Master Thesis

A new concept exploration method to support innovative cruise ship design.

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Thesis for the degree of MSc in Marine Technology in the specialization of *Ship Design.*

A new concept exploration method to support innovative cruise ship design

By

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Conoship International

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Preface

The combination of theory and practice have fascinated me from the beginning. Having the opportunity to combine both the recently developed preliminary design tools with commercial concept development have provided both great insight and most interesting challenges. As preparation of my doctoral studies, the application of the current state of research on this test-case involving cruise ship design showed both opportunities and possibilities as well as limitations of this new method.

The past couple of months this master thesis has been written for the MSc Marine Technology programme at the Delft University of technology. What once started as an idea, has grown into comprehensive research. Everything what grows needs to be taken care of and the idea of this graduation project has been developed in close cooperation with Professor Hopman and Guus van der Bles.

Throughout this thesis I received help, support and input from many people whom I would like to thank. I would like to mention some of them here. First my supervisor professor Hopman both for his valuable input during this work as well as for the opportunity to continue this work in a doctoral study. Secondly I would like to thank ir. Guus van der Bles for the great time I had over there up in the cold North. At Conoship he provided a listening ear and many valuable experiences. During the last couple of months I enjoyed the daily supervision of dr. Austin Kana. His never ending patience helped me to properly formulate my graduation work into this thesis. I would also like to thank dr. ir. Sape Miedema for his time while taking place in my graduation committee.

I would also like to thank Mark Roth for his time while working on the general arrangement drawings presented at the end of the results chapter. I am looking forward to see you proceed the work on analysing the architectural layout of the different designs generated by the IECEM approach. I would also like to thank my co-workers both at Conoship and at the University for the various discussions we had.

Motivation is key during a graduation project and during the tougher parts of the project friends and family played an important role there. Especially I would like to mention my fiancée for her patience and understanding when I decided to leave for Groningen after having spent half a year in Finland previously and most of the summer in Asia.

Koen Droste
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Nomenclature

T_{des}	Design draft
AECO	Arctic Expedition Cruise Operators, an association to regulate and stimulate safe and sustainable cruising practises in the Arctic region.
CLIA	Established in 1975, Cruise Lines International Association (CLIA) is the world's largest cruise industry trade association, providing a unified voice and leading authority of the global cruise community. CLIA supports policies and practices that foster a safe, secure, healthy and sustainable cruise ship environment and is dedicated to promote the cruise travel experience.
CoB	Center of Buoyancy
CoG	Center of Gravity
DMO	Defence Material Organization, the organization responsible for the procurement of all Dutch defence material such as the Navy's vessels.
FSS	Fire Safety Systems code, an IMO regulation which addresses fire regulation on ships. Main influencers in cruise ship design are the maximum area of one fire zone $1600m^2$ and the maximum length of a fire zone, 48m.
GMt	Transverse stability
IAATO	International Association of Antarctica Tour Operators, A member organization founded in 1991 to advocate and promote the practice of safe and environmentally responsible private-sector travel to the Antarctic.
IACS	International Association of Class Societies
IECEM	Interactive Evolutionary Concept Exploration Methodology, a concept exploration methodology based on the Packing Approach which facilitates an interactive exploration process, by allowing the user to alter the criteria and select preferences in between the search attempts, and uses a Genetic Algorithm to guide the search process, (Duchateau, 2016; van Oers, 2011)
LCB	Longitudinal Centre of Buoyancy, the location of the center of buoyancy with respect to the length of the ship. Usually relative to the centreline of the rudder but in case of the Ship Synthesis Model it is relative to the 0 of the envelope.
LCG	Longitudinal Center of Gravity, the location of the center of gravity with respect to the length of the ship. Usually relative to the centreline of the rudder but in case of the Ship Synthesis Model it is relative to the 0 of the envelope.
MARPOL	The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.
NAM	Nederlandse Aardolie Maatschappij, a Dutch oil company
NCL	Norwegian Cruise Lines, third biggest cruise line in the world
OoO	Object of Objects, consist of multiple objects which together form a system or space such as a generator room exiting of an space object and one or more generator objects.

Packing Density	The volume occupied by the placed objects divided by the total available volume in the hull and superstructure (Duchateau, 2016)
pax	Passengers
RCCL	Royal Caribbean Cruise Lines, second biggest cruise line in the world
SAR	Search and Rescue operations
SOLAS	Safety Of Life At Sea, regulation concerning the ships structure, equipment and manning to ensure safe operations. Established in 1914, two years after the famous Titanic accident and nowadays managed by the IMO
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 was adopted on 7 July 1978 and entered into force on 28 April 1984. The main purpose of the Convention is to promote safety of life and property at sea and the protection of the marine environment by establishing in common agreement international standards of training, certification and watchkeeping for seafarers.
SWBS	Ship work breakdown structure
TEU	Twenty-foot Equivalent Unit, a standard size for a twenty foot container.
VCG	Vertical Centre of Gravity, the height of the center of gravity above the keel.

Summary

This study applies the Interactive Evolutionary Concept Exploration Methodology which is based on the Packing Approach developed at the University of Technology Delft. This method is applied to the design of a cruise vessel at Conoship International to solve the following research question:

How could the Interactive Evolutionary Concept Exploration Methodology contribute to the design of an unique cruise vessel for Conoship to position itself in the market of small cruise vessels?

The first phase of this research focused on a market study. Based on this market study the polar regions as a niche-market have been selected. A ship operating in this niche-market needs to reposition itself twice a year from the north to the south and vice versa. Therefore the resulting deployment schedule took into account that two periods of six weeks will be used for this repositioning and two weeks are reserved for maintenance and upgrades. This results in two nineteen weeks seasons in the Arctic and Antarctic region respectively. The ships active in this niche-market vary strong in luxury level as well as in operational scenario. Therefore it is chosen to study three different operational scenarios and three different luxury levels.

Operating a cruise ship in the polar regions is subjected to additional regulation such as the IMO Polar Code on top of the standard regulation. The second phase studies both the characteristics of the selected niche-market and the regulations to see how they help define the Ship Synthesis Model.

The third phase elaborates on the method applied. An important requirements is the ability to generate and analyse designs for both the different operational scenarios and luxury levels. To do this, the financial performance indicators are defined. Those calculate both the building costs and operational expenses. For the nine different combinations of operational scenario and luxury level the potential earnings are estimated. These three items together are used to select a suitable design. The last part of the third phase deals with the implementation of all the information gathered in the Ship Synthesis Model used to research those variations.

The fourth and final phase is about the actual concept exploration. The concept exploration exists of one exploratory run and four steering runs. These four steering runs are used to extend the solution set to include a specific type of solutions. In this case the steering runs have been used to include the shortest design, the cheapest design, and more Medium and Fast operational scenario designs. The results have been influenced by limitations of the model. Two specific situations have been studied, one involving the floodable length which was limiting the minimum length of the designs and one about the generator size which influenced the generation of faster operational scenario designs.

The resulting design has been selected based on a trade off between the building price and the operational costs. Within the final dataset many similar designs occur, therefore the final design is presented together with some statistics about the similar designs. The resulting design is further progressed into 2D arrangement drawings. With the resulting design it is presented how the Interactive Evolutionary Concept Exploration Method contributes to the design of an unique cruise vessel for Conoship.

Four recommendations for future work are done. The first one focussing on selecting and grouping similar designs in a dataset. The second one is about developing a more sophisticated selection process. The third recommendation continues on the arrangement drawing. Within this research the resulting design has been selected based on its financial performance and the layout of spaces was not considered in the selection process. To better use the information obtained from the arrangements future development is required. The last recommendation concerns the ranking of the designs and is related to the data provided to the genetic algorithm.

Chapter 1. Introduction

Universities are the biggest source of scientific research and as a product of this research new theories and guidelines for practice are generated. Adapting these theories as a company provides a strong base for innovation and is key to survival for the European ship building industry, (Hopman, 2007). Within this study the Interactive Evolutionary Concept Exploration Methodology (IECEM) is used which is based on the Packing Approach developed at the University of Technology Delft, (Duchateau, 2016; van Oers, 2011). This method is applied to the design of a cruise vessel at Conoship International.

The IECEM theory has been developed in close cooperation with the Dutch Defence Material Organization (DMO) and has been applied almost solely within the DMO. This application in the field of cruise ship design is a first and therefore provides valuable experience with the application of such a tool. Expected is that these experience will contribute to the further development of the tool in possible follow up studies.

This study in that sense aims to demonstrate the application of the newly developed theory IECEM and providing methodological experience to Conoship about the use in practise. Therefore this introductory chapter will elaborate on the cruise industry and Conoship firstly. After that the reasons of using the IECEM will be discussed. This chapter will end with presenting the research goal, the research questions and an overview of the layout of the thesis.

1.1 Conoship International

Conoship International, hereafter named Conoship, is a ship design and engineering office located in the Northern part of the Netherlands in the city of Groningen. With strong roots in the Northern Dutch shipbuilding history and founded in 1952, they claim to be a world market leader in short sea ships. Most of the projects done here try to raise the standards in the industry in terms of fuel efficiency or overall performance. Last year these efforts were rewarded as the ship of the year prize went to the Kroonborg, a ship where Conoship was involved with the hull shape and hydrodynamic design, minimizing the motions of the ship in waves. Traditionally Conoship has designed mostly coastal and short sea general cargo vessels but in more recent years the scope broadened and all sort of unique vessels have been the result of that. Such as the earlier named Kroonborg, a maintenance vessel for the NAM, a Dutch oil company, but also the pilot station vessel Polaris. The design of these complex service vessels is often configuration driven, as one of the main design requirements is the operability of the vessel or the comfort levels. Aspects as stability, manoeuvrability and seakeeping are most critical and all of these are influenced by the ships configuration. Being able to research multiple concept configurations in an early stage of the design process generates a better insight in the influence of different design features on the overall design. This is where the interest in the IECEM originates from.

Recently multiple orders were done in the small cruise vessel sector. Also at Conoship multiple customers have shown interest in the design of a small cruise vessel. The design of a small cruise vessel is a rather uncharted territory for Conoship. The hypothesis is that the application of IECEM can help to improve the knowledge of the influence of a design configuration on the performance of a vessel but it can also help to learn about the importance of certain requirements in case of a specific ship type.

1.2 Cruise ship design

The design of a cruise ship is a large and complex process. One of the reasons behind this is the huge number of stakeholders involved in the process for instance: owners/operator, a shipyard, multiple design and architecture offices, suppliers, engineering offices and many more depending

(a) The Pilot Station Vessel Conoship and Barkmeijer developed for the Dutch Pilot association.

(b) The Kroonborg, the result of a project of the NAM, Wagenborg, Royal Niester Sander and Conoship.

Figure 1.1: Conoship projects

the situation. This results in a group of engineers and specialists from other disciplines with different field specific knowledge who all contribute to the design of the cruise vessel. The interplay of all these people and disciplines make the design complex. The complexity has even lead to the development of specialised educational programs as presented by Ahola et al. (2009). Here a combination of different participants with field specific knowledge is used in the project teams in the courses.

Besides this multidisciplinary element, the cruise ships designs have to comply with an increasing number of regulations and have to meet up with higher customer expectations making the product more complex. The industry of highly specialized, custom ships is dominated by European builders as it requires high building quality and the building process itself is a complex process with a lot of subcontractors. One of the strengths of the European ship building industry is its high level of innovation and the innovative SME's (Molemaker et al., 2009).

The cruise industry has been growing since its existence and the annual passenger growth percentage has been about 6-7% for the last couple of years, see figure 1.2. With the expression "the cruise industry", within this thesis specifically meant is the industry of ocean going cruise vessels. Inland river cruising is seen as a different branch and left out of consideration within this research. Within the total market, the segments for luxury and speciality cruises is showing passenger growth percentages of 20% (Goldstein, 2015). The orderbook for new cruise vessels is growing with the orders placed for 2019 now introducing over 50 000 berths capacity to the market, in comparison with 33 500 berths in 2010, see (Cruise Industry News, 2016*a*).

The cruise industry can be divided in multiple segments based on the size of the ship and the customer attracted. Within the segments of the huge cruise vessels, Europe is already a market leader in the design and production of cruise vessels with the German/Finnish Meyer Werft, the Italian Fincantieri, and the French located STX France. Recently a new yard opened in the Northern part of Germany as a result of an heavy investment campaign of Genting Hong Kong which resulted in the acquisition of Lloyd Werft and Nordic Yards. The newly established Lloyd Werft Group adds additional capacity to supply in the growing demand for cruise ships and to support the companies own growth strategy for the cruise brands in their portfolio, see (Genting Hong Kong, 2016). All these shipyards are mainly active in the large cruise ship segments with an exemption made for Fincantieri, their subsidiary VARD secured an order of multiple smaller cruise vessels. For years this segment of large vessels has been the driving force of the growth in the cruise industry. The segment of smaller vessels is served with old ships which often were modified and have originally been built for other services such as research. At the moment a lot of this old tonnage is being replaced and additional capacity is ordered at shipyards. The demand for small cruise vessels is high and a lot of developments are going on with brands expanding their fleet and charterers planning their own newbuild projects. These small vessels form an interesting niche as these vessels tend to be rather complex. Often these vessels will have to be able to sail in the most harsh conditions with utmost comfort for its passengers.

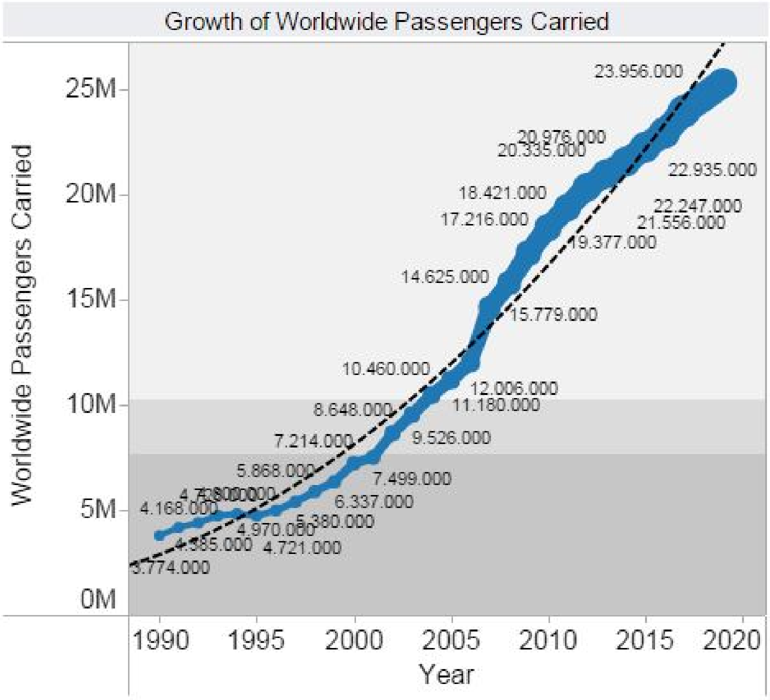


Figure 1.2: The passenger growth from 1990 till 2020 (Wahlstrom, 2015)

This in combination with the SECA/NECA regulations and the IMO's Polar Code make that these small vessels have a lot of requirements to comply with. The combination of regulations, the increasing customer expectations and the multidisciplinary design aspects make this sort of vessels technical challenging and with right they can be called 'complex specials'.

1.3 Interactive Evolutionary Concept Exploration Methodology

Concept exploration is a phase in preliminary ship design which includes studying a huge number of possible solutions in order to find the most feasible direction in which to develop a concept design. The downside of concept exploration is that it takes a lot of time and the directions to research are hard to identify. Besides this, there is no clear optimum and the amount of variations are tremendous. Therefore the initial search direction might not be the right one or a design requirement might change because it enables a more 'effective' design. A more effective design is considered a design which better fits the needs of the owner. Another aspect is the ship type, as more service focused ships such as naval ships, offshore vessels, floating production and storage units and also cruise ships have a large amount of systems and spaces onboard with different interactions between these systems. For these types of ships to make a proper estimations of design variables a configuration needs to be made to account for the interaction between these systems. The IECEM supports a ship designer in preliminary design as it generates large series of designs, presents them to the designer, and based on the designer's feedback can search for better designs. The generation of designs is based on the creation and analysis of configurations in the form of 3D ship models. Because the configuration of the different designs is taken into account it gives a realistic representation of a possible ship design and with all the designs together of the entire design space. Therefore it is hypothesized that the IECEM is as a valuable tool for cruise ship design.

