logic.

Grasshopper allows designers to define parametric relationships among geometric elements by connecting modular components in a visual workflow (Figure 1). This facilitates the generation of adaptive models where changes in input parameters automatically propagate throughout the design. Such flexibility is particularly valuable in ship design, where iterative modifications must be evaluated rapidly while maintaining compliance with space, safety, and operational requirements.

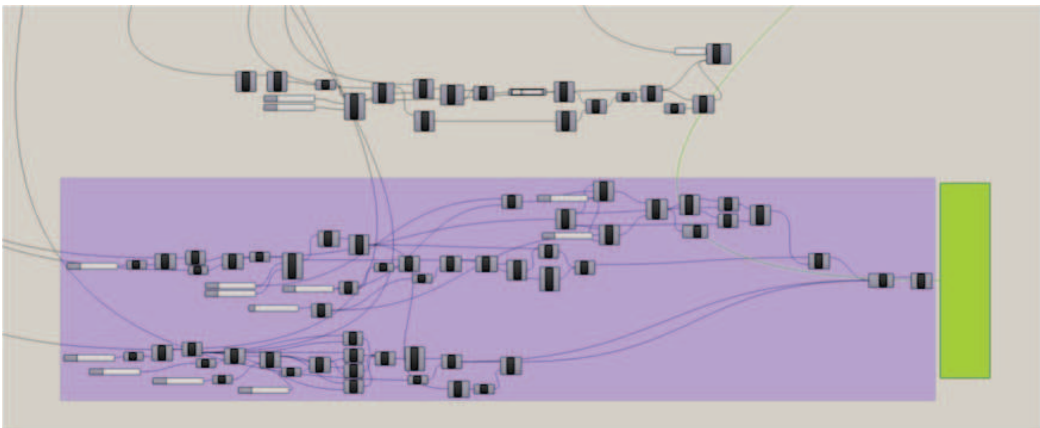

Figure 1. Grasshopper interface showing the parametric workflow used to define spatial rules and generate design alternatives through modular components.

The methodology developed in this study captures the essential features of a passenger vessel's main deck, integrating functional zoning, circulation, and accessibility constraints (Figure 2). A set of key input parameters was established to guide the automatic generation and evaluation of general arrangement alternatives. These include:

- Embarkation longitudinal position;
- Number and width of main corridors, influenced by evacuation and flow efficiency criteria;
- Location of sanitary facilities.

Each parameter was encoded as a variable within the Grasshopper environment, where logical conditions ensured that spatial rules were consistently satisfied. For instance, minimum corridor widths and unobstructed escape routes were enforced through geometric constraints and exclusion zones.

The model was composed of several functional layers:

- Geometric kernel: defines the hull envelope, structural bulkheads, and reference surfaces for layout operations;
- Zoning and allocation module: automatically distributes seating areas, corridors, toilets, and staircases based on parameter values and predefined zoning logic;
- Constraint management system: filters invalid or non-compliant configurations (e.g., overlapping elements, insufficient clearance);
- Evaluation interface: calculates layout-specific performance metrics in real time.

By modifying input variables, the model produced a wide array of spatial configurations, each assessed according to a set of design-relevant indicators:

- Total Seating Capacity: represents the overall number of seating units available within the designated area;
- Accessibility Index: a metric derived from the average distance between seating positions designated for individuals with reduced mobility and key functional areas, such as the main entrance and restrooms. It quantifies spatial accessibility and ease of reach;
- Comfort Score: a spatial indicator calculated as the average distance between each seat and the centerline of the nearest circulation corridor. This metric reflects the ease of access to movement paths and the overall spatial comfort experienced by seated users;
- Longitudinal Center of Gravity (*LCG*): the weighted average position of the estimated passenger load along the longitudinal axis of the space. It serves as an indicator of the spatial balance and distribution of occupants.

In particular, the use of Grasshopper enabled a flexible and responsive design workflow, where the impact of design decisions could be visualized, quantified, and revised in real time.

