Layout Analysis of Polar Expedition Cruise Ship in Early Stage Design

-- by accounting for subjective preference and fuzzy logic theory

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TU Delft

Layout Analysis of Polar Expedition Cruise Ship in Early Stage Design

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By

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TU Delft

Preface

This thesis could be the biggest achievement after my two years and a half journey in Delft University of Technology, it also can be the finest conclusion of my six and a half year studying in Marine Technology. The memory of last one year for this thesis together with the previous one and a half year studying the courses will never fade in my life and the experience within it will be extraordinarily precious to my whole life. Hereby I want to thank all the people who help me for constructing my dream in the ocean, their support is just like the shiniest pearls to light up my way forward during last one year.

To begin with, I would like to express my grateful thanks to my daily supervisor, Dr. Austin Kana for continuously inspiring and encouraging me when I feel confused during the work on this thesis. To some extent, his guidance and advice has broken some of my conventional thinking set and influenced me to a more independent and creative way. Besides, I would like to thank Prof. Hans Hopman for always sharing the valuable thoughts from the big context of ship design problems. His critical attitude and extensive knowledge within Marine Technology has contributed a lot for my master thesis. In addition, the feedback and comments from Dr. Peter de Vos during the green light meeting is much appreciated as well, his support is of value to me when finalizing the thesis report.

Then I would like to thank the PhD student from ship design track, Koen Droste for providing the packing datasets on which my case studies in the thesis are based, and the useful guidance on the packing approach. Furthermore, I would like to thank Mark Roth as well for pointing out the possible future work concerning post-processing the concept designs in his thesis, from which the idea of this thesis is somehow generated and evolved. The efforts from other master students in marine technology is also appreciated for sharing their opinions towards the sample questions in the questionnaire.

Special thanks to Jiyuan Zeng and Shimeng Zhao. As the closest Chinese seniors and friends of mine since I came to the Netherlands, their special talents and positive attitudes have always inspired my interests towards many aspects and helped me tackle many difficulties in study and troubles in life. In addition, I wish to thank Jaswinder Singh and Muhammad Fareza as well, the struggling and chilling moments with them are unforgettable and worth remembering.

Finally, I would like to thank my whole family for their selfless care and unconditional love. I would like to express my sincerest gratitude to my mom, my dad and my sister for being the most peaceful harbor in my deep heart forever.

Chuan Sun
Delft, March 2019

Abstract

The design of polar expedition cruise ship is not a trivial task to the naval architect due to the complex nature of the ship itself. Concept exploration are hereby required to improve the understanding of the design problem and identify its challenge as well as possible solutions. However, it is always difficult to generate the technically-feasible design solutions while still satisfying multiple and potentially conflicting performance criteria for the polar expedition cruise ship. There are currently two ways of optimizing the concept design: manual optimization and computer-optimization. A design spiral can be used to illustrate the typical design procedure of manual optimization which widely used in shipbuilding industry. The computer-based optimization, such as the Packing Approach developed by TU Delft, can semi-/automatically generate a set of design solutions. After the generation of these design solutions which are unknown in many performance behaviors, it is necessary to post-process them and increase the quality of those designs created from both optimization methods. Design rationale is an effective way to serve as qualitative metrics in post-processing the configuration layouts of the concept designs. However, the ambiguity and potential conflicting aspects within the design rationale are difficult to handle by the current post-processing method while fuzzy logic theory can be utilized to cope with the design problems involving subjective and ambiguity. Hence, it is proposed to develop a new methodology to better post-process the concept design of a polar expedition cruise ship.

In order to tackle the conflicting aspects during the analysis, this thesis aims to analyze the internal layout from multiple objectives. After creating the design rationale base for the polar expedition cruise ship, seven design objectives are selected to categorize the configuration rules. A weight factor matrix is also introduced in order to distinguish the seven design objectives. The next problem is how to establish the suitable mathematical description to represent the architectural relations within the internal layout of the ship mentioned in design rationale base. The Euclidean distance and Manhattan distance are two typical mathematical measurements regarding different purposes. Fuzzy system is utilized to find the function between numerical inputs and the performance utility of the ship. After extracting the numerical relations from the layout and feeding them into a fuzzy system, a crisp output, which can indicate the performance regarding specific design objective of the ship, can be obtained, thus making the quantitative layout analysis possible.

To further test the applicability of the developed methodology, there are two case studies conducted in this thesis. The first case study is conducted within a Packing dataset for polar expedition cruise ship. Five different layouts are selected and further investigated from seven design objectives. By introducing a metric for combining multiple performance utilities of the ship, the total performance utility of the ship can be calculated. This analysis shows different packing results can be distinguished by the developed methodology, and it is also possible to select the packing results with higher quality.

The second case study is seeking to manually modify the concept designs and improve the layout quality by making use of the developed methodology. The 'most feasible' design among the five designs generated by packing approach and a real polar expedition cruise ship from Damen are used. The method shows that the selected concept design from packing approach can be further improved through the manual adjustment of some shipboard systems. For the real Damen ship, the layout performance of it can be evaluated as well after simplifying the GA to the form of early concept design. This demonstrates that the method is applicable in assessing the layout created from both layout optimization methodologies. Future research concerning better incorporating the developed methodology into current mainstream layout optimization methods is therefore worthwhile for the naval architect to investigate.

CONTENTS

Glossary

GA	General Arrangement
CoG	Center of Gravity
DBB	Design Building Block Approach
ISA	Intelligence Ship Arrangement
TUD	Delft University of Technology
UCL	University College London
UM	University of Michigan
IECEM	Interactive Evolutionary Concept Exploration Method
CAPEX	Capital Expenditures
OPEX	Operating Expenses
CI	Consistency Index
CR	Consistency Ratio
RI	Random Index
LOA	Length overall, [m]
H	Total Height, [m]
T	Draft, [m]
MF	Membership Function
CMI	Correlation Minimum Inference
CPI	Correlation Product Inference
CD	Centroid Defuzzification

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1

INTRODUCTION

This thesis is about providing a new perspective in analyzing the general arrangement of the polar expedition cruise ship, and then using the insight gained by the evaluation of these layouts to further improve the internal layout of this type of ship. This chapter is initiated by the background knowledge and the description of specific ship design problem, after which the research objective and thesis outline will be elaborated as well.

1.1 Background

Cruise shipping uses a cruise ship or liner to provide cruise passengers with pleasure voyages including good service onboard and shore excursions. Among the cruise ships, the expedition cruise ship is designed for expedition operations in both remote polar and tropical regions to maximize the experience of the passengers. Especially for the polar expedition cruise ships operating in more complex polar environment, the design of these kinds of ships, therefore, should also be compliant with other certain regulations such as Polar Code, making this type of ship more unique.

The current ships being used for polar expeditions come in four categories: adapted from Wergeland et al. (2010):

- Research Vessels (often refurbished to obtain close to cruise quality)
- Icebreakers (used to access the extreme north)
- Vessels with no ice capability (operate in sheltered waters)
- Purpose-built ice class vessels (a few purpose-built cruise vessels with high ice class)

The research vessels and icebreakers were originally built for polar research decades ago, a large portion of them were built in the Soviet-era. With the booming of the polar expedition market, many retired vessels were refurbished to offer the passengers with polar adventure. A typical ship refurbished from a research vessel is given in Figure 1.1 (a). The vessels with no ice capability are not designed for extremely remote cruising and tend to operate in sheltered waters. The newly-built ice class vessels are the type designed especially for polar expedition, see Figure 1.1(b).

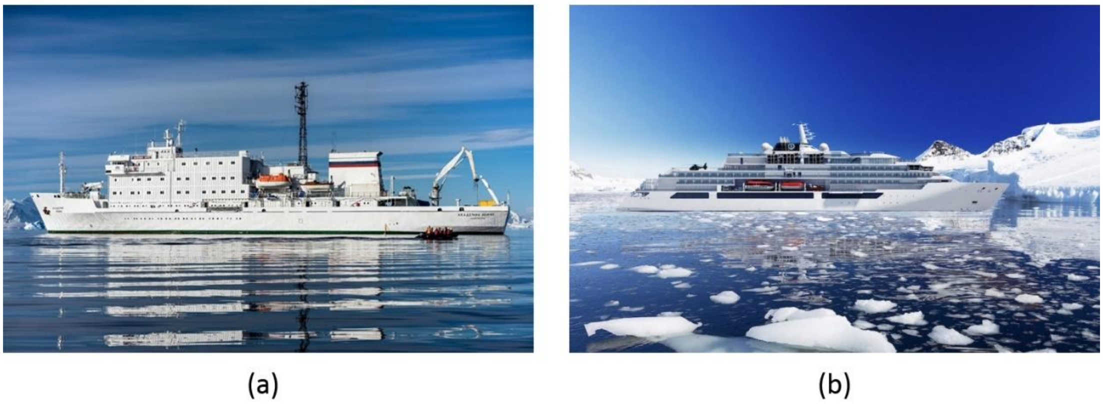

Figure 1. 1 Two types of polar expedition cruise ship *Alesha et al. (2017) and Cruise News (2018)*

The current role in providing the polar exploration is gradually shifting to the purpose-built ice class vessel. According to Cruise Industry News (2018), there is a fast growing in the number of purpose-built expedition cruise ships instead of renovating more obsolete research vessels or icebreakers for the expedition cruise market, see Figure 1.2. The upcoming years will witness a drastic increase for the market capacity, meanwhile the total estimated berths and the number of expedition cruise ships will grow along the way as well. It is also estimated that 22 purpose-built expedition cruise ship are about to launch from 2019 to 2022 with mainly focus on small and medium-sized ships.

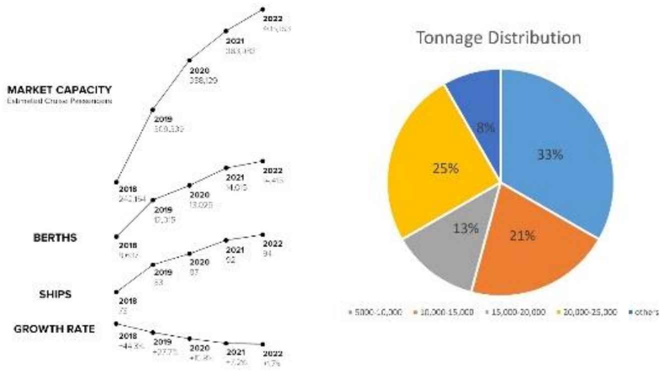

Figure 1. 2 Future trend of expedition cruise ship market according to *Cruise Industry News (2018)*

The dramatic increase in the order for new purpose-built ship in polar expedition cruise market can attribute to the increasing demand of expedition cruise from people. Besides a common problem for the refurbished vessels might also change the passengers' minds for new type due to the general arrangements of former ships are not always satisfactory. Taking the research vessel for example, the original goal of the ship is polar research, which means the start point of the layout design for this ship can carry sufficient research devices and machinery instead of providing the passengers with adequate accommodations and multiple functional or entertainment areas. The sup-optimal designs after renovation such as squeezing of the cabins and less service facility provision can make the refurbished ships less competitive than the new type. As the purpose-built vessels with high ice class can provide the passengers onboard with more friendly and comfortable environments as well as multiple functional services, people are more likely to choose this type among the four categories for polar expedition cruising. As a result, the competitiveness of polar expedition cruise ship will largely depend on the quality of the GA itself. A good layout design for the ship is therefore worthwhile for naval architect to research. Since the design of new polar expedition cruise ship is conducted in several stages where the level of certainty increases while the design margin decreases, the early stage design plays a major role in creating the final solution, *L. Salvatori (2018)*. Hence, this thesis will focus on the early stage design of a small-sized polar expedition cruise ship.

1.2 Research Motivation

The polar expedition cruise ship can be categorized into the type of configuration-driven ship whose performance is strongly influenced by the arrangements of primary spaces. For instance, one of the primary goals of the expedition cruise ship is to provide passengers with excursion experience, this ability is then largely influenced by the configuration of the mudroom and the Zodiacs launch and recover system. Hence, the configuration of internal spaces of the expedition cruise ship can dictate the extent to which it is able to perform its mission.

However, the design of this type of configuration-driven ship will also bring distinctive problems to the naval architects. The nature of having the possibilities of positioning many primary spaces implies the existence of possibly conflicting aspects within a constrained design space. The spatial conflicts, for instance, could occur due to the interaction between large portion of accommodation blocks and multiple functional facilities such as public space and huge Zodiacs. Besides, high-dimensionality due to large degree of preliminary design freedom making the design complicated as well. For example, exploring various design solutions of the expedition cruise ship for different operational scenarios and luxury levels, while all feasible under the design requirements, is not a trivial task.

To combat the complex nature of designing the polar expedition cruise ship during early stage ship design, TU Delft packing approach was developed and turned out to be very efficient in exploring the design problem by generating a large set of design solutions. Although the data comes in great quantities, the quality of the design regarding the layout is poor, *K. Droste et al. (2018)*. As a result, further improvement with respect to these layouts deem necessary due to the insufficient layouts. *M. Roth (2017)* developed a post-processing method to analyze the general arrangements of the packing results of polar expedition cruise ship by making use of network theory. It showed the applicability of design rationales in evaluating the architectural aspects of the designs and enabled a fast and higher quality design selection for further examination. Hence, post-processing the concept results coming from concept exploration will be beneficial for further design of the polar expedition cruise ship, this thesis will focus on developing a new method in analyzing the general arrangements of the polar expedition cruise ship whereby further improvements to the solution can be reached. Finally, the insights gained from the method will contribute to a GA for polar expedition cruise ships with better layout quality for further design.

1.3 Problem Description

As the design of expedition cruise ship belongs to the configuration-driven ship designs, the common layout design problems that the configuration-driven ships face are also applicable to the expedition cruise ship. It has been identified the main challenges in layout design for configuration-driven ships, *K. Droste et al. (2018)*. Two of them are listed below:

1. The amount of rationale used to create a layout is a challenge.
2. Finding a proper balance between the individual and potentially conflicting requirements after collecting all the rationale remains a difficult task.

The first challenge indicates there are various rationales including safety regulation and comfortability standards for example, influencing the layout quality of the ship. The second challenge implies it is hard to balance all requirements and design rationales which are sometimes conflicting within the layout of the ship. Given the two main challenges, the problems in this thesis arose:

As a typical configuration-driven ship, during the early ship design of polar expedition cruise ship, the concept exploration ought to create a set of feasible designs meanwhile still maintaining the diversity. A post-processing method regarding these designs will help the naval architect quickly analyze the results and gain more insights for further design. There are many concept exploration methods to generate the GA of the polar expedition cruise ship, how to better analyze the results from concept exploration will directly affect the outcome of the concept design. In order to evaluate and possibly improve the layout of the polar expedition cruise ship, the design rationales are used to provide a metric. However, different designers might have different objectives to evaluate the performance of the ship according to its layout, so there are many design objectives to guide the analysis of GA, such as operability and redundancy, etc. Thus, it is necessary to set up a design rationale database with respect to the polar expedition cruise ship and classify the various design rationales into a series of design objectives, then a scoring metric of the layout quality can be established accounting for performances within different design objectives.

Besides, the design rationales consist plenty of vaguely defined, conflicting and subjective considerations, opinions, and preference as well as a plethora of explicit requirements and constraints, Nick (2008). The subjective considerations from the experts are somehow too ambiguous to effectively analyze the layout quality of the ships, thus bringing plenty of difficulties in trading off different potential conflicting decisions. For example, the accommodation block on the polar cruise ship should be adjacent to the rotation center of the ship for the design objective of seakeeping capability. It would be not easy for a naval architect to tell how far is adjacent or not. As a result, the outcome of a certain design option regarding the placement of the accommodation cannot be quantitatively measured. To tackle this problem, fuzzy logic theory structures and concepts will be used in this thesis to evaluate layout quality within the architectural relations of the ship, as it can identify something as being somewhat good or bad. Hence, a crisp layout quality can be quantified when considering all classified design rationales.

1.4 Research Objective

The architectural performance of concept exploration results of a ship comes in different levels of quality, this thesis aims to analyze both fictional and real concept exploration results for polar expedition cruise ships from different design objectives thus improving the understanding of the design problem within early stage design process. Supported by earlier background knowledge, the following research objective reads:

"Develop a method to the quantitatively analyze and improve the layout of the polar expedition cruise ship from different design objectives, accounting for subjective preferences and fuzzy logic theory."

The method can help the naval architects better define and trade the design objectives from the layout perspective of expedition cruise ships. To approach this research objective, the following research questions have been raised:

- How to classify the design rationales into different design objectives?
- How to develop the method for analyzing the internal layout considering all design objectives and design rationale?
- How can the fuzzy logic theory be used to analyze the design rationale?
- How to evaluate and improve the layout of a polar expedition cruise ship during the early stage design process based on the method?

1.5 Thesis Outline

This thesis will be divided into 8 chapters. The first chapter introduces a general background of the expedition cruise ship as well as the common design problems for this type of ship. Moreover, the specific problems of this thesis will be discussed, after which the main research objective of this thesis together with its corresponding research questions will be defined to seek the solution of the problem.

Chapter 2 gives an overview of the ship design process and ship arrangement methodologies and how current tools and methods help with the design within the early stage ship design. Besides, the drawback of current approaches will be identified and discussed, a more elaborated problem description will be defined as well.

Chapter 3 discusses how the developed design rationale for polar expedition cruise ship can be classified into a series of selected design objectives. After that, the weight factors for different design objectives will be determined. Then a dimensionless measurement of proximity based on the design rationale within the layout of the ship will be introduced as well.

Chapter 4 serves to introduce the background of fuzzy logic theory and how the mathematical theory can be incorporated into the methodology in this thesis. After that, the function between the design rationales and the layout quality of the ship will be established with the help of fuzzy system. As a result, a quality metric of the layout considering all design objectives will be given. Besides, a simplified layout will be created to demonstrate the applicability of the method developed in this thesis.

Chapter 5 demonstrates how the method is applied to five concept designs generating from packing approach, the possible optimal design among the five will be selected and moved forward to further study.

Chapter 6 focuses on manually improving the concept designs of polar expedition cruise ship based on the insights gained from the analysis. The 'most promising' design selected in Chapter 5 and a real ship from Damen shipyard are discussed respectively.

Finally, Chapter 7 summarizes the conclusions by answering all the research questions and further discussions and recommendations will be discussed in Chapter 8.

2

LITERATURE STUDY

This chapter will conduct a literature study on which this thesis is based. It is initiated by an overview of design process within ship design. Then the development of ship arrangement methodologies as well as the main design tools will be introduced. In addition, the limitations of current design tools and the post-processing method will be explained. Finally, the research scope and the methodology overview will be given.

2.1 Introduction

The design of a polar expedition cruise ship, like many other complex ships, will inevitably be a complex process including many engineering disciplines. Naval architect often attempts to combine the efforts of many different disciplines as well as project stakeholders into a coherent and cost-effective design solution, *T. Duchateau (2016)*. By iteratively creating and comparing concept designs, also known as concept exploration, will help the naval architects gain the insight and finally make well-considered decisions within the design process.

However, the concept exploration for the ship is very problematic. The initial description from the customer are not always clear, it could lead to many varied design options and variables and therefore creating a multi-dimensional design space. As the design ought to obey the basic laws of physics and principles within naval architecture, this will exclude some combinations of design variables. Meanwhile the multi-dimensional performance space can be also created after measuring different combinations of variables, when considering additional requirements such as motion behavior, it can in turn restrict the shape of design space, the relation can be seen in Figure 2.1. As a result, it is still difficult to create a technically-feasible solutions for the ship while still meet the multiple performance criteria during the concept exploration. Given the challenge stated during concept exploration phase for polar expedition cruise ship, the following sections will conclude the role of early stage ship design and how the methods in solving the problems evolved.

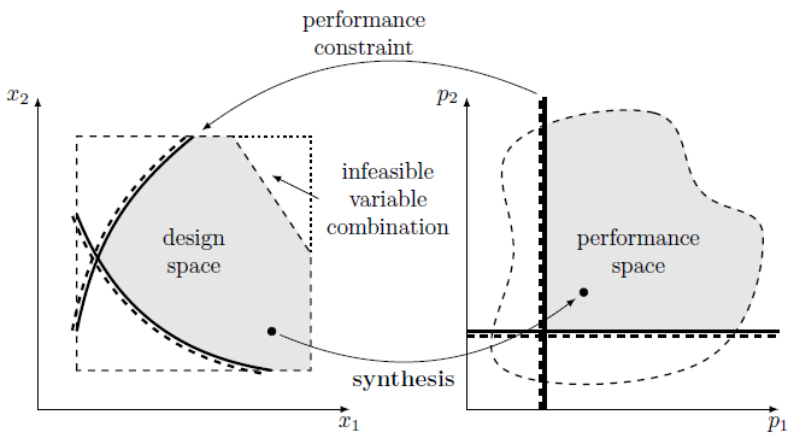

Figure 2. 1 The relation between design and performance space *Duchateau (2016)*

2.2 Early Stage Ship Design

The ship design process can be described in three consecutive design phases: early stage ship design, contract design, and detailed design, *K. Droste et al. (2018)*. As the initial steps of the ship design process, early stage ship design acquires the full understanding of the design problem as well as a rough idea of its solution, meanwhile the initial configuration of spaces is formed. The residual phases focusing on increasing the level of detail of a single design, from the goal of drafting a contract to building the actual vessel eventually.

The early stage ship design process is always fed with information and insights from supporting design studies, which are used to assess the feasibility, performance and cost of the changing requirements and accompanying solutions, *Duchateau (2016)*. To this extent, the early stage ship design process can also be divided into three different sub-processes, *K. Droste et al. (2018)*.

1. Concept explorations
2. Concept studies
3. Concept design

Early stage design is often initiated by performing concept exploration. It is concluded that the main goal of concept exploration is to improve the understanding of the design problem and identify its challenges and possible solutions, *K. Droste et al. (2018)*. Hence a diverse set of design solutions can be generated after concept exploration. Then the concept studies mainly focus on evaluating feasibility and learn the characteristics of the set designs. Finally, concept design will select and refine the design by means of the new acquired knowledge of the design problem and possible solutions.

During the early ship design phase, the overall composition of the ship can be directly related to the arrangement of systems or spaces on board, *M. Roth (2017)*. *J. Hope (1981)* states that: "the general arrangement design, as a system engineering process, is a unique blend of experience and judgement combined with the systematic evaluation of performance". Then the objective of ship arrangement design is to optimize the ship as a total system. *J. Gillespie (2012)* summarizes the progression path of ship arrangements into three methodologies: manual design optimization, computer-based optimization and post-processing sets of feasible solutions.

A design spiral can be used to illustrate how the early stage ship design is proceeding in the real ship industry. As is depicted in Figure 2.2, the general arrangement initiates the whole design process, following by a series of specific operations, a feasible design can be finally derived after enough iterations.

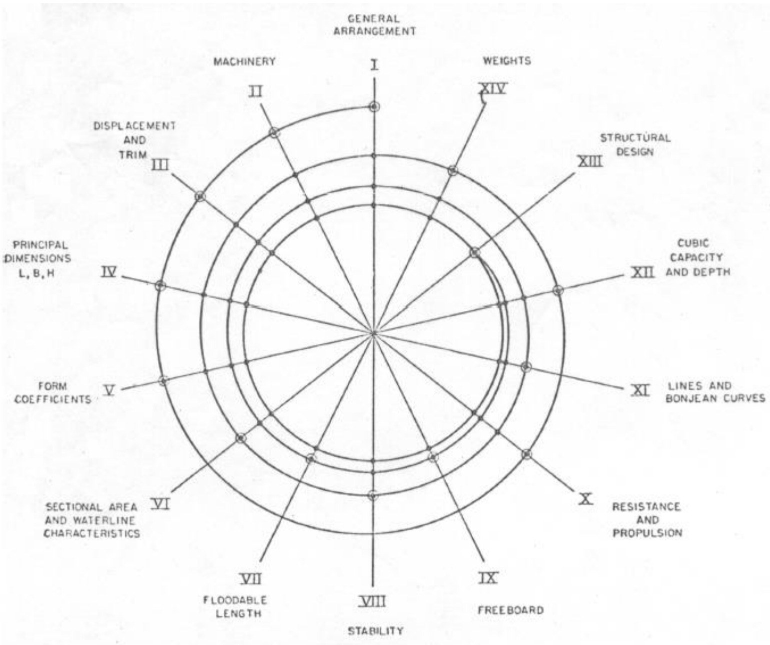

Figure 2. 2 General design spiral *Evans (1959)*

The conventional approach in real ship industry to ship arrangements involves drawing deck plans by hand, either on paper or within a generic computer aided design tool. The procedure of the traditional approach to the complex layout problem is starting from defining main compartments, followed by more refined functional compartment definitions, and finally systems, *A. Cort et al. (1987)*. As is illustrated in Figure 2.3, the manual nature of this iterative process gives naval architects a close connection with the design and design evolution. The knowledge gained through the process can also be used to provide feedback to the requirements elucidation process and for further analyses. For manual optimization, the whole process can be divided into two phases, concept exploration comes up with initial solutions and post-processing gave the naval architect more insight on improving the initial solutions to feasible solutions. However, it is tedious and time-consuming for the manual optimization due to too many spaces or systems onboard although it is always the case for naval architects in the shipyard.