The IECEM is the result of a chain of developments in the field of preliminary ship design. The IECEM used in this study is based on the Packing Approach (van Oers, 2011), a method to generate large series of ship configurations based on an initial set of systems and requirements.

The Packing Approach has already been applied in multiple concept studies, see (Wagner, 2009; Wagner et al., 2012), but the approach developed by (Duchateau, 2016) uses a feedback loop which allows modification of the initial design requirements based on the gained insight in the exploration process.

The main benefits of applying the IECEM in a preliminary ship design process are that it allows the designer or naval architect to gradually explore the possible designs as the methodology allows the naval architect to provide feedback to the search algorithm during the search process. It provides insight in the effect of system solutions on the ship's overall performance as one can generate designs with different solutions for the same system, as for instance different propulsion plant concepts as was done by Zandstra (2014). It also aids the designer in elucidating the right design requirements and objectives for a difficult and complex design.

1.4 Goal of the research

Based on the above mentioned introduction the research goal can be formulated as:

> *"To apply the interactive evolutionary concept exploration method as developed by (Duchateau, 2016) in a design process for complex, space critical service vessels and demonstrating this application for the concept design of the Conoship cruise vessel."*

1.5 Research Questions

The previous section stated a goal, to fulfil this goal a set of research questions have been formulated. These exist of a main research question and multiple sub-questions to help answer the main question and eventually reach the research goal.

Main Research Question

How could the Interactive Evolutionary Concept Exploration Methodology (IECEM) contribute to the design of an unique cruise vessel for Conoship to position itself in the market of small cruise vessels?

Sub-questions

1. **Which niche-market in the current market for small cruise ships is interesting for Conoship to design for?**
    - What kind of companies are involved?
    - What are the trends in passengers and their need?
    - How can different market segments be distinguished and which specific relevant (economical) indicators ($/pax*night) can be assigned to these segments?
    - Which promising niche-markets can be identified?
    - Which most promising niche-market can be selected for Conoship?
    - What characteristics distinguishes this niche-market with respect to the cruise ship design?
2. **What regulations, requirements and conditions limit the design space for the cruise vessel?**
    - How do the characteristics from the niche-market translate to design requirements?
    - Which rules and regulations are to be considered in this niche-market/general?
    - What additional input does the Packing Approach need?
3. **How to develop a design process for a cruise ship which integrates the IECEM to obtain the expected benefits of the IECEM?**

- What are the expected benefits of using the IECEM?
- Which modifications are required to be applicable for cruise ships and to obtain the benefits?
- How will the results of the IECEM result in a concept general arrangement?
- How will the new design process look like integrating the IECEM and possible modifications?

4. **What is the most promising cruise ship concept design for Conoship to enter the defined niche-market?**
    - How to use the design process to create a Conoship cruise vessel?
    - Is the resulting cruise ship concept design indeed the "most promising"?

1.6 Layout of this thesis

To answer these questions research is committed and the results of this research are presentedin the form of this thesis. To properly support the presentation of these results, the report is structured comparable to the research questions and sub-questions stated in Section 1.5. Hence Chapter 2 will deal with the market research to provide answers to the first sub-question and find a suitable niche-market.

Based on the selected niche-market and relevant regulation the naval architectural requirements will be presented in Chapter 3.

After that Chapter 4 will discuss the design process with the IECEM integrated. It will further elaborate on the required modifications and how the performance of a design is expressed. To check the accuracy of the applied methods a validation is done in Section 4.6. Here a model is made similar to an existing Conoship design and the results of the calculation are compared with the values obtained from the existing methods. Finally it will conclude with the definition of the Conoship cruise ship model. This model will be used to study the variations resulting from the market study to find the Conoship cruise ship design.

The model developed in Chapter 4 will be used to explore the design space. Therefore multiple search objectives are sequatially used to get a complete set of solutions. This process and the set of results are presented in Chapter 5. This chapter ends with the selection of the resulting design for which a 2D conceptual layout is drawn.

Chapter 6 will deal with the conclusions and thereby answer the main research question in the first section. Furthermore it will present the contributions done with this research and finally present a recommendations for further research to be done.

6

Chapter 2. The Market Research

2.1 Introduction

To start with, general information about the cruise industry is presented to introduce the current situation in the industry. The design driven innovation(DDI) (Acklin, 2010) method highlights the importance of interaction with stakeholders and their involvement in the design process. Their involvement should improve the market power of the resulting product. An overview of the stakeholders is provided in section 2.3. Passengers are a stakeholder in the product as they are the end user of the product. Traditionally in the field of User-Centred Design (Abras et al., 2004) the passenger as a user would be a major study field and therefore deserve a prominent position in the market study. The topic of the next section will be how the trends and developments in cruise and general tourism influence the cruise industry and its passengers and in how far these trends influence the ship's design. Although the research starts with a broad scope, the market study converges to a specific niche-market. This niche-market will form the starting point of the design process and is documented in Section 2.6.

The Marine Design Manifesto (McCartan et al., 2014) states that, to enable the European ship design industry to properly address the future challenges the industry faces, a new multidisciplinary approach to ship design is required. In this manifesto the process of DDI comes forward as a method to innovate a product and as such open up a new market segment. To facilitate this process a market research is conducted to investigate the possibilities in the cruise industry. The goal is twofold, on one hand it is to see the opportunities created by technological innovations, market trends and new regulations. On the other hand it improves the designer's knowledge base needed for cruise ship design. By both an extensive literature research as well as by expert discussions the knowledge base is strengthened and insights in the cruise industry are gained. These forms of respective quantitative and qualitative research guarantee that both broad and in-depth knowledge is gained, to have both an overview of the industry and more distinguished knowledge on specific topics. Additional literature research might be conducted during a design stage to find specific solutions or to gain additional knowledge necessary for the direction the design process is heading.

The second part of this market study will focus on the opportunities in the market. The DDI model proposed in Acklin (2010), calls this the impulse. These opportunities/impulses could be innovations in technology, new demands or trends from customers, new regulation or adoptions needed to serve certain areas, but also something the company has learned or the outcome of a recent R&D project.

2.2 General information

In 2015 the cruise industry served 22.4 million people. To do so nearly 300 ships were used, providing a capacity of more then 480 000 berths (Wahlstrom, 2015). The number of people attending a cruise has been rapidly increasing for the last 25 years, an average of 6.5% every year (see Figure 1.2). As the demand has been steadily growing over the years, so are the cruise ships. Both in number and in size with six new ocean going ships added to the fleet in 2015 and a total of 33 new ocean going vessels currently on order for the 2015-2020 period (Frank and Duffy, 2014). According to the list published by CruiseCritics, (Cruise Critics, 2015), 13 out of the 36[1] new ocean going cruise ships on their list are smaller than 1000 passengers indicating the growth in the smaller ship segment. Figure 2.1 gives an overview of newbuilds.

Focussing on Europe specifically, 6.39 million Europeans were taking a cruise in 2014 making Europe the second biggest source of passengers. With the Mediterranean as a major destination,

[1]They have a different publishing date explaining the difference in total number as new orders came in after publishing of the 2014 annual report of CLIA.

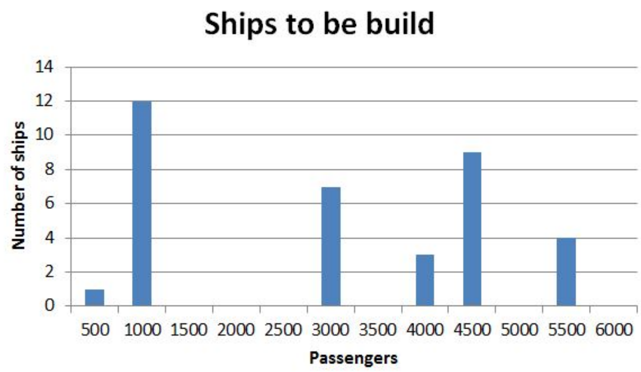


Figure 2.1: Histogram with the expected newbuildings 2016-2022 based on data from (Cruise Critics, 2015).

Europe is also the second biggest destination after the Caribbean. Besides being an important source and destination, European shipyards are responsible for the build of nearly all cruise ships. In total the cruise industry is responsible for €40 billion economic impact and 350 000 jobs. This indicates the importance of the cruise industry for Europe (Vago, 2015).

Ships have different properties one can use to categorize them. In the cruise ship industry often the amount of passengers the ship is able to carry is used to indicate the size of the ship. One common definition, which is adopted in this thesis, is the one proposed in Cruising & Cruise ships from Ward (2015). That one defines four different ship sizes, namely:

- Boutique ship: 50 to 250 passengers
- Small ship: 251 to 750 passengers
- Mid-size ship: 751 to 2000 passengers
- Large resort ships: 2001 to 6500 passengers

Besides passenger counts, another logical measurement could be gross tonnage (GT). The downside of this is a not constant relationship between GT and passengers. Luxury vessels for instance have a higher GT/passenger ratio then Mass-market vessels. This rate is often called the space ratio and is regarded as an important parameter to define a ships luxury level. Ward (2015) uses the following rating to translate the space ratio in subjective terms:

- 50 and above: outstanding
- 30 to 50: very spacious
- 20 to 30: not very spacious
- 20 and under: very cramped

2.2.1 Cruise market segments

The total cruise market receives an average of 6.5% more passengers every year, but some segments reported higher rates such as 21% more passengers for American Luxury and Expedition brands, see (Sheivachman, 2015). To get a better overview of this market one can divide it in different segments. A common segmentation is provided by Biederman (2008) and a similar segmentation can be found in the Cruise Ship Companies List, (Chanev, 2015). According to these sources the cruise market can be divided in five segments with accompanying characteristics:

- Contemporary market: The focus within a Contemporary market is not on the destination but more on what the ship has to offer. The most important design driver here is called the 'Wow-effect'. The typical examples here are the floating resorts of today such as the "Oasis" class of Royal Caribbean Cruise Lines.

  - Fares: \$50 to \$300 per day/person
  - Itineraries: 3 to 10 days, typical 7 days. Mainly Caribbean or Mediterranean.
  - Passengers: Mixed first timers and return passengers, from young to 50's, singles or couples.
  - Ships: Large, resort-like experience, lots of on board activities.
  - Examples: Carnival Cruises, Royal Caribbean Cruise Lines, Costa Crociere and MSC.

- Budget market: Very similar to the Contemporary market but often with older, smaller ships offering less on board activities.
  - Fares: \$30 to \$150 per day/person
  - Itineraries: 3 to 7 days, mostly in Europe or Caribbean.
  - Passengers: Mixed first timers and return passengers, dominated by young passengers. Mostly regional source market (Due to the cost of the flight ticket vs the costs of the cruise itself).
  - Ships: Large or Mid-sized ships, resort-like experience ships, older.
  - Examples: Carnival Cruises, Royal Caribbean Cruise Lines, Costa Crociere and MSC.
- Premium market: Destination and ship are more or less equally important, the prices are higher compared to the Contemporary market making it a little more exclusive. Usually the Premium market offers more sophisticated service and more exclusive itineraries.
  - Fares: \$150 to \$500 per day/person
  - Itineraries: 3 to 17 days
  - Passengers: Mostly first timers, kids and families. But also experienced passengers
  - Ships: Mid-sized ships, large ships
  - Examples: Disney lines and Celebrity cruise lines.
- Luxury market: This was the first market within cruising, nowadays only a relatively small portion of the market. Cruising durations are longer than average and since it is the most exclusive form of cruising it is also the most expensive one.
  - Fares: \$400 to \$1000 per day/person
  - Itineraries: huge variety
  - Passengers: Experienced passengers, average 62-63 years old
  - Ships: Mostly Boutique and small sized ships
  - Examples: Crystal Cruises, Hapag-Lloyd Cruises and Seabourn.
- Speciality market: This market contains many unique cruises such as sail cruises (Star Clippers) and social cruises (Fathom[2]). Most operators in this market have boutique or small sized ships. The biggest sub-market is formed by the adventure/exploration market. Due to the high potential for this segment, this will be further discussed:
  - Adventure/exploration market: has similarities with the Luxury market, the duration of the cruises is often longer than the contemporary or premium market. The destination is the main purpose of the journey. The ship is a good way of experiencing the destination but a combination of travel means might also occur. This market can be combined with the luxury market but exploration cruises can also be on very basic ships. The main difference with the luxury market is the more active and exploring character of the journey.
    * Fares: Strongly depending on the itinerary, \$150 to \$500 per day/person
    * Itineraries: 7 to 14 days

[2] Also see (Fathom, 2016) about this new Carnival Concept.

  * Passengers: Vary by itinerary
  * Ships: Boutique to small sized vessels
  * Examples: Lindblad-National Geographic Expeditions, Hurtigruten, Galapagos cruises and Voyages to Antiquity

Table 2.1: A summary of the main characteristics of the cruise market Segmentations

Segment	Fares $/day/person	Ships	Passengers	Income
Contemporary	$50-300	Large	30-65, families	$40 000+
Budget	$30-150	Mid-sized/Large	30-65, families	$40 000+
Premium	$150-500	Mid-sized	40+	$70 000+
Luxury	$400-1000	Small	50+ avg 62	$120 000+
Expedition	$150-500	Boutique/Small	avg 62	$120 000+

2.2.2 Relevant economical indicators

To asses the performance of a vessel or a sector it is common to assign one or more economical indicators. Such an indicator generally presents a statistical value which is used to measure the performance of the indicated sector or vessel. A more common name is a Measurement of Performance (MoP) or a Key Performance Indicator (KPI) although an indicator does not always have to be a KPI or a MoP.

Since the cruise sector is a combination of the tourism sector and the shipping sector, standard shipping indicators as $\frac{fuel[kg]}{Cargo[ton]*Distancetransported[miles]}$ will not be sufficient (people are rather light and most of the fuel is actually used by the hotel load and not the propulsion). The standard indicators are focused on transportation and not leisure. Although comparable is the $\frac{\$}{pax*night}$ where in for instance the container shipping industry one would determine the cost per TEU, in cruise shipping the costs per passenger per night can indicate the money making potential of a vessel. A note needs to be made here as in the Contemporary and Budget market segments, roughly half the revenue is made with onboard sales. An indication of these costs per night can be found in financial year reports.

An important characteristic of a cruise vessel is the luxury level. This determines the segment it falls in and the customers it attracts. To indicate the level of luxury a very general measurement is the space ratio often expressed in GT per passenger. As discussed earlier another metric could be the passenger crew ratio, where more crew per passenger is often seen on more luxurious ships. The downside of this ratio is that a reduction in the nautical crew, translates to a reduction in the service level while actually the ships efficiency increased. One final metric is the cabin size to measure the luxury level, as bigger cabins provide more private space onboard for a passenger. The cabin size both indicates the luxury level of one ship compared to another (in this case one should compare the average cabin size), but also the different levels possible within the ship. Most ships have multiple different classes of cabins with prices varying depending on size, features (bathtub for instance) and the deck the cabin is located on.

Besides luxury indicators, economical indicators are an important MoP. Where the luxury indicators might be very important for the positioning of the vessel in the cruise ship market. The economical indicators determine the viability of the design. One already named is the $\frac{\$}{pax*night}$ ratio. Where the dollars can be costs, earnings or expected profit. One needs to determine the scope of costs, as for a design perspective it might be building costs but it could also be lifetime costs. Lifetime costs enable the designer to rectify increased building costs due to investments that reduce the lifetime costs. Though this enlarges the design freedom it also requires a more extensive analysis of the financial aspects of cruise ship operations. Within lifetime costs different sorts of costs can be determined such as capital costs, operating costs and voyage costs. The capital costs are strongly correlated with the building price of a ship, the higher the building price, the more capital the project requires and the more costs it will have. Typical examples of this are the interest paid for a morgue or dividend paid to shareholders. Operating costs are costs that one has for operating a vessel. The most important ones are insurance, maintenance, crew and overhead. Even without making a journey these costs occur. The last cost group involves the voyage costs. These costs are for instance the fuel burned by the engines and the consumables used by the passengers. In earnings there is a differentiation as well, as some cruises offer all-inclusive while others charge you for the fare, excursions and onboard gratuities separately.