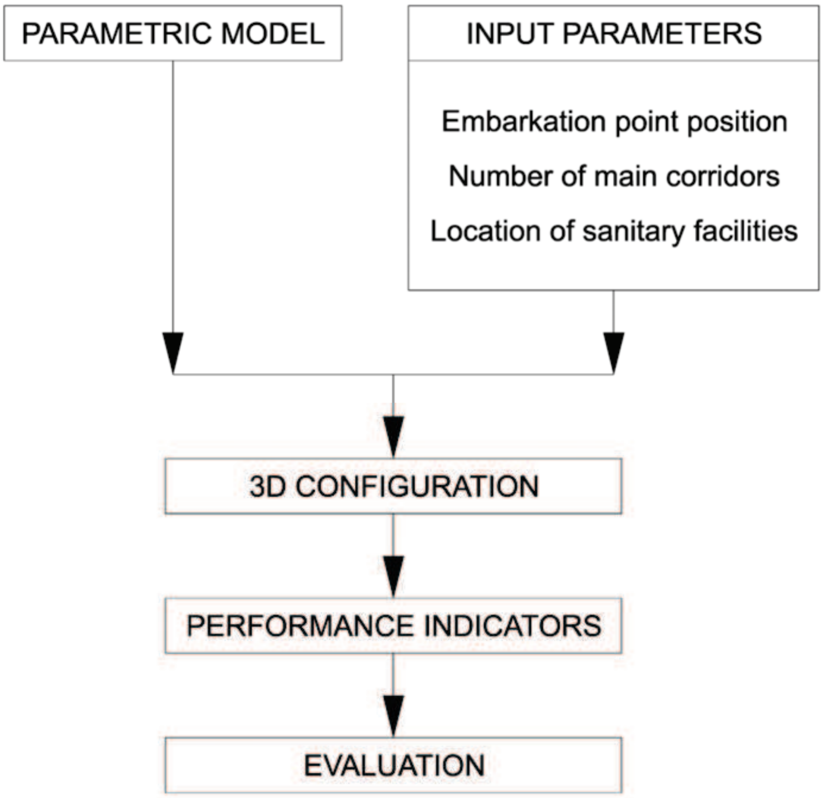

Figure 2. Proposed methodology.

3. Case study

A case study was conducted on the passenger vessel designed for coastal national navigation. The vessel exhibits an overall length of 22.81 meters and a maximum beam of 5.30 meters. Manufactured in Glass Reinforced Plastic (GRP), a material widely adopted in boatbuilding for its favorable strength-to-weight ratio and durability, the vessel's gross tonnage is measured at 24.37 GT.

The vessel features a dual-deck layout comprising a main deck and an upper deck. In particular, the main deck (Figure 3) serves as the primary passenger accommodation area; however, its spatial layout presents certain limitations in terms of accessibility and comfort. Access to the deck is provided solely via an entrance located at the forward section (bow) of the vessel. Two restroom facilities are positioned at the aft section (stern), which poses significant challenges for passengers with reduced mobility due to the distance and circulation constraints along the deck.

Passenger seating is arranged in two parallel rows of four fixed seats each, for a total capacity of 123 seats. In addition, there are four seats which are reclining, designed to create additional space as needed to accommodate passengers with reduced mobility. The central aisle between the rows has a width of 1.20 meters, compliant with current regulatory standards governing passenger vessels.

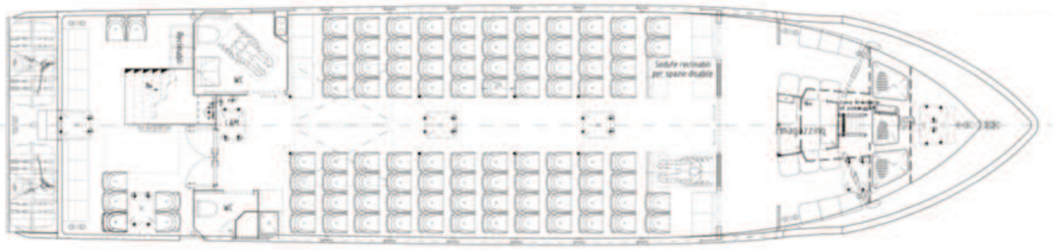

Figure 3. Main deck General Arrangement plan.