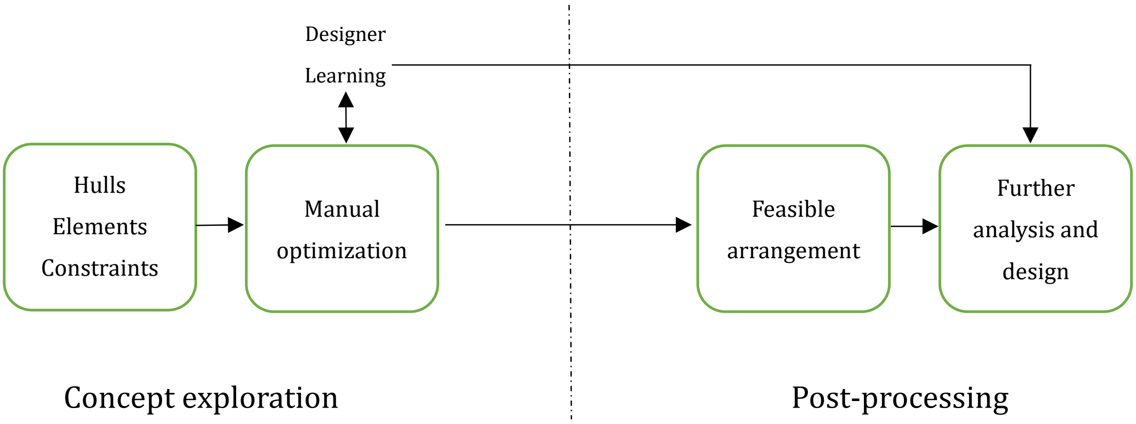

Figure 2. 3 Manual optimization with post-processing, adapted from *Gillespie (2012)*

With the fast development of the computer, some academic approaches were developed to (semi-)automatically generate the concept designs. The elemental information and basic thought processes used in the previous manual approach were captured in database format, together with the development of rational evaluation mechanisms, making it possible to have the computer-based optimization, *Gillespie (2012)*. However, the set of feasible solutions is often a non-dominated set with potentially hundreds of design variables, *B. van Oers et al. (2008)*. This computer-optimization style will exclude the designers from learning. In order to keep the designers involved within the design process, post-processing the "best" designs deem necessary. In Figure 2.4, a post-processing method is implemented by the designer thus making it possible to select the most feasible arrangement from multiple feasible arrangements. Meanwhile the designers can also learn a lot from the post-processing procedure and use the gained insights for further analysis and design.

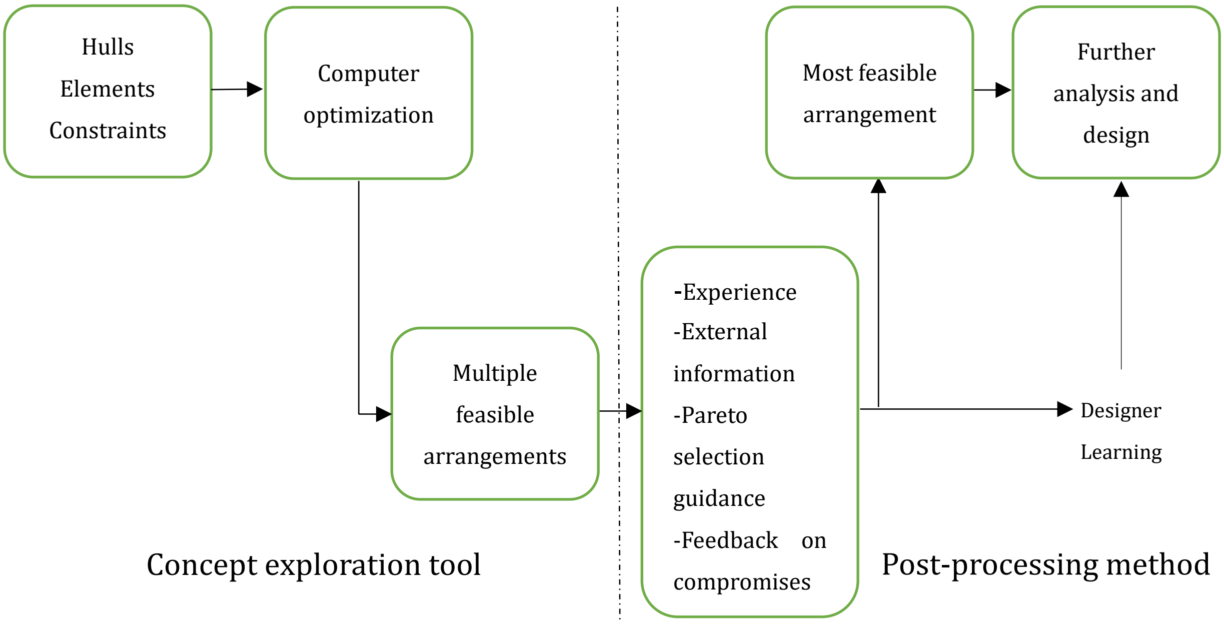

Figure 2. 4 Computer-based optimization with designer selection, adapted from *Gillespie (2012)*

2.3 Concept Exploration Tool

In support of concept exploration for more detail earlier in the design process, recent years have witnessed the development of three novel architectural ship synthesis models. University College London (UCL) has developed a manually-driven approach, the rest of two are driven by evolutionary algorithms from University of Michigan (UM) and Delft University of Technology (TUD). Their characteristics can be summarized in Table 2.1:

Table 2. 1 Comparison of concept exploration tools' characteristics, adapted from *Gillespie (2012)*

	DBB	Packing	ISA
Architectural	3D full ship	2.5D/ 3D full ship	2D deck
Driver	Volume	Volume	Area
Diversity	Overall	Overall	Arrangement
Speed	Days/ Manual	Hours/ automated	Hours/ automated
Concepts generated	Few	Thousands	Hundreds

The frame of Design Building Block approach (DBB) developed at UCL (see *D. Andrews et al. (1997)*) is rather a generic approach to modelling complex engineered systems than an approach to design. Instead of simply a numerical one, Andrews focuses on the spatial representation of the ship in preliminary design. Hence, DBB approach was created to provide ship designers an architecture-oriented framework for generating visual, 3-D geometric ship layouts by using integrated computer-assisted analysis. Intelligent ship arrangement (ISA) developed by UM (*see M. Parsons et al. (2008)*) has the primary goal to assist the arrangements designer to create ship arrangements with the maximum amount of intelligent decision-making support. All the tools except ISA allow full variation of both layouts together with overall ship characteristics, and the ISA and Packing can generate a large set of designs within hours while DBB approach merely allow a few solutions within days, *Duchateau (2016)*.

2.4 TU Delft Packing Approach

The packing approach which assists in the concept exploration process, as a tool developed at Delft University of Technology, can automatically generate a large and diverse set of low level of detail feasible ship designs by using a bin-packing algorithm into a parametric ship description coupled with a genetic search algorithm. The naval architect then can use the resulting designs which reflect the most promising trade-offs within design requirements. As is illustrated in Figure 2.5, the basic process of the packing approach consists of three main steps, adapted from *Duchateau (2016)*:

1. **Packing algorithm.** As the input of packing approach, it combines building blocks (systems and spaces), packing-rules (rules of how these blocks might be packed) with initial variables to generate the architectural description of the ship.
2. **Estimate characteristics and performance.** Based on the ship description, performance measures and technical characteristics of each design solutions are calculated, examples are: cost, weight, resistance, speed, (fuel) range, hydrostatics and simple (damage) stability.
3. **Genetic search algorithm.** The constraints and objectives combine performance measures to assist search for more promising and feasible solutions. The default objective is to maximize the packing density, thus stimulating the generation of denser designs, and the typical constraints ensuring meeting the non-negotiable requirements are: all building blocks are packed, the vessel floats upright, sufficient stability, and the ship meets its speed and range. If all constraints are met, the design with its performance will be stored. On the other hand, the output of the genetic search algorithm is also the new variables for the packing algorithm to create new design, then the set of the feasible solutions will all be stored in a database.

The packing method was firstly introduced and developed by *B. van Oers (2011)*. After that *B. van Oers et al. (2012)* simplify packing approach by describing the ship in 2.5D in order to reduce the computational effort, the 2.5D modelling approach have been subsequently applied in designing several types of complex vessels such as MCMV and passenger cruise vessel, (see *R .Zandstra (2014)*, and *K. Droste (2016)*).

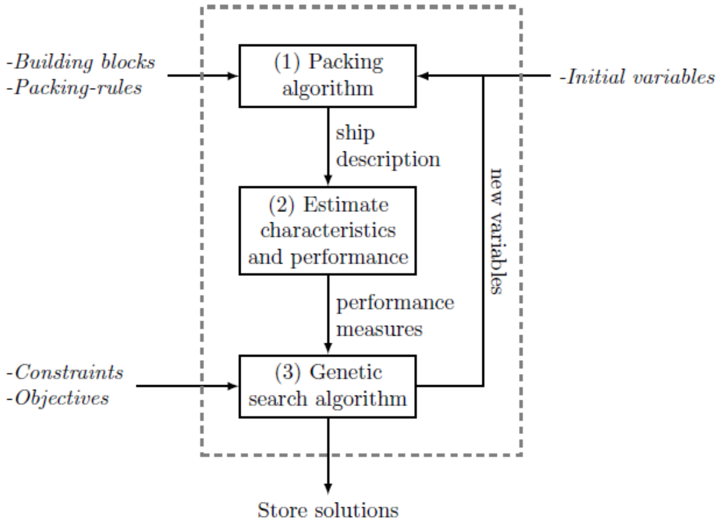

Figure 2. 5 Packing-approach process with required inputs *Duchateau (2016)*

2.5 Post-processing the Initial Concept Designs

The previous sections have introduced the common approaches for two different types optimization methodologies, post-processing the initial concept solutions is of great necessity for both manual and computer-based methodologies. The core idea of post-processing is to establish the performance metric whereby the designers can determine whether the initial solutions are better or worse, after which the insight can be gained and used for further design phases, this is extremely important to Packing approach due to it can automatically generate a thousand of designs with unknown layout quality. Design rationale has been proved useful within the current post-processing methods since it can capture the reasoning behind the design decisions. As is recognized, the decisions are taken in all phases of the design process. Every decision, however, ought to be justified by rationale in good design practice. It is also noticeable that design rationale has been used to support quality assurance aspects of design, and thus it can convince stakeholders that designers were doing the correct things. Design rationale has been studied and applied in naval architecture. DeNucci (2012) has firstly introduced a method of capturing design rationale for complex ship general arrangement design. The method interviews many naval architects to identify preferable and unpreferable features presented in some designs, generating the corresponding rationale as well as a rationale database.

The configuration rules are obtained to describe the desirable and undesirable object configuration in the design, and there are four terms included in the configuration rules, *T. Denucci (2012)*:

1. **Object 1**
2. **Priority**
3. **Relevant design feature**
4. **Object 2**

The first term refers to one of the objects in the ship design, the second term indicates the subjective importance of the configuration in the design. Designers must select one of the following priority terms: *shall*, *shall not*, *should*, *should not*, *can* and *can not* or supply a user-defined descriptor. The third term describes the preferred spatial relationship between the two objects. For instance, *adjacent to*, *below*, *above*, etc. The final term refers to either a second object in the ship design or an absolute position such as *global position*, *midsection* and so on. To be noticed, the priority terms in this thesis are all set as: *should*, *should not*, the other descriptors will not be considered.

By incorporating the design rationale into the post-processing method, the architectural relations within the internal layout of the ships are possible to gather by the designers and provide a good direction for them to post-process the initial concept designs. As is shown in Figure 2.6, the performance metric can be created after the extraction of architectural relations within the layout and the qualitative properties obtained from design rationale, then the analysis towards these concept designs is possible whereby the naval architect can gain more insight through the evaluation results.

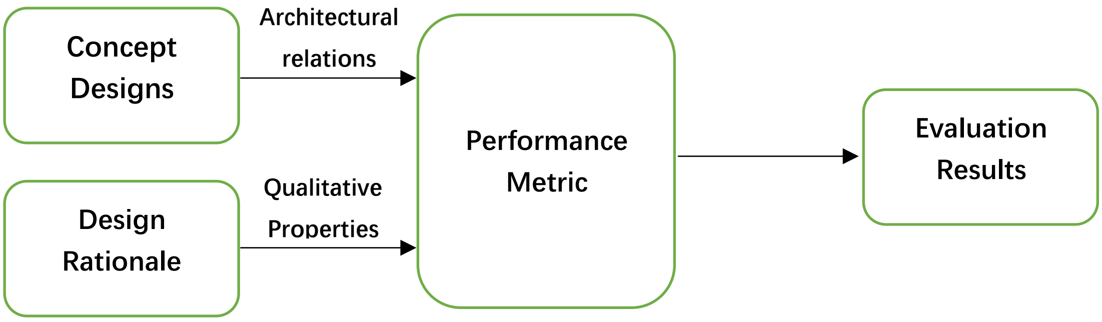

Figure 2. 6 Gaining design insight from post-processing method

By making use of network theory and captured design rationale, *M. Roth (2017)* developed a post-processing method to quantitatively analyze the qualitative arrangement features from the designs generated by the packing approach. He created a measure of performance which tended to capture the entire performance of the general arrangement into a single score, finally it turned out, according to the overall performance score, that the method can analyze the layout quality of different design results from their spatial or architectural relations. However, some restrictions can be identified, and they can be categorized into two aspects:

1. **Unable to handle the ambiguity of the design rationale**

Quantitative analysis of general arrangements needs to identify the desired qualitative properties in the design, *M. Roth (2017)* used Denucci's method and rationale database as quality metrics to calculate the performance from the architectural relations of the design results. However, it is always hard to identify the effectiveness of a design option due to the ambiguity of the design rules. According to the design rationale, the accommodation area on board a ship, for instance, should not be near the bow due to the high acceleration in the bow sector, then the relative location of the accommodation area to the bow brings the problem: how much will the design option contribute to the performance for the objective of seakeeping capability. A Boolean expression of only zero or one for the scoring algorithm would be inadequate in layout analysis. The fuzzy logic theory hereby is proposed to better handle the ambiguity of the design rules, and crisp outputs can therefore be obtained when it comes to the performance utility of different objectives.

2. Unable to deal with the possible conflicting design rationales

As is mentioned before, it is a challenge for naval architect to find a proper balance among all the design rationales which are individual and sometimes conflicting. As is depicted in Figure 2.7, a packing layout of an expedition cruise ship is analyzed by some of the corresponding design rationales. In case of *Redundancy* for instance, the two generator rooms onboard should not be placed adjacently while they are recommended placed closely when it comes to the objectives of *Cost feasibility*. The bridge system should be placed before the midsection of the ship to acquire a good performance in *Operability*, but the rotation center of the ship, which can be the ship's center of gravity, normally is in or after the midsection, see Table 2.2.

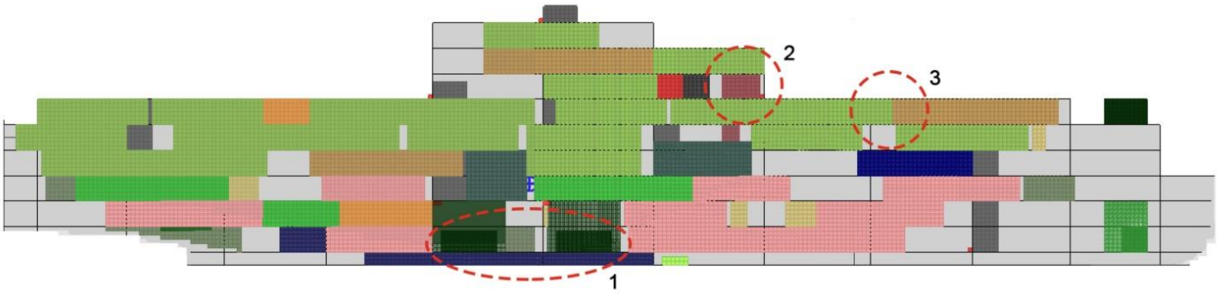

Figure 2. 7 Side view representation of an expedition cruise ship design with conflicting layout issues

Table 2. 2 Conflicting Rationales

CONFLICT#	OBJECT #1	OBJECT#2	RATIONALE	DESIGN OBJECTIVE
1	Generator Room 1	Generator Room 2	Adjacent	Cost Feasibility
			Separate	Redundancy
2	Bridge System	Global Position	Before the Mid	Operability
			Near the rotation center	Seakeeping Capability
3	Accommodation	Restaurant	Adjacent	Logistics
			Separate	Habitability

2.6 Research Scope

To give a better illustration of the thesis scope, the system engineering V-diagram is presented, see Figure 2.8. The primary function is closely related to the operational process, leading to the support functions and systems that need to be incorporated in the design and finally have influence on the performance and effectiveness of the design. This thesis will focus on analyzing the configuration data from packing approach as well as the real polar expedition cruise ship, relating the physical attributes to performance characteristics.

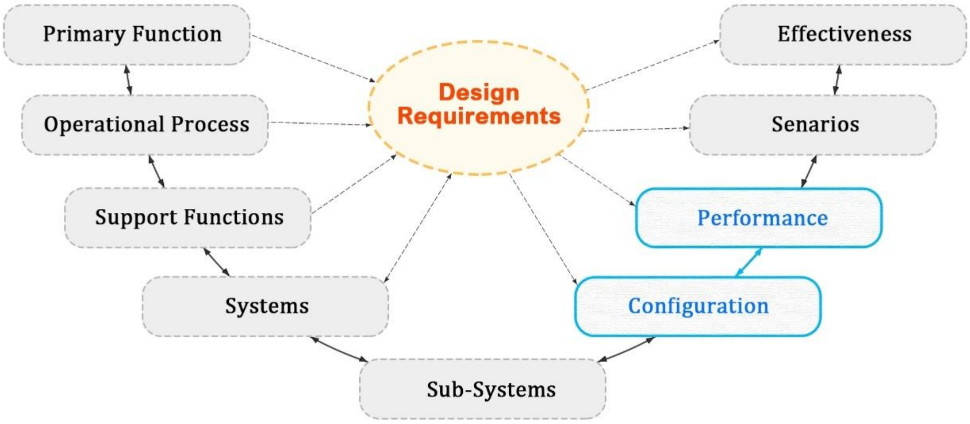

Figure 2. 8 System engineering V-diagram, *K. Droste et al. (2018)*, including the research scope

The main goal of this thesis is to introduce a new perspective for analyzing the general arrangements of both fictional and real polar expedition cruise ships and give the naval architects the tool to better make decisions about layout. Furthermore, this thesis tends to separate the analysis into different design objectives, the focus is still on the spatial or architectural relations of the layouts instead of the dimension parameters solely such as length, beam or block coefficient, etc. The spatial relations extracted from computer-generated or actual design concepts will then be categorized to evaluate the performances regarding different design objectives through the fuzzy system. As a result, the insight gained from the evaluation results can be used to further modify these layouts. The project overview is illustrated in Figure 2.9.

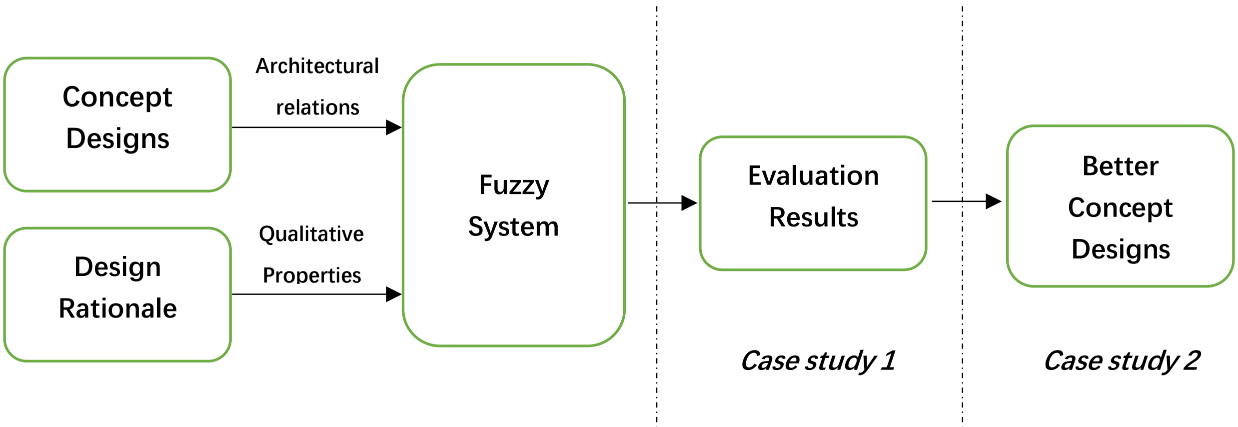

Figure 2. 9 Project Overview

3
METHOD

This chapter will introduce the method to quantitively analyze architectural relations within the layout of the polar expedition cruise ship. It aims to build up the design rationale base for the polar expedition cruise ship and then categorize different configuration rules into different design objective. Besides, it will also discuss the mathematical description from the architectural layout of the ship, numerical descriptions according to the configuration rules from the internal layout of the ship are therefore created for further use.

3.1 Introduction

For the quantitative analysis of general arrangement, the preferred qualitative properties ought to be identified. However, different designers might make different decisions due to their own personal preference. *M. Roth (2017)* uses Denucci's method and rationale database as quality metrics to do a quantitative assessment of design results generated by packing approach but were unable to handle the ambiguity of the design rationale and cope with the possible conflicting design rationales. In order to figure out the potential conflicting design rules, a classification of various design rationales for the expedition cruise ship seems necessary. After that, the performance metrics according to different design objectives can be derived to evaluate the performance from the architectural relations of the concept designs.

Before setting up the configuration rationales for expedition cruise ships, one needs to know the general shipboard spaces for the expedition cruise ship. *K. Droste (2016)* defined a series of systems for the polar expedition cruise ship, see Table 3.1. These spaces are allocated to different systems to fulfill various functions of an expedition cruise ship. For instance, the *entertainment system* may include the theater, casino, shops, etc. The *accommodations* comprise officer accommodation block, passenger accommodation blocks and crew accommodation blocks.

Table 3. 1 Shipboard spaces in expedition cruise ship

Generator Room	Central Hall	Hospital System
Bow thruster System	Bridge System	Entertainment System
Propulsion Room	Accommodations	Zodiacs System
Funnel System	Lifeboat System	Boarding System
Funnel Connection	Emergency Generator	Mudroom system
Restaurant System	Galley system	Fuel Tank System
General Stores	Stabilizer System	Ballast System
Laundry System	Stair	
Technical/Auxiliary System	Emergency Control Room	

3.2 Classification of Design Rationale

Objectives are properties used to compare alternatives. In the context of configuration rationale, the design objectives are selected from a collection of predefined terms or user-defined terms which are determined by the designer, and they are typically referred to as the "-ilities", *T. Denucci (2012)*, (see Table 3.2):

Table 3. 2 List of possible predefined rationale objectives *T. Denucci (2012)*

Affordability	Maintainability	Social Acceptability
Availability	Operability	Supportability
Economic feasibility	Producibility	Survivability
Habitability	Reliability	Vulnerability
Logistics	Safety	Designer defined

Based on the design rules for the cruise ship used by *M. Roth (2017)* and the applicable designer rationales for the general ship design summarized by *T. Jasper (2017)*, together with the knowledge from the perspective of naval architect, the configuration rationales for polar expedition cruise ship can be developed. When reviewing all the design rationales, the following objectives are selected or defined to classify the rationales, see Table 3.3. To be noticed, the current analysis on the GA in this thesis is solely focusing on the internal features within the layout, *Economic Feasibility* will discuss how the GA affects the building cost such as the length of piping rather than the financial parameters such as CAPEX or OPEX. For the design rationale whose **Object 2** is rotation center, it is required to decrease the sea sickness, which is one of the criteria of seakeeping performance. Thus, these rules can be classified into the defined objective of *Seakeeping Capability*. As for the design rationale: "accommodation should be grouped", it is required to increase the atmosphere of people's living environment, so it can be guided to the objective: *Habitability*.