To get some feeling for the earning potential of the different type of vessels a comparison is made of three specific vessels and a selected number of cruises. For the National Geographic Orion the prices of the six different room types are compared for five different cruises by determining the earnings/square meter/day/person, (Table 2.2). The different cabin types differ in size with three different sizes ($16m^2$, $21m^2$ and $32m^2$) and in location, both on different decks and within the same deck. A similar comparison is made for the Scenic Eclipse, where the NG Orion is a expedition vessel build in 2003 and refitted in 2014, the Eclipse is a purpose build luxury cruise vessel which will enter service in August 2018. Table 2.3 shows the same comparison for a 21 days round trip from Ushuaia, Argentina to the Antarctic region.

Table 2.2: Example of cruise prices for the National Geographic Orion on a 14 day round trip through the Antarctic area.

Cabin Types	Price(€) [1$ = .88€]	m^2 cabin	Deck	Number of suites	€/m^2/day /$person$
Category 1	11 757	16.3	2	8	51.52
Category 2	12 637	16.7	2	14	54.05
Category 3	13 015	20.3	3	19	45.80
Category 4	14 010	21.4	4	2	46.76
Category 5	16 852	21.4	4	6	56.25
Category 6	19 254	32.1	4	4	42.84

Table 2.3: Example of cruise prices for the Scenic Eclipse on a 21 days round trip to the Antarctic region

Cabin Types	$Price$(€) [1$AUS$$ = .67€]	m^2 cabin	Deck	Number of suites	€/m^2/day /person
Verandah suite (DA)	22 107	32	5	66	32.90
Verandah suite (D)	21 437	32	5		31.90
Verandah suite (C)	22 308	32	6		33.20
Deluxe Verandah Suite (DD)	22 308	38	5	29	27.95
Verandah Suite (B)	23 179	32	7		34.49
Verandah Suite (CD)	23 179	32	6		34.49
Verandah Suite (BD)	26 395	32	7		39.28
Verandah Suite (A)	24 117	32	8		35.89
Deluxe Verandah Suite (AD)	24 988	38	8		31.31
Spa Suite (S)	30 817	48	8	14	30.57
Spa Suite (S1)	32 157	48	9		31.90
Panorama Suite (P)	35 909	56	6	2	30.53

When comparing the results from the both tables it should be noted that the original price of both vessels, $36 million and $175 million respectively and the number of cabins 53 and 115 respectively help to give a different cost side of the vessel. Furthermore it could be noticed that the biggest room on the NG Orion is equal in size to the smallest room on the Eclipse. The third vessel is the Celebrity Eclipse, a vessel way bigger in size and operating in the Premium market segment since entered into service in 2010. The vessels operates among others in the Mediterranean to show her 2850 passengers the beautiful cities along its coast. The information from Table 2.4 shows that the earnings per m^2 are way lower, but taking into account the lower crew to passenger ratio and the separately billed onboard earnings it is clear that the business models for the different segments differs as well. Concluded can be that in order to use the operational costs of the vessel as a MoP for the design an additional analysis of the specific market segment might be required.

Table 2.4: Example of the earnings for the Celebrity Eclipse on a 15 days round trip from Southampton to the Western Caribbean area.

Cabin Types	Price(€)[1$ =.88€]	m^2 hut	$€/m^2/day/person$
Inside stateroom	2 243	16.2	9.23
Ocean view stateroom	2 771	16.3	11.33
Veranda stateroom	3 123	17.8	11.70
Suite	5 675	27.9	13.56

Other interesting economical indicators are Net Present Value (NPV), Return on Invested Capital (RoIC) or Return on Equity (RoE) as they give insight to the profitability of the investment in the ship. Determining these values requires rather specific knowledge about the capital costs and earning rates and are therefore a study on their own. Acknowledging their existence they are not used in this research.

2.3 Stakeholders in cruise shipping and the design process

A stakeholder is a party which has an interest or an influence on a specific company or project or on which that specific company or project has an influence on. The stakeholders that influence the design process are most important for a better understanding of this process. First a brief overview of the involved parties in the cruise process are given. After this the focus will be put on the four most important parties during the concept design study.

In the cruise industry multiple parties are involved in the process. These stakeholders can have different influences on the process and therefore may have different views towards the ship used in the cruising process. For example, a Cruise Line Operator's main interest is the earning potential of the vessel and the risk of the project as these influence the profitability of his investment. While class authorities' main concern is about the safety of the vessel and its environmental impact. The following lists with examples of different stakeholders is composed based on the stakeholder declarations in the year rapports of Royal Caribbean Cruise Lines and Carnival Cooperation, (Heldewier and Hilton Spiegel, 2013; Fain, 2013).

- Cruise Line Operators
- Tour operators
- Destination managers
- Technical management
- Crewing company
- Shore personnel
- Port Authorities/Pilots/Tugs
- Suppliers
- Entertainment/Excursion partners
- Travel Agents
- Sales/Marketing companies
- NGO
- Media
- Public
- Passengers
- Ship designers
- Shipyard (newbuild,repair,maintenance)
- Technical consultants
- Trade Associations
- Regulation authorities
- Charterers
- Financing companies/Banks
- Shareholders
- Insurance companies
- Researchers

The list of stakeholders is rather long and mapping all their influences on each other and the cruise ship design would be a tremendous effort of which the yield is unclear. Therefore it is chosen to only mention the few considered most important within this project. Passengers would be a logical one to start with. As they are a major user as well, Section 2.4 will further elaborate on their role. The cruise line operators are the first stakeholders on the list. They often are the owner of the vessel and it is their job to operate the vessel and sell cruises. They are the closest to the passenger market and have the best position to describe the passengers' wishes and needs. Because of this, they also posses a lot of experience and information about cruise ship operations and therefore are a valuable source of information for the designers.

Trade associations are mentioned here as important stakeholder as they have a strong influence on new policies. Besides this they are a good source of information. They form policies to support the industry's values and conduct economical studies to quantify the impact of the cruise industry to a local economy or to better map a piece of the passenger market.

The third mentioned stakeholder are the different financing parties. They are key to the development of the economical performance analysis added to this design study.

2.4 Passengers

Passengers play an important role in cruise ship design as they strongly influence the layout and features of the ship. Passengers form the main group of users of the cruise ship and therefore the way they use it strongly influences the design. Besides passengers another important group of users are the crew. They are often in a smaller number and not paying for the product but being a part of it. The design philosophy of User-centred Design states that the way the users use the product should be studied in order to facilitate their needs in the design of the product. This user research is mainly done by a desktop research, where possible it by interviews with cruise line operators.

To describe the passengers certain characteristics are used such as age. The age of passengers for instance influences the facilities necessary onboard and the activities the ship has to accommodate. For example a passenger population with an average age of over 60 will most likely not go on jet-ski rides, but might prefer an elevator onboard or need extra medical facilities. The third subsection will describe the way the passengers use cruise vessels. Starting with how they used to do it an ending with how that has been changing lately.

The typical passenger can be described by means of characteristics. This description is important input for the design process and are usually the result of a market research done by the cruise line operator. General characteristics used to describe a passengers group are: age, interests, spendable income, country of origin, preferred destinations, occupation, and size and composition of the travel company. Additional characteristics such as, loyalty and market segment of interest are added. An extensive profile of the North-American traveller is researched by the CLIA (CLIA & Partners, 2015). This is an example of a source market passenger profile, meaning that in the North-American passenger market one can find these kind of passengers and characteristics. A brand usually has a passenger profile which fits with their brand and is more related to the destination market. Table 2.5 shows a simplified example of such a profile, comparing that to the North-American profile one could see that the brand profile is more specific. Instead of showing the percentage of people travelling in a persons party, they indicate that they aim for the 50% that travels in a 2 person party. This way the brand aims for a specific group of the North-American cruise tourists.

In the case of this study a destination market profile could be used as input for the design. The design is not made for a specific cruise brand, therefore there is no specific brand profile that can be used. To come to a more specific passenger profile a choice will have to be made whether to specify the ship for more older or younger passengers, couples or families and active exploring or scenic cruising. This destination market profile has to be studied in order to choose a good set of markets and after the market is chosen, should be further specified for the specific passengers the ship is aimed for.

The characteristics of the passenger profile influence the ship design requirements in multiple

Table 2.5: Example of a cruise profile for the Holland America Line (Based on personal communications)

Market profile HAL	
Age	60+
Income	$ 70 000
Market Segment	Premium
Country of Origin	The Netherlands, The United States and Canada
Party Size	2
Occupation	Retired

ways. The different kinds of passengers profiles and where they come from are highlighted above. The following summation will briefly highlight the influence these different characteristics have on the design requirements. These resulting design requirements are sometimes referred to as the 'soft' requirements as they make the vessel more suitable for this group, but the availability and the amount of it is not fixed and often this is where trade offs need to be done.

- *Age*, the average age of the passengers partly defines the activities onboard and ashore. Therefore it defines equipment the ship has to fit onboard in order to comply to their demands. This may influence the size of medical facilities, spa , gymnasium areas, or even part of the equipment as bikes, diving gear or walking sticks.
- *Spendable Income*, determines the affordability of a cruise and the maximum onboard revenue which can be made. When looking at the spendable income in the North-American passenger profile, it also indicates the demand for different cruise segments as people with a higher spendable income most likely will not go for mass-market cruising. In this sense the spendable income is a good measurement for the required luxury level.
- *Country of Origin*, determines the cultural background of passengers, as this is determines how a ship should look like and what they like to do and see during their holiday. This can be seen at the ships currently being refitted and redesigned for operations in China and the rest of Asia. *Cruise Business Review* (2015) gives more detailed information about the newest vessel of Norwegian Cruise Lines (NCL) which is extensively redesigned to serve the Chinese market. But also travel distances, if combined with the spendable income will tell you how far people are willing to travel for a certain cruise or if they prefer cruising in their own region (which is commonly seen in Australia for instance).
- *Size and composition of the travel company*, this strongly influences the size of the cabins and the different types of cabins onboard. Numbers obtained from the 2014 North American Cruise Profile analysis of the CLIA indicate for instance that by far the most American passengers are married, 84%, that most of them travel in a group of two, 50%, and 20% in a group of five or more, see Figure 2.2. An example of an increasing type of cruises anticipating to this are the single cruises. Where cruise lines make special offers for single-occupancy rooms while normally one has to pay the full fare when travelling alone.
- *Occupation*, the occupation of a passenger among others influences the duration of their trip. As retired or unemployed people can leave home for longer periods than most employed people can. It also influences the kind of cruise they might desire as employed people with a stressful job might rather take a more relaxing cruise with high service treatment to a warm destination in order to recharge their batteries. Where others might sooner go for longer trips to more exclusive destinations. Occupation also determines budget as it is closely related to the spendable income.

2.5 Trends and developments in the Cruise Industry

The cruise industry is subjected to trends and developments in the area of regulation, technology or science comparable to the rest of the tourism and maritime sector. These trends and devel-

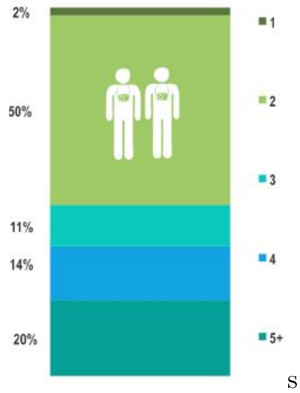


Figure 2.2: Percentage of 2014 passengers and the size of their party size, (CLIA & Partners, 2015)

opments influence the ships in terms of size, itinerary, efficiency and operations. For example, the trend where food onboard plays an increasingly important role, the onboard dinning venues have to be upgraded and the process of supplying food to the vessel changes so that more food is bought locally. To get a better understanding of these phenomena various sources are consulted in a desktop research to view how these trends and developments have changed the industry in the past, Subsection 2.5.1, and what can be expected in the future, Subsection 2.5.2.

2.5.1 What we saw in 2015

2015 brought Wifi onboard ships of the major cruise lines, US politics improved relations with Cuba possibly enabling cruises to visit Cuban ports in 2016[3] and with all acquisitions and new build orders the small ships segments is booming. These are examples of major developments positively influencing the cruise shipping industry.

The though political situation in Turkey resulted in major cruise lines cancelling there local operations and new emissions regulations resulted in heavy financial investments and refits throughout the fleet, (Heldewier and Hilton Spiegel, 2013). These indicated some more negative developments, although one could argue that the new emissions regulations leads to less emissions and therefore supports the environment, which makes it a positive development.

Small Cruise Vessels

Viking Ocean Cruises entered the market of oceangoing cruises on April 2015 with the Viking Star, this sister company of Viking River Cruises has five additional ships on order. With a successful river brand (49% market share) they are now planning to expand this experience to the coastal region, (Parker and Niemelä, 2015). Their ships will have a capacity of 930 passengers and the size will be around 47 800 GT, giving it the ideal properties to visit cities as Venice, Italy according to Viking Cruises Chairman Torstein Hagen.

One interesting event is the acquisition of Crystal Cruises by Genting Hongkong. Following this acquisition Genting/Crystal announced major expansion plans with the order for three new ocean going vessels, the acquisition of five river cruise vessels and an order for three new jets for the newly established Crystal Luxury Air brand. Together with the recently acquired Luxury Yacht, Crystal is investing in different niches of the luxury segment. Besides Crystal Cruises, Genting further invested in Loyds Werft to procure the capacity needed to build their new vessels[4]. The most interesting feature of the new ocean going ships is that the apartments onboard are for sale. This opportunity creates the possibility to have your own place onboard a cruise ship (Runnette, 2016).

[3]At the time of writing the first permit has been granted to the new Fathom brand for a cruise to Cuba.

[4]Eventually at the start of 2016 they also acquired Nordic Yards to further increase there shipbuilding capacity as a response to the high demand for cruise ships.

The third interesting development in this field are the expansion plans of Lindblad Expeditions. With the recent announcement of the newbuild order for two 100 passenger expedition vessels, see (Williamson, 2015; Nichols Brothers, 2015), and acquisition of Via Australis for cruising in the Galapagos region, see (Chrusciel, 2015). Lindblad Expeditions organizes its cruises in cooperation with National Geographic and are successfully delivering great cruise experiences to this niche together. Last year Lindblad Expeditions merged which effectively made it an public listed company, see (Gregg, 2015). By doing this they raised the capital they needed to order these newbuilds, but as indicated in the article this might be followed by additional orders or acquisition as they strive to improve their market position.

Besides these major movements other cruise lines in the smaller (< 1000 passengers) cruise vessel segment are also increasing capacity as small vessel cruising is booming. Windstar bought three vessels from Seabourn Yachts and Compangnie du Ponant took delivery of its newest vessel adding another 264 passengers capacity to the market.

Trending Locations

Besides new vessels or vessels changing ownership, there are also exciting developments in the field of destinations. A few location really jumped out, Asia is finally breaking through with all three big cruise lines moving into Asia. Norwegian Cruise Lines (NCL) announced it next breakaway-plus class vessel will be serving the Asian market with a custom interior design to Asian standards, (*Cruise Business Review*, 2015). Where Royal Caribbean Cruise Lines (RCCL) will send its new Ovation of the Seas to China. After already having deployed three other vessels there, among others Quantum of the Seas a sister ship from the same class as Ovation. Besides that, Carnival Cooperation signed an agreement to develop a Chinese cruise brand with both existing and new vessels, with the new vessels being build in China. They also signed a Memorandum of Understanding with Italy's Fincantieri and China State Shipbuilding Cooperation. Finally Genting Hongkong announced that the new vessel they are building at Meyer Werft, will be serving its new brand called Dream Cruises. A dedicated Chinese brand which initially will get two new ships, the first one in 2016 and the second one in 2017 aiming at the premium market. All these companies are going to serve the Chinese Cruise Market with some extensions to Japan as well, for more see (*Cruise Business Review*, 2015, p8).

Besides Asia, Australia and New Zealand are reporting fast market growth with 20% and 10% respectively. Although the size of these markets in absolute passengers numbers is small compared to Caribbean numbers, in relative growth they are the number one and three fastest growing cruise passenger markets in the world (position two goes to France) (Goldsbury, 2015). This can also be seen by dedicated Australian brands such as P&O Australia which expanded its fleet during 2015 and is reporting record bookings for 2016 (P&O Australia, 2016). All these developments indicate a challenging industry with lots of potential for the future. The following section will elaborate on the predicted trends for 2016[5].