4. Results and discussion

To establish a benchmark for performance evaluation, an initial digital model of the reference vessel was developed. This included a 3D reconstruction of the hull (Figure 4) and a detailed reproduction of the general arrangement of the main deck (Figure 5): in particular, the bulwarks of the first tier of superstructures and the walls of the restrooms were modeled in 3D with consideration of their actual thicknesses. Seating elements shown in red in Figure 5, on the other hand, were represented as simplified 3D parallelepipeds. The corridor area is highlighted in green, while the dedicated seating for passengers with reduced mobility is framed in blue.

From the general arrangement, the total number of seats could be identified. Key performance indicators (KPIs) associated with this baseline configuration are summarized in Table 1.

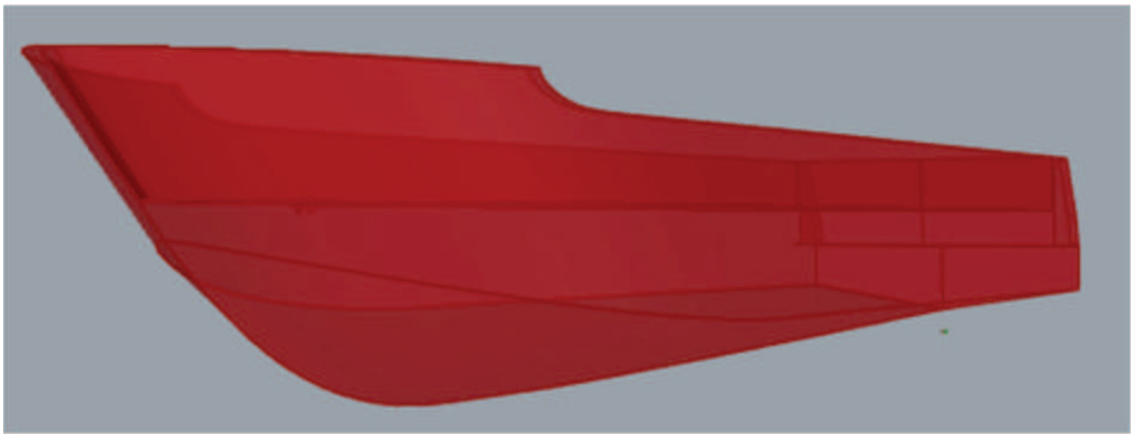

Figure 4. Benchmark 3D Hull.

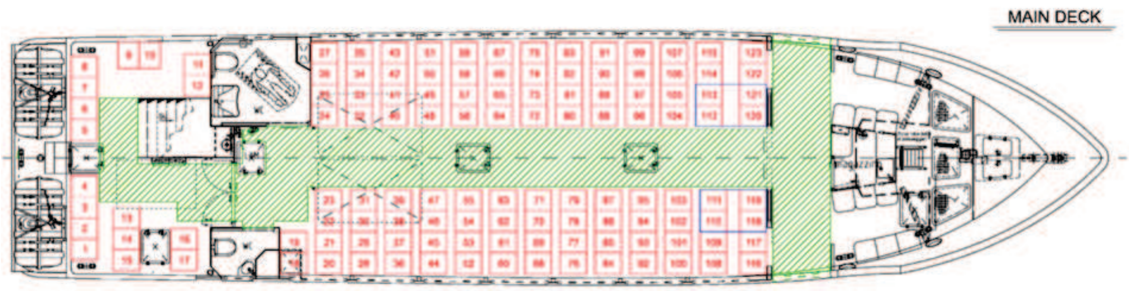

Figure 5. Reproduction of the General Arrangement plan of the Main Deck.

Table 1. Key performance indicators of the baseline configuration.

Design	Seats (/)	Accessibility (m)	Comfort (m)	*LCG* (m)
0	123	5.83	1.54	9.80

Following the definition of the baseline, a parametric study was conducted by varying key layout variables related to passenger accessibility and spatial organization on board. The following variables were selected:

- Entrance Location: Stern and Bow;
- Corridor Configuration: single central aisle and dual lateral aisles;
- Toilet Location: Stern and Bow.

By combining all possible configurations of these three binary variables, a total of 8 distinct design alternatives were generated (Table 2).