Table 3. 3 List of selected or defined rationale objectives

Seakeeping Capability	Logistics
Safety	Operability
Economic feasibility	Redundancy
Habitability	

After setting up the rationale database as quality metrics and splitting the design rationales into different design objectives, one can start to evaluate which of these layout decisions are better or worse for corresponding design objectives. Table 3.4 lists 21 design rationales and corresponding design objectives for polar expedition cruise ships.

Table 3. 4 Design Rationale and corresponding Design Objectives for Expedition Cruise Ship

Design Objective	***Design Rationale***
Seakeeping Capability	*Accommodation should be near the rotation center*
	Bridge system should be near the rotation center
Logistics	*Main Galley system should be adjacent to Restaurant system*
	Passenger accommodation should be adjacent to Entertainment system
	Passenger accommodation should be adjacent to Restaurant system
	Galley system should be adjacent to the General store system
	Main Galley system should be adjacent to on Main Deck
Safety	*Fuel tanks shouldn't be adjacent to the Accommodation*
	Lifeboat system should be adjacent to Accommodation
Operability	*Zodiac store shouldn't be too high above the waterline*
	Cruise officer accommodation should be adjacent to the bridge system
	Crew accommodation should be adjacent to crew dayroom
	Lifeboat system shouldn't be too high above the waterline
	Bridge should be forward of Mid
Economic Feasibility	*Fuel tank should be adjacent to Generator room*
	Propulsion room should be aft of Mid
	Generator room should be adjacent to Generator room 2
Redundancy	*Hospital primary system shouldn't be placed adjacent to second hospital solution*
	Generator room shouldn't be adjacent to Generator room 2
Habitability	*Accommodation should be adjacent to Accommodation*
	Accommodation shouldn't be adjacent to Generator room
	Accommodation shouldn't be adjacent to Propulsion room
	Accommodation shouldn't be adjacent to Technical/Auxiliary system
	Accommodation shouldn't be adjacent to Restaurant system

3.3 Determination of Weight Factors

As the design rationales are categorized into multiple design objectives, it is necessary to introduce weight factors in order to evaluate the importance of different design objective. The Analytic Hierarchy Process (AHP) is utilized as a tool to compare different design objectives. The AHP, as a multi-attributes decision-making tool, are not merely used to determine criteria weights, while the other part is not discussed in this thesis. As is illustrated in Table 3.5, there is a 9-point scale proposed in AHP tool to compare different criteria.

Table 3. 5 Grade scale for criteria comparison

Definition	Intensity
1	A and B equally important
3	A is weakly more important than B
5	A is strongly more important than B
7	A is very strongly more important than B
9	A is extremely or absolutely more important than B

The criteria are the design objectives categorized in Table 3.4. The comparison matrix below is generating from the average from several graduated master students in SDPO track of TU Delft, Appendix A listed the sample questions in the form of a questionnaire.

Seakeeping Capability	1.0000	1.3797	0.1841	1.6829	4.9593	1.4414	0.8706
Logistics	0.7248	1.0000	0.1813	1.9332	2.8094	1.1247	0.6988
Safety	5.4310	5.5152	1.0000	4.6179	7.9498	3.9363	3.8823
Operability	0.5942	0.5173	0.2165	1.0000	4.1694	1.1914	1.2457
Economic Feasibility	0.2016	0.3560	0.1258	0.2398	1.0000	0.3511	0.3432
Redundancy	0.6938	0.8891	0.2540	0.8394	2.8484	1.0000	0.7155
Habitability	1.1487	1.4310	0.2576	0.8027	2.9137	1.3977	1.0000

Next step is to check whether the comparison matrix is consistent, this can be verified by calculating the **Consistency Ratio** (CR). Before that the **Consistency Index** (CI) needs to be defined:

$$\mathrm{CI} = \frac{\lambda - n}{n-1} = \frac{7.2236-7}{7-1} = 0.0373 \tag{4.8}$$

Where λ is the largest eigenvalue of the comparison matrix, n is the number of the design objectives. Then following by:

$$\mathrm{CR} = \frac{CI}{RI} = \frac{0.0373}{1.32} = 0.0282 \tag{4.9}$$

The **Random Index** (RI) is set as 1.32 as there are seven objectives, finally the consistency ratio is equal to 0.0282, which is less than 0.1, hence the comparison matrix is considered cardinally consistent. The weight of design objectives can be obtained from the principal eigenvector. Since the value of performance utility is from 0 to 1, the weight vector then needs to be normalized to sum equals 1 in accordance with the performance utility.

$$\begin{pmatrix} 0.2494 \\ 0.2026 \\ 0.8791 \\ 0.1949 \\ 0.0673 \\ 0.1756 \\ 0.2250 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.1251 \\ 0.1016 \\ 0.4409 \\ 0.0978 \\ 0.0337 \\ 0.0881 \\ 0.1129 \end{pmatrix}$$

3.4 Proximity Measurement

The configurations rationales describe the preferable relative locations of two systems. Then it is necessary to measure the distance between them for further analysis. As is shown in Table 3.4, **Object 2** can either be the specific shipboard system or a global or absolute position. Before diving into the proximity measurement, the global or absolute positions need to be labeled, see Figure 3.1. H is the distance from bottom deck to top deck (including the deck height), L is the overall length of the ship. The *Stern* section is defined as L/4 part from the left and *Bow* section is other L/4 part from the right, leaving the residual part as *Mid*-section.

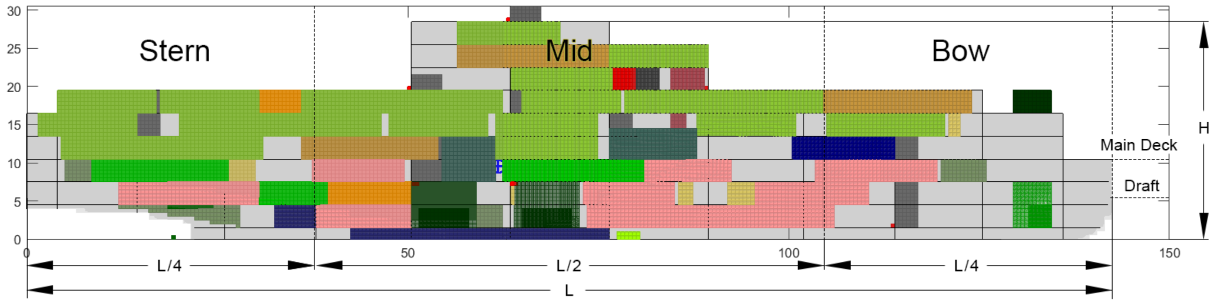

Figure 3. 1 Global position

When it comes to the measurement of the proximity, Euclidean distance and Manhattan distance are the two most useful formulations for distance. The Euclidean distance describes the absolute distance between two reference points, and it can be used to describe the interactions of objects, such as noise, vibrations, etc.

$$\text{Euclidean Distance} = \sqrt{x^2 + z^2} \tag{3.1}$$

The Manhattan distance, which also known as "city block" distance, accounts for the travel path, and it can be used to deal with problems concerning logistics effort or personnel movement.

$$\text{Manhattan Distance} = \Delta x + \Delta z \tag{3.2}$$

For the logistics effort or personnel movement within multi-decks onboard, it is necessary to take account of the location of stair cases. Hence the proximity measure for information flow through different decks needs to be modified. As is depicted in Figure 3.2 to Figure 3.4, all the staircases onboard are assumed as the vertical access shaft, and there are two alternative travel paths from system A to system B if they are in the same interval from Stair A to Stair B. In this case, the possible movement for personnel could be either in black arc or blue arc, therefore the distance is considered as: $[(x_2 - x_1 + x_3 - x_1) + (z_2 - z_3)]$ and $[(x_4 - x_2 + x_4 - x_3) + (z_2 - z_3)]$, respectively. The shortest path will be taken into account in this thesis, hence the travel path with minimum travelling distance is used as input for evaluate the logistic effort, where the minimum travelling distance is defined as:

$$\text{Modified Distance} = \min\left(\mathrm{x_a} + \mathrm{x_b} - 2\mathrm{x}_{\mathrm{stair}_{\mathrm{left}}}, 2\mathrm{x}_{\mathrm{stair}_{\mathrm{right}}} - \mathrm{x_a} - \mathrm{x_b}\right) + \Delta \mathrm{z} \tag{3.3}$$

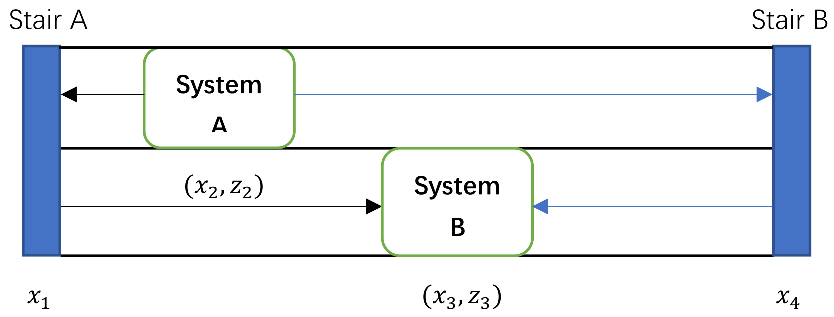

Figure 3. 2 Travelling path including staircases

If system A is not in the same stair case interval as system B does, then even if taking the stair case into consideration, the travelling distance will have no relation with the location of all the staircases because the horizontal distance is always $(x_3 - x_2)$. Hence, the modified distance can be still measured by Equation 3.2.

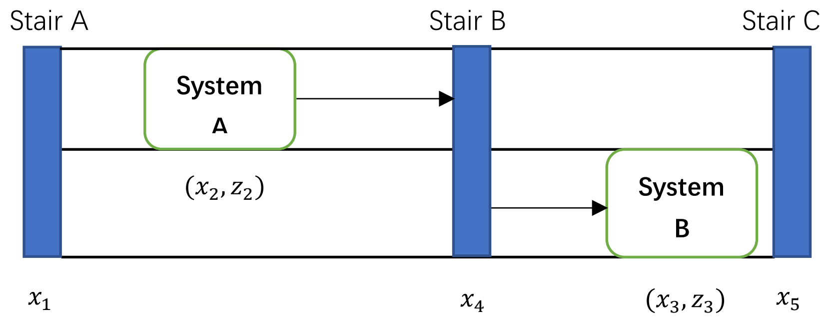

Figure 3. 3 Travelling path including staircases

Another case involving the use of staircase can be described by Figure 3.4, there is only one staircase located in one side that connects the different decks, the travelling path, in this case, can be only in the black arc without other alternatives. To tackle this situation, two imaginary vertical shafts will be utilized, the locations of the imaginary staircase x_4 will be either a sufficiently large number 1000 for example in the bow side or a sufficiently negative number -1000 for instance in the stern side. As a result, the distance can still be calculated by Equation 3.3, the minimum distance will be the actual travelling distance.

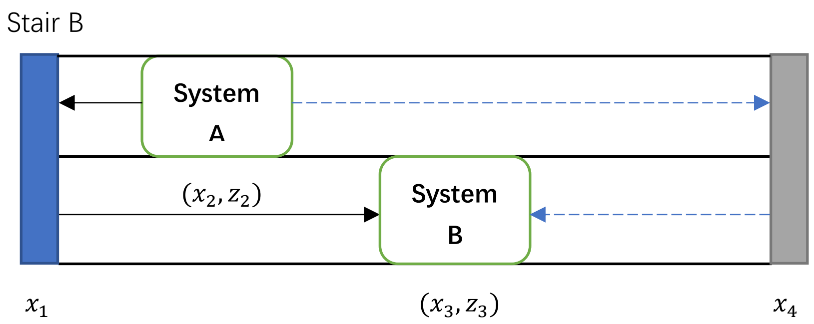

Figure 3. 4 Travelling path including staircases

When it comes to the interaction between system A and system B, it is also of necessity to consider the number of these two systems. As is seen in Figure 3.5, scenario A is measured by distance between single system A and single system B. When the number of system B is multiple, interaction will be measured by average distance between system A and each system B. Scenario C illustrates the interaction among multiple system A and multiple system B, and it is measured by the average distance between each system A and each system B.

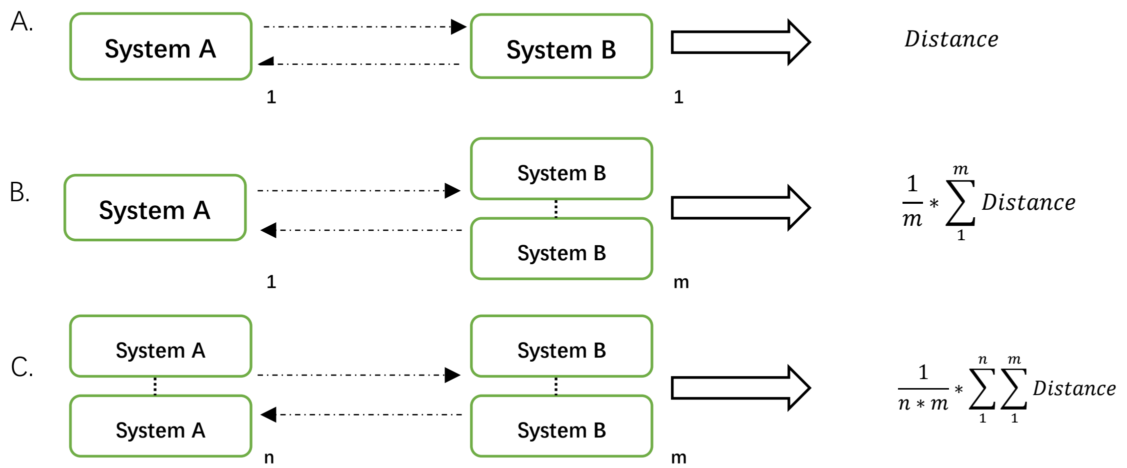

Figure 3. 5 Interaction between A and B

As the proximity measures between different systems within the layout are defined, the configuration aspects described by design rationale can therefore be converted to a series of numerical values for GA analysis.

3.5 Nondimensionalization of Distance

When measuring the distance of two systems onboard, the vertical distance is far smaller than the horizontal distance, it would be not sufficient to consider the actual sum of these two distances when measuring the proximity of two systems. Considering a small-sized polar expedition cruise ship with overall length of 130m and height of 26m. In this case, it is quite common for people to travel 30m horizontally while not possible to travel 30m vertically. Besides, people are more likely to travel horizontally within the same deck rather than going up or down. Hence, vertical distance ought to weight more than horizontal distance within the total distance. A generic solution will be nondimensionalization of all the measuring distance. As all the measuring distance is based on two-dimensional physical architecture of the ship, the overall length L and height H (see Figure 3.1) can be used to nondimensionalize all the positions of the systems, then the weight for vertical distance is higher than horizontal distance due to H is far smaller than L. Another reason for using the nondimensional distance instead of actual distance can be attribute to the variation of main dimensions for different polar expedition cruise ships. Although they are all belongs to small-sized group, the main particulars of the ships cannot be completely identical, then using the nondimensional distance could be more appropriate to expand the analysis to whole small-sized group. The dimensionless distance equations are listed below:

$$\text{Dimensionless Euclidean Distance} = \sqrt{(\frac{x}{L})^2 + (\frac{z}{H})^2} \tag{3.4}$$

$$\text{Dimensionless Manhattan Distance} = \Delta\frac{x}{L} + \Delta\frac{z}{H} \tag{3.5}$$

$$\text{Dimensionless Modified Distance} = \min\left(\frac{x_a + x_b - 2x_{stair_{left}}}{L}, \frac{2x_{stair_{right}} - x_a - x_b}{H}\right) + \Delta\frac{z}{H} \tag{3.6}$$

3.6 Conclusions

This chapter discussed how the design rationale base for a polar expedition cruise ship can be categorized into different selected design objectives and introduced a weight factor to the different design objectives for further tradeoff analysis. Then proximity measurement for different systems within the internal layout are defined as well. The next chapter is going to describe the introduction and the usage of fuzzy logic theory, whereby a weighted performance metric can be established accounting for the architectural relations extracted from the layout.

4

FUZZY LOGIC THEORY

Fuzzy logic theory is a method of system analysis that connects traditional methods of analysis and the real-world relationships between variables that are not unambiguous. As is mentioned before, the design rationale for a ship is somewhat qualitative and subjective, then by making use of fuzzy logic theory, a clear analysis of the general arrangement from different design objectives can therefore be reached. This chapter will introduce the fuzzy logic theory as well as a mathematical understanding to the problem.

4.1 Introduction to Fuzzy Sets Logic, and Fuzzy Systems

Fuzzy logic was primarily designed to represent and reason with some form of knowledge which would be expressed in a linguistic or verbal form. However, when using a language-oriented approach for representing knowledge about a certain system of interest, one is bound to encounter a number of non-trivial problems, *J. Hellendoorn (2006)*. For instance, it is not easy to decide a certain number *x* from a given set is *large or not*. According to *J. Hellendoorn (2006)*, three groups of answer can be developed:

- **Threshold**
- **Estimators**
- **Conservatives**

The group called *threshold* persons will find a threshold *d*, if *x<d*, then *large*, and if $x \geq d$, then *not* large; *Estimators* might use the full continuum of the scale according to how large or how small they think the number is, it is only to a certain degree for them to agree the fact of number being *large*; *Conservatives* will partition the sets into three subsets: {*large*}, {*not large*} and either {*large*} or {*not large*}. Due to the fuzziness of a property is characteristic of an object, fuzzy logic was, therefore, motivated to handle the inherent vagueness in knowledge representation.

Instead of accepting that something had to be a member of a set (1) or not (0), *Zadeh (1965)* firstly introduced the concept that the conventional crisp sets could have a varying degree of membership μ(x) between zero and one. A continuous membership function (MF) or fuzzy utilities then can be used to define how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. As is illustrated in Figure 4.1, a typical fuzzy utility is used to express a requirement for ship speed to achieve a particular mission, *M. Parsons (2009)*. The region with U(x)=0 is totally unacceptable to the designer while the region U(x)=1 is fully desirable. The fuzzy region between the minimum threshold and design goal is a subjective, with fuzzy quantity between 0 and 1.

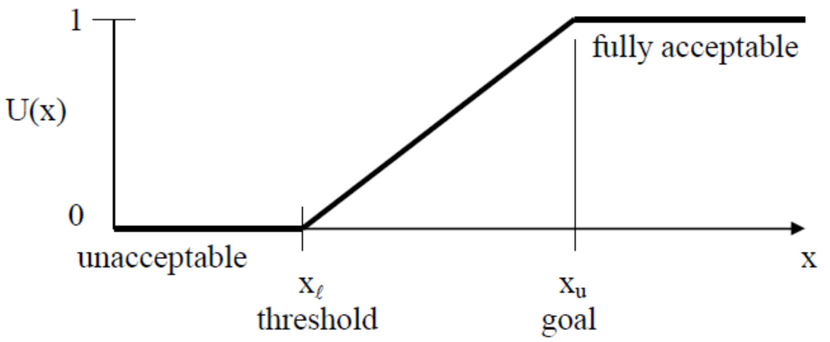

Figure 4. 1 A typical fuzzy utilities U(x) *M. Parsons (2009)*

Fuzzy logic theory can be utilized to deal with the many engineering design problems involve issues that are subjective and ambiguous. *J. Li and M. Parsons (1998)* developed fuzzy decision models to forecast the behavior of the world shipping community in tankers, *M. Parsons and J. Nam (1999)* applied the fuzzy logic theory to hull form development of the tanker.

4.2 Classic Fuzzy Systems

The classic fuzzy system is a nonlinear mapping of crisp inputs to a crisp output(s), it consists of four operations, as is depicted in Figure 4.2:

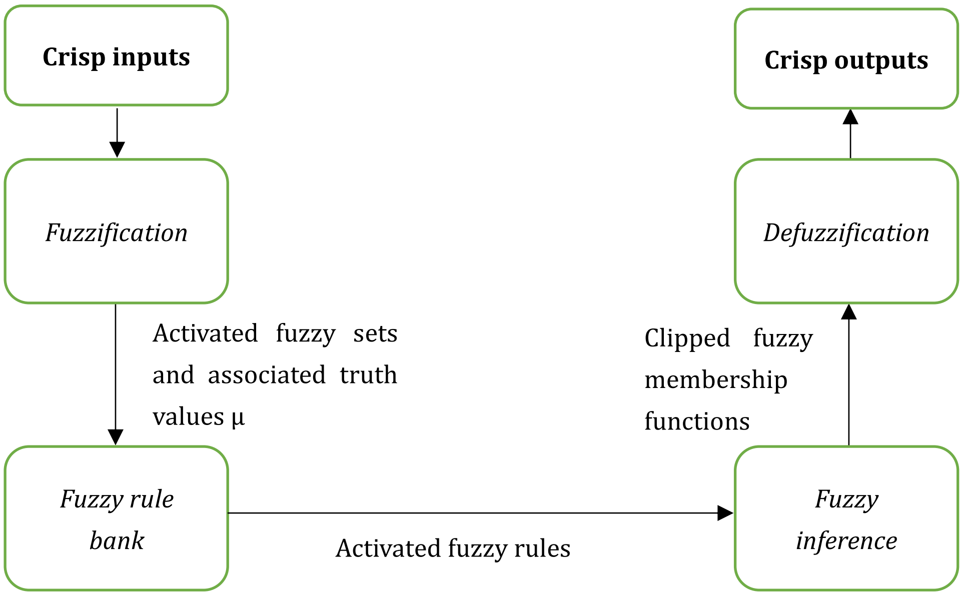

Figure 4. 2 Classic fuzzy systems *A. Kana (2018)*

4.2.1 Fuzzification

As the first operation in classic fuzzy systems, fuzzification will guide a certain element into several sets simultaneously, with the value of MF represents the percentage of a certain set. Unlike the crisp set where the MF of a certain element is either 1 or 0, fuzzification will convert the crisp inputs to membership in fuzzy sets with corresponding truth value µ. For a design input x to a certain requirement, for example, three sets can be derived: {Undesired}, {Marginal}, and {Desired}, as is shown in Figure 4.3. When the design input x is 1.5, $\mu\_Undesired\ (x = 1.5) = 0.5$, $\mu\_Undesired\ (x = 1.5) = 0.5$, which means this design input x can be 50% undesired and 50% marginal to the requirement.

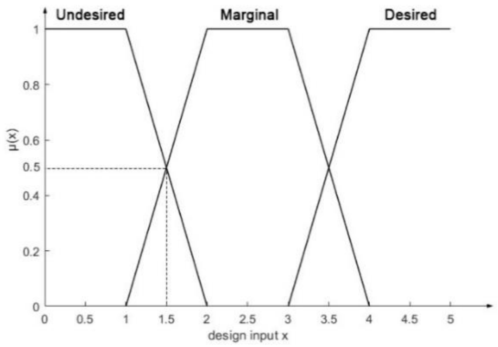

Figure 4. 3 Fuzzy set example

4.2.2 Fuzzy Rule Bank

The second operation is to set up a fuzzy rule bank, where the rules are in the form of **IF…AND…THEN** statements to determine the fuzzy set of output. There are abundant sources where the rules are derived, such as existing design rules, expert opinion, engineering logic and history, etc. An example of output sets can be seen in Figure 4.4, five sets including: {Very Low}, {Low}, {Medium}, {High} and {Very High} are used to represent different performance levels regarding a certain design objective. As is illustrated in Table 4.1, if the input 1 belongs to the set {Undesired} and {Marginal}, input 2 belongs to set {Undesired}, then the performance level for this design objective is considered as {Very Low} and {Low}.