2.5.2 What we might see in 2016

As indicated a lot has been going on influencing the cruise sector and as to be expected, 2016 will bring a whole lot more. With oil prices extremely low, the American economy on the rise and a strong dollar, going on a foreign holiday for an American has never been so attractive. Skift magazine bringing 2016's Mega-trends already declared 2016 'Year of the American Traveller' (Clampet and et al., 2016).

This year the first social cruises will take place, with Carnival Cooperation's Fathom brand making cruises to the Dominican Republic where passengers will help locals, for instance by teaching them English. Another trend predicted by Cruise Critics (Spencer Brown, 2016), is the increase in cooperation between cruise lines and organizations, such as Lindblad and National Geographic, Holland America Lines and the National Rijksmuseum, and Royal Caribbean Cruise Lines and The Forbidden City (The Palace Museum in Beijing), (Lee and Zhang, 2016; Andrews, 2016).

[5]The predictions are part of the market research that was finished early 2016, by the time of writing most of the prediction where indeed happening.

Another trend is the all-inclusive trend, where all-inclusive might become really all-inclusive. Cruise lines start to offer more complete package prices, so no more drinks or WiFi bills afterwards. By offering drinks, Wifi and flight packages during booking, the cruise lines offer a more inclusive package in advance. On the other hand the separate packages provides them with the opportunity to advertise with a cheap fare price, which then during booking will raise as package deals are added, (Spencer Brown, 2016).

With people becoming more and more environmentally conscious and the new SECA regulation entering into force, additional investments in systems to meet these regulations and to deliver on the expectations of passengers are required. To comply with the SECA regulations, a frequently chosen strategy is a refit with a scrubber installation, but enrolling this for the entire fleet takes time. Another applied solution is the switch to low sulphur solutions, such as MGO, as indicated in John Tercek's presentation at CLIA, (Tercek, 2013). Alternatively last year the first vessels on LNG have been ordered by Carnival's Costa group. This order involves four vessels, two for the Costa brand and two for the AIDA brand, with dual-fuel LNG engines and a maximum capacity of 6600 passengers or a double occupancy of 5000 passengers[6].

2016 will bring brand expansions with Scenic cruises starting a ocean cruise division with the order for a 228 passenger luxury vessel and the option for a second one. The vessel is set to enter service in 2018 and features multiple helicopters, a fleet of zodiacs and a seven-person submarine. Furthermore the vessel has 1A Super ice class, six speciality restaurants, four bars and lounges, a heated pool with retractable roof, $450m^2$ spa, a 240-seats theatre and a gym, (Coulter, 2016) This ship will combine the best of luxury cruising with expedition cruising. With the 1A Super and special zero-speed fin-stabilizers allowing it to navigate through though sea conditions while having a broad range of luxury facilities onboard.

Another predicted trend is about food. In fact it already started in 2015 but it will most likely gain momentum in 2016. The onboard cuisine is strongly gaining importance, as can also be seen in the Scenic Eclipse with six different dinning venues. But also by the big brands which are constantly improving their food offer. Clampet and et al. (2016) states that food is influencing our travel experience significantly and that connecting food with the visited locations will enhance the guest experience. An example is the increase in locally procured supplies by cruise lines. Using local products and safeguarding their quality increases the passenger experience. Besides the increasing use of local products, also the dinning options themselves are arranged more flexible. With more flexible seatings in dinners and more different places to choose from.

Today's passenger is increasingly more of a traveller than a tourist. Meaning that they require more freedom and flexibility which enables them to customize their journey with extra pre- or post-cruise hotel stays, extra time in ports to visit places on their own or exclusive excursions. This is all focused on creating their own unique travel experience. One of the ways this is enabled is by including overnight port-stays and by offering more flexibility in the flight option to and from their cruise. But also pre- and post-cruise programs are offered to passengers to personalize their travel experience even more. These longer or overnight port-stays provide the travellers with more free time, which again enables them to customize their trip even more with onshore restaurant experiences or theatre. Besides these options another one is the availability of bikes in port. When providing bikes larger parts of the place visited are reachable, enabling people to discover more of the town on their own peace. In the luxury segment this even goes as far as adding in between flight to visit more places in a cruise without having to be on the ship during the "less interesting" parts.

2.6 The Niche-market

As a result of the market study a niche-market, or a combination of niche-markets, has to be found. This will be used as a starting point of the concept exploration study, the first phase of the cruise ship design process. To do so five niche-markets will be defined in Subsection 2.6.1. From those five niche-markets the most suitable options will be selected and further described in

[6]The difference between maximum capacity and double occupancy capacity comes from the difference in staterooms, where in practise cruise vessels have staterooms which can accommodate up to six passengers a room. When determining the double occupancy rate one assumes two passengers a cabin.

Subsection 2.6.2. This description will contain properties such as the ship size, market segment, passengers targeted and area of operations chosen for this design.

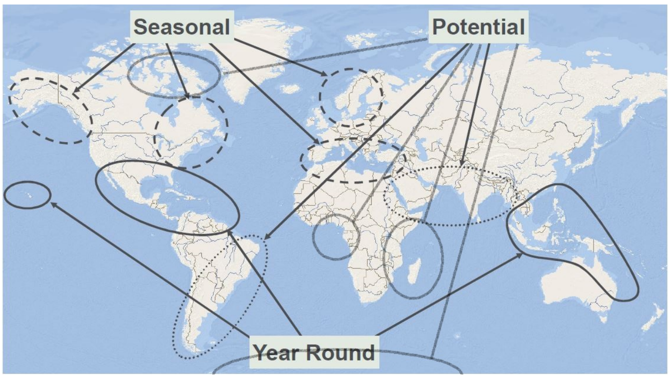


Figure 2.3: Map with cruise areas from (Jantunen, 2013) additional potential areas have been added by the author

Figure 2.3 gives an overview of different cruising areas in the world. Divided in year-round, seasonal and potential locations. These seasonal locations already give away that usually a cruise ship visits multiple locations in a year as only a limited number of areas are interesting the entire year. Besides that, even in the year-round locations the capacity of cruise berths available is not constant for the entire year. Figure 2.4 indicates the capacity changes in an area over the course of the year.

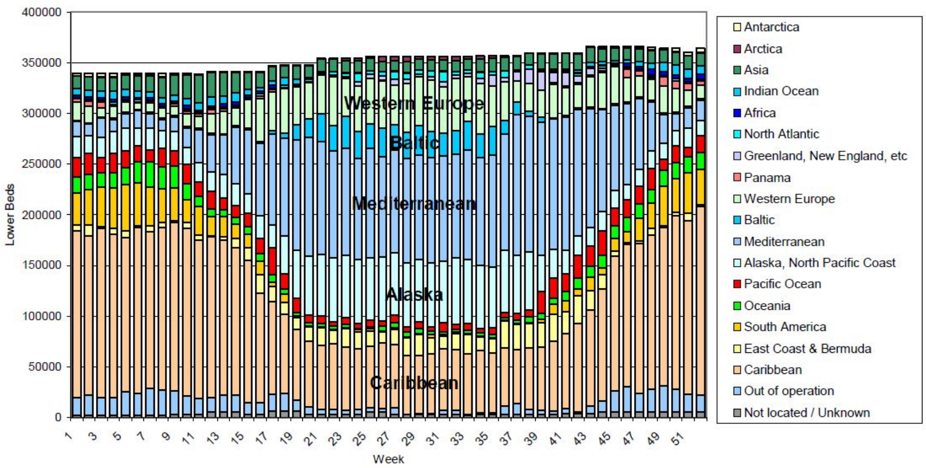


Figure 2.4: The total capacity in cruise beds over the year for different locations in the world, from (Jantunen, 2013).

This knowledge implies that there shouldn't be just one niche-market to design for but instead one should collect a number of potential locations and markets which the ship can visit during a year. While doing this one can pick a single main market and adapt the ship to function in the others as well. How this is done exactly strongly depends on the different requirements of the chosen niche-markets.

2.6.1 Top 5 Most Promising Niches

Many articles, papers and newsitems have been studied from cabin pricing policies to visitor management practises and from ice-breaking trimarans to energy passive cruise vessels (Ladany and Arbel, 1991; Dowling et al., 2011; Aker Arctic, 2015; McCartan and Kvilums, 2013). This provided a broad basis of knowledge to start a market definition from. Besides market specific properties, there are some general specifications for the design mentioned.

General specification

At the start a couple of properties of the design are already known. The intended vessel should have a maximum of 250 passengers and would therefore fit the boutique size of cruise ships. The reason behind this is that a ship this size fits best in the Conoship's portfolio and the earlier studied trends show that there is a lot of growth and new-building activity in this size. Below some of the market advantage smaller cruise vessels have are named.

The smaller ships usually don't serve the mass-market segments as their costs per berth are too high to compete with the huge vessels. As they can't differentiate themselves on the lowest price, they will have to offer other advantages. One of them is the size itself, lots of people prefer the smaller size ship because they are less crowded. Another advantage is the ability to visit ports which bigger ships are unable or not allowed to visit. This could be because the port is unreachable for bigger ships due to a limitation in draft for instance. Nowadays ports often limit the amount of passengers they allow, (Cruise Industry News, 2016*b*). These limits protect the town from being overrun by cruise tourists and stimulate more sustainable cruise tourism.

Another place where these limits can be found are the polar regions. Although the regulation here is more special as the organization developing them is a cooperation of operators and companies active in the polar regions. These operators united themselves in the International Association of Antarctic Tour Operators (IAATO) and Arctic Expedition Cruise Operators (AECO) association to agree on their own rules for operating in the polar regions. The following limits are common in these areas:

- Ships with more than 500 passengers, no landings at all.
- Ships with less than 500 passengers, 100 passengers at the same time.
- Maximum group size depends on location but usually less then 30 passengers.
- The ratio of guides to passengers should be at least 1:20, although safe operations or local guide lines might require more.

This shows that while operating in the polar regions it might be wise to limit the amount of passengers to 200 as this results in 2 groups which can go ashore once a day.

Resulting 5 most promising niche-markets

The first niche-market offers European city-trips where the strength of the small ships provides the possibility to get close to the city center. Because of this no additional bus trips are required, the time people spend in town sightseeing is maximized. Besides the ability to get closer to the city centre, a smaller ship should be more flexible in arranging visits, overnight stays and excursions to maximize the cruiser's experience. This trip can be conducted with two types of passengers. The groups of Asian people which currently travel by bus for an Europe-in-5-days trip and American river cruise passengers. A cruise variant for the Asian type of trip provides more comfort and the option to travel during the night while sleeping. Also the ship can be used for briefings prior to the day excursions and shows/entertainment in the evening to maximize the experience during the journey. In 2012 KPMG published an extensive report covering the Asian middle class and more recently CLIA commissioned a research executed by Business Research & Economic Advisors (BREA) about the economic contributions of cruise tourism in South-East Asia, (Andrew and Yali, 2012; BREA, 2014). The CLIA/BREA report shows the economic potential and influence the cruise industry already has in this region, but also the potential new customers. The KPMG report further describes the so-called Asian middle-class, a group of rich and relative young Asians which have the means to go cruising. As important factors the report states that: quality, trendiness and user experience, especially buyer experience, are important factors for luxury products. Combing this with the European cities should give a rich and impressive experience with lots of freedom and many options to personalize the trip.

Besides the option with Asian passengers, there is one with American passengers. These passengers are already visiting the European rivers and form the main share of river cruise passengers. The American traveller distinguishes themselves by having previous cruise experience (as they are expected to be returning river passengers), having a higher average age and mostly interested in the cultural and scenic experiences they cannot get at home (the cultural difference between America and Europe is smaller). This option acts upon the trend predicted in the Skift Trend report (Clampet and et al., 2016), where an increase in American foreign tourism is expected because of the strong dollar and low oil prices. The potential of this market is recognized by Viking Ocean Cruises, a newly established cruising brand from the well-known Viking River cruises. They take their river cruise formula to go coastal cruising with brand new vessels(Parker and Niemelä, 2015).

Within this niche-market possibilities to further differentiate could be adding bikes to the ship. This enables passengers to discover cities from a different perspective and cover more distance in a day. This also suits with the trend that passengers become more active. The ship needed in this niche needs to be sufficiently small and manoeuvrable to enter the sometimes narrow harbours close to the city centres. Meanwhile it needs to be able to achieve considerable speeds in order to see enough cities and sights. In the case of the Asian passenger profile an analysis of the current bus trips can be used to determine a business case and operation profile for the ship to be designed.

The second niche-market is dedicated to the Polar regions. Most small ships nowadays have some form of ice class enabling them to visit these regions to some extend. Most vessels offering cruises in these regions are belonging to the segment of expedition vessels which exists of former icebreakers and research vessels. These ships have been refitted for this purpose, an overview can be found in Ward (2015). From this overview one can conclude that the average age of these expedition vessels is high, around 33 years old. With all the new regulations, the SECA/NECA, EEDI, Polar Code, Ballast Water Management and probabilistic damage stability 2009 to name a few, there is a good opportunity for new vessels replacing the old ones and meanwhile increasing the capacity in this segment. The polar regions in this form are in an unique situation as sustainability and the environment are regarded very highly.

Here again two options are considered for the passengers. First the older passenger with more free time and financial resources to go for a 4 week cruise. The ship itself in this case doesn't require high level luxury with butler service but rather focuses on the trip and support the experience of sailing through the Arctic area. This is done by adding lecture room facilities to educate people about the surroundings they sail through and by facilitating landings on the poles.

The second option is based on younger passengers around the age of 45. These people in high income jobs have the budget to travel the world but basically lack the time. Therefore their time available for the trip is 1 or 2 weeks. They look for the same sort of experience, with visits to the poles and interesting lectures to maximize their experience. This market as well has some challenges. The logistics are often considered a challenge on their own, for sure for the second group of passengers. Where the distance one can do by a normal airline is limited and in order to reduce the sailing time, charter flights are needed. Another challenge is to come up with something new. Recently STX France presented their 'Ulyseas Concept', Damen came with a range of 'SeaXplorers' and Sunstone with project 'Unlimited'. In order to draw attention the design needs to have something else. The third challenge one has to face is that these ships often are a combination of multiple markets. The season in the polar regions only lasts for a maximum of five months a year for both Polar regions. Where five months is the utmost maximum and access to the entire area can be limited during some periods. Meaning that the ship will sail in other regions part of the time. Last this niche-market in particular is subjected to lots of extra regulations where it has to comply with such as the Polar code.

South America offers an interesting third niche-market. The coastal region from Argentina upwards and especially the Amazon river shows as a region with lots of natural and cultural resources. MSC cruises already operates along the coast and Hurtigruten sails inland on the Amazon river, but the combination of the coastal cities and villages and the inland scenery along the Amazon river is considered a growing niche-market. Simon Douwes, itinerary planner at Holland America Line (HAL) indicates an increasing demand as a result of the improving safety. The advantage of small vessels is in the access to the smaller ports and the Amazon river. Smaller vessels also fit better with the local tourist facilities in this area. The season in this region usually last from November till March, roughly depending on the exact area. Besides this season one should keep in mind the rain and dry seasons. This niche-market doesn't have a specific passenger profile defined as it is a more easy to combine niche-market with the sort of passengers strongly depending on the ship's luxury class and size, as well as with the brand operating the vessel.

The fourth niche-market is located in the region around New Zealand, the Philippines, and French Polynesia. The strength of small vessels in this region is the possibility to approach even the smallest islands. Travelling here with a small group supports sustainable tourism as small local communities are better able to handle these numbers. Lastly the small group supports the way people experience their visit on the islands and villages. The type of cruises here vary greatly, from sail cruises to luxury and leisure cruises or adventure cruises. Also the size of the vessels and companies differ a lot, Royal Caribbean Cruise lines with the 2112 passenger Raddiance of the Seas while Paul Gaugin cruises with the 88 passenger Tere Moana. The duration is often longer, most-likely because the people going there have to travel far. The logistics here form a challenge as there aren't that many major airports in the area. And since most passengers currently come from Northern America and West-Europe, most have to travel far. In this niche-market the growth in cruise passengers in New-Zealand and Australia might create an opportunity as this overcomes part of the logistic problem. In the region there are also multiple countries with their own regulation as French Polynesia for instance has the French regulation. Lastly in this area there are Cyclone season from November to January.