Particular attention was given to the placement of seats dedicated to passengers with reduced mobility (PRM), their corresponding toilet facilities, and the boarding entrance. The design objective was to minimize the average distance between these elements, thereby maximizing the Accessibility Index (where lower values indicate better accessibility).

Similarly, as the Comfort Score is defined as the average distance between each seat and the centerline of the nearest corridor, lower values correspond to more convenient and accessible seating arrangements and thus better user comfort.

Using Grasshopper, the 8 design alternatives were automatically generated by varying the input variables. The corresponding KPIs were computed for each configuration and are presented in Table 3, while visual layouts of each design are provided in Figure 6.

Table 2. Key performance indicators for each design alternative.

Design	Entrance Location	Corridor Configuration	Bathroom Location
1	Stern	Central corridor	Stern
2	Stern	Central corridor	Bow
3	Stern	Two side corridors	Stern
4	Stern	Two side corridors	Bow
5	Bow	Central corridor	Stern
6	Bow	Central corridor	Bow
7	Bow	Two side corridors	Stern
8	Bow	Two side corridors	Bow

Table 3. Key performance indicators for each design alternative.

Design	Seats (/)	Accessibility (m)	Comfort (m)	*LCG* (m)
1	119	3.05	1.54	10.91
2	121	3.05	1.54	10.75
3	95	3.05	1.12	9.20
4	95	3.05	1.12	9.11
5	123	1.90	1.54	10.92
6	121	1.90	1.54	10.76
7	99	2.05	1.21	9.25
8	97	2.05	1.21	9.05