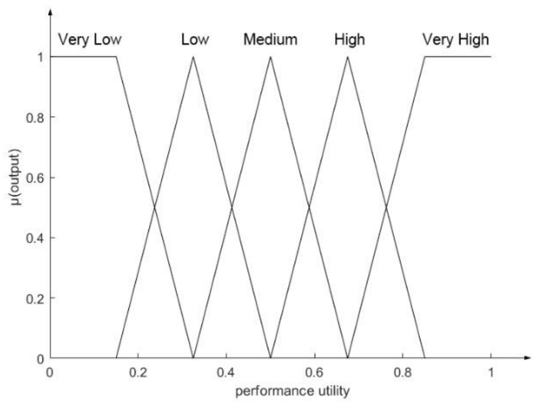

Figure 4. 4 Output membership example

Table 4. 1 Fuzzy rules example for two inputs

		Design Input 1		
		Undesired	Marginal	Desired
Design Input 2	Undesired	Very Low	Low	Medium
	Marginal	Low	Medium	High
	Desired	Medium	High	Very High

4.2.3 Fuzzy Inference

After the associated fuzzy rules are activated, the third operation is to find a proper fuzzy inference scheme which can establish the strength (true values) μ associated with outputs. There are two most inference schemes: **Correlation Minimum Inference** (CMI) and **Correlation Product Inference** (CPI). In this thesis, **Correlation Minimum Inference** is chosen as the inference scheme. Continuing the given example, if the input 1 belongs to the set {Undesired} with truth value of 0.5, and input 2 belongs to set {Undesired} with truth value of 1, then the truth value of performance level for this design objective is considered as {Very Low}: $\mu\_(output - Very\ Low) = \min[\mu_{input1-Undesired}, \mu_{input2-Undesired}]$. In this case, the minimum value will be 0.5, hence the output MF is clipped at μ=0.5. Likewise, the output MF for {Low} will also be clipped at μ=0.5, see Figure 4.5.

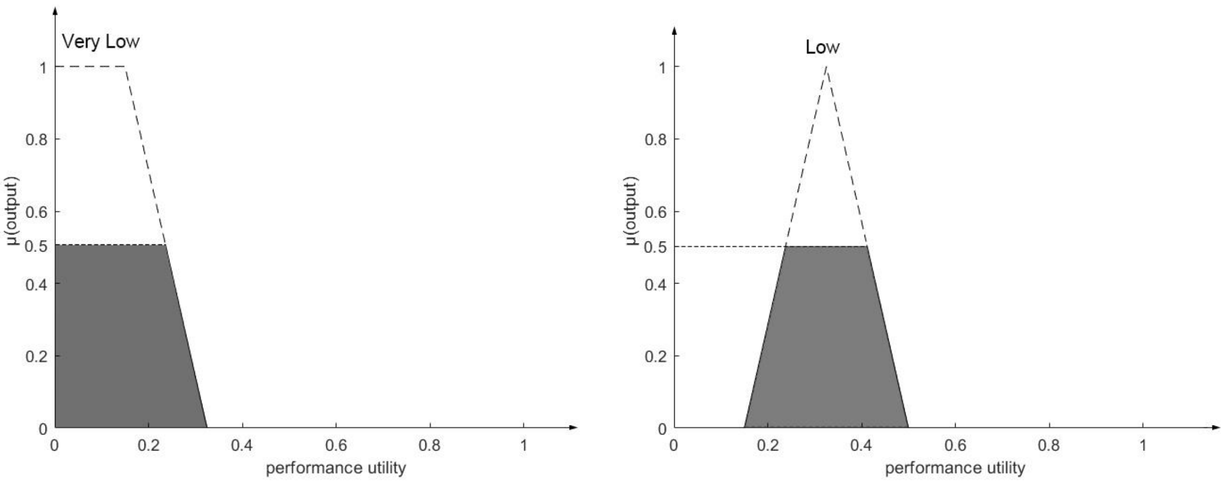

Figure 4. 5 Clipped membership function

4.2.4 Defuzzification

Finally, the eventual operation is defuzzification which provides a way to average or interpolate among all the active rules based on their clipped output membership functions. The most common defuzzification scheme, called **Centroid Defuzzification** (CD), has the equation as follows:

$$\text{crisp output:}\ \ y = \frac{\sum a_r x_r}{\sum a_r} \tag{4.1}$$

where a_r is the area of the clipped output fuzzy set membership function, x_r is the centroid of the clipped output fuzzy set membership function and r are the number of active rules. Following the example, a crisp output will be obtained according to the clipped areas and the corresponding centroid locations.

4.3 Fuzzification of Input and Output for Design Rationale

The proximity description in design rationale is too ambiguous to quantitatively evaluate the layout quality of the ship, while fuzzy logic theory can find a way to cope with the ambiguity of the design rules. As is mentioned before, design rationale proposed a preferred relevant design feature between two objects onboard. For example, system *A* should be adjacent to *system B*. However, the state of being "*adjacent*" will bring the problem for designer, hereby it is necessary to fuzzify the attribute into multiple sets. Then the attribute of "either *adjacent* or *not adjacent* can be handled with a certain truth value.

Likewise, two input fuzzy sets can be defined accordingly for different design rules. In Figure 4.6, there are two thresholds to distinguish two different states of the input. The input is at state 1 before **threshold 1** with the truth value of 1, which means the input is at **State 1** with the probability of 100%. When the input is still increasing, the truth value of the input being at **State 1** is decreasing, meanwhile the truth value of the input being at **State 2** is going up. The truth value of the input being at **State 2** is less than 1 until the input value is exceeding **threshold 2**.

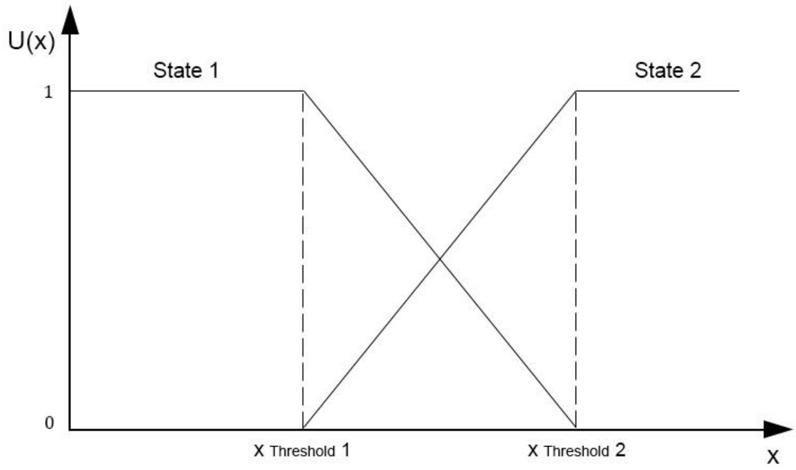

Figure 4. 6 Membership function of input

The performance utility is the output from the general arrangement analysis. Here it is assumed that each design input is equally contributing to the performance utility, it is also recognized that each design input has two states. Thus, ***N*** inputs, which means ***N*** rationale rules, will need ***N+1*** output fuzzy set to illustrate different levels of performance utility. For instance, there are five design inputs to decide the performance utility regarding a specific design objective. If **State 1** is desirable to the design rationale, then **State 2** is not desirable to the design rationale, *vice versa*. The sequence of different design inputs does not change the outcome due to their equal importance to the performance utility. When establishing the rule bank, five design inputs will have six outcomes ranging from five desired contribution to no desired contribution at all, leading to six different utility levels: {Very Low}, {Low}, {Medium Minus}, {Medium Plus}, {High} and {Very High}. The output membership function in this case is shown in Figure 4.7.

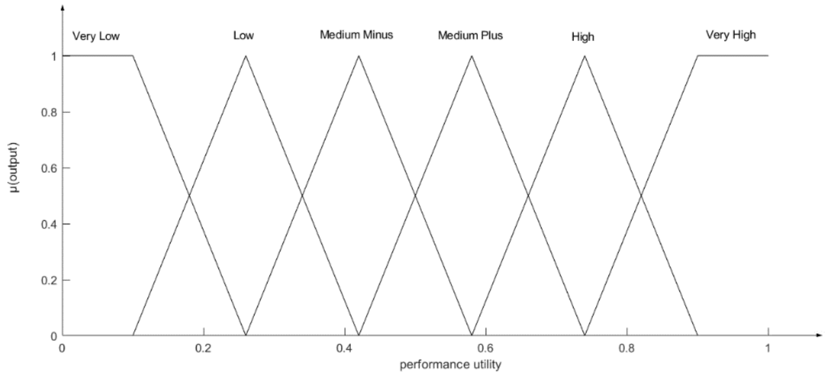

Figure 4. 7 Membership function of output

After the four operations in fuzzy system, a nonlinear mapping from the design rationale to performance output deems possible. In Figure 4.8, the proximity descriptions from the design rationale can be converted into a series of design inputs which can be in turn fed into the fuzzy system, a crisp output can therefore be derived. Likewise, the nonlinear mapping process can be expanded to multiple design objectives, finally the performance utilities of all selected design objectives can be obtained, making the quantification of the layout quality from different design objectives possible.

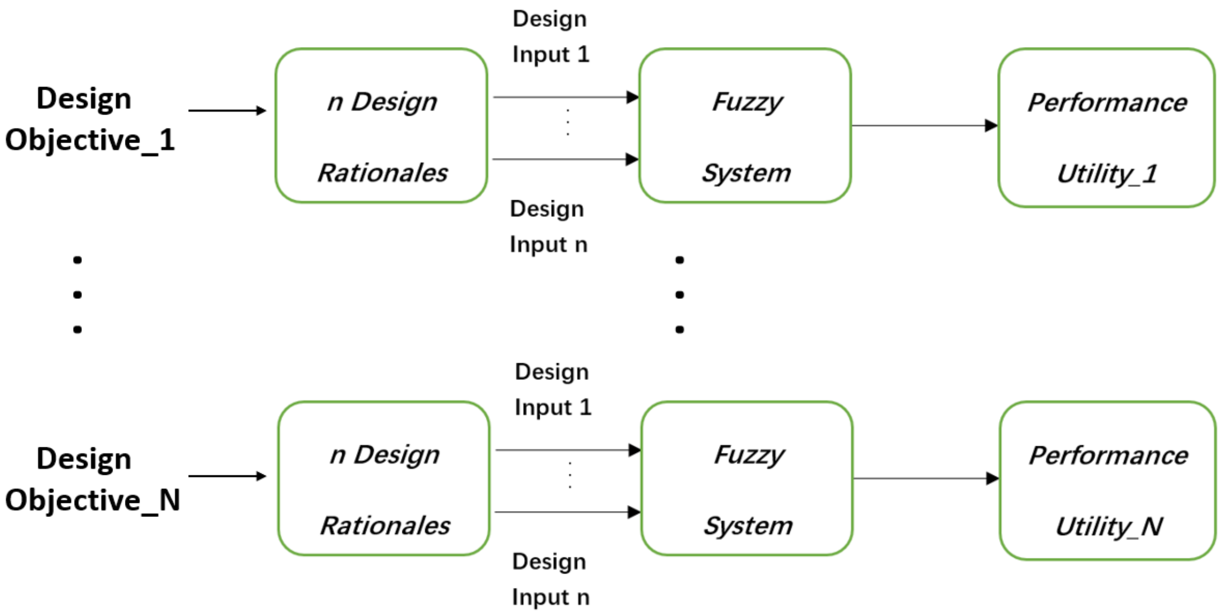

Figure 4. 8 Nonlinear mapping from design rationale to performance output

4.4 Total Utility performance of the Ship

In order to evaluate the performance resulting from the configuration of the expedition cruise ship, a quality metric is introduced. Establishing the different proximity measurements based on corresponding design rationales, the numerical results can be generated, which in turn can be fed into the fuzzy system, the crisp performance utility from different design objectives can be obtained as well. It is further assumed that every design rationale within the same design objective is equally contributing to the performance utility of that design objective, while the weight of different objectives differs. Hence, the summation of the performance utility regarding the design objective multiplies its weight factor will contribute to the total utility of the expedition cruise ship, see Equation 4.2.

$$U_{ship} = \sum \text{weight factor}_i * U_i \qquad (4.2)$$

Where U_i is the utility values for design objective i. The value of U_{ship} then can reflect the proper extent of the design regarding the layout quality of the ship, the largest U_{ship} will correspond to the 'most promising design' which has proper balance in different design objectives. Furthermore, physical improvement to certain worse GA will also be quantifiable based on the quality metric.

4.5 Application Demonstration

In the following section, an example is given to illustrate the applicability of theory and the quality metric before extending to the concept design results of the expedition cruise ship. For the sake of simplicity, five design rationales concerning the design objective of *Operability* instead of all is selected. The corresponding systems are listed in Table 4.2, the vertical staircases will be excluded in this section.

Table 4. 2 Allocated systems with assumed position

Space	System Type	X	Z
1	Zodiacs System	20	5
2	Lifeboat System	15	5
3	Bridge System	25	7
4	Cruise Officer Accommodation	15	7
5	Crew Accommodation	25	3
6	Crew Dayroom	15	3

Considering a section from sideview of a ship, as is illustrated in Figure 4.9, different spaces in the sideview represent the locations of different systems onboard the expedition cruise ship.

Figure 4. 9 sideview of a simplified layout

Assuming the main particulars of the ship are as followed:

Table 4. 3 Assumed main dimension of the ship

Main Parameters	
Length	40m
Height	8m
Draft	2m

Based on the proximity measurements according to five design rationales, five inputs are therefore defined:

$$INPUT_1 = \frac{z_1 - T}{H}$$

$$INPUT_2 = \frac{|\, x_3 - x_4 \,|}{L} + \frac{|\, z_3 - z_4 \,|}{H}$$

$$INPUT_3 = \frac{|\, x_5 - x_6 \,|}{L} + \frac{|\, z_5 - z_6 \,|}{H}$$

$$INPUT_4 = \frac{z_2 - T}{H}$$

$$INPUT_5 = 1 - \frac{x_3}{L}$$

The membership functions of fuzzy inputs and output are defined according to Figure 4.6 and Figure 4.7 in Chapter 3. After conducting the four operations within the classic fuzzy system, the performance utility, which is the output of the fuzzy system, can be derived, as is depicted in Table 4.4. The results also indicted that both Zodiacs system and the lifeboat system are not close to the waterline with the truth value of 1. The cruise officer accommodation is adjacent to the bridge system, followed by the truth value of 0.83. The crew accommodation is adjacent to the crew dayroom with the truth value of 1, and the bridge system is forward of the midsection of the ship with the truth value of 0.75.

Table 4. 4 Input and output values of fuzzy system for Operability

System Names	State 1	State 2	Threshold 1	Threshold 2	x_i	μ_State1	μ_State2
Zodiacs Store Waterline	Not Too High	Too High	0.15	0.3	0.375	0	1
Officer Accom Bridge System	Adjacent	Not Adjacent	0.2	0.5	0.25	0.83	0.17
Crew Accom Crew Dayroom	Adjacent	Not Adjacent	0.25	0.75	0.25	1	0
Lifeboat System Waterline	Not Too High	Too High	0.15	0.3	0.375	0	1
Bridge System Mid	Forward	Not Forward	0.25	0.75	0.375	0.75	0.25
OUTPUT	0.49						

The output, as the performance utility of the layout in design objective of operability, is 0.49. According to the output membership function in Figure 4.7, the layout utility of the ship concerning Operability is mostly in the {Medium Minus} level, further improvement deems necessary. In this case, the crew officer's accommodation is recommended to place closer towards the bridge system and the Zodiacs store system or lifeboat system ought to be placed on lower deck, see Figure 4.10. The new results are given in Table 4.5, the performance utility regarding Operability is increased from 0.49 to 0.69 after the improvement, which means the quality of the GA is nearly improved to {High} level.

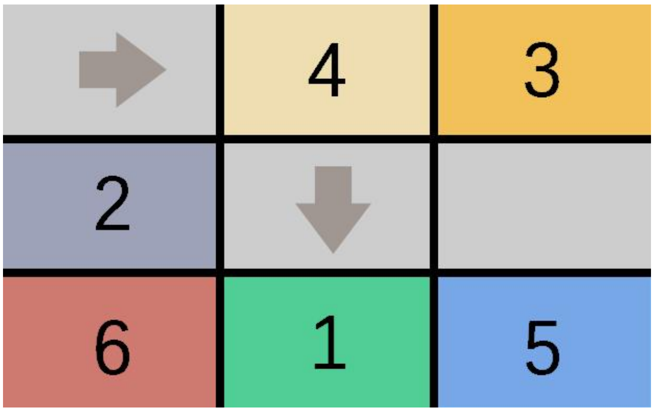

Figure 4. 10 Improved layout

Table 4. 5 Input and output values after improvement

System Names	State 1	State 2	Threshold 1	Threshold 2	x_i	μ_State1	μ_State2
Zodiacs Store Waterline	Not Too High	Too High	0.15	0.3	0.125	1	0
Officer Accom Bridge System	Adjacent	Not Adjacent	0.2	0.5	0.125	1	0
Crew Accom Crew Dayroom	Adjacent	Not Adjacent	0.25	0.75	0.25	1	0
Lifeboat System Waterline	Not Too High	Too High	0.15	0.3	0.375	0	1
Bridge System Mid	Forward	Not Forward	0.25	0.75	0.375	0.75	0.25
OUTPUT	0.69						

4.6 Conclusion

This chapter discussed the possibility of applying fuzzy logic theory in analyzing the spatial relations within the sideview layout of an expedition cruise ship, by taking account of several design rationales. Moreover, it also showed how the method can further help with potentially improving the layout quality by rearranging some of the shipboard systems. Next chapters will expand the evaluation to five packing designs and incorporate all the design rationales proposed previously to find out the 'most promising' design which has the highest total performance utility. Based on that design, some further possible recommendations regarding the layout will be elaborated as well.

5

CASE STUDY ON PACKING RESULTS

This chapter will perform a case study aimed at evaluating five concept designs generated from Packing Approach and selecting the 'most feasible' design among the five based on the developed metric. The implementation of the method will be discussed considering seven design objectives. Besides, the numerical inputs of fuzzy system as well as corresponding layouts will be compared from several design objectives.

5.1 Selection of Packing Results

A series of designs will be discussed in this section, it will include one design chosen by *K. Droste (2016)* and three best designs together with a worse design filtered by *M. Roth (2017)* to reflect different layout quality according to Roth's scoring metric. As is depicted in Figure 5.1, a total dataset of more than 20,000 design concepts generating from packing approach for a polar expedition cruise ship has been filtered into three group. The designs in red region are very likely to be deleted due to the lower scores while the designs in green regions show great possibilities to be selected because of the highest scores. Hence three best designs from the green region, one worse design from the red region and one design from the white region are selected to compare the results from the method in this thesis.

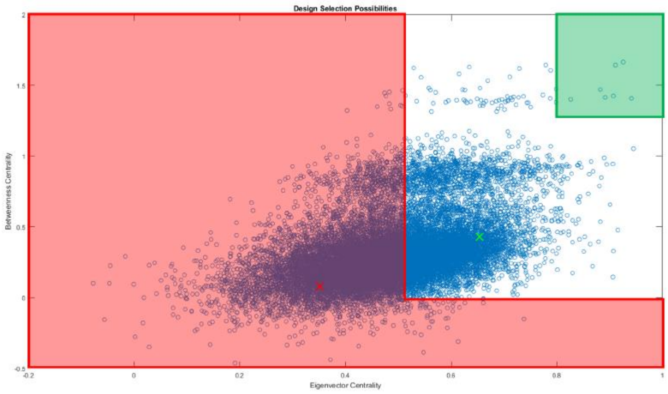

Figure 5. 1 Possible Improved Design Selection *M. Roth (2017)*

The main parameters of these designs are given in Table 5.1:

Table 5. 1 Main parameters of selected ships

Design ID	A	B	C	D	E
Length [m]	150	135	148	139	146
Height [m]	25.5	21.5	28	28	25.5
Draft [m]	5.72	5.04	5.75	5.73	5.8
Displacement [m^3]	8612	6907	8669	8007	8992
Quality Region	Green	White	Green	Green	Red

5.2 Implementation of Method

Based on all classified configuration design rationales and fuzzy logic theory, the specific dimensionless distances between different systems mentioned in the rules can be derived as the inputs for the fuzzy model. Then the performance utility of different design objectives will contribute to the total performance utility of the internal GA, thus layout quality of the polar expedition cruise ship. The different inputs will be described as follows:

5.2.1 Seakeeping Capability

The configuration descriptions to maintain the seakeeping capability of the ship mainly involve the distance from the bridge system and accommodation blocks to the center of rotation of the ship. In this thesis, the center of gravity of full-loaded ship is assumed as the center of rotation of the ship, which can be derived through the packing dataset. $INPUT_1$ for seakeeping capability is the non-dimensional Euclidean distance from accommodation block (object 1) to the CoG of the ship (object 2). As there are many accommodations blocks onboard, $INPUT_1$ will be the average distance of all the accommodation blocks to the CoG. $INPUT_2$ for seakeeping capability is the non-dimensional Euclidean distance from bridge system (object 1) to the center of gravity of the ship (object 2). According to the rationales, both accommodation blocks and bridge system are preferably placed near the CoG to acquire a good performance utility in seakeeping capability. The parameters in the membership functions for the two inputs are listed in Table 5.2:

5.2.2 Logistics

Design rationales for logistics are introduced to decrease the logistic effort onboard. Taking the interaction between main galley and the restaurant system for instance, the food cooked in the main galley ought to be delivered to the restaurant with less logistic effort. As is mentioned before, it is also necessary to include the use of staircases for multi-deck transportation. The numerical value of $INPUT_1$ is the modified Manhattan distance between the main galley system and restaurant system, and the two systems should be placed adjacently to reduce the logistic effort. Likewise, the passenger accommodation blocks are preferably placed near the entertainment system, since there are multiple passenger accommodation blocks and multiple entertainment systems onboard, definition of $INPUT_2$ matches the scenario C, thus average modified Manhattan distance between each passenger accommodation block and each entertainment system. $INPUT_3$ will suit scenario B, average modified distance from passenger accommodation blocks to each restaurant system. $INPUT_4$ is the average modified distance from each galley system to each general store system, calculating according to scenario C. As the main galley on board is preferably placed in the main deck, $INPUT_5$ is the difference of deck number of main galley system and main deck. The parameters in the membership functions for the five inputs are given in Table 5.3:

5.2.3 Safety

For the design objective of safety, fuel tanks shouldn't be distributed near accommodation area, the lifeboat system is preferably placed near the accommodation for the sake of evacuation. There are multiple fuel tanks and multiple accommodation blocks while one lifeboat system onboard. Hence, $INPUT_1$ is the average Euclidean distance between each fuel tank and each accommodation block, and $INPUT_2$ is the average Manhattan distance from lifeboat system to each accommodation. Table 5.4 shows the main parameters in the membership functions for the two inputs.

5.2.4 Operability

Operability aspects were introduced in the previous simplified application, however some of the previous definitions should be modified due to the use of staircase. $INPUT_1$ is the vertical distance between the Zodiacs store and the waterline of the ship and $INPUT_4$ is the vertical distance between the lifeboat system and the waterline. $INPUT_2$ is the modified Manhattan distance from cruise officer accommodation to the bridge system. $INPUT_3$ will be calculated consistent with scenario B, thus the average modified Manhattan distance from crew dayroom to each crew accommodation blocks. Finally, $INPUT_5$ is the relative location of the bridge system to the bow, the smaller numerical value indicates bridge system is closer to the bow of the ship. The parameters of membership functions for the five inputs are depicted in Table 5.5.

5.2.5 Economic Feasibility

The economic feasibility of the layout will mainly focus on the in the aspects such as the reduction the length of the shaft line and fuel piping instead of the total building cost of the ship. $INPUT_1$ is the average Manhattan distance from each fuel tanks to each generator room in accordance with scenario C. $INPUT_2$ is the relative location of the propulsion room to the stern of the ship. As two generator rooms are preferably built adjacently to save money, $INPUT_3$ is the relative horizontal distance between the two generator rooms. Table 5.6 gives the particulars of the membership functions for these three inputs.

5.2.6 Redundancy

When it comes to the design objective of redundancy, the locations of two similar systems including two hospital rooms and two generator rooms are used to evaluate the performance utility of the layout. $INPUT_1$ is the Euclidean distance between the two hospital systems and $INPUT_2$ is the non-dimensional horizontal distance between the two generator rooms. Table 5.7 shows the information of the membership functions for the above two inputs.

5.2.7 Habitability

The objective of habitability is used to describe how comfortable the people are when they are living on the ship, it can be mostly attributed to the surrounding environment of the accommodation blocks. For instance, accommodation blocks should be grouped and not be placed adjacent to any of the big vibration/noise sources or smell sources. Hence, the following inputs will be defined by the distance of between the accommodation blocks and heavy machinery and restaurant. $INPUT_1$ is the standard deviation of all the Euclidean distances of all accommodation blocks except the officer accommodation to the CoG of the ship. $INPUT_2$ and $INPUT_4$ are the average Euclidean distances from each accommodation block to each generator room and technical/auxiliary system in accord with scenario C, $INPUT_3$ is the average Euclidean distance from each crew accommodation block to propulsion room. To be noticed, the influence of restaurant brings is assumed to retain in the accommodation blocks located in the its deck rather than the accommodation blocks in upper or lower decks. $INPUT_5$ is then defined as average horizontal distance between these accommodation blocks and the restaurant. The definition of the membership functions for the five inputs are illustrated in Table 5.8.