The last niche-market pointed out, is located in Africa. The CBI, an organisation of the Dutch Ministry of Foreign Affairs, indicates cruising as a potential interesting form of tourism for a number of countries in Africa: Kenya, Tanzania, Mozambique, and Madagascar. The advantages of cruising opposite to land based travels is that the means of transport are more comfortable and safe due to the bad infrastructures on land. Therefore making a cruise provides the opportunity to see multiple cities in multiple countries without constantly having to fly or drive uncomfortable roads or long train rides. The countries themselves have plenty to offer, from spotting 'the Big Five' in the wildlife resorts to authentic local culture in the original tribal villages. Doing this with a smaller vessel enables again to visit the smaller ports, for sure in Africa where the availability of cruise terminals is limited. The smaller ships better suit the capacity of local facilities for tours and excursions. The current cruise offer to Africa consists of longer trips with an average around 20 days. This looks rather long but can be explained by the fact that dedicated Africa cruises are rather rare, most cruises visiting Africa are repositioning cruises going from the south (Antarctica or Australia) to the Mediterranean or Europe. Developing cruises solely taking place in the African continent clearly brings some challenges with it. The political situation in some of the countries is very unstable with all sorts of militias forming threat for tourists. Also the extreme poverty among fisherman and villagers along the coast have led to piracy practices. In order to resolve this issues the NAVO launched multiple missions to Mali and the Gulf of Aiden for instance. Therefore nowadays most parts of Africa are safe to travel. Even the countries themselves see opportunities in the cruise sector with multiple related projects such as the development of a dedicated cruise terminal in Cape Town and initiatives such as the Cruise Indian Ocean Association.

2.6.2 The Conoship Niche-market

The Niche-market selected for the Conoship Cruise Vessel will serve a combination of locations with seasons completing each other. Figure 2.5 shows how such a combination looks like in case of the HAL's fleet. Because these fleet deployment schemes provide good insights in seasonality and possibilities, another example of Lindblad Expeditions is included in appendix A.

From the start the polar regions seemed really attractive. They have a growth in demand and

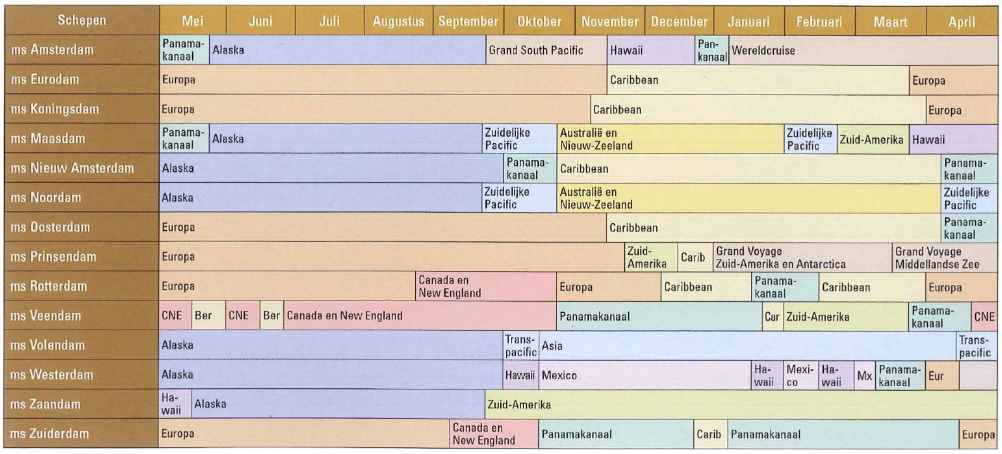


Figure 2.5: The areas of operations of the HAL fleet during the year

the capacity is very limited and old (SunStone Ships, 2016). Recent new-build orders confirmed that operating in this area is attractive as most of the new-builds have polar-class. Besides the polar regions themselves, also the number of cruises in the North-west passage increases. According to articles read on Cruise critics and based on the deployment schemes the maximum deployment times in the polar regions are five months in each region. From May to September for the Arctic region and from November to March for the Antarctic. These are the maximum times possible and one should therefore take in consideration that at the start it might still be rather cold. Besides the temperature, cruises at the start of the season might be limited to restricted areas due to the presence of ice. This leaves the periods around April and October open for deployment elsewhere. This time can be used to organize cruises elsewhere taking in consideration the need to go from North to South as the ship has to reposition. Other regions possible during this time period are Western Europe, the Baltic or the Mediterranean.

In order to operate in the Arctic conditions the vessel needs to have an ice-strengthened hull, the exact consequences for this will result in additional hull weight and depend on the class needed. Besides ice-class the ship will have to host a fleet of inflatable zodiacs in order to make landings on the poles. All sorts of special ice navigation equipment, from sonar systems to heat cameras and ice radars are necessary to provide safe navigation leading to a more advanced bridge design. The ship will need so called mud-rooms, spaces where people can get rid of their landing outfit and life-jackets after boarding the cruise vessels from the zodiac. To ensure safe operations the ship should have an endurance of about 6 weeks, as a crossing through the North-west passage takes about four and a half weeks, and it is chosen to comply with safe-return-to-port regulations. This last one might not be demanded, depending on the size of the vessel, but is highly recommended as search and rescue (SAR) operations in the polar regions are hard. Also the responsible countries for the SAR operations in that area might restrict access if they consider a vessel less safe. The helicopter requirement differs on the luxury level, being able to receive a helicopter in case of emergency is a safety aspect. But when one has it's own helicopter onboard it can also be used for trips and excursions to more vacant places, such as skiing from a glacier for instance. In this last case the helicopter provides an extra form of entertainment, an extra experience to the customer and therefore this is considered luxurious.

When studying comparable, existing or new designs for this segment, huge variations are seen in both luxury level as well as operational scenario. Where for instance Lindblad Expeditions offers cruises on very basic ships for an average two week period in this region, Scenic cruises offers longer cruises on their new Scenic Eclipse ship and a third operator AntarcticaXXL offers one week cruises. To better understand the consequences of these luxury levels and operational scenarios the design process will be continued with a concept exploration.

Chapter 3. Requirement Definition of The Conoship Cruise Ship

3.1 Introduction

Before the Ship Synthesis Model can be built it needs to be clear what should be in there. In order to get to a list of systems and spaces this section will go through the characteristics of the selected niche-market to find out which requirements these bring in. The most influencing regulation applicable to this design is consulted in Section 3.3. To complete the overview of the required systems and spaces there are some more general items to consider such as the hull form. This will be discussed in Section 3.4. Together these requirements will form the basis of the SSM and give shape to the design space researched.

3.2 Characteristics to requirements

Subsection 2.6.2 already highlighted some examples of characteristics of ships sailing in the chosen niche-market of Polar Expedition Cruises. These characteristics can be divided in negotiable and non-negotiable characteristics. For example, the different luxury options as helicopters, pools and other toys are a marketing choice. Though the ice-strengthening is non-negotiable for cruising in the Polar region. Some of the characteristics are translated to fixed design requirements or system solutions, while for others multiple options can be chosen. For instance the storage location of the zodiacs which is either on deck or in a covered storage in the hull while the presence of mudrooms is fixed and their initial size is set at $25m^2$. These decisions are made to limit the design variations and reduce the number of variables. The underlying philosophy is that a variation in mudroom size for instance is not providing interesting design variations and not having the mudroom is limiting operations severely. In a comparable way the decisions for different options or fixed choices are made.

The first item to name are the Zodiacs, these small boats are used to enable passengers to reach the shores and glaciers for land based excursions where the ship is unable to dock. This is specifically done with Zodiacs as they are easy to land on beaches and glaciers where the normal tender boats, which often are multipurpose lifeboats, can not come so close. Figure 3.1 gives an impression of storage spaces and facilities related to these Zodiacs. These Zodiacs require a space to store onboard, two options are considered: storage on deck as can be seen in figure 3.1a or an indoor storage as in figure 3.1c. Besides the storage space the Zodiacs needs a fuel store as they operate on a different fuel type as the ship itself. Because the primary operations of this ship take place in environmentally vulnerable places, it improves the way people experience their time at sea and it eases the Zodiac related operations, it is suggested to fit this ship with electrical Zodiacs, as build by Zodiac Milpro (2015). These Zodiacs exist and are currently used by Hapag Lloyd. This type of Zodiac is fitted with an electrical engine working with an battery. This reduces noise levels during operations, it does not require a separate fuel system as the batteries can be charged from the ship's grid and it disturbs the local environment less both with the emissions but also with the high frequency sound normal outboard engine produce. The third item linked to the Zodiac operations has to do with boarding the Zodiacs. This can be done by a boarding station at midship as can be seen in figure 3.1b or via the stern. In both situations when leaving the ship in polar conditions, appropriate clothing has to be worn. Therefore a so-called mudroom is required. Within this space passengers are prepared with proper clothing and drinks before leaving on the Zodiac. Often this space is close to the hospital facilities as this is the way to return passengers back to the vessel when they are wounded. In case the indoor storage solution is chosen this can be combined with boarding facilities. For the other situation in which the Zodiacs are stored on the deck, the boarding station has to be located close to the waterline and adjacent to the mudroom. The size of the mudroom is set fixed at $25m^2$. The storage space either on deck or inside the hull needs to fit 10 Zodiacs, for sizing the earlier named MK 5 is used. This provides 150 persons capacity sufficient for a 100 passenger landing party with guides. The resulting dimensions of the storage space are 7m long by 15m wide and one deck high. This should provide sufficient space to store five stacks of two boats.

(a) Multiple Zodiacs stored on deck

(b) An expedition ship with a Zodiac boarding station midships.

(c) Indoor storage

Figure 3.1: Visualisation of systems related to Zodiac operations

The next item on the list is the ice-strengthening. In order to safely and sustainably operate in the Polar regions the ship needs a polar class notations. For all ships[1] constructed after 1 March 2008 the IACS Unified Requirements shall be applied. The ships complying with these rules will get a Polar Class notation from category 1 to 7, with one being the highest and seven roughly equal to Finnish-Swedish ice-class 1A notation, PC6 is comparable with 1A Super. The different classes differ in requirements for the hull structure and requirements for machinery. With the PC1 notation allowing a ship to operate year-round in hard polar conditions and PC6 & PC7 only allowing spring and summer operations.

Besides the IACS regulation one also has the IMO Polar Code. This code is an addition to SOLAS, MARPOL and STCW, it deals with extra requirements for the structure, where it mostly refers to the IACS Unified regulations, but it also deals with regulations concerning pollution in the Polar region caused by ships. For instance ships in the polar regions are not allowed to discharge sewage into the sea without processing it in a suitable treatment plant and all tanks containing oil, fuel or sewage bigger then $30m^3$ shall be removed at least 0.76m from the shell. For the STCW part, the IMO Polar Code requires additional training for the crew and additional navigation systems at the bridge. The PC6 notation seems most suitable for this design as it protects the ship against first and medium year ice encounters. More heavier Polar Code classes are only interesting if one plans to sail into the ice, which is usually avoided in the case of passenger vessels.

Another specific characteristic for this niche-market are helicopter facilities. As the biggest part of the polar regions is hard to reach, a helicopter provides a unique option to see these places and offers an unique experience while travelling through this region. The other aspect

[1]Icebreakers are excluded as they have a different class notation

with a helicopter is the additional safety it provides. In case of an emergency, such as one of the passengers having an accident, the helicopter can be used for a smooth and safe evacuation to a 'nearby' hospital or back to the ship.

There are multiple options in this as it is partly dependent on the luxury level the ship is aiming at. Option 1: the ship has no helicopter facilities at all. Option 2: the ship has facilities to receive helicopters, when it is necessary. The ship has the space to land a helicopter on a dedicated piece of deck. Option 3: the ship has an own helicopter including an hangar, fuel storage and a workshop. As it is chosen within this study to compare building costs and expenses of the different scenario and luxury levels, the helicopter is left out as it requires a lot more information about all the necessary systems, building costs and operating expenses. Besides it is unclear what it would do to the potential earnings to estimate the benefits obtained.

The expedition cruise vessels bring their passengers to the most exclusive places in the world. For them to fully experience the surrounding they are in, these cruises are often joined by specialists, biologists, naturalist or photographers. Often these specialists provide lectures preparing the passengers on what they will see during the day. In this way their experience is extended and they will get better understanding of what they are visiting. To do this the ship needs to be fitted with some form of presentation facilities or auditorium. This space can be combined with a theatre or a lounge. For instance on the top deck, where the presentations can be given while you have a full view around you of the area. For this design the location of these lecture rooms varies for the different luxury level as could already be seen in Table 4.3

When translating this niche-market's characteristics to design requirements the different Polar Codes were studied. Within the IMO Polar Code there are also zero discharge regulations. This states that garbage and sewage should be properly treated in onboard facilities or should be disposed in harbours to be processed in onshore facilities. Since a cruise ship produces lots of garbage and sewage, onboard treatment seems to be the best option. Another argument for advanced onboard treatment is the fact that cruise ships have a large influence on the waste infrastructure of the local villages it visits. Butt (2007) discusses the high impact of cruise ship generated waste on the city of Southampton's waste infrastructure. Here one can see that handling the waste of cruise vessels for a developed city already provides issues. Therefore the ship itself has additional space besides storage tanks to properly store and treat the generated waste. The space required for this is mainly technical space. therefore an additional $20m^2$ is reserved. This technical space should be as close as practically achievable to the storage tanks and space. For the storage of black and grey water a tank with a size equal to $0.3m^3$ a person has been arranged. For garbage a storage and handling area of $50m^2$ has been fitted in. The location of both spaces can be down in the hull although access to the main deck is required for unloading. The tanks if sized bigger then $30m^3$ need to be removed from the shell by 0.76m, as is obligated by the Polar Code zero discharge regulation.

A set of stabilizers is fitted on the ship to improve motions and thereby raise the comfort level on board the vessel. These small expedition cruise vessels frequently visit areas where sea conditions are very rough, the stabilizers should help provide the comfort and safety during this crossing. These stabilizers should be located near the bilge radius of the ship's cross-section at half the ship's length, as that is the most effective place to locate them. The length of the system is set at 3m, the beam at 2m and the height at 1m based on the Rolls Royce Aquarius stabilization at rest, retractable stabilizers.

3.3 Regulations

Regulations influence the design of ships as was already seen for the polar code influencing the ships structural weight. Within this section multiple other rules will be named and the requirements they put on systems and spaces on board will be indicated. Based on a description of the Holland America Line (2013) and a presentation given by Aarnio (2014), the following rules and regulations are consulted:

- IMO Polar code

- IACS Requirements concerning Polar code
- MLC 2006
- IACS Bridge design
- IAATO/AECO regulations for operations in the polar region
- Safe-Return-to-Port
- SOLAS
- Guidelines of the CLIA

The Polar Code has already been discussed earlier, the MLC 2006, the Maritime Labour Convention, will be discussed next. This piece of regulations mainly covers the working conditions of crew members. The MLC provides guidance on the minimum required sizes of crew cabins, dayrooms and messes. The information is used to size the crew facilities. The mess and dayroom as it is combined has to have a size of $1.5m^2$ a crew member for non-passengers ships. For passenger ships these regulations do not provide any minimum requirement, therefore $1.25m^2$ a crew member is used from Practical Ship Design (Watson, 2002). The room should be sized for the number of crew member it has to serve per seat. So if there would be two dinner shifts the room has to be sized on half the crew size. As it also has to serve as a day-room it has been chosen to size it on 80% of the crew. This leaves some out as they are probably sleeping or on duty.

Furthermore the size of crew cabins is acquired from the MLC. The initial size is based on 4 person cabins and is a minimum of $14.5m^2$. Contradictory to normal vessels, crew accommodation onboard a passenger vessel is allowed to be located below the waterline. Besides these 4 person cabins, some single and 2 person cabins are required for officers. 2 of these need to be located near the bridge for the captain and navigating officer. For these 2 the size is set at $14m^2$, the $8.5m^2$ minimum with some space for a day-room. The others will be in the belly of the ship and will have the $8.5m^2$. Based on comparison ships 20% of the crew cabins will be two person or single cabins.

The IACS Bridge Design regulation provides guidance in the layout of the bridge. The bridge has a certain standard layout with consoles which can be seen in figure 3.2. Besides this layout the free angle of vision is very important and needs to be around 225 degree. The dimensions of the bridge are set at full beam and a length of 4.5m, this allows sufficient space to be able to look the full 225 degree and walk around the obligated consoles. The full beam is necessary to look alongside the vessel and allows for bridge wings is required in a later design stage.