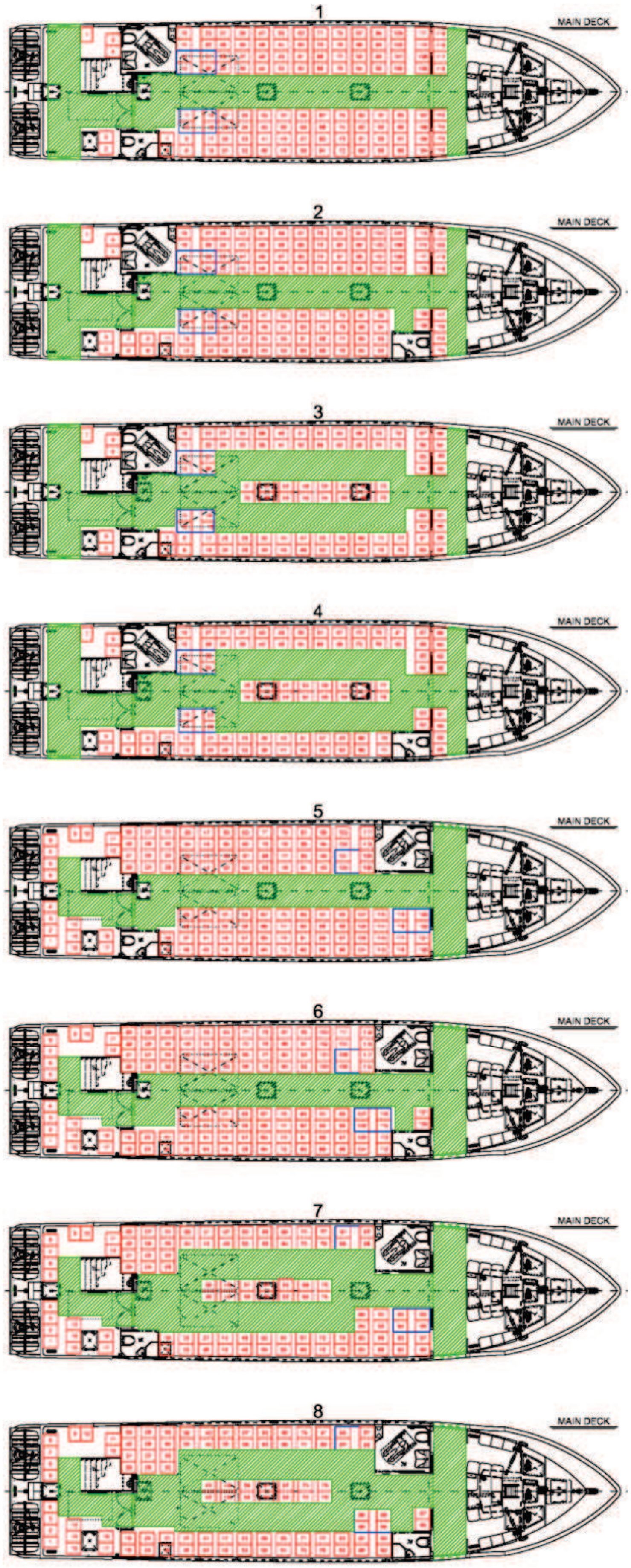

Figure 6. General Arrangement plan of the Main Deck for each design alternative.

The application of a rule-based, performance-oriented methodology has enabled the systematic generation and evaluation of a wide range of alternative layout configurations.

Compared to the baseline arrangement, all parametric variants demonstrate meaningful shifts across key performance indicators (KPIs), highlighting the potential of this approach to support evidence-based design exploration.

Accessibility metrics reveal a general trend toward enhanced spatial inclusion, with several configurations achieving substantially lower Accessibility Index values relative to the original setup. This suggests improved conditions for passengers with reduced mobility and illustrates the capacity of the method to support inclusive design considerations.

Comfort levels, measured through proximity-based metrics, vary across the configurations. While some alternatives align closely with the baseline value, others exhibit reduced comfort distances, reflecting adjustments in seat-to-corridor relationships. These variations highlight how subtle spatial reconfigurations can influence user experience within the same volumetric constraints.

In terms of seating capacity, a number of alternatives maintain comparable values to the baseline configuration. This continuity suggests that improvements in accessibility or comfort do not necessarily entail a reduction in functional performance. Such results demonstrate how the method supports the identification of balanced trade-offs across multiple design objectives.

The LCG indicator provides additional insight into the distributional effects of layout changes. Variations in the placement of key elements, such as services, entrances, and sanitary facilities, lead to observable shifts in mass distribution, offering valuable feedback for considerations related to vessel stability and operational dynamics.

Overall, this study demonstrates that the use of parametric generation and rule-based evaluation facilitates rapid, multidimensional exploration of design alternatives. Rather than prescribing a singular optimal solution, the approach empowers designers to investigate a diverse solution space and make informed decisions based on quantifiable performance criteria.

5. Conclusions

This paper introduced and validated a flexible 3D parametric modeling methodology for the early-stage design of ship GA plans. By combining rule-based spatial logic with performance-driven evaluation, the approach enables rapid generation, visualization, and analysis of multiple layout alternatives within a structured and repeatable design framework.

In contrast to conventional GA development that is often linear, expert-dependent, and difficult to iterate, the proposed method facilitates systematic exploration by parameterizing key spatial variables and directly linking geometric configurations to quantifiable performance indicators such as accessibility, comfort, capacity, and load distribution. The case study presented here demonstrates the method's applicability in handling complex spatial relationships and delivering objective data to support design decision-making from the earliest project stages.

Beyond the specific case examined, the methodology is inherently generalizable and scalable, offering potential applications across a wide range of vessel typologies and operational contexts. The integration with Grasshopper ensures accessibility for designers while preserving flexibility and customization, fostering collaborative workflows among naval architects, engineers, and other stakeholders. Moreover, this methodology holds significant promise for enhancing accessibility and inclusion by enabling the early integration of design requirements for passengers with reduced mobility.

Future developments will expand the scope of the methodology to encompass the full vessel architecture, including the placement of major onboard systems and technical equipment. This extension will enable rapid assessment not only of interior layout quality but also of global vessel behavior in terms of stability, longitudinal balance, and comprehensive passenger distribution. Furthermore, the parametric structure of the workflow allows for the systematic generation of a design database comprising feasible alternatives, each verifiable against geometric and operational constraints. Such a database could serve as a valuable resource in both iterative design processes and long-term decision support systems.

In conclusion, the proposed approach represents a significant step toward a data-informed, human-centered, and performance-integrated design paradigm. By bridging geometry and evaluation within an interactive and extensible modeling environment, it opens new avenues for early-phase innovation and optimization in ship design.

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