Table 5. 2 Parameters in input membership functions for Seakeeping Capability

System Names	State 1	State 2	Threshold 1	Threshold 2
Accommodation CoG	Near	Not Near	0.3	0.5
Bridge System CoG	Near	Not Near	0.3	0.5

Table 5. 3 Parameters in input membership functions for Logistics

System Names	State 1	State 2	Threshold 1	Threshold 2
Main Galley Restaurant	Adjacent	Not Adjacent	0.25	0.75
Passenger Accom Entertainment	Adjacent	Not Adjacent	0.25	0.75
Passenger Accom Restaurant	Adjacent	Not Adjacent	0.25	0.75
Galley General Store	Adjacent	Not Adjacent	0.25	0.75
Main Galley Main Deck	Adjacent	Not Adjacent	1	3

Table 5. 4 Parameters in input membership functions for Safety

System Names	State 1	State 2	Threshold 1	Threshold 2
Fuel tank Accommodation	Adjacent	Not Adjacent	0.3	0.5
Lifeboat system Accommodation	Adjacent	Not Adjacent	0.3	0.7

Table 5. 5 Parameters in input membership functions for Operability

System Names	State 1	State 2	Threshold 1	Threshold 2
Zodiacs store Waterline	Not Too High	Too high	0.15	0.3
Officer Accom Bridge system	Adjacent	Not Adjacent	0.2	0.5
Crew Accom Crew Dayroom	Adjacent	Not Adjacent	0.25	0.75
Lifeboat System Waterline	Not Too High	Too high	0.15	0.3
Bridge System Mid	Forward	Not Forward	0.25	0.75

Table 5. 6 Parameters in input membership functions for Economic Feasibility

System Names	State 1	State 2	Threshold 1	Threshold 2
Fuel Tank Generator Room	Adjacent	Not Adjacent	0.15	0.3
Propulsion Room Mid	Aft	Not Aft	0.25	0.75
Generator Room Generator Room	Adjacent	Not Adjacent	0.15	0.5

Table 5. 7 Parameters in input membership functions for Redundancy

System Names	State 1	State 2	Threshold 1	Threshold 2
Primary Hospital Second Hospital	Adjacent	Not Adjacent	0.1	0.25
Generator Room Generator Room	Adjacent	Not Adjacent	0.15	0.3

Table 5. 8 Parameters in input membership functions for Habitability

System Names	State 1	State 2	Threshold 1	Threshold 2
Accommodation Accommodation	Grouped	Not Grouped	0.1	0.3
Accommodation Generator Room	Adjacent	Not Adjacent	0.25	0.5
Accommodation Propulsion Room	Adjacent	Not Adjacent	0.25	0.5
Accommodation Auxiliary System	Adjacent	Not Adjacent	0.25	0.5
Accommodation Restaurant	Adjacent	Not Adjacent	0.25	0.5

After the determination of two threshold values for different inputs and the corresponding membership function of output for each design objective, the fuzzy rule bank can therefore be set up in accordance with the design rationale. As is mentioned earlier, the fuzzy inference scheme is chosen as Correlation Minimum Inference and defuzzification scheme is selected as Centroid Defuzzification. The four operations within the fuzzy system can be modeled in the MATLAB Fuzzy Logic Toolbox, Appendix B has demonstrated the example for Economic Feasibility in steps. As a result, the crisp outputs generating from the fuzzy system can be further incorporated in the performance metric, the total performance utilities of five selected ships can be obtained and evaluated.

5.3 Evaluation of the Results

After applying the methods to the five packing results of a small polar expedition cruise ship, the total performance utility of these five concepts can be obtained in Table 5.9:

Table 5. 9 Evaluation results of five ships

ID	Seakeeping Capability	Logistics	Safety	Operability	Economic Feasibility	Redundancy	Habitability	U_ship
A	0.45	0.57	0.55	0.58	0.58	0.29	0.71	0.54
B	0.42	0.35	0.65	0.58	0.60	0.18	0.71	0.54
C	0.58	0.50	0.68	0.66	0.60	0.15	0.80	0.61
D	0.55	0.49	0.60	0.69	0.60	0.18	0.77	0.57
E	0.45	0.58	0.60	0.62	0.48	0.50	0.83	0.60

A different rank occurred comparing the results with the previous filtered results by *M. Roth (2017)*, the designs with worse score has the second highest performance utility among the five chosen designs while the performance utility of the other four designs nearly followed the same quality trend as the filter indicated. The divergence might come from the following reasons:

- Different design rationale base when analyzing the results
- Different logic when measuring the proximity of different shipboard systems
- Different metrics used when calculating the results of the design

The design rationale base in this thesis added the rules related to the global position such as the bow section and the CoG of the ship instead of merely focusing on the relative connections between the shipboard systems. Rather than using a Boolean expression of only zero or one, the use of fuzzy logic also changed the results. Moreover, the scoring metric in this thesis is summation of the performance utility concerning one of the design objectives times the corresponding weight while Mark used a single metric accounting for the importance of shipboard systems, thus neglecting the effect of conflicting rationales. Despite the divergence of the results, the design has the highest total performance utility among the five still belongs to the 'better quality region' from the filter. Hence, the Design C can be selected and moved forward to further study.

It is also noticeable that the total utility performance of the ship is involved with the weight factor generated from human decision which somehow means subjective. In this case, it is worthwhile to conduct a sensitivity analysis to figure out how the selection result vary due to the change of weight factors. It is hereby proposed to compare the current results of these five ships with the unweighted total performance utilities of them, an unweighted matrix is introduced in accordance with the weighted matrix. As there are seven design objectives defined during the whole analysis, the unweighted factor for each design objective is set as 1/7. After recalculating the total performance utilities of five ships, the results are shown in Figure 5.2. The total performance utility of each ship is all reducing by 0.1 to 0.4 when using the unweighted metric, this may due to extreme importance of safety, which is accounting for nearly 45% within the weight factors, and the five ships were performed relatively better in safety than some of the less important design objectives. In addition, when calculating by the weighted metric, Design C will be the most promising design among the five while Design E will be the most promising design if all design objectives are not weighted. Hence, there will be a distinctive difference when selecting the 'most promising' design. It can be also concluded that the design selection for packing results should be based on the specific context regarding each design objective. The different weights for different design objectives are acceptable, the selection result would be meaningful only under a certain priority foundation laid to different design objectives. Since the weighted matrix introduced in this is also created by subjective preference, the selection from this metric, however, does not necessarily mean that Design C is the absolute best design among the five, but it would be great interest to investigate Design C given on the specific design preference.

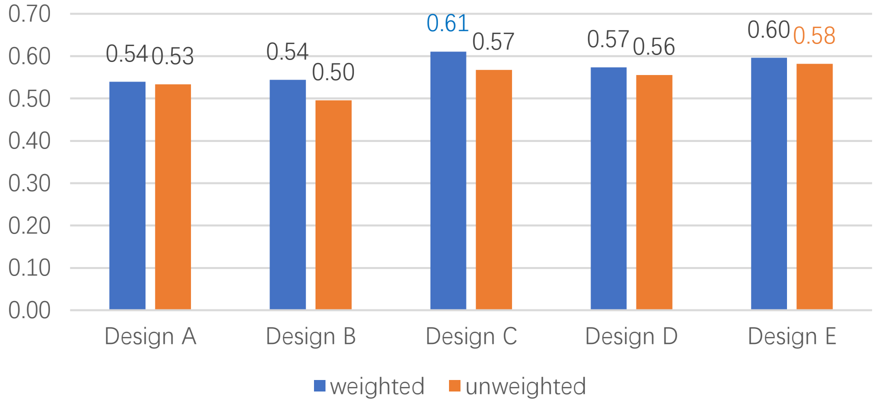

Figure 5. 2 Comparison of weighted and unweighted results

Before improving the specific design, one needs to know the most desirable features with respect to seven different design objectives among the five designs. As is illustrated in Figure 5.3, Design C has the highest performance utility in the design objective of: seakeeping capability, safety and economic capability; The Design E then has the highest performance utility in the design objective of logistics, redundancy and habitability; The Design D got highest performance utility in operability and economic feasibility as well. Moreover, it is of necessity to understand how the input values of the fuzzy model can influence the quality of the layouts. Thus, the comparisons within the design objectives deem necessary as well. To illustrate the relations, some distinctive results from several designs objectives are selected and analyzed in the following sections.

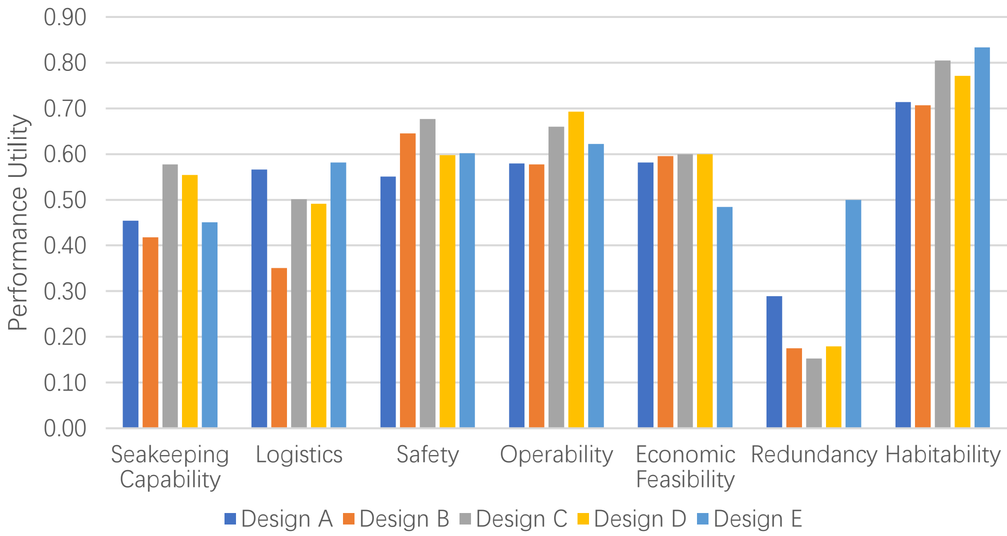

Figure 5. 3 Performance Utility Distribution

5.4 Comparison within Design Objectives

Considering the results from design perspective of seakeeping capability in Table 5.10, the values of $INPUT_1$ generating from the design with highest and lowest performance utility differed from 0.32 to 0.35, leading to a significant drop in the truth value of being near, which is a desirable feature, from 0.92 to 0.76. When manually inspecting the two layouts, it can be found in the Figure 5.4 that the accommodation blocks in the Design C (including both green region and pink region for passenger and crew accommodation) are more clustered near the CoG than that of Design B. Some passenger accommodation blocks in Design B are also found placed near the bow section of the ship while barely happened in Design C.

Table 5. 10 Comparison of numerical inputs within Seakeeping Capability

System Names	ID	State 1	State2	x_i	μ_State1	μ_State2
Accommodation	Design C	Near	Not Near	0.32	0.92	0.08
CoG	Design B	Near	Not Near	0.35	0.76	0.24

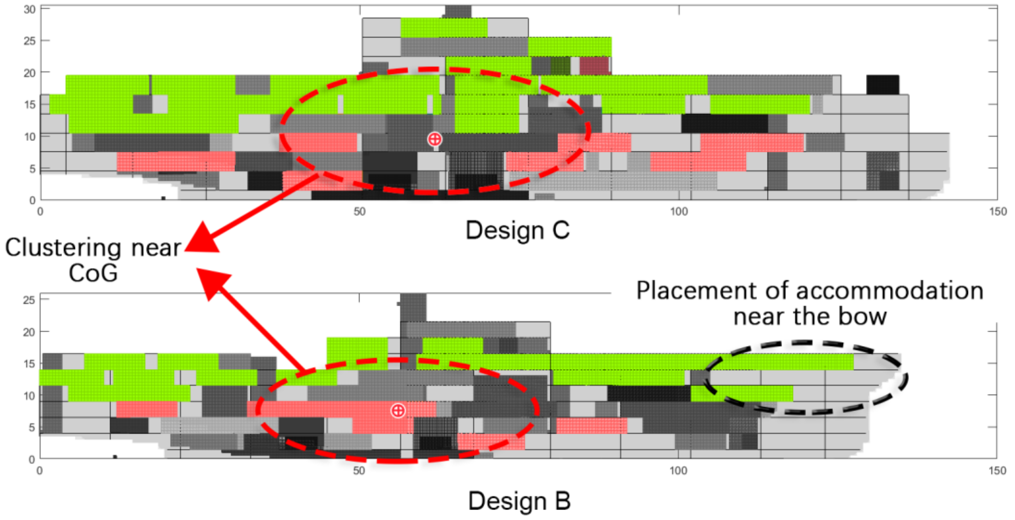

Figure 5. 4 Comparison of architectural features within Seakeeping Capability

A remarkable difference within the two designs occurred when taking account of $INPUT_1$ for design objective of safety. In Table 5.11, both designs are not desirable based on the rationale separating the fuel tanks and the accommodation blocks. However, the Design C is considered a slight better than the Design E partially due to the better relative locations of fuel tanks and accommodations blocks. In this case, when relating back to the layouts of the two designs, the undesirable feature that fuel tank being close to accommodation block is identified in both designs, see Figure 5.5. However, there are less disadvantageous arrangements in Design C than that of the Design E.

Table 5. 11 Comparison of numerical inputs within Safety

Systems	ID	State 1	State2	x_i	μ_State1	μ_State2
Fuel Tank	Design C	Adjacent	Not Adjacent	0.48	0.12	0.88
Accommodation	Design E	Adjacent	Not Adjacent	0.43	0.37	0.63

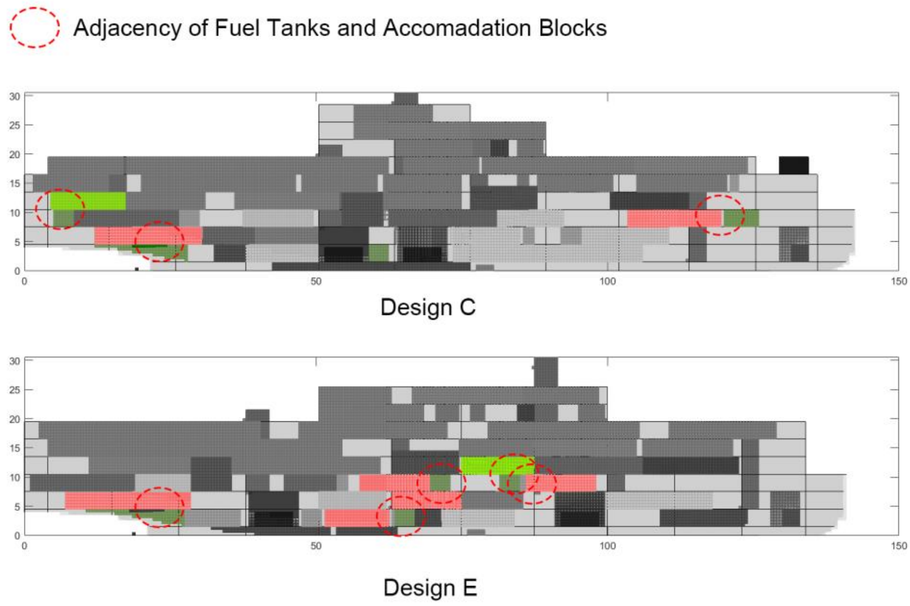

Figure 5. 5 Comparison of architectural features within Safety

When comparing the numerical results from the design objective of redundancy, Design E is considered the best in the five designs while Design C is regarded the worst in layout quality. As is shown in Table 5.12, it can be concluded that both designs placed the two medication systems adjacently. Meanwhile design E totally separated the two generator rooms while design C still placed the two adjacently. After manually inspecting the two designs, these features can be identified in Figure 5.6.

Table 5. 12 Comparison of numerical inputs within Redundancy

Systems	ID	State 1	State2	x_i	μ_State1	μ_State2
2 Medication systems	Design E	Adjacent	Not Adjacent	0.04	1	0
	Design C	Adjacent	Not Adjacent	0.02	1	0
2 Generator rooms	Design E	Adjacent	Not Adjacent	0.36	0	1
	Design C	Adjacent	Not Adjacent	0.09	1	0

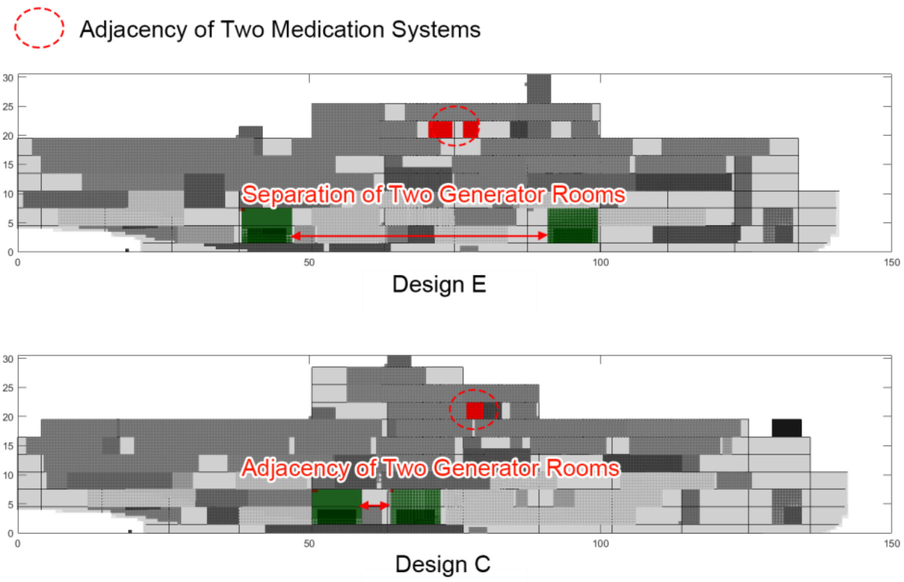

Figure 5. 6 Comparison of architectural features within redundancy

5.5 Conclusions

This chapter conducted a case study on evaluating the layout quality of five concept designs from the packing approach. After applying the method developed in the previous chapters, the quality of each design from different design objectives can be quantified by performance utility, making the quantitative evaluation on the layouts feasible. Although the quality rank of the five packing results coming from the method in this thesis is different from the rank based on the metric established by *M. Roth (2017)* due to the given reasons, the variances of results generating from this method can relate back to the correspondent advantageous or disadvantageous features within the layouts. Thus, the method used in this thesis is applicable to analyze the layout quality of the packing results. Next stage is going to improve the 'most promising' design selected from the method and apply the method to a real expedition cruise ship, this will be discussed in the following chapter.

6

LAYOUTS IMPROVING

The previous chapter has illustrated different performance utilities generating from the method can reflect different levels of layout quality. To further explain the usefulness of the method, layout improving is therefore required. The following chapter will focus on not only the selected packing design, but also a real expedition cruise ship. As is mentioned earlier, a number of layout issues still can be identified within the 'most promising' design, the insights gained from the architectural relations within the packing design will be used to improve the layout quality. When it comes to the real cruise ship, the current general arrangement is highly-detailed for commercial representation, as detail design is out of the scope of this thesis, the GA will be simplified to the form of early stage design, on which the layout evaluation and possible improvements will be based.

6.1 Potential Improvements for Selected Packing Result

According to the analysis of layout quality, the design C scored highest in the total performance utility of layout. As is shown in Figure 6.1, the base line of layout quality for each design objective is setting as 0.6 to represent beyond {medium} according to the general fuzzy rule bank. However, the scores within the seven design objectives are ranging from 0.15 to 0.80, which means the 'most promising' design generated by packing approach is still not qualified considering these four out seven design objectives. Next, it is necessary to modify the GA of the design by manually adjusting the placement of some shipboard systems without changing the main dimension of the ship.

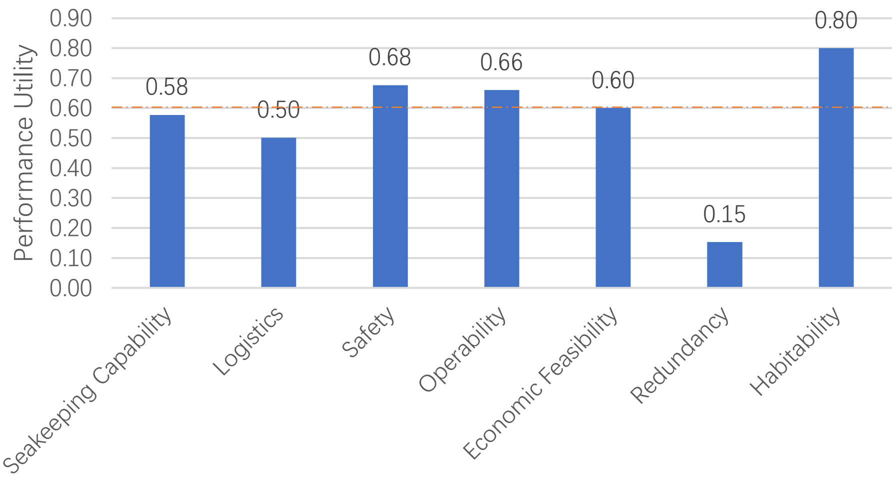

Figure 6. 1 Distribution of performance utilities within 7 design objectives

6.1.1 Identification of Layout Issues

By analyzing the numerical results of all outputs from the fuzzy system, the layout issues are firstly discussed for individual design objective, they are further highlighted in Figure 6.2 :

- ***Seakeeping Capability*****:** the passenger blocks in deck 9 and 10 together with the bridge system are relatively far from the CoG of the ship (1), increasing seasickness to the corresponding passengers and captains onboard.
- ***Logistics*****:** the main galley is far from the restaurant and two galley systems are not really close to the general stores, which are both adding more logistic efforts for information flow.
- ***Safety*****:** Some of the accommodation blocks are found directly adjacent to the fuel tanks (2), which will put the crew member in that area at risk.
- ***Operability*****:** some of the crew accommodation blocks are slightly far from the crew dayroom (3), adding unnecessary transferring effort for the crews.
- ***Economic Feasibility*****:** the fuel tanks in deck 4 are separated far from the generator rooms (4), this will increase the total length of fuel piping.
- ***Redundancy:*** the two medication systems in deck 8 are adjacent (5) to each other and the two generator rooms are also close to each other (6).
- ***Habitability:*** one crew accommodation block is placed right above the propulsion room (7), two crew accommodation blocks are found placed near the generator rooms (8), one crew accommodation block is found adjacent to the technical/auxiliary system (9), and some passenger accommodation blocks in deck 7 are placed too close to the restaurant (10).