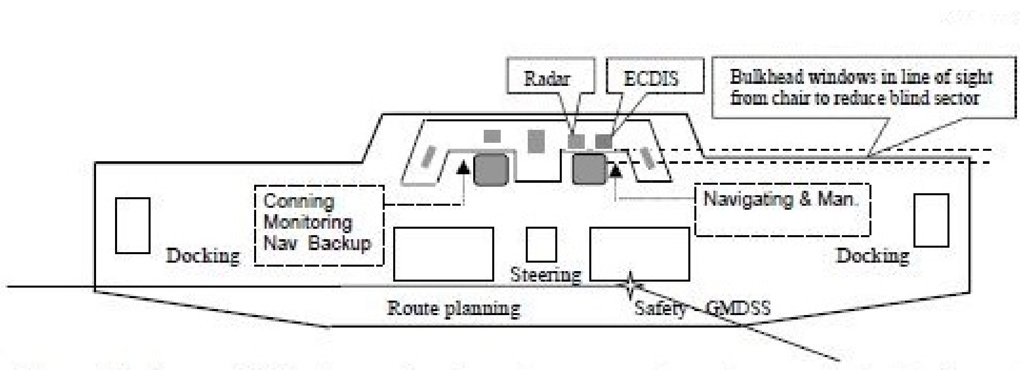


Figure 3.2: Layout of a bridge for size estimation(IACS, 2011)

The IAATO and AECO both are member organizations to regulate and control the operations in the Antarctic and Arctic regions respectively. As they are member organizations, their regulation is only binding to their own members. Anyway most operators in the polar regions become member as besides adding regulations, they also manage the ships operating in the area. Making sure that the ships are spread over the area. They can also help in the coordination of SAR operations as every member has to hand in travel schedules. Amongst others they provide guidelines for good practice ship operations and visitor management situations in the Polar regions. These influences on the design requirements can be seen in the fuel choice, HFO, the standard heavy fuel oil used in the shipping industry, is banned in the polar regions. Therefore the fuel type considered should either be a distillate oil or liquefied natural gas (LNG). The third option is a combination of both, as the availability of LNG in the polar regions is limited. Within the concept study the solutions under consideration will be limited to MGO only. Besides the fuel type also the number of Zodiacs is influenced by these guidelines, as a ship is allowed to only have 100 passengers at the shore at any given time. Therefore a group size of 200 passengers provides you with two times half a day a shore. The number of Zodiacs is based on a 100 person group with guides, Zodiac operators and possibly some gear. Besides that, having some Zodiacs at the ship as spares and for smaller sightseeing trips without landings results in a total of 10 Zodiacs.

The next part of regulation to consider is the Safe-Return-to-Port (SRtP) regulation. This regulation's main principle is that after an incident, which does not exceed the damage threshold, the vessel should be able to safely return to port under its own power while providing safe areas for the persons onboard. This regulation applies to passenger ships and ferries with a length of 120m and more or 3 or more main vertical zones(MVZ). It requires that the essential systems of a ship will continue operating at least long enough for the ship to return to safety in case of damages as a result of fire or flooding. Main considerations during concept design are the need of two separated generator rooms and propulsion rooms. But also fire control stations, food preparation areas and hospital functions require redundancy. In the preliminary guidelines of the Germanischer Lloyd for Safe Return to Port Capability of Passenger Ships (Germanischer Lloyds, 2009, Annex A) an initial set of requirements has been proposed to help the preliminary design to comply with the SRtP demands.

The first system considered is the propulsion system. As is the case with most cruise vessels nowadays, this ship will be fitted with a diesel-electric power configuration. This means that a set of generators will provide the electrical energy used by the ship for both the propulsion and the hotel functions (kitchens, HVAC, lightning). The ship will have two separate generator rooms as a result of the SRtP-regulation and each engine room will initially have two generator sets providing the operator with a rather simple but flexible configuration. The generators will be chosen based on the required power and all four generator sets will be the same which should make maintenance easier. The required power the generators have to provide is determined by the method described in Subsection 4.5.1 and is based on the propulsion power and the hotel load. The size of the generator sets will be acquired from a database with example generators. The generator with sufficient capacity to produce the required total power will be selected taking into account the total number of available generators (3 generator for normal operations and one spare generator for redundancy). The size of the generator rooms is based on the dimensions of the selected generator set and the ship. The length of the room is equal to the generator length + 3 meters, the beam is equal to the ship's beam with a reduction of 2 times 1.8 meters for the double hull. The height is fixed at 2 deck-heights.

The required propulsion power will be provided by two azimuth thrusters. When installed in separate propulsion rooms this complies with the SRtP-regulation. Another advantage of using these thrusters is that they increase manoeuvrability, which is a must for vessels visiting the smaller ports. Besides manoeuvrability, the Dynamic Positioning (DP) capabilities of the vessel benefit from the use of thrusters. DP is often used by all sizes of cruise vessels as anchoring such a vessel is a rather tremendous operation and in a lot of places highly impracticable and undesired. For instance in deep uncharted Polar waters or above vulnerable reefs. The azimuth propulsion system exists of a thruster located outside on the ship's hull and an electrical engine located inside, directly connected to the thruster. The size of this system is also acquired from an example database. The size of the propulsion room is set as 6m in length and 4m in beam with one deckheight in height. The dimensions of the pod are based on the required propulsion power as determined based on the resistance calculation and power prediction method described earlier.

Besides the propulsion and generator rooms other critical components of the propulsion/power system are the switchboards. Each generator room has its own switchboard room and there is a separate emergency switchboard fitted with the emergency generator as well. The switchboards rooms are merged with auxiliary systems and are put in two separated auxiliary rooms. These two have to be in different compartments as well to provide redundancy in case of fire or flooding. The size of these rooms is set at $30m^2$ each. Furthermore they need to be as close as possible to the generator room to minimize the amount of cabling.

The last item in the propulsion and electricity plant is the fuel storage. The volume of fuel required depends on the engine chosen and the required endurance of the ship. For this research the endurance is determined as six weeks, the duration of a North-West passage with an additional safety margin. Therefore based on the six week endurance, the specific fuel consumption of the engine, and the required power the required amount of fuel can be determined. Finally as the tanks can never be completely filled nor emptied the estimated amount of fuel is divided by 0.8. The amount of fuel is divided by the density and split in four separate tanks.

Besides strong demands on the propulsion and electrical system the SRtP-regulation also demands food preparation and storage to be redundant. The solution for this is found in a separate second kitchen which will be in the vicinity of the lounge and be primarily used to serve the breakfast from. Therefore it will be smaller in size but still hold all functions vital to prepare food in case of emergency. The size of the main kitchen is based on a value adapted from Watson (2002) and a reference design from Conoship and is set at $0.5m^2/person$. For the second kitchen as it is meant for smaller occasions and breakfast food a size of $0.25m^2/person$ is used. In case of an emergency the people will have to eat in multiple shifts.

As mentioned previously the storage requires redundancy, therefore additional capacity should be used in a different Main Vertical Zone (MVZ). Freshwater will initially be made by a freshwater plant but will be made redundant by a daytank in a separate compartment of $15m^2$. This complies to the SRtP-regulations as they demand 7L a person a day for a minimum of a week. The general/dry stores are estimated at $140m^3 + \frac{0.1m^3}{day*person}$ (Watson, 2002). An initial estimate gives a total storage space of $560m^3$ or $187m^2$ for 300 persons and a period of two weeks. This seems to be an acceptable first estimate based on a comparison with available example ship designs.

The hospital also needs to be redundant and therefore needs to have a second location. The design guidelines from the earlier named GL document suggest the option to equip a crew cabin with this functionality. Because of their location and size, one of the officers cabins near the bridge can be equipped with this function. These officer cabins are located higher above the waterline and closer to the lifeboats which in case of evacuation shortens the distance the wounded have to travel. An other advantage is that these rooms are bigger in size than standard crew cabins. To foresee this cabin from the necessary equipment, a store will be fitted close to it with a size of $10m^2$.

To effectively fight fire and emergencies a fire and emergency control station is appointed. In case of a cruise vessel complying to the SRtP-regulation, the fire and emergency control station needs to be redundant and therefore there needs to be a second one in a different MVZ. The first one should be close to or combined with the bridge. The second one could be located at the rear of the ship in the vicinity of the lifeboats. The advantage of this is that it can be used to lead an evacuation from, whilst being close to the lifeboats. The size of these are set to $9m^2$ for the remote one, and $6m^2$ for the one near the bridge.

IMO regulations, such as SOLAS for instance, are also mandatory for cruise ships of course. One of the examples of configuration critical aspects of SOLAS regulation is the capacity and location of lifeboats. Passenger ships on international voyages shall have lifeboats for minimum of 75% of the persons onboard, liferafts for the remaining $0 - 25\%$ and spare liferafts for 25% of the persons onboard according to the Life Saving Appliance (LSA) Code. Standard lifeboats have a maximum capacity of 150 people and are optionally combinable with a tender boat. Regulation 17 of the LSA code allows exemptions on the maximum capacity of lifeboats, as can be seen on most of the bigger cruise vessels. These exemptions are only granted if one can prove that the safety of the persons onboard is not reduced by using the bigger lifeboat. This is often done by evacuation simulations. Since the number of persons on this vessel will be rather limited the lifeboats used here are of 150 persons capacity and has dimensions equal to the one in the example. The location is also limited by the LSA code as 1.5 times the length of the lifeboat forwards of the propeller and at least 2m above water when the ship is listed 20 degree and trimmed 10 degree either way. This last part will be simplified initially to 6m above the design waterline, as this is the 2m plus the additional height of the ship at 20 degree list rounded to deckheights.

Another important SOLAS requirement is the emergency generator. The emergency generator needs to be located above the bulkhead deck and should provide sufficient power in case of an emergency when the main generators are down. The emergency systems to be provided with power are the lighting systems, the navigation systems, essential engine room equipment, emergency pumps, internal and external communication systems and systems supporting the 'orderly' evacuation of the ship. The size of the emergency generators depends on the size of these systems which in turn are related to the size of the ship. Basically it can be separated in a constant part for the navigational equipments etc. and systems that vary for the size of the ship such as emergency pumps and engine room equipments. As this requires information and a level of detail not yet known, a 200kW emergency generator set is selected. For sizing the Generac SD200 is used, this includes a tank etc and measures 1.55m in length, 0.54m in width and 1.18m in height. As the emergency generator room also has to contain its own switchboard, the size of the room will be set at 4m in length, 2m in width and one deckheight.

Stairs are a critical aspect in cruise ship design. They strongly influence the logistics and the evacuation process onboard. The size of staircases are regulated by the SOLAS and are dependent on the total amount of persons using them during an escape scenario. As the analysis of such an scenario needs a initial configuration, it is chosen to fix the initial size of the staircases at 3m by 3m. For both the sizing of corridors as well as stairs the amount of persons using them in different evacuation scenarios needs to be known. This can only be known after configuring the systems and spaces in an initial design. The solution applied here is to fix the initial dimensions of the stairs and to leave corridors out. The space required for corridors is included in the space required for the accommodations. In the future, work could be done to ease the process of adding corridors in an early stage model or in a two stage approach as will be further discussed in the recommendations in Section 6.3. Each MVZ has its own staircase which goes from the lower decks all the way to the topdeck.

Lastly, there are guidelines formulated by the CLIA for their members to stimulate them to do business even more sustainable and safer. Examples of this are extra spare lifejackets near the muster stations or lifeboat embarkation points in excess of the IMO required amount, guidelines on planning passages and extensive guidelines on waste and energy management, (Darr, 2016). These guidelines are for the bigger part operational guidelines or guidelines specific for certain areas of the ship and therefore too detailed to take into account already. Other regulations which might prove of interest in later design stages are those of the United States Public Health (USPH), Passenger Vessel Accessibility Guidelines (PVAG), or the Cruise Vessel Security and Safety Act 2010 (CVSSA). Those regulations deal with hygienic matters related to food disposal for instance, accessibility standards for disabled people and safety and security systems and measurements onboard such as peep holes in doors of cabins. The final thing to mention is the layout of hallways, rooms and corridors in terms of safety evacuation (Aarnio, 2014). Many rules and guidelines do exist and for passengers ships this seems to be an important feature to consider.

3.4 General requirements

This subsection will deal with objects as the hull, laundry and ballast systems. These items originate from the cruise market in general or from the ship's nautical functions and are not direct topic of optimization. Meaning that while it will be present in the designs, the HVAC is not especially studied to find the best and cheapest solution give different sizes of cruise ships and HVAC solutions.

One of those items is the hull itself. The hull consists of the shape of the underwater body of the ship and the topside shape. This shape is used to pack all systems in and therefore can also be named container or envelope. The shape used consists of a foreship, midship cross-section and aftship and is scaled to the desired size. This is done by inserting a midship section based on the midship cross-section. And by adapting the length, beam and draft of the foreship and aftship shape. The most important properties for the hull shape are the length (L), beam (B), draft (T) and maximum height (H). These parameters determine the size of the ship itself and are strongly dependent on all the systems and spaces it has to house.

Table 3.1: Initial boundaries on the hull dimensions

Lower boundary		Dimension		Upper boundary
110	$<$	L	$<$	150
17	$<$	B	$<$	22
3	$<$	T	$<$	7

Cruise or passenger vessels usually have a reception or central hall area comparable to the lobby of an hotel. This is the area where passengers board the ship when docked in a port. It needs to be big enough for people to get together before leaving the ship but also provide a good first impression and have good access to other areas in the ship. To serve as an entrance to the vessel it has to reach from side-to-side. With a length around 12 meters there should be sufficient space to house a reception desk, a small office or a small store, kiosk or bistro. The deckheight is initially set at one standard deckheight.

The laundry room is set to $40m^2$ based on a comparison ship.

When travelling through the cold Polar regions or the warm and humid Caribbean regions the conditions onboard have to be controlled carefully to ensure a comfortable trip. Therefore HVAC systems are fitted onboard. Besides HVAC, technical space is also required for all sorts of other equipment onboard not named yet such as fire-fighting systems, pumps and electricity converters. This is grouped together as technical space and its size is related to the total volume of the ship. Based on numbers gained from Watson (2002) the volume of the technical spaces is set to 4% of the displacement. This volume is divided over 6 different spaces as the technical space is usually spread over the ship.

Critical for stability is the ballast system. The Ballast Water Convention requires treatment of ballast water before discharging it back into the ocean to prevent the spread of species outside their natural habitat. For any newbuild such a treatment systems should be considered as the convention will enter into force soon. he space for such an installation is included in the technical space. The space required for the ballast water tank depends on the volume required. The ballast water is mainly used to compensate for the difference in departure and arrival condition, thus the consumed fuel, goods and oil. Therefore the ballast water capacity is determined based on the fuel tank capacity and the stores. The total ballast water capacity is set to be equal to 80% of the sum of the fuel capacity and the stores capacity.

Chapter 4. A Design Process based on IECEM

4.1 Introduction

As a result of the market study, it is chosen to study the influence of the ship's luxury level and operational scenario on the economical performance of the design. To do this the concept exploration method has to comply with some requirements as discussed in section 4.2. The chosen concept exploration method is the Interactive Evolutionary Concept Exploration Method (IECEM). This will be described in section 4.3 with special focus on how it is used for this study. The fourth section will cope with some theoretical aspects of the Ship Synthesis Model (SSM), the actual definition of the SSM will be described in section 4.7. Section 4.5 will elaborate on the applied measurements of performance(MoPs), these MoPs are used to rank the different designs and select the best design. The IECEM is compared to an existing Conoship design to check the accuracy of the MoPs. This validation is further shown in Section 4.6. The last section provides the implementation of the requirements and characteristics into a SSM.

4.2 Method Requirements

Based on an initial study of the method, the results of the market study and discussions at Conoship the decision was made to study the effects of a variation in the luxury level and operational scenario of the ship on its economical performance. Besides these, the influence of a different solution for a single system on the costs and performances of the ship was a point of interest to study. To study these influences the resulting configuration needs a basic level of feasibility, meaning that they have to comply with basic naval architecture criteria such as stability. The entire search is directed to generate more favourable designs. Subsection4.2.4 therefore will discus optimality and define an objective function. These four topics together form a set of requirements to the approach used and will be further discussed in the following subsections.

4.2.1 Operational Scenario

As discussed in section 2.6, there is a variety in operational scenarios. With an operational scenario, aspects as the duration of a cruise, the average speed sailed, the maximum speed and the distance sailed in a cruise are described. As previously suggested the ship will serve a combination of niche-markets, it will sail a 19 week period in and around the Arctic region. After that it will reposition to the Antarctic region in a 6 week period, making smaller cruises along the North-American east coast and the South-American west coast as can be seen in figure 4.1. After the arrival in the Antarctic region the ship will spend a 19 weeks period cruising in the Antarctic region. Finally the ship will reposition again in a 6 week period to the Arctic region. The remaining two weeks are reserved for maintenance, inspection and conversion.

Cruising in the Polar regions is more difficult compared to other regions as there is no major airport nearby. In case of the Antarctic region passengers will fly to Ushuaia and board the ship there. This means that the first and last 550nm of the cruise exists of crossing the Drake Passage. Based on this three operational scenarios are established, for the first one the ship will use a speed of 11kn to do this crossing and thus spend roughly two days on the crossing. In this scenario the ship will offer nine day cruises of which four days are spend on the journey to the Antarctic region and five days are spend in the Antarctic region. With the other two scenarios the speed to travel to the Antarctic region is raised to 16kn and 22kn, but the time in the region is kept on five days. The idea is that by shortening the time travelling to the region

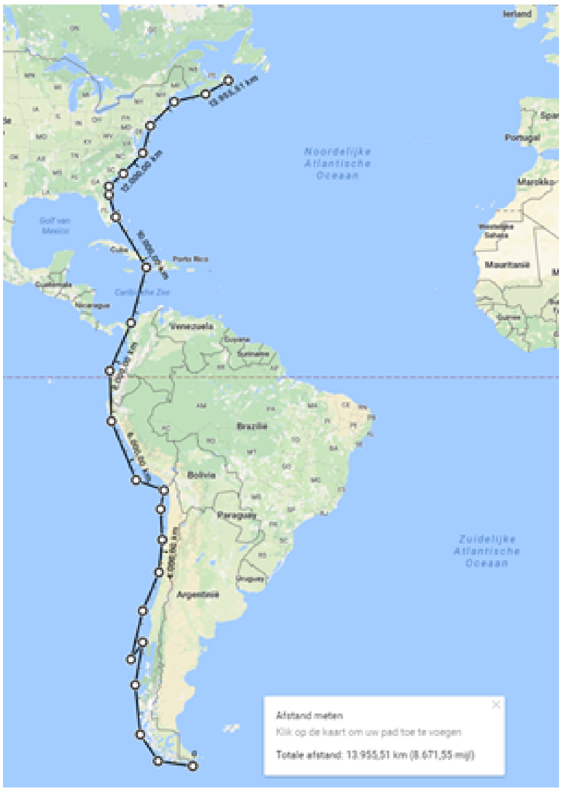


Figure 4.1: Example route from the Arctic region to the Antarctic region

more cruises can be offered and the earnings a day are higher making the ship more profitable while offering the same time in the Antarctic region. Table 4.1 gives an oversight of the difference in operational parameters for the three types of cruises. The trade-off here is that by raising the speed the required propulsion power increases and therefore both the building costs are expected to raise as well as the fuel consumption. The IECEM should therefore provide insight in the effect of these operations on the ship's expenses and the ship's earnings.

Table 4.1: The three different cruises varied within the IECEM

Speed	Days in transit	Days visiting the Area	Total days	Number of trips
11	4	5	9	14
16	3	5	8	16
22	2	5	7	19

The speed in the Antarctic region is set to 8kn and is fixed for all three different scenarios as they will offer the same sort of experience while in the area. The cruises in the Arctic area are rather similar and within this research are kept the same. The example route showed in Figure 4.1 is used to determine the operational settings for the six weeks repositioning period from north to south and vice versa. The required transit speed is determined based on the time it takes to sail and the required speed for the transit to the area as given in Table 4.1. The transit towards the polar area, the speed in the area, the speed while repositioning between North and South and the maximum speed are presented in Table 4.2. The repositioning speed is set at 16 knots, given the distance of the route in Figure 4.1 it will take 20 days of non stop sailing to complete the journey. Taking into account that there is a 6 week, 42 day period reserved for the repositioning, there is sufficient time to do cruises during the repositioning. For the slower operational scenario, number one, the repositioning speed is lowered to 13 knots for reasons of over powering in its normal operations. The maximum speed is set at the maximum of the repositioning speed or speed to region + 1kn. This little extra speed margin is applied to increase the ship's capability to make up for delays.

Table 4.2: The different design speeds applied in the design process.

	Operational scenario		
	Slow	Medium	Fast
Repositioning speed [kn]	13	16	16
Speed to region [kn]	11	16	22
Max speed [kn]	14	17	23
Cruise speed in Polar region [kn]	8	8	8

The above described operational scenarios will be used as input of the concept exploration study and are therefore considered as an requirement to the method, as it should be able to handle these different scenarios as well as similar scenarios in case of future changes.

4.2.2 Luxury levels

Within the small vessel expedition cruise segment one can distinguish two type of ships: the ultra-luxury vessels such as those recently ordered by Scenic Cruising or Crystal Cruises, (Scenic cruises, 2015). And the more basic expedition vessels such as those operated by National Geographic-Lindblad or Quark expeditions, (National Geographic Lindblad, 2016). The biggest difference is in what is here called the on board luxury; the size of the rooms, number of restaurants, entertainment features and pool sizes. Within this research the choice is made to go for the more basic expedition vessel as this better fits the Conoship portfolio and an earlier project already resulted in a ship suitable for the luxury segment. Within this basic concept a couple of variations will be considered to identify the influence of such a variation on resulting configuration and performances. The translation to the different luxury levels is made in terms of sizes and availability of objects. For this study the following objects are used to construct three different luxury levels.

The size of the passengers cabins is the first object varied. Where cabin sizes in this segment usually lie around $24m^2$, cabin sizes of $32m^2$ and $40m^2$ will be compared to see the influence of the bigger rooms on the ship layout. All the passenger rooms will be located in the superstructure and on the outside.

The number of restaurants are fixed, there is a lounge located higher on the ship where drinks can be consumed and breakfast may be served and there will be a full serve restaurant which is able to seat the entire group of passengers. For both places it is important to be able to look outside and enjoy the surroundings while consuming your meal. Especially with the lounge as it will be used for pre-excursion briefings as well. The size of the restaurant is set at $1.6m^2$ a person.

For the lounge, auditorium and theatre the size is varied based on the luxury level, see Table 4.3. In the basic luxury level no separate theatre will be fitted, the briefings with instructions just before going ashore will be held in the lounge and the ship itself is focused on the shore experience. The theatre will be fitted in case of a Normal or Luxe level, where the $20m^2$ is needed for the stage and besides that a space per passenger is used. In case of the Luxe level a separate auditorium will be installed for half the capacity of passengers as there is an operational limit on the amount of people sent ashore, as is discussed in Section 2.6.

Not only objects and systems were varied, also the crew to passenger ratio and the costs of the food are taken into account. The more crew per passenger the better the crew is suited to provide en-suite service and special requests. Therefore the crew to passenger ratio is often seen as a luxury indicator although this implies that improvements in efficiency of the on board operations reduces the level of luxury. The costs of food are used as a measure of the food luxuriousness because food is considered an important part of the passenger experience during a cruise (Oates, 2016).

Besides this, there is an unlimited amount of options available for consideration, such as a pool, pub, disco's or even a brewery amongst others but for now they are left out of consideration

Table 4.3: Options for different objects varying for the three luxury levels

Name:	Basic	Luxury Category Normal	Luxe	Seats (% passengers)
Restaurant	1.6 $m^2/seat$	$1.6m^2/seat$	$1.6m^2/seat$	100
Lounge	$1.55m^2/seat$	$1.55m^2/seat$	$1.85m^2/seat$	100
Cabin size	$24m^2$	$32m^2$	$40m^2$	100
Theatre	0	$20m^2 + 1.55m^2/seat$	$20m^2 + 1.55m^2/seat$	100
Auditorium	in lounge	in theatre	$1.5m^2/seat$	50
Crew/passenger ratio	0.6	0.8	1.0	-
Food costs per passenger	65€$/day$	75€$/day$	85€$/day$	-

as they strongly depend on brand strategies of an operator and at the moment no specific operator is involved. The current configuration therefore will generate a basic ship which includes all necessary objects and can be customized for a specific customer in a later stage.

4.2.3 Feasibility

In general there are two types of requirements, the negotiable and the non-negotiable requirements. Non-negotiable requirements have to be met, this can be because the design won't be safe otherwise or will be infeasible to build. These non-negotiable requirements are implemented in the packing algorithm as constraints, meaning that every design will have to comply with minimum or maximum values in order to be considered feasible. The MoPs are discussed in Section 4.5, here six special ones are discussed as they are used to judge feasibility. van Oers (2011) names six constraints securing the feasibility of a design.

1. *The space constraint*, this constraint ensures that all systems as defined in the SSM are configured in the design. It should ensure sufficient space in the design for all systems to properly function.

2. *Draft/Buoyancy constraint*, is defined as the design draft minus the actual draft. When the actual draft, which is based on the actual displacement, is deeper then the design draft, the draft used for the hydrostatic calculations and the power prediction, the hydrostatic calculations and power prediction are invalid and the buoyancy of the design becomes an issue.

3. *Stability constraint*, is used to ensure that the ship will float upright. This is achieved by requiring a minimum GMt. A maximum GMt is used to filter out the extreme designs and because a high GMt results in rude ship motions. Besides the GMt constraint, the damage stability is implicitly included as the floodable length calculation is used for positioning the bulkheads.

4. *Trim constraint*, the trim constraint is necessary to assure the longitudinal division of weight. This ensures that the design in a later stage is able to float upright. The trim constraint limits the distance between the Longitudinal Center of Gravity (LCG) and the Longitudinal Centre of Buoyancy (LCB).

5. *Reserve Buoyancy constraint*, during the packing process the bulkheads are placed based on a floodable calculation and a user-defined damage length, as will be further explained in Subsection 4.5.3. If the bulkheads can not be placed while meeting the floodable length requirements, the design fails on the first constraint. If they can be placed, the reserve buoyancy constraint is met.

6. *Speed, Endurance and Range constraint*, these properties are defined in the operational scenarios and are used to size the propulsion plant and fuel tanks. In this way the constraint, just as with the reserve buoyancy constraint, is met as long as all systems get packed.

These constraints are applied to support initial feasibility. During post-processing additional constraints might be applied to further reduce the feasible number of designs. The implied limits are presented in Table 4.4.

Table 4.4: The limits used with the feasibility constraints

Property	Value
Damage length percentage	3% of $L_{oa} + 3m$
Minimum freeboard	3.5m
Delta CoG_x	6m
GMt_{min}	0m
GMt_{max}	10m
Min. Packing Density	0.3

4.2.4 Optimality

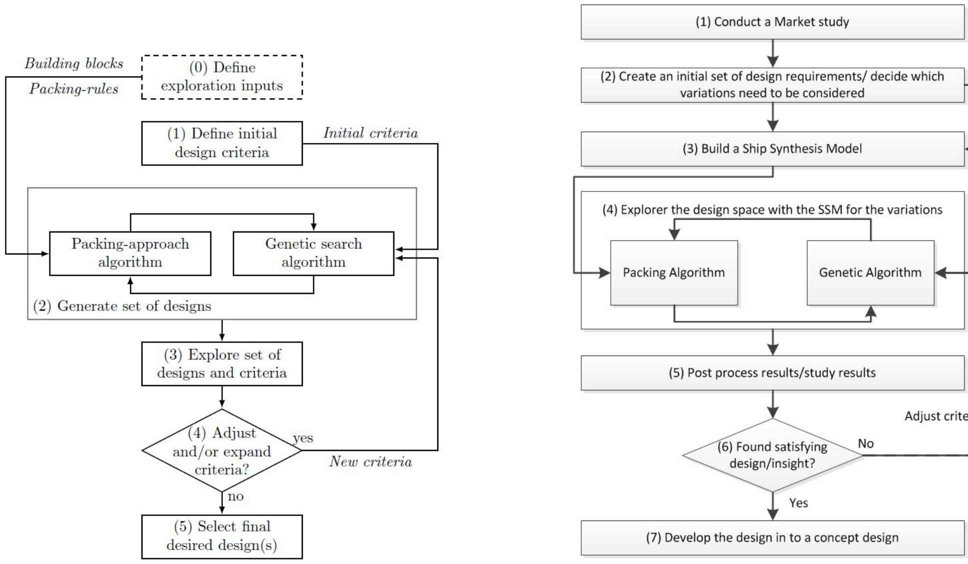
The IECEM distinguishes itself because it does not require you to define the 'best design' up front. Instead it allows to enter the soft constraints piece by piece during the search iterations enabling the user to steer the search process based on insights and knowledge gained from the process (Duchateau, 2016). The initial objective will be minimizing the negative packing density, as defined as the volume occupied by the placed objects divided by the enclosed volume of the ship. Additional negotiable design requirements can be added as extra objectives during the design iterations. The reason behind this is twofold, first when adding them as an objective a design will not fail but can only be better or worse depending on its compliance with the objective. Second it narrows the search during the process, but ensures that a good overview of the design and solution space is kept. This ensures that based on the search results the objectives can be altered as priorities might shift depending on the acquired results.

Also different objectives can be added to make sure that the acquired solutions fill the entire solution space. For instance by looking to the maximum packing density it is likely that the minimum length will not be found. This method of searching allows the designer to slowly define what is called the desired solution, the set of design requirements which define the design with the most preferable characteristics. This method has been used before in previous studies with the packing approach by van Oers (2011); Zandstra (2014); Duchateau (2016). Additional requirement which can be added may include more strict dimension restrictions, locations of systems or objects, or constraints on the luxury level or operational scenario. Each step in the search path is called a 'run', the first run usually is the Exploratory Run as it is used to get a general overview of the design space. The other runs are called Steering Runs as they tend to steer the search progress to fully explorer the design space. The applied search path within this research will be described in Chapter 5.

4.3 Description of the process

The process to form a design is adopted from Duchateau (2016) and altered to fit the situation see Figure 4.2. The initiation phase in which the inputs are defined in Figure 4.2a numbered 0, is in the adopted process a market study as most input will be obtained from the market study and the niche-market resulting from this market study. Besides the market study also regulations and publications will be consulted for informations but this is considered part of the market research as the chosen market has a strong influence on it.

1. The first step is a market study and is meant to provide an initial starting ground for the design process. This initial step should provide sufficient information to have a global understanding of the necessary capabilities of the ship. Therefore the market will be studied to see trends and understand the current demand for cruises and cruise vessels, besides the market study other sources of information are regulatory institutions, as different markets



(a) Description of the Concept Exploration process as described in (Duchateau, 2016)

(b) Description of the Concept Exploration process as described by the author

Figure 4.2: Diagram of the original and adopted Concept Exploration process, see (Duchateau, 2016)

and categories of vessels may have different regulations. A clearer image of these regulations will assist in analysing existing tonnage and the requirements for a new vessel. The market study results in a niche-market with characteristics and a operational scenario.

2. The second step focusses on setting the boundary conditions on the design space. Which negotiable or non-negotiable design requirements will be topic of the exploration study and what can be varied to meet these requirements. For instance within which boundaries the length or the beam of the vessel can be changed. During this step it is not only important to think of what one wants as the possible results, but also how one wants to measure these results. What MoPs should be used to compare the different designs and judge about their performances. These requirements are seen as an 'initial' set of requirements as they often change during the design process. Based on the information collected, a list of required systems and spaces can be assembled after which step three can start and a SSM can be made to pack design from by the IECEM.

3. Step three starts with the translation of the requirements and variations to a set of objects and Object of Objects(OoO), these objects will form the SSM. The main requirement for the SSM is that is able to generate designs for the different variations described to study. By generating the designs for the variations described in Step 2, insight in their performances can be acquired in Step 5.

4. Step four is where the real design process starts, although one could argue that some of the most important decisions are taken when limiting the design space, here the actual concept exploration starts. Steps four to six represent the iterative design loop where designs are generated, evaluated and based on the gained insights provides feedback. Hence this is the interactive evolutionary part of the concept exploration (Duchateau, 2016).