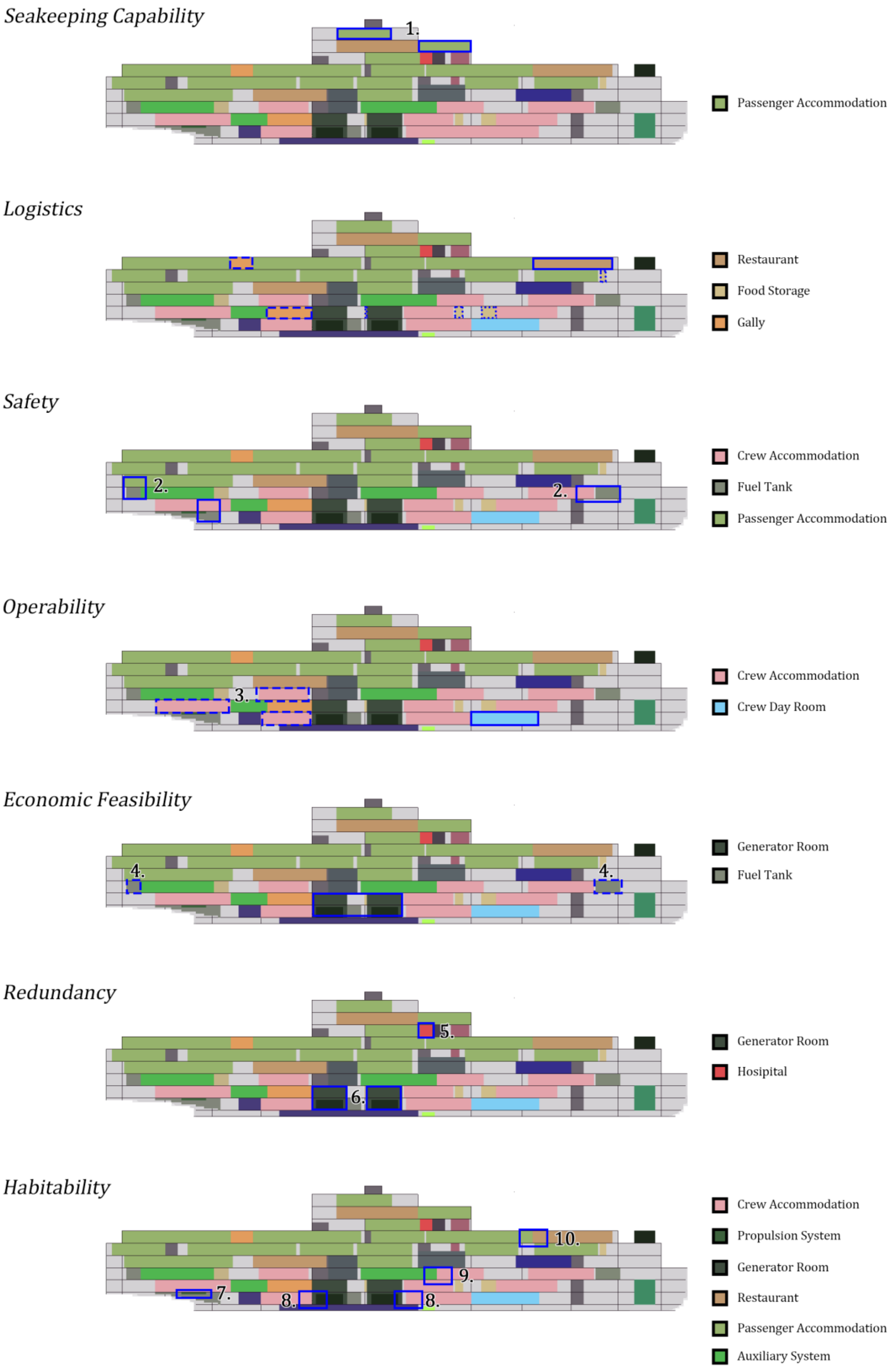

Figure 6. 2 Identification of layout issues of selected packing design

6.1.2 Improvement on the layout

Given these undesirable architectural features within the layout of the concept design, the major modifications are listed as follows, Figure 6.3 highlights the changes within the original concept design, Figure 6.4 shows modified deck layout with better visualization.

- ***Passenger & Crew accommodations (Red)***: The passenger accommodation block 20 in the top deck is moving downwards the deck 8 and accommodation block 11, 15, 19, 9, 12, 3, 1 are moving towards the stern section to cluster with the other passenger accommodation blocks. The crew accommodation blocks 3, 7 are moving up to deck 4 and clustering with other crew blocks while accommodation block 2 is exchanging the location with the crew dayroom within the same deck. Besides, the crew accommodation block 8 is slightly rearranging towards the stern section and placing adjacent to block 1, and crew accommodation block 4 is slightly moving to the bow section.
- ***Galley systems (Purple)***: The main galley in deck three is moving towards the bow section, the second galley system in deck 7 is relocated adjacent to the restaurant system within the same deck.
- ***Entertainment systems (Light Green)***: The lounge in the deck 9 is moving to the top deck, leaving the previous space for accommodation blocks, the other entertainment systems such as theater is keeping remain the same location.
- ***Bridge & Medication systems (Dark Green)***: The bridge system is slightly moving away from the bow section. The secondary hospital solution is transferring to deck 5 in order to separate the two medication systems for higher performance utility in redundancy.
- ***General Stores Systems (Cyan)***: The general stores 1,2 in deck 3 are moving towards the bow section and placed adjacent to the main galley system, the general store 3 in deck 6 is moving upwards and placed adjacent to the second galley system, and the general store 4 in deck 3 is moving between the crew accommodation block 5 and technical/auxiliary system 1 to separate these two systems.
- ***Generator rooms & Technical/Auxiliary systems (Blue)***: The generator room 1 is moving towards the propulsion room and generator room 2 remains the same location. The technical/auxiliary systems 1, 2 are slightly moving towards the stern, allowing the space for the crew accommodation block 3 and general store 4.
- ***Fuel tanks (Yellow)***: Fuel tank systems 1, 3 in deck 4 are moving lower to deck 2 and placed between the two generator rooms.

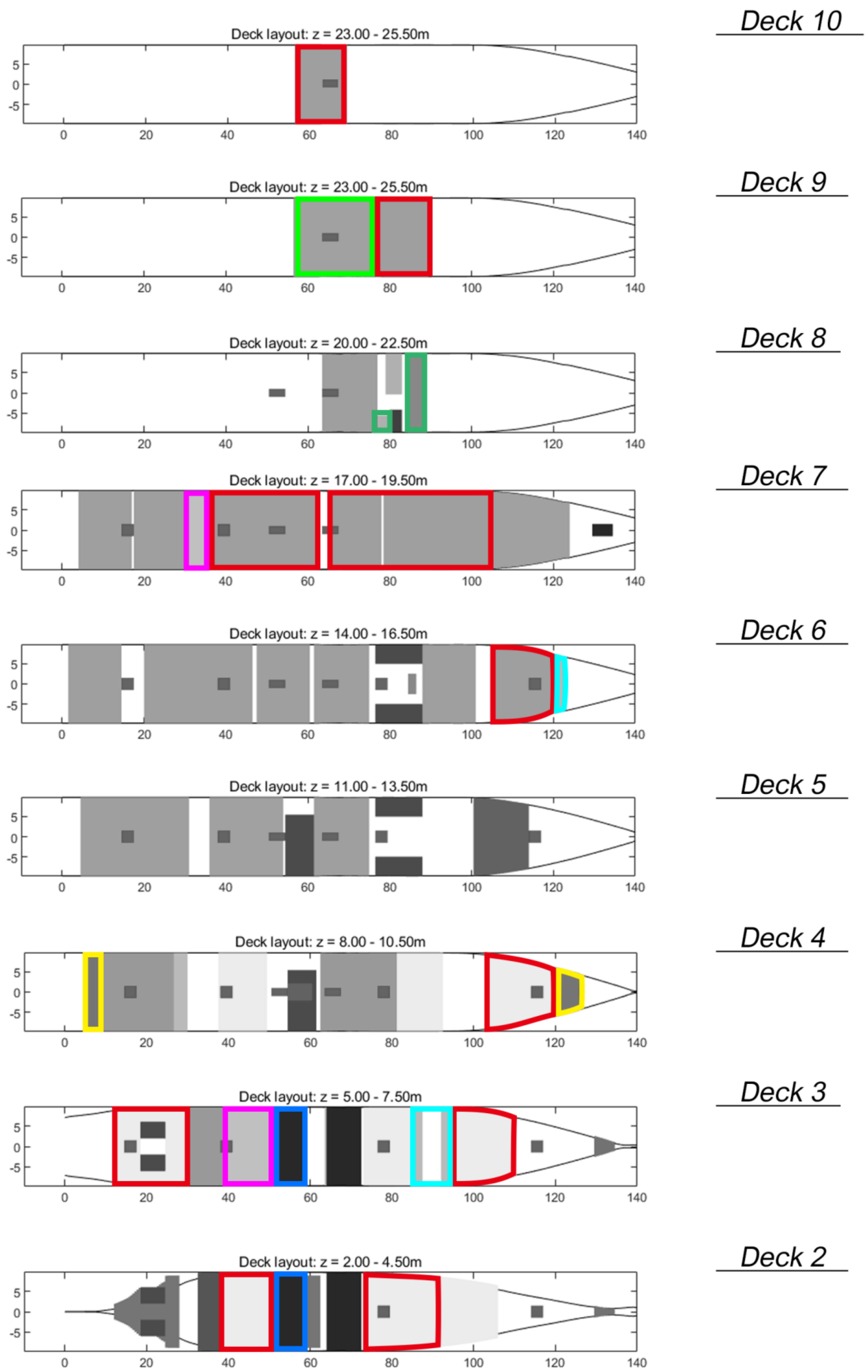

Figure 6. 3 Layout of original concept design

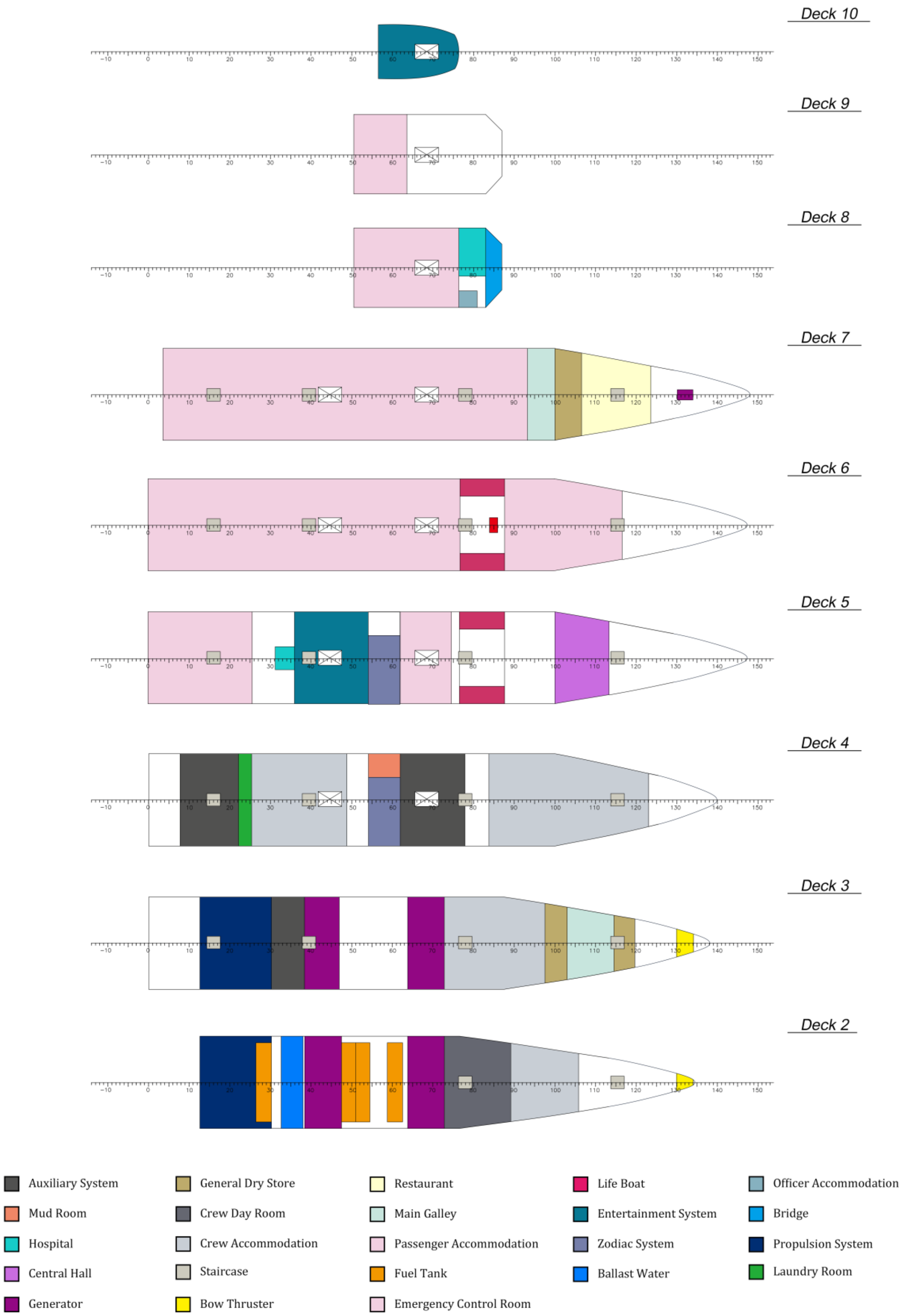

Figure 6. 4 Modified layout with better visualization

6.1.3 Analysis on the Improved Layout

After manually improved the GA of the ship, it is necessary to evaluate the layout and find out how the layout quality is improving regarding different design objectives. As is earlier mentioned, the main dimension of the concept deign is remain the same, it is assumed that the modifications do not change the CoG of the ship due to the main changes within the layout are exchanging the systems or replacing the systems in the previous void spaces.

After relocating the positions of all systems onboard, the architectural relations can be extracted from the improved layout so that it can be further used as the inputs for fuzzy system. The results are illustrated in Figure 6.5. The modifications above can be related back to increases in each design objectives, especially for the design objectives of redundancy and economic feasibility, the performance utilities are rising to 0.53 and 0.83, respectively. When it comes to the other design objectives, there are slight increase distinguished as well. To be noticed, the outputs for design objective of redundancy and seakeeping capability are close to, but somehow still below 0.6, the reasons for the former is that the two generator rooms cannot be separated further within the current layout due to the spatial conflicts with other systems, such as technical/auxiliary systems in this case, and the reasons for the latter objective is that it is not possible to place all the accommodation blocks near the CoG of the ship due to the large amounts, the compromise that some portion of the accommodation are being placed relatively away from the CoG have to be made.

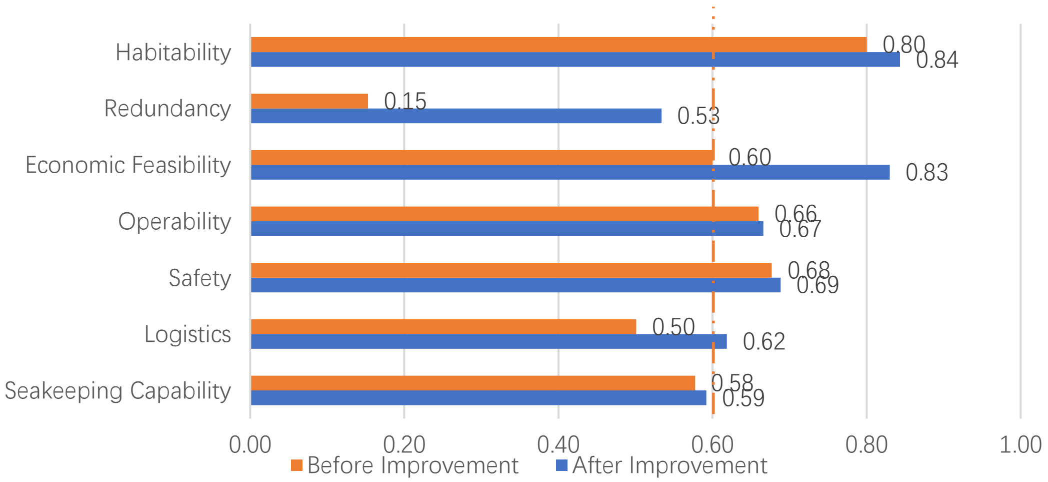

Figure 6. 5 The comparison of results before and after modification

6.2 Layout Analysis of a Real Ship

In order to further test the applicability of the method, a real polar expedition cruise ship from Damen shipyard is hereby selected and analyzed. However, the current GA of the ship offered by the *Damen shipyard (2016)* is a very detailed and mature design for commercial purpose, only the layout above deck 2 is available and presenting. Hence, the coming layout analysis is conducting based on the exiting systems onboard. Besides, the variation in types of different systems onboard also make the previous rationale database for packing designs not fully applicable for the real design, some rationales are deleted and reformed accordingly. For example, there is a hangar for helicopter onboard, new rationales for this system will be added. The generator rooms are not presenting in the existing layout, rationales regarding that system then is hereby not considered in the evaluation. The main parameters of the ship are given as Table 6.1:

Table 6. 1 Main Dimensions of Damen Ship

Main Dimensions	
Length	134.4 m
Breadth	22 m
Draft	5 m
Height	29.5 m

6.2.1 Layout Simplification

Since detailed concept design of the ship is out of the scope of this thesis, the current GA is therefore simplified into the form within the early stage design phase. Besides, the accommodation area including the passenger accommodation, crew accommodation and officer accommodation is generally divided into same-sized blocks in accordance to the packing designs. The simplified layout of the polar expedition cruise ship is shown in Figure 6.6. After allocating different areas to different shipboard systems, their two-dimensional positions can therefore be estimated. Appendix E has listed all the shipboard systems with corresponding x, z positions based on the simplified layout.

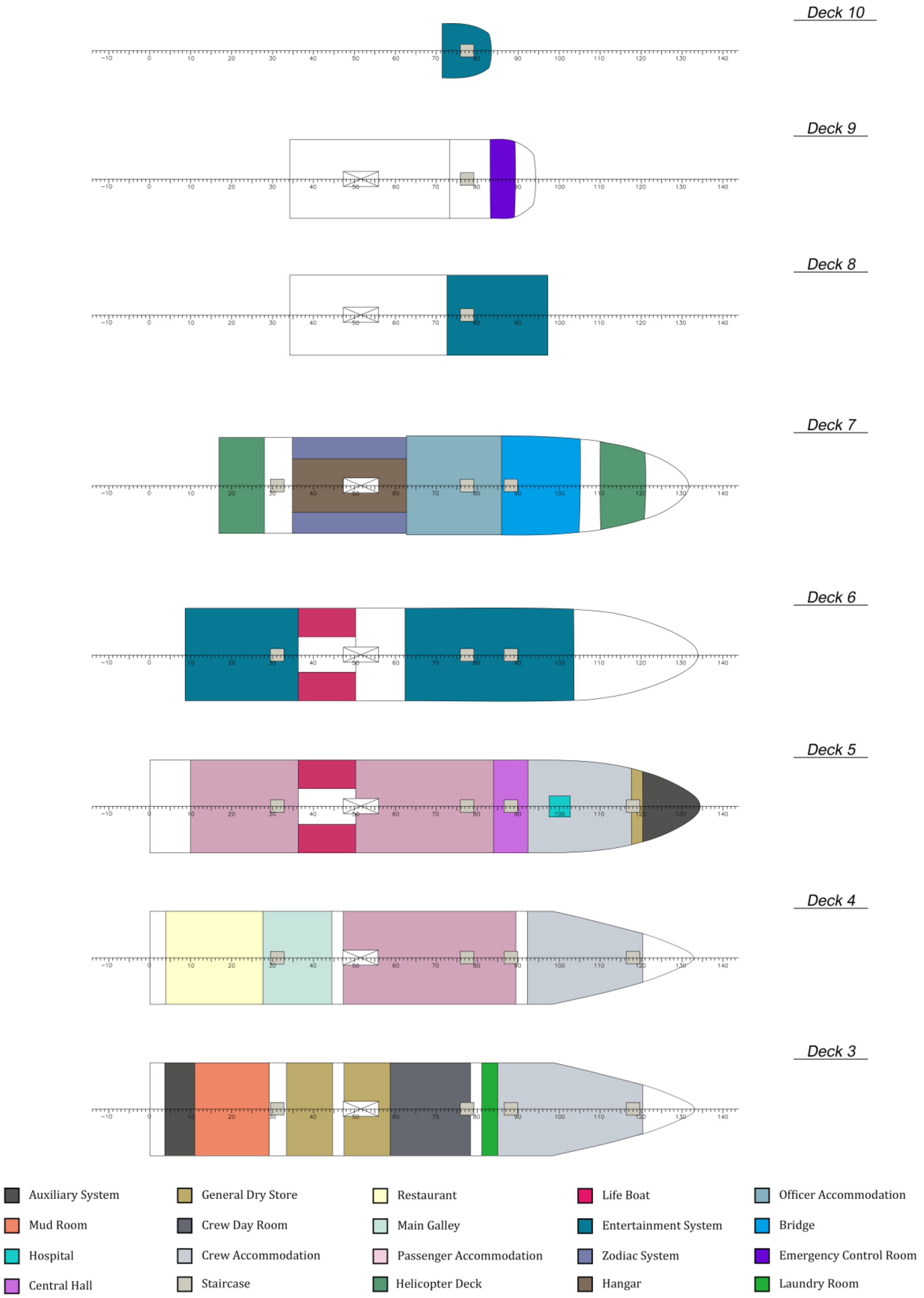

Figure 6. 6 Simplified Layouts for Damen polar expedition cruise ship

6.2.2 Setting up Design Ratinales

As is mentioned earlier, the previous rationales for the packing results are not fully applicable to the real ship, some adjustments ought to be made accordingly. The design objectives including the economic feasibility and redundancy will not be discussed due to the missing locations of related systems. The design rules involving the flight deck and hangar system are added into design objective of safety and habitability, respectively. They are "the flight deck shouldn't be adjacent to the accommodation" and "the hangar shouldn't be adjacent to accommodation". The rules for missing systems such as fuel tanks, propulsion system and generator will be deleted from the rationale base as well.

6.2.3 Evaluation on Real Ship

After assuming the x, z locations of different systems within the layout, the analysis can therefore be conducted similarly to the previous analysis whereby performance utilities for different design objectives can be derived to quantitatively analyze the layout quality.

The performance utilities of layout for five design objectives are illustrated in Figure 6.7. Likewise, if the base line of layout quality for each design objective is set as 0.6 based on personal preference, this layout can be regarded as a decent design regardless of the relatively low performance utility for the design objective of operability. A decent design does not necessarily mean the layout has to score as high as possible from each design objective. If the layout quality of the design is satisfactory from the most important design objective safety for example and can still score high in some of the design objectives, habitability in this case, then this design can be accepted for further use.

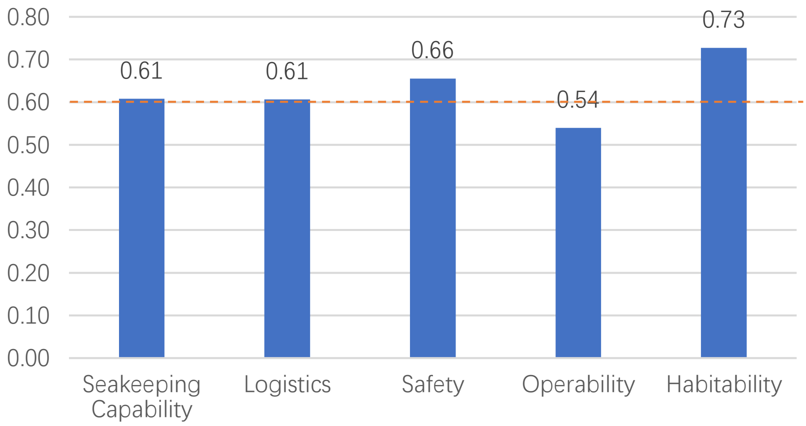

Figure 6. 7 Performance utility distribution for Damen ship

On the other hand, since the performance utility of the design is 0.54 from the design objective of operability, it is therefore worthwhile to modify the locations of the operability related systems. As is depicted in Table 6.2, the results show that the officer accommodation is adjacent to the bridge system with truth value of 1, while the Zodiacs system and the lifeboat system are placed too high from the waterline with truth value of 1 and 0.93, respectively. Besides, the bridge system is forward of Mid-section of the ship with truth value of 0.94, the crew dayroom is adjacent to the crew accommodation with truth value of 0.8. To sum up, the lifeboat system and Zodiacs system should be placed to the lower decks as the current locations for both are nearly unbeneficial according to the design rationales. In addition, the bridge system can be placed more towards the bow section of the ship to acquire better visions for the captains.

Table 6. 2 Input and output values of fuzzy systems for Operability

System Names	State 1	State 2	Threshold 1	Threshold 2	x_i	μ_State1	μ_State2
Zodiacs Store Waterline	Not Too High	Too High	0.15	0.3	0.47	0	1
Officer Accom Bridge System	Adjacent	Not Adjacent	0.2	0.5	0.16	1	0
Crew Accom Crew Dayroom	Adjacent	Not Adjacent	0.25	0.75	0.35	0.8	0.2
Lifeboat System Waterline	Not Too High	Too High	0.15	0.3	0.29	0.07	0.93
Bridge System Mid	Forward	Not Forward	0.25	0.75	0.28	0.94	0.06
OUTPUT	0.54						

6.3 Conclusions

This chapter has discussed the potential improvements on the selected packing design based on the evaluation results, a modified layout is also generated after manual adjusting the location of some systems. The analysis of the modified layout also revealed the performance utility for each design objective has increased to a higher level. Besides, a real polar expedition cruise ship from Damen is also simplified into the form of an early stage design in order to further test the applicability of the method. After slightly adjusting the design rationales and assuming the x, z positions of each systems, the evaluation on the layout quality of the real ship can be conducted as well, and further improvements regarding the operability related systems are also raised. To be noticed, the manual modification on the packing design is to demonstrate how the gaining insights from the analysis is used for manual optimization, the better way of incorporating the method will be discussed in the Chapter 8.

7

Conclusions

The complex nature of polar expedition cruise ship has made the design of this type of ship a challenging work. Concept exploration initiates the early stage ship design within the whole design process for complex vessels. The main goal of concept exploration is to generate initial technically feasible solutions. However, there are always many, sometimes even conflicting performance criteria to further constrain these technically feasible solutions, making it difficult to generate fully satisfied concepts for further study. The current methods for optimizing the concept designs lie in twofold: manual optimization and computer-based optimization. The former is mostly done in the real ship industry while the latter is addressed by academic approaches. In order to optimize the concept designs from technically feasible level to higher feasible level, a post-processing method is deemed necessary to improve the initial concept designs for both optimization methods.

The essence for post-processing initial concepts is to establish the performance metrics for whole analysis phase. The spatial relations within the internal layout of the ship and corresponding design rationale has been used to provide the metrics for filtering the initial concept designs, the ambiguity and potentially conflicting aspects within the design rationale, however, is limiting the effectiveness of the current post-processing method. The main research objective of this thesis is therefore raised and reads as follows:

Develop a method to the quantitatively analyze and improve the layout of the polar expedition cruise ship from different design objectives, accounting for subjective preferences and fuzzy logic theory

Based on the given research objective, four research questions are listed to answer the main research objective. This chapter will discuss and summarize the finds for each research question to assure the proposed research objective in this thesis is reached.

How to classify the design rationales into different design objectives?

Design rationale base for polar expedition cruise ship can be established according to *M. Roth (2017)* and the applicable designer rationales for the general ship design summarized by *T. Jasper (2017)* as well as the knowledge from the perspective of naval architect. Besides, *T. Denucci (2012)* has predefined the list of possible objectives for comparing alternatives in the context of configuration rationale. With respect to the specific rationale base for polar expedition cruise ship, each single design rule can be attributed to one or several design objectives. After reviewing all design rules in the rationale base, seven design objectives are selected or defined, which in turn involve multiple design rules in the rationale base. In sum, the seven design objectives roughly cover all the spatial or architectural aspects within the internal layout of the ship, they will be used to guide the whole analysis in this thesis.

How to develop the method for analyzing the internal layout considering all design objectives and design rationale?

To quantitatively evaluate the layout quality, the quantitative measurement of the spatial relations within the layout deems necessary. Due to the design objective-based nature of the method, weight factors for assessing the importance of different design objectives are firstly introduced. The Analytic Hierarchy Process (AHP) is utilized as a tool to help compare different objectives. A questionnaire including 3 main questions (see Appendix A) was presented to five mater students in SDPO track. After collecting and processing their opinions, a weight factor matrix is generated for further use. In addition, a specific proximity measurement according to the configuration rationale is also required. The ship is then divided into three sections: Stern, Mid and Bow from the sideview. As for measuring the proximity of different systems, Euclidean distance and Manhattan distance are used, where the former can describe the interactions of objects such as noise and vibrations and the latter copes with logistic effort onboard. The two formulations for distance can be used to describe every aspect mentioned in the rationale base. As for logistics effort, more details need to be addressed due to the traveling path between two systems especially for the case of multi-deck movement. Hereby it is proposed three traveling patterns distinguished by the relative location of system and staircase. Besides, there are three scenarios defined to further explain the interaction between two systems due to the variance in amounts for the two systems.

Nondimensionalization of all measuring distance is proposed as well to further expand the analysis to larger group of concept designs of polar cruise ships. Different ships cannot be completely identical from the perspective of main dimension of the ships, an absolute description of the distance may not be applicable for different-sized ships. Therefore, the nondimensionalization of distances will help eliminate the influence of different size. Furthermore, the current way of nondimensionalizing the measuring distance can also show the vertical distance contributing more than the horizontal distance to the total distance as the overall length of the ship is far larger than the height of the ship, which can in line with the fact that people onboard are more willing to travel horizontally rather than vertically.

How can the fuzzy logic theory be used to analyze the design rationale?

Now that the qualitative description for each configuration rationale within the corresponding design objectives can be translated into the form of nondimensional measuring distance, it is still hard for the naval architect to decide how the distance can reflect the quality of the layout. The fuzzy logic theory is hereby utilized to cope with ambiguity within the rationale. The fuzzy utility function can be used to measure the effectiveness of a design option which can be considered as fully unacceptable, fully acceptable or something between them with specific truth value. A classic fuzzy system which contains four consecutive operations can nonlinearly map crisp inputs to crisp output(s), *A. Kana (2018)*. For one design objective in this case, the inputs are the multiple measuring distance involved while the output is considered as the performance utility, which can reflect the quality level of the internal layout from that design objective.

There are two states identified for each configuration rationale in this thesis. Considering the rule: Object A should be adjacent to Object B. In this case, the {State 1} can be regarded as {Adjacent} whereas the {State 2} is {Not Adjacent}. Two thresholds are also defined to strictly categorize the membership functions for input into either fully adjacent, fully not adjacent or something between the two with a specific truth value. Likewise, the output membership function can be defined by different sets to illustrate different levels of quality. The guidance rule behind is that the better design option, adjacent of two objects in this case, will lead to higher performance utility and *vice versa*. In conclusion, there will multiple design rationales to constrain each design objective and each design rationale within that design objective will be considered as an input to the fuzzy system. After the four operations within the fuzzy system, a crisp performance utility, which are the quantitative analysis result of the internal layout from that design objective. Hence, the whole analysis towards the general arrangements of the ships is possible by accounting for all selected design objectives together with their corresponding design rationales.

How to evaluate and improve the layout of a polar expedition cruise ship during the early stage design process based on the method?

The fuzzy logic theory has been addresses as an effective way to cope with the constrains generating from the design rationale, the next stage will focus on how to implement the developed method and analyze the concept designs including both the packing results and real concept design from the ship industry.

With respect to concept designs generated from packing approach, the problems are always coming up as huge numbers and different quality levels. A scoring metric will be created based on the mathematic understanding of the post-processing method. Chapter 3 has introduced a weight factor matrix for different design objectives combining different designers' preferences. By summing up all the weighted performance utilities, a total performance utility of a single ship can be therefore generated and used as a metric to analyze different concept designs. The design that has higher total performance utility is considered as better design from the internal spatial relations within the layout. As a result, this method can be further incorporated into the packing approach and supported as extra constrains to help the packing approach generate the designs with higher quality, this will be further elaborate in Chapter 8.

In addition, the single performance utility from a specific design objective can provide a manual guidance for further use to the naval architects in the real ship industry. If one finds the concept design has lower performance utilities in some design objectives during the early stage design process, then the designers can relate back the undesirable aspects to the corresponding rationales and know how to further improve the layouts. For the potential conflicting rationales, the designers can also find the involved design objectives and adjust the relative location between the mentioned systems until the performance utilities from these conflicting design objectives all have reached to an acceptable or higher level.

The sections above have structured and answered the main research objective of this thesis through four sub-research questions. To further demonstrate the applicability of this method, two case studies were hereby performed. The following sections will discuss how the developed method can help the designer gain more insight during the early stage design phase of polar expedition cruise ship.

Chapter 5 is the first cases study based on the concept design created from packing approach. *K. Droste (2016)* applied the packing approach for generating a set of concept designs of polar expedition cruise ship and *M. Roth (2017)* has preliminarily filtered these designs into different layout quality groups based on his own metric. As a result, five concept designs from different quality levels are selected in this thesis. After gathering the locations of each systems and the main dimensions from the dataset, the non-dimensional distances can be therefore calculated and fed into the different fuzzy systems specifically built upon their corresponding design objectives, the performance utility from each design objective can be obtained. The total performance utilities of five different ships can also be calculated by the metric introduced in Chapter 4, making quantitatively evaluating the internal layout of the ships possible. For purely single selection, the design with the highest total performance utility is regarded as the ‘most promising’ concept design among the five selected designs from the perspective of internal layout. Furthermore, it can be concluded that different metrics used when analyzing the layout of the ship will lead to different comments regarding which one is better or worse, and different priorities of ship design objectives can create different selection result as well.

Chapter 6 is the second case study focusing on further manually modifying the concept designs of the polar expedition cruise ships, which includes both the ‘most promising’ design from the packing approach and a real Damen polar cruise ship. To be mentioned, manually modifying the packing results may be less necessary and useful for automated ship design, the purpose of doing this is to demonstrate how the analysis results can be used to further improve the layout quality to a higher quality from a single goal of post-processing the concepts, because it does not necessarily mean the selected concept design created from the packing approach can be fully satisfied, manually modification is then required if that is not the case. When reviewing the all the performance utilities from the seven design objectives, the designer can relate the undesirable design aspects to the inputs resulting in lower performance utilities, the designer can therefore adjust the less desirable relative locations of different systems onboard accordingly. With respect to manual optimization, which is quite a common way for the ship design industry, a commercial polar expedition cruise ship from Damen shipyard is chosen. However, the full deck layout of the ship is not available, the analysis is then solely based on the given layouts. After adding more related rules and deleting the unrelated rules from the design rationale base, evaluation of the layout from five design objectives is possible and further recommendation for possibly improving the layout can also be raised according to the results.

The two case studies have demonstrated that by combining the qualitative properties from the design rationales and fuzzy logic theory, the quantitative analysis towards the internal architectural layout of the polar expedition cruise ship is an applicable path to move forward to help with the naval architect in gaining more insight during the early stage design of a polar expedition cruise ship. The overview findings are listed below:

- The importance of different design objectives will always vary to different designers, a specific and clear priorities of different design objectives are prerequisite to make the post-processing procedure meaningful to whole design process.
- The change of the locations of shipboard systems within initial concept design can vary the performance of the ship from multiple mission objectives.
- It may be hard to generate a design which is fully satisfied from all design objectives. The design which performs good in some of the design objectives while satisfying the basic requirements in the other design perspectives can be also regarded as decent.
- Post-processing procedure is necessary to ship designers for both manual optimization and computer-based optimization of layout, the insight gained from this procedure can either be a guidance for manual improvement or extra constrains in refining better solutions.
- Fuzzy logic theory can be an effective method to solve the ship design problems involve subjective and ambiguous issues, and fuzzy logic evaluation is also useful in handing the conflicting constrains during the early stage ship design.

8

DISCUSSIONS AND FUTURE WORK

The previous chapter has given the answer of each research questions in order to clarify the main research objective of this thesis. This chapter will firstly discuss the limitations of current method and the possible solutions accordingly. Next, the discussion of the better usage of this method will also be elaborated. In a word, this chapter will serve as recommendation to point out the possible direction for future research.

Improving from design rationale aspect

During the phase of capturing the design rationales for expedition cruise ship, the current assumption is that every configuration rule within the rationale base is equally important to the performance utility of the corresponding design objective. However, the priority of the rationale rule is being neglected in this thesis. *T. Denucci (2012)* has defined the four terms associated with text-based rules, the second term is provided as *priority descriptor* which describes the subjective importance of the configuration in the design. For different type of requirements mentioned in the rationale rules, they can be either *compulsory requirement* or *non-compulsory requirement*. For example, the two rules are raised in constraining the design objective of safety. In this case, the priority of description of fuel tanks and accommodation is higher than that of lifeboat system and accommodation, where the former can be regarded as compulsory while the latter is non-compulsory. As a result, the first rule should be weighted more than the second. Likewise, different priority should be considered for other design objectives, which can make the whole analysis process more reasonable.

The possible solution for better justifying the importance of the configuration can be started by considering the priority sequence of the descriptor. *T. Denucci (2012)* also identified the different types for descriptors. In accordance with the quantitative analysis, a priority index can be introduced to each type of priority descriptor, see Table 8.1. From mandatory proximity relationships to preferred and desired relationships, the priority term can be selected as: *must*, *should*, and *can* or other user-defined term. Hence the priority index can be created to quantitatively illustrate the different importance of the configuration relationships. The next stage can therefore be incorporating the priority index into the fuzzy system, by adjusting the weight of different inputs, a modified performance utility is possible to obtain.

Table 8. 1 classification of priority descriptor

Priority Descriptor	Priority Index
Must/Must not	9
Should/Should not	6
Can/Can not	3
User-defined	User-defined

Lacking in Design Objective

The current selection of the seven design objectives is a general way to analyze the architectural relationships within the layout of the polar expedition cruise ship. It does show the applicability of the splitting the design rationale into multiple design objectives, however, more detailed aspects are still being disregarded from the analysis process. The evacuation performance of the ship, for instance, is only partially considering within the safety aspect. A better way to handle this problem may be extracting or redeveloping the configuration rules related to evacuation performance and make them as extra constrains for the analysis process.

Lacking in Design Rationale

Another problem occurred when categorizing the design rationales to the design objectives, the description of proximity relationships concerning the design objectives might be too general to fully indicate the performance resulted from those design objectives. It is still necessary to add more elaborated description according to the design objectives. For example, there are only two rules developed for the design objectives of redundancy and seakeeping capability, it might be less convincing for the naval architect to draw the conclusion from the two-rule-based results. For the design objective of logistics, although there are currently five rules identified, it maybe also possible to cover more aspects into logistics. Hence, further research can also focus on exploring more detailed configuration rules and adding them into the corresponding design objectives. The possible direction for evacuation as is mentioned may refer to *R. Joustra (2018)* where he used a Markov Decision Process model to analyze the evacuation performance of the ship, the valuable configuration description might be possible to identify through the analysis results. The design objective from logistics aspect was further attacked by *J. le Poole (2018)*, a logistic model was developed whereby the logistic performance of the ship can be evaluated, the evaluation process might be interesting for the designer as well to investigate in order to add more constrains into the design objectives of logistics.

Modifying the Inputs for Fuzzy System

The well-defined inputs for the fuzzy system will improve the analysis results. The inputs defined in this thesis are mostly simplified into the form of average dimensionless distance especially for interactions of multiple systems between multiple systems. The assumptions are made that the size of multiple systems which belong to the same type, accommodation block for example, are approximately close to each other. However, it might not always be the case that they are close to each other in size especially for a real ship. Hence, it is worthwhile to consider the influence of size to highlight the inner difference among multiple systems belonging to the same type.

Better Usage of the Methodology

The scope of the thesis mainly focusses on the design of a polar expedition cruise ship, it shows the applicability of better analyzing the internal layouts of one type of the complex ships. Due to the complex nature of those ships, further research can be shifted to other types of complex ships. Starting by capturing the design rationale for specific type of complex ships, the method is able to help the naval architect generate better layouts for both manual or computer-based optimization aspects.

The analysis method in this thesis currently only demonstrates a selection process regarding the concept design created by packing approach, a manual modification for the selected design is subsequently conducted to further improve the layout quality of the ship. However, the manual procedure cannot essentially generate better layouts for the computer-based optimization to a large extent. In order to expand the usage of the method, a possible direction will be incorporating the current method into the packing approach. As is mentioned before, the importance of each design objective may vary to different designers, the designer can choose some of the design objectives which are more important to the total design requirements, and then the performance utilities coming from these design objectives can be added to the initial constrains, serving as extra constrains in refining the ship synthesis models within the packing approach. Besides, the total performance utility of the ship can be set as extra constrain as well if the designers are more interesting to the total architectural relations from the internal layouts.

Conclusions

This chapter generally gives the recommendation of this thesis in twofold. The future research can either focus on modifying the method itself due to the limitations of current assumptions for instance or expanding the usage scope of current methodology. In sum, the developed methodology makes it possible to incorporate fuzzy logic theory into the post-processing procedure and provide more insight in the architectural relations within the layout of one type of complex ships to the designers, further investigation into the recommendation will be of benefit to designers in finding more feasible concept designs during the early stage ship design process.

Appendix A
Sample questions

Appendix A contains a questionnaire created to determine weights of different design objectives. The questionnaire consists of the description of background and three sample questions, the results coming from the results will be used in the AHP application to obtain the weight matrix in this thesis.

The layout design for the polar expedition cruise ship is extremely important from the perspective of the ship designer. When analyzing the layout quality of this type of ship, the following design objectives are selected as the criteria to reach the layout analysis from different aspects.

- *Seakeeping Capability*
- *Logistics*
- *Safety*
- *Operability*
- *Economic Feasibility*
- *Redundancy*
- *Habitability*

Now the main goal of this questionnaire is to generate a weight factor for these design objectives. To be noticed, these criteria are based on the architectural or spatial relations among different systems within the general arrangement of the ship. For example, the performance in *Seakeeping Capability* is partially measured by the relative location between the accommodation blocks and the center of rotation of the ship. *Logistics* is the measured by the extent to which the information within the layout is able to transfer. *Safety* could mean the risky parts in the layout such as whether the fuel tank is adjacent to the accommodation block. *Operability* can be measured by how convenient and efficient for the crews onboard to fulfill their duties within the layout. *Economic Feasibility* will mainly focus on the spatial aspects such as if the length of the shaft line and fuel piping is appropriate instead of the total building cost of the ship. *Redundancy* is decided by the location of the similar systems including generator rooms and hospital rooms. The aspects concerning *Habitability* can be measured by, for instance, whether the accommodation blocks are grouped to maintain a good living atmosphere.

Based on the description above, please answer the following questions:

1. How do you rank the different design objectives (from **most important** 1 to **least important** 7)?

Seakeeping Capability	**Logistics**	**Safety**	**Operability**	**Economic Feasibility**	**Redundancy**	**Habitability**

2. Following the question 1, how do you feel about A over B (referring to the Grade scale below)?

Definition	Intensity
1	A and B equally important
3	A is weakly more important than B
5	A is strongly more important than B
7	A is very strongly more important than B
9	A is extremely or absolutely more important than B

B / **A**	**Logistics**	**Safety**	**Operability**	**Economic Feasibility**	**Redundancy**	**Habitability**
Seakeeping Capability						

3. Similarly, filling the upper right part of the comparison matrix (the bottom left part is the reciprocal of upper right part).

B / A	Seakeeping Capability	Logistics	Safety	Operability	Economic Feasibility	Redundancy	Habitability
Seakeeping Capability	**1**						
Logistics		**1**					
Safety			**1**				
Operability				**1**			
Economic Feasibility					**1**		
Redundancy						**1**	
Habitability							**1**

Appendix B

Steps in fuzzy logic toolbox

This appendix demonstrates the steps for the design objective of *Economic Feasibility* in MATLAB Fuzzy logic toolbox in accordance to the classic fuzzy system. The main steps are summarized as:

1. Defining the membership functions for all the inputs and outputs.
2. Establishing the fuzzy rule bank based on the specific design rationale.
3. Relating the result to the previously defined inputs.
4. Incorporating the results to the performance metric.

Figure B.1 to B.3 shows the membership function plots for three inputs respectively. Figure B.4 depicts the membership function plots for the output. Figure B.5 presents the fuzzy rule bank within the fuzzy system in the form of IF…AND…THEN statements to determine the fuzzy set of output. Figure B.6 and B.7 are the relating results of different inputs and corresponding output.

The configuration rules and corresponding mathematical measurements for Economic Feasibility are given as:

Table B. 1 Design rules and distance measurement

Design rules	Input	Distance Measurement
Fuel tank should be adjacent to Generator room	1	Average Manhattan Distance
Propulsion room should be aft of Mid	2	Euclidean Distance
Generator room should be adjacent to Generator room 2	3	Euclidean Distance

Based on the description in Table B.1, the membership functions for all the inputs are defined below:

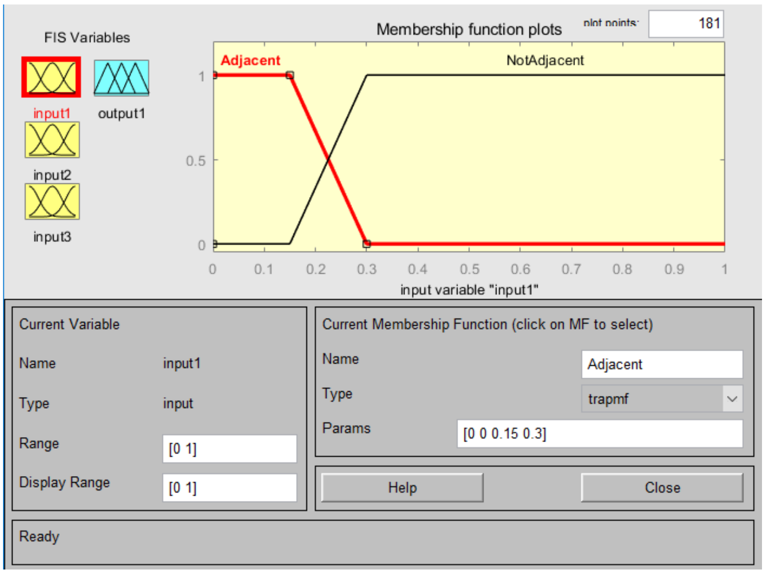

Figure B. 1 Membership function plots of Input 1

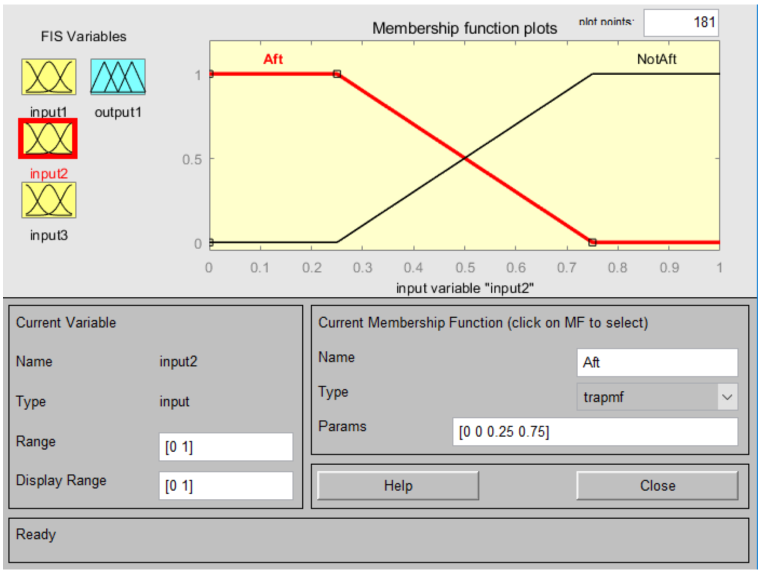

Figure B. 2 Membership function plots of Input 2

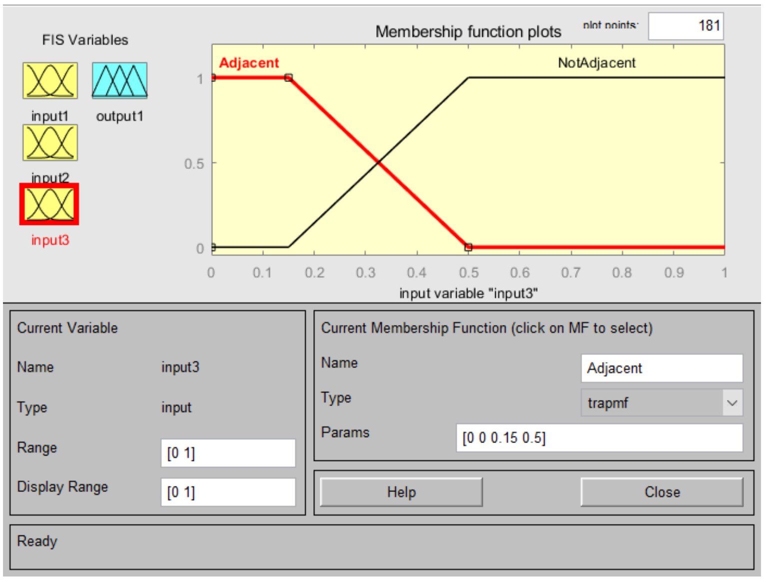

Figure B. 3 Membership function plots of Input 3

Similarly, the output can be classified into four sets: {Low}, {Medium Minus}, {Medium Plus} and {High} to represent different levels of performance utility for design objective of Economic Feasibility:

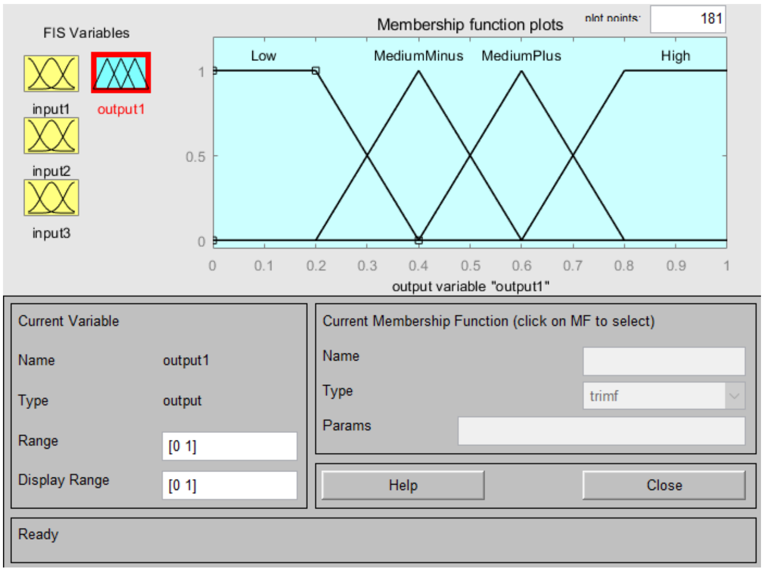

Figure B. 4 Membership function plots of output

The fuzzy rule banks can be obtained based on the qualitative description from the configuration rules:

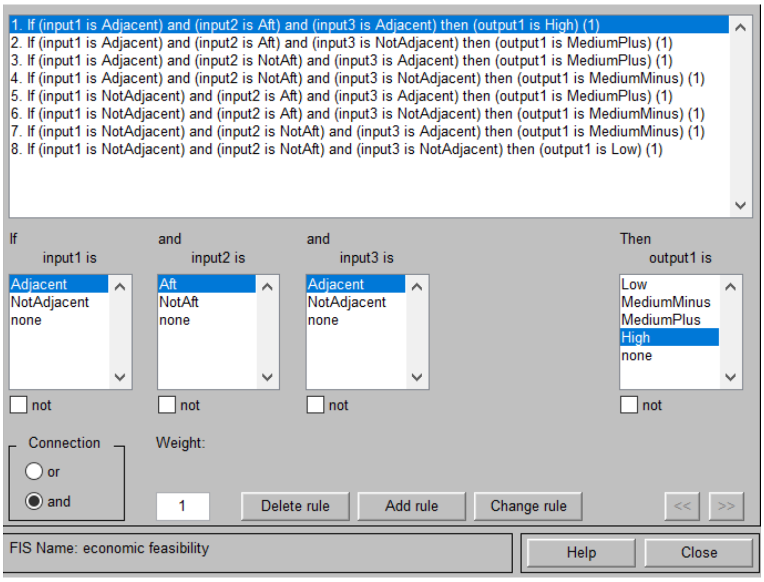

Figure B. 5 Illustration of fuzzy rule bank for design objective of Economic Feasibility

The relating results from the fuzzy tool box have two alternative representations. Figure B.6 shows the resulting surface of the output relating to the first two inputs. Figure B.7 illustrates how the performance utility of Economic Feasibility varies according to the change of three inputs.

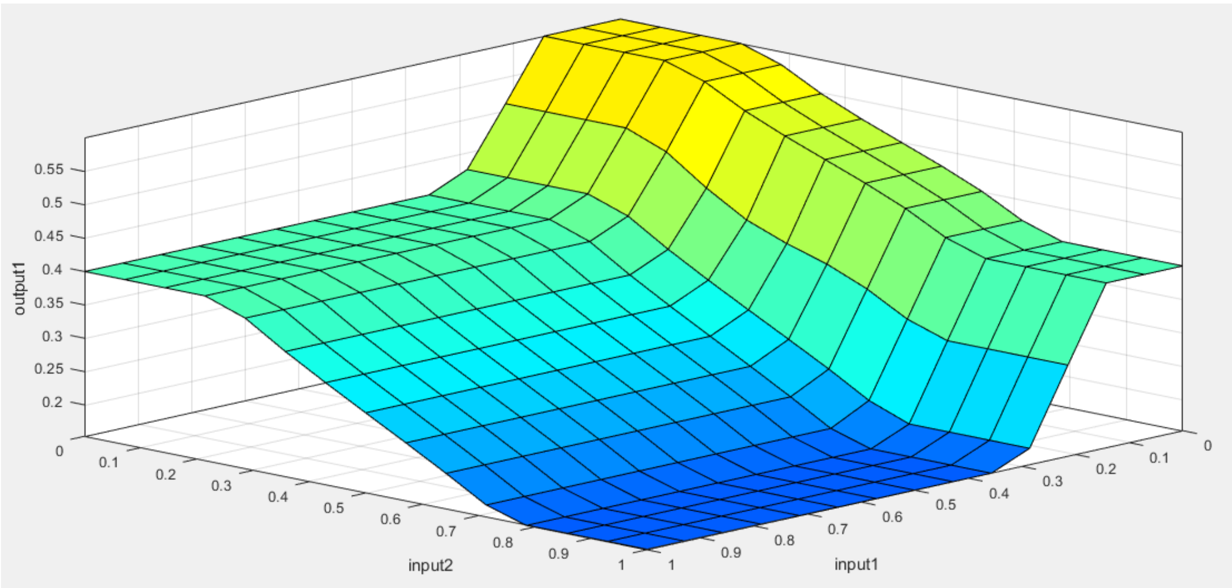

Figure B. 6 Resulting surface considering Input 1 and Input 2

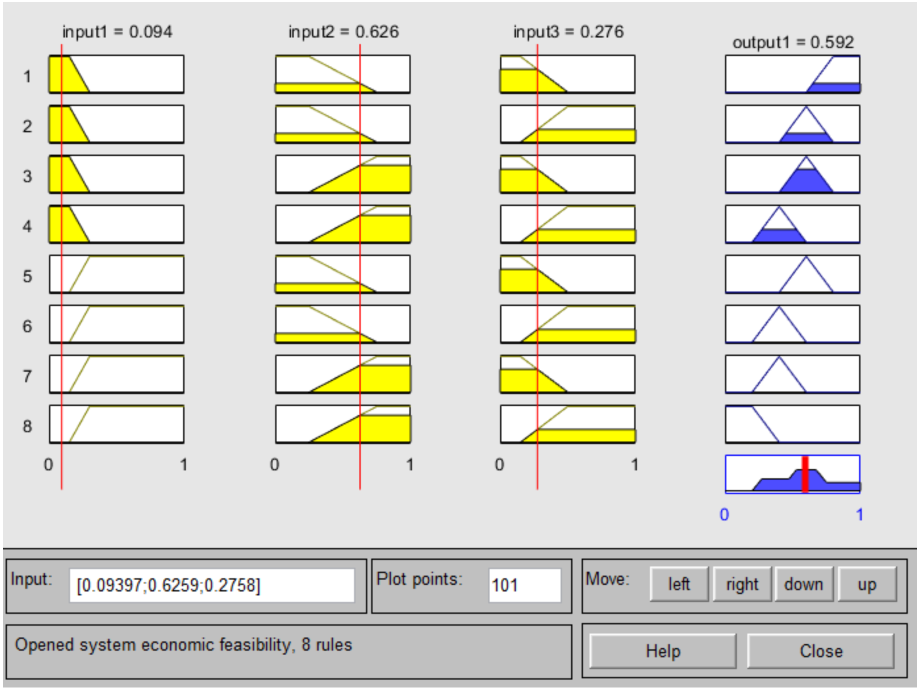

Figure B. 7 Results representation for different inputs

Appendix C

Overview of Packing concept designs

In this appendix is presented the sideview and main characteristics of five selected concept designs for polar expedition cruise ship generated from the Packing Approach.

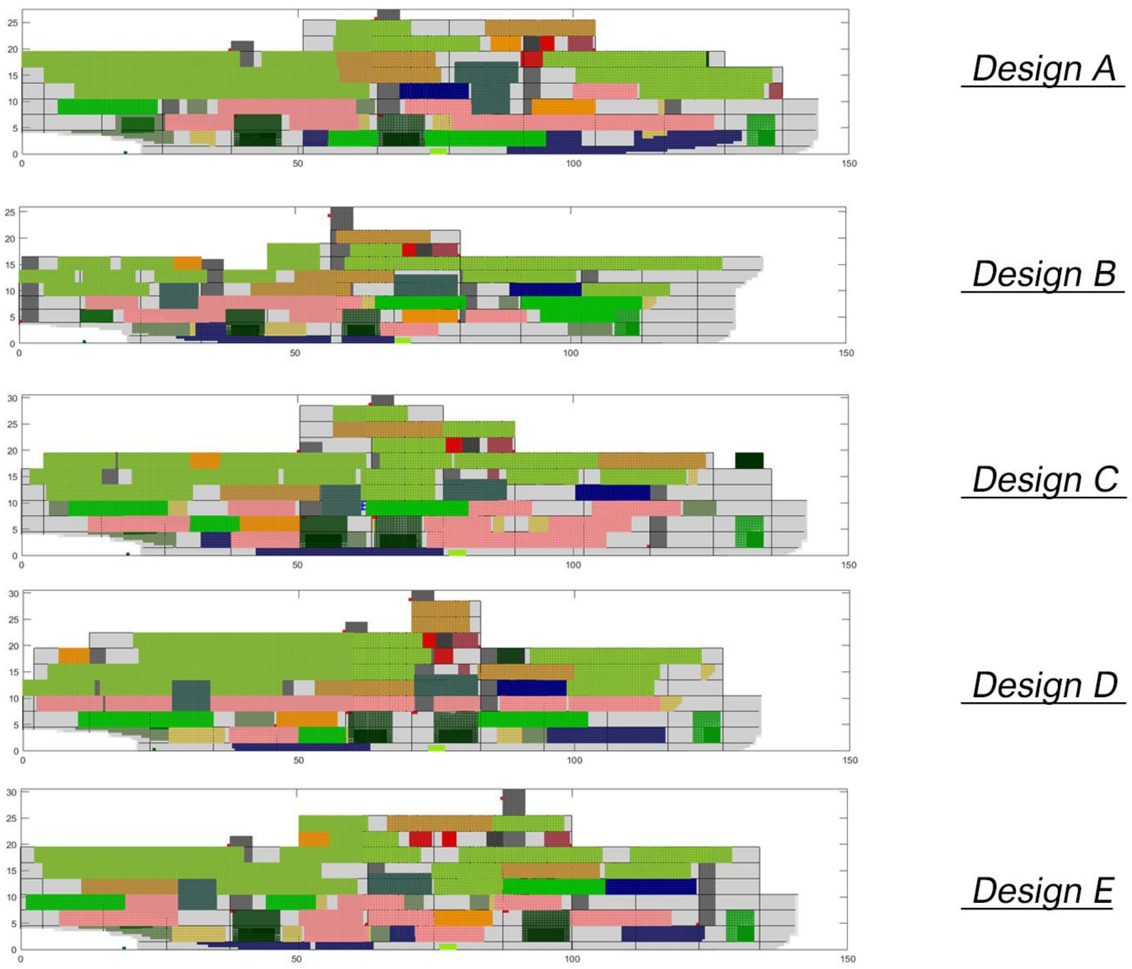

Figure C. 1 Sideview of five selected concept designs

Table C. 1 Main characteristics of five selected concept designs

Design ID	A	B	C	D	E
Length [m]	150	135	148	139	146
Height [m]	25.5	21.5	28	28	25.5
Draft [m]	5.72	5.04	5.75	5.73	5.8
Displacement [m^3]	8612	6907	8669	8007	8992

Appendix D
Design brief and General Arrangement of Damen Ship

This appendix shows the design brief and the general arrangement of the polar expedition cruise ship from Damen Shipyard.

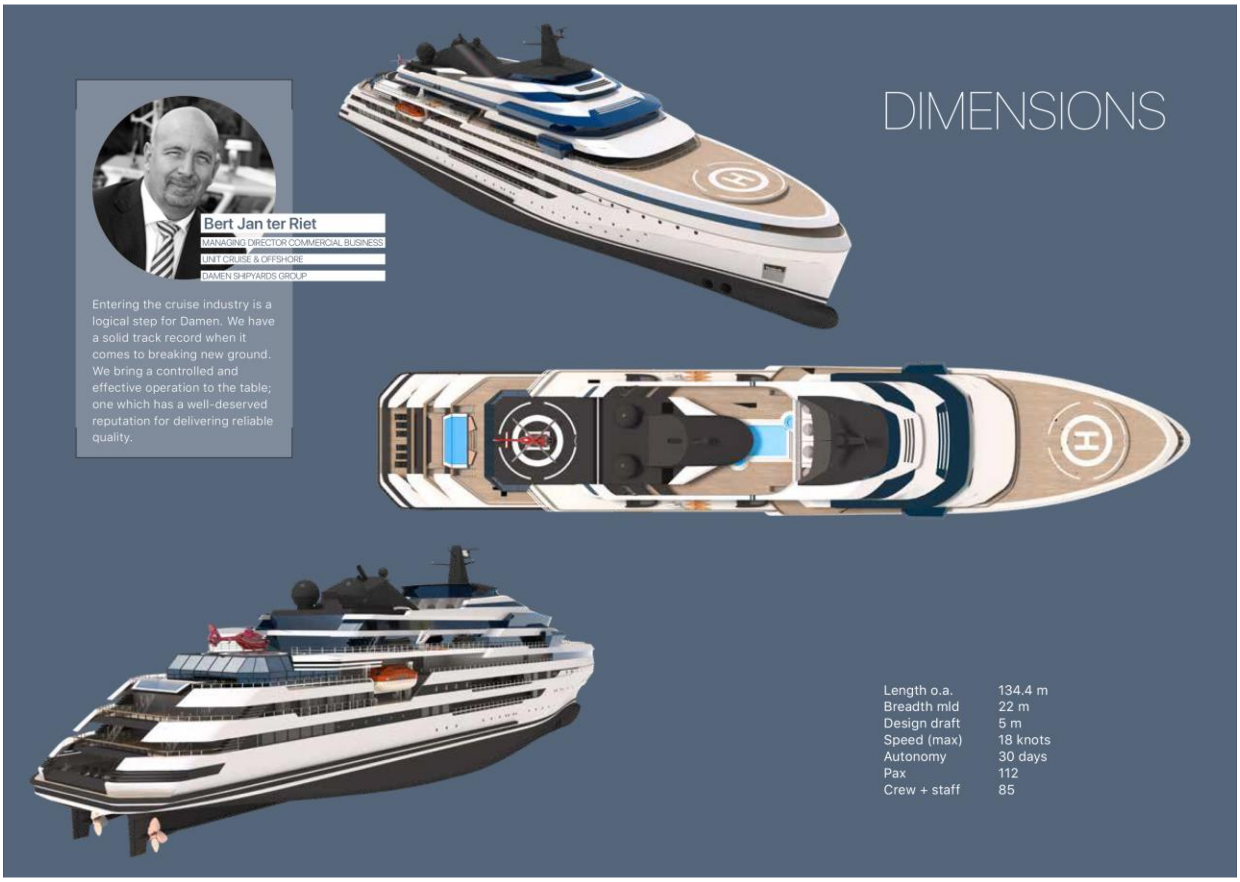

Figure D. 1 Main dimensions of the polar expedition cruise ship from Damen Shipyard

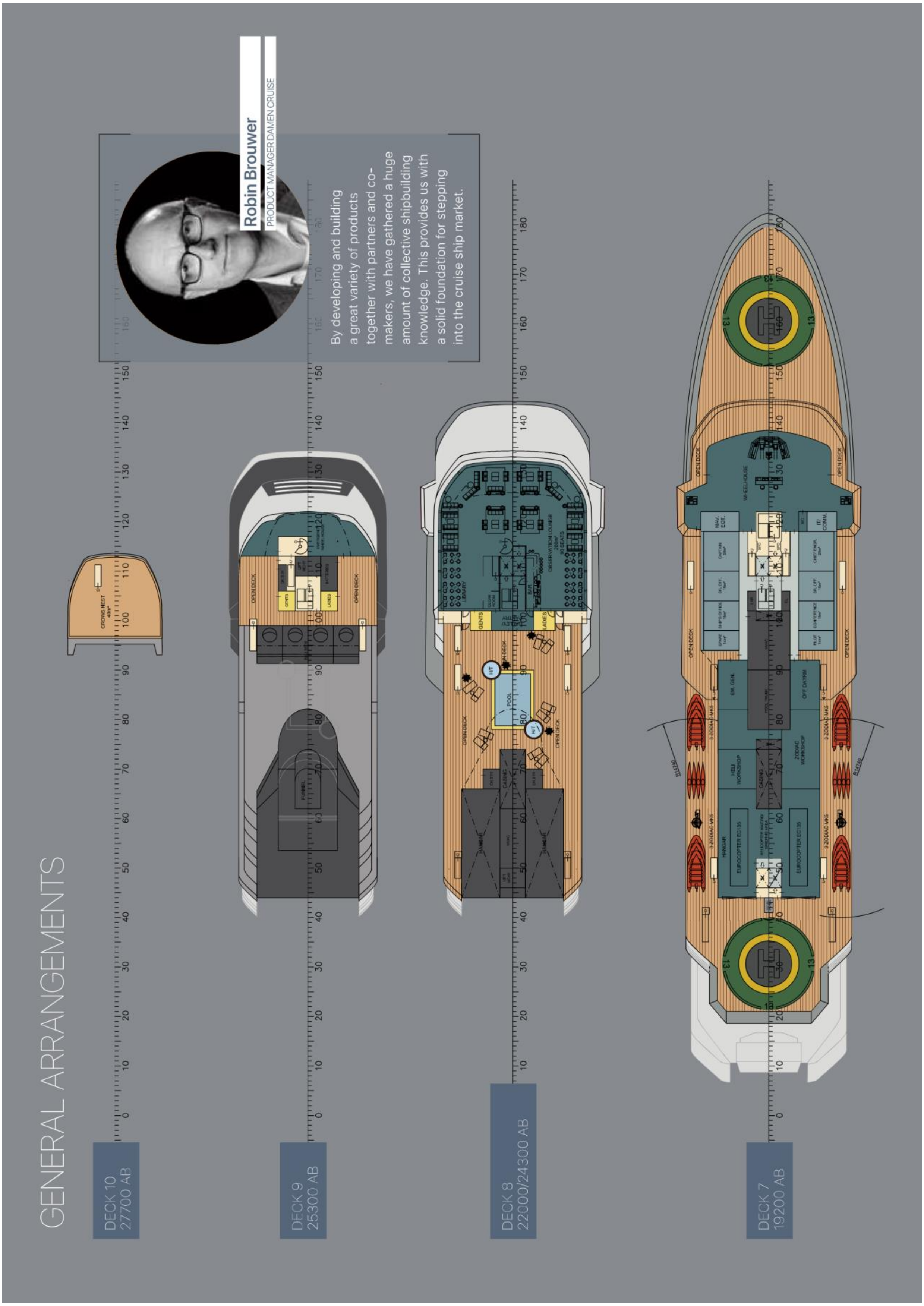

Figure D. 2 Main dimensions of the polar expedition cruise ship from Damen Shipyard

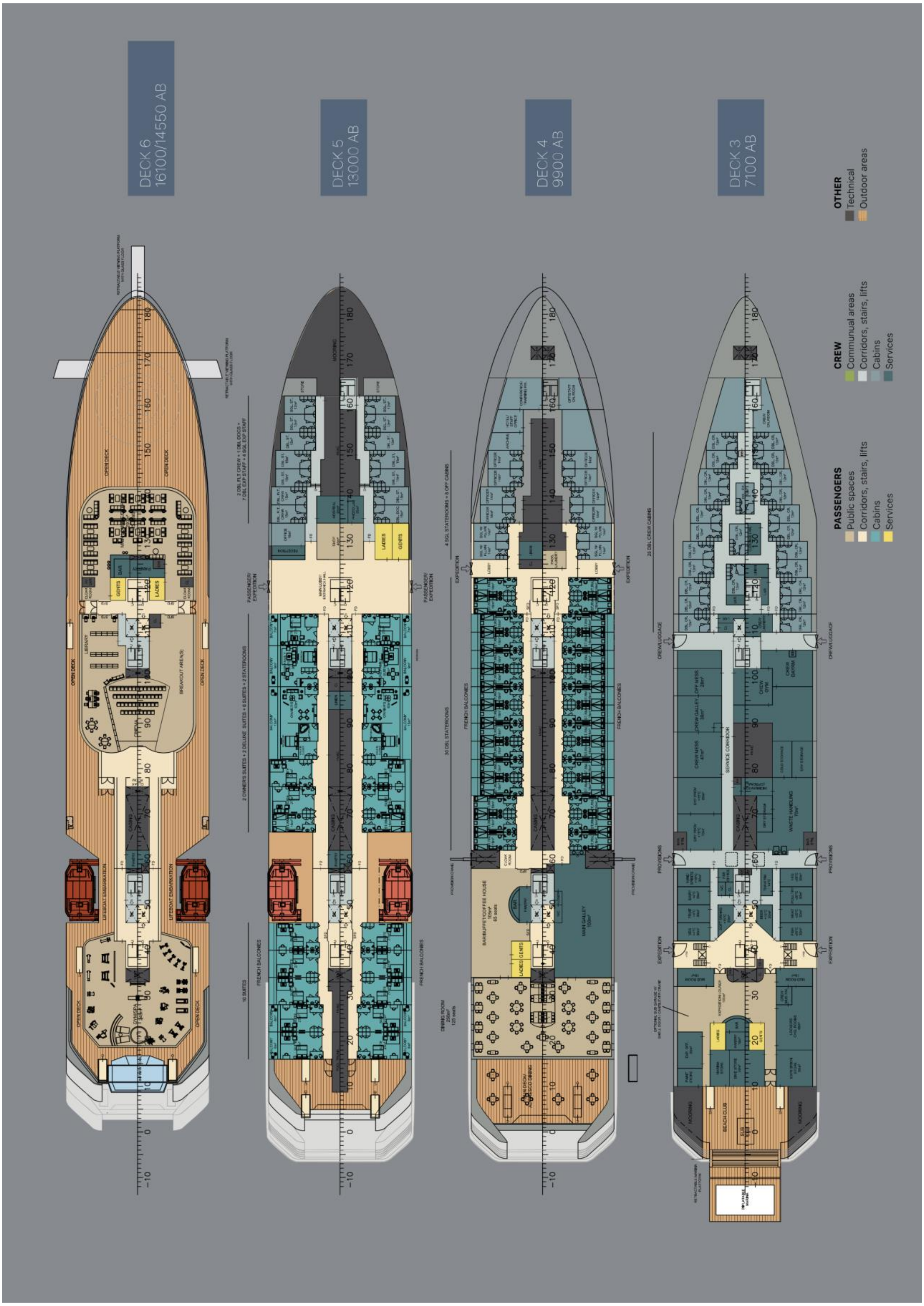

Figure D. 3 General Arrangement of the polar expedition cruise ship from Damen Shipyard

Appendix E

System classification and position estimation

This appendix listed the system names and the estimated positions of the Damen polar expedition cruise ship used in the second case study conducted in Chapter 6. Since the polar expedition cruise ship from Damen shipyard is a mature and commercial product, the general arrangement of the ship is therefore simplified into the form of early stage ship design in accordance with the method. The different systems and their corresponding positions extracted from the simplified layout given in Chapter 6 are hereby listed in the Table E.1. To be noticed, the staircases are simplified as the vertical shafts in the layout, the specific z positions of all staircases are not considered in the method.

Table E. 1 Shipboard systems classification and estimated positions

System names	x	z
Stairs 1	31.2	N/A
Stairs 2	77.6	N/A
Stairs 3	88.2	N/A
Stairs 4	118.1	N/A
Central Hall	88	13
Bridge system	96.5	19
Officers Accommodation 1	81	19
Officers Accommodation 2	69	19
Lifeboat system	43.2	13.5
Emergency Control room 1	86	25
Hospital System	100.3	13
Zodiac system	48.9	19
Mudroom system	20.1	7
Main Galley system	36	10
Restaurant system	15.9	10
General Store System 1	39.1	7
General Store System 2	54	7
Laundry system	83	7
Entertainment system 1	22	16
Entertainment system 2	72.7	16
Entertainment system 3	93.4	16
Entertainment system 4	84.9	22
Entertainment system 5	77.35	27
Technical/Auxiliary systems 1	7.4	7
Technical/Auxiliary systems 2	126	13
Accommodation block 1	51.4	10
Accommodation block 2	59.9	10
Accommodation block 3	68.3	10
Accommodation block 4	76.8	10
Accommodation block 5	85.2	10

Accommodation block 6	14.4	13
Accommodation block 7	23.1	13
Accommodation block 8	31.8	13
Accommodation block 9	54.4	13
Accommodation block 10	62.9	13
Accommodation block 11	71.3	13
Accommodation block 12	79.8	13
Crew accommodation system 1	92	7
Crew accommodation system 2	102	7
Crew accommodation system 3	113.5	7
Crew accommodation system 4	98.3	10
Crew accommodation system 5	112.2	10
Crew accommodation system 6	99	13
Crew accommodation system 7	112	13
Crew dayroom	68.6	7
Hangar	48.9	19
Helicopter deck 1	22.5	19
Helicopter deck 2	116	19

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