   Step four, the generation of designs, consists of the packing algorithm which generate the designs and the genetic algorithm which steers the generation process based on the feasibility criteria and the objective function. The generation of designs knows three phases:

4.a The first phase in which the hull and decks are defined. In this stage the main dimensions of the ship are determined and sufficient information about the hull shape is known to do an resistance and propulsion power analysis. This analysis can then be used to determine the size of the propulsion installation.

4.b In the second phase all major systems influencing the subdivision of the hull are defined. For instance the generator room which needs to be in one compartment is a influencer of the locations of the bulkheads. But also a stabilizer as its location strongly influences its effectiveness. The last system to be defined is the bulkhead system. After the bulkhead system this phase is finished and another set of analysis can be done such as the definition of Main Vertical Zones. The definition of MVZ's can in turn be used for the location of stairs.

4.c The third and final phase consists of all systems remaining. These systems are ordered in a decreasing level of complexity. As for instance ballast tanks potentially could be fitted in any left over void or double bottom space. Where fuel tanks are already a bit more complex as they should have a clearance to the hull of 0.76m. After successfully completing the third phase all systems are defined and the actual packing process is done. Now all the other performance parameters are calculated and the criteria and objective feedback is returned to the Genetic Algorithm.

5. Step five, the processing of the results, this is done within the interactive environment of the applied IECEM software. Here custom plots can be made of different design variables to allow for quantitative analysis as well as the visual representation of individual results to do some more qualitative analysis. To study more general trends and effects versus looking to the layout of individual designs.

6. Step six, The loop of these steps is broken when sufficient insight is gained. Although of course the term 'sufficient' is rather vague, in practise this would probably result in a combination of having promising design results within a time constraint.

7. Finally step seven takes the resulting outcome of the IECEM study, the 3D-models, trend lines and insights to continue the design process and develop a concept design.

4.4 Ship Synthesis Model

The Ship Synthesis Model contains all objects used to describe the ship concept. The objects in the model can either describe systems, such as engines, lifeboats or generator sets, but also spaces such as a bridge, a passengers cabin or a double bottom tank. To organize all these objects in the model there are so called 'Packing Systems' or 'Objects of Objects'. These 'Packing Systems' contain multiple objects which represent components and together form a systems such as a generator room. These individual objects can have different properties such as volume or area, mass, CoG, or a relative location. To further illustrate this an example of a generator room is provided, this generator room exists of an space and two engines as shown in Figure 4.3. Besides these two there is a third object, a logical object, which is used to position the exhaust stack above the generator room and does not have any physical properties as weight or volume. The generator is selected from a database with example generators based on the power required for the current design. The generator room is dimensioned on the length of the selected generator and the ship's beam. This way the object of objects will vary for every different design as the required power is both related to resistance as to the hotel load, see Subsection 4.5.1 for more details on the power prediction method.

The generator room itself is a part of the ship's propulsion system of which an example is shown in Figure 4.4. The entire propulsion system in the example exists of seven OoO; two generator rooms, a propulsion room, two exhaust stacks and two sets of exhaust piping. The small, square red blocks are logical objects just like the dark grey ones. They constrain placement of the exhaust stack to a nearby bulkhead. The pink surfaces are blocked space, they prevent

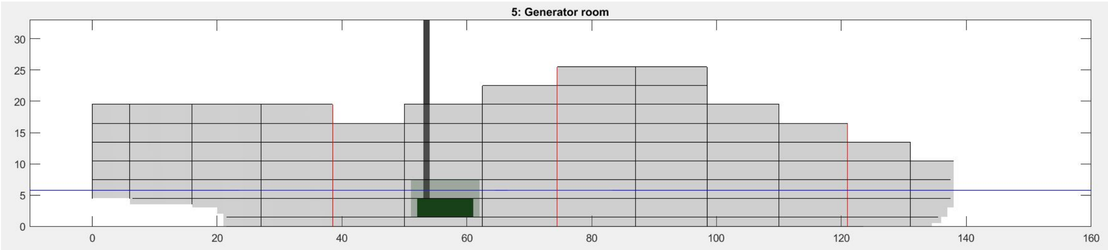


Figure 4.3: The generator room object

other objects blocking the exhaust stacks and ensure a sufficient airflow around the exhaust stack. The most important part is that the space above is blocked as lengthening the stacks is rather easy, in the situation of Figure 4.4 the rear exhaust stack is partly obstructed by a compartment but this could be easily fixed afterwards by raising the exhaust a deck or two.

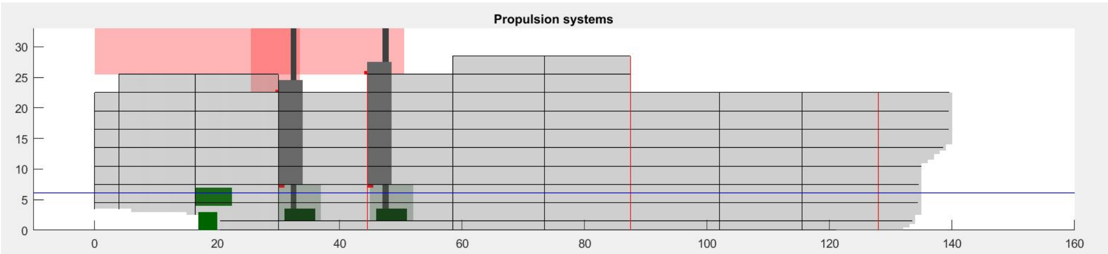


Figure 4.4: An example of a configuration of the propulsion system.

The SSM is thus built based on 'Packing Systems' or 'Objects of objects'. One of the advantages of using these Objects of Objects to cluster the separate objects is that they can be placed in once, thus instead of placing the engine room space object and then separately placing the engine in there, the algorithm places the engine room Object of Objects and uses local position coordinates to place the engine with respect to the space. Overlap management and the transverse position is also done for the Object of Objects as a whole instead of every object separately. The exact functioning of these features is more thoroughly described by van Oers and Hopman (2012).

The objects itself represents a system or space on board of the ship, but as mentioned in the example of the engine room there are also logical objects and objects blocking space. In total there are seven different object types as defined in van Oers (2011) and adopted in the Packing based IECEM by Duchateau (2016).

1. *Envelope object*, to model the hull and superstructure shape.

2. *Subdivision objects*, to model bulkheads and decks.

3. *Hard objects*, to model physical objects with a fixed shape (for example engines, lifeboats or bowthrusters).

4. *Soft objects*, to model physical objects with a variable shape. Often volume or area based objects or spaces (for example fuel tanks, cabins or restaurants).

5. *Free Space objects*, to model space blocked for clearance of the exhaust or the required viewing arc from the bridge.

6. *Connection objects*, to model connections between objects such as the exhaust piping in the example of Figure 4.4 that connects the generator rooms with the exhaust stacks.

7. *Logical objects*, to model local constraints in the model such as the location of the exhaust stack next to a bulkhead, but also to model.

Based on these object types all the OoO or Packing Systems are build in the SSM. The order in which the OoO are packed in a possible ship design is fixed by the order in which they are modelled, this order is based on the number of constraints for that OoO, the size of the objects in the OoO and the hard objects before the soft objects as the soft objects can form themselves around the hard objects (Zandstra, 2014). This translates to an order in which the hull and decks are first and second respectively, closely followed by the most constrained and biggest OoO's. A list with all the OoO's and there order as applied in this research is given in section 4.7.

4.5 Measurement of Performance

One of the advantages of the use of the IECEM is that it allows insight into the link between the design space and the performance space. In order to study this link, a performance space needs to be defined. This performance space is defined by one or multiple performance parameters, for example the ship's resistance, stability and costs. For each performance parameter a method of evaluation needs to be defined and implemented. While defining this it is important to keep in mind the performance parameters which are already available in the packing algorithm and which, with some minor alternations, can be reused (Duchateau, 2016; Takken, 2008). Within this study the following performance parameters will be used: resistance and propulsion power, intact stability, building costs and operational costs. Now the MoPs used and the required modifications are briefly discussed.

4.5.1 Resistance/Power

The power required to propel the ship is based on the resistance and the speed and efficiencies of the ship. To predict the resistance the statistical method of Holtrop & Mennen is usedHoltrop and Mennen (1982, 1984). The input values of the method are obtained from the scaled hull shape and the design variables. This method results in a total resistance which is then converted to a required propulsion power under the assumption of the efficiencies of Table 4.5. Besides the gearbox and the total propulsion efficiency, a 25% seamargin has also been taken into account.

Table 4.5: Efficiencies used to determine the required propulsion power

Efficiency	-
Gearbox	0.98
Total propulsion efficiency	0.68
Seamargin	25%

The required propulsion power is determined at two speeds, a cruising speed and a maximum speed. The power required for the maximum speed is used to size the engines while for the fuel consumption both the power at cruising and top speed are used in combination with the endurance at those speeds. Based on the required power the diesel generators and the azimuth propulsion is selected from a database lookup of existing engines. Before selecting the generators the total required power is determined by adding the hotel load to the required propulsion power. The hotel load is determined by Formula 4.1, where the power density factor of $0.0745kW/m^2$ is obtained from van der Meer (2014). The power density factor is determined for nominal loads, therefore the $\frac{maximum}{nominal}$ load factor is used to determine the maximum hotel load.

$$Hotel\_load = floor\_area * power\_density * \frac{Max\_load}{Nominal\_load} \tag{4.1}$$

The maximum total load is then divided by three to determine the required power of one generator set. In total four of these generators will be installed, meaning that one spare generator is taken in to account. The azimuth propulsion is sized on the maximum propulsion power. Therefore this performance parameter is used to asses what the performance of the ship in terms of resistance as well as input for the size of the equipment. Eventually the same method is reused after configuring a design to check if it still complies with the actual draft and displacement.

4.5.2 Intact stability and lightweight

The intact transverse stability (GMt) is one of the feasibility criteria used by the algorithm. Therefore the packing approach has a functionality to determine the GMt based on the center of buoyancy (CoB) and the center of gravity (CoG) of the ship. Where the center of buoyancy is determined for the scaled hull shape, the center of gravity of the ship depends on the weight distribution.

Another feasibility criteria is the difference between the design draft and the actual draft. The actual draft is based on the ship's lightweight and displacement. When the actual draft is deeper then the design draft the resistance of the ship will be higher than what the engines are sized for and the ship will not maintain its required speeds. It will also most likely also fail its freeboard requirement, making it infeasible.

The third feasibility criteria related to the weight of the vessel is the trim condition. This criteria tends to minimize the longtitudinal distance between the CoB and CoG and thereby minimizing trim. The trim is also dependent on the weight distribution.

These feasibility criteria depend on the weight distribution of the vessel. This weight distribution in turn is based on the configuration of spaces and systems on board and the individual weight of each item. To approach the lightweight and CoG of the ship as to properly evaluate the performance of the ship, a method to determine the weight distribution is used, based on the areas and volumes of the systems on board (Takken, 2008; Duchateau, 2016). These areas and volumes are multiplied with density factors to obtain a system weight. Within these density factors multiple different system types are distinguished such as 'Passengers Accommodation', 'Propulsion room' or 'Void'. Not only system types but also different weight categories are used. A distinction is made between 'Structural weights', 'Propulsion system weights', 'Electrical systems weights', 'Command and Communication systems weight', 'Auxiliary system weight' and 'Outfit and Furnishing weight' as this distinction is most common in ship work breakdown structures (SWBS). Besides a weight based on volume or area, an option has been included to add discrete weights with their own specific CoG. In this way a engine can be modelled in the engine room or a lifeboat can be modelled on deck. To obtain a CoG of the volume and area based weights, the volumetric CoG of the object is used in case of a volume based object or the CoG of the area in case of an area based weight. The individual weights and CoGs are then combined to a lightweight and a ship center of gravity.

In the process a couple of corrections are applied to the weight. The 'Structural weight' group of the spaces close to the main deck and the bottom of the ship are corrected as they deliver a bigger contribution to the sectional modulus to withstand the bending moment. Furthermore the length of the ship is also related to the structural weight, shorter ships tend to have a relatively heavier construction. Therefore a correction is applied to the structural weight for the ship's length.

Most of this system functioned without any required modifications as it is one of the more essential parts of the configuration tool. Although the density factors had to be altered to fit for cruise vessels as outfitting in accommodations, restaurants and public spaces on board cruise vessels tends to be more heavy compared to navy vessels. Because of reasons of confidentiality the used factors are not published. One other alternation done to the system is the introduction of secondary weight objects in the 'Structural weight' group. As normal secondary objects don't add to the structural weight but rather to one of the other groups, a main engine adds to the 'Propulsion system weights' group. This secondary object which adds weight to the 'Structural weight' group is used to model the presence of ice-strengthening. As a smaller cruise ship in the scope of this design project might require a polar class notation, ice-strengthening needs to be considered. Because the weight of the extra steel to reinforce the hull is located mainly around the waterline this is modelled as a discrete mass object. One other option considered is altering the structural weight groups for the different systems, but this would increase weight among the whole ship and not reflect correctly to the CoG, it would be too high due to all the structural weight added to the super structure.

4.5.3 Damage Stability

The floodable length calculation is used by the IECEM to place the bulkheads. Based on a method proposed in Herner et al. (1952) the permissible floodable length curve is estimated at the design draft (T_{des}). Bulkheads are placed accordingly using the permissible floodable length, as described in van Diesen (2007). Therefore the ship should comply to simplified deterministic damage stability regulations.

In 2009 the probabilistic damage stability regulations entered into force. For small ships complying to the probabilistic regulations tends to be challenging. In practice analysing the probabilistic damage stability in early concept design phases improves the feasibility of the design results. The damage stability calculations in case of the probabilistic calculations are rather extensive and require a more advanced space model than the SSM build in this research. Therefore it is noted that more extensive, probabilistic damage stability could benefit the design efforts in early stages of the design process but it is also decided not to pursue this within this research. Instead a recommendation has been written in section 6.3.

4.5.4 Fire safety

The fire safety system (FSS)code International Maritime Organization (2001), addresses fire safety on board vessels. It is active in multiple stages such as prevention, fire fighting and safe evacuation. One of the regulations in the FSS code is the fire zones or Main Vertical Zones (MVZ), these MVZs are restricted in length and area, meaning that one space on board a ship is not allowed to be larger then $1600m^2$ or longer then 48m. Opposite the watertight bulkheads which only have to go up to the main deck or bulkhead deck, the fire zone bulkheads have to go all the way up and need to be A60[1] isolated. This means that they influence the design as they mostly define the zoning in the ship's superstructure. Each MVZ needs to have it's own staircase, the dimensions of this staircase depends on the number of people on board using them in case of an emergency. As the layout of the ship is yet unknown, just as the number of persons present on each decks it is impossible to determine the dimensions of the staircases. Therefore these dimensions are initially fixed at 3m by 3m. Within the space configuration tool, an additional function is developed to determine the location and size of the MVZs. Based on the length of the vessel, the number of zones is determined. Within the current bulkhead configuration, a combination of bulkheads is selected which comply with the length and area requirements for MVZs.

The configuration of the MVZs is used to determine the required number of main staircases and each staircase is given a space constraint for the specific MVZ they are assigned to. In this way, the space consuming staircases are already considered in an early stage and every zone will have sufficient space to fit the staircase on the different decks. One exemption is made for the forward MVZ, if the length of the MVZ is less then 10m no staircase is fitted as the default staircase would be to big and cause the design to fail. In a similar fashion multiple other spaces can be separated over different MVZs to ensure redundancy on board the vessel, for instance the generator rooms, kitchens or emergency control rooms as required by the Safe-Return-to-Port (SRtP) regulations. With the stairs a proof of concept is given, to further implement this some additional development is required as for now the systems which need to be in separate MVZs are manually programmed in the MVZ part of the program code. If this has to be done for multiple systems, it would be better to give the object representing the system or space a property that indicates whether or not it has to be separated.

[1] A60 is an isolation grade as described in the FSS code, where the 60 means that the isolation has to be able to withstand the fire for 60 minutes.

4.5.5 Costs modelling

One of the most important performance parameters in commercial ship design is the economic performance of the vessel. Within this research the economical performances provide a basis to study the effects of different luxury levels and operational scenarios for a cruise vessel. To be able to directly relate the variations in the ship synthesis model to the economic performance, multiple economic parameters are calculated such as the building costs, the operating expenses and the earnings.

The first item is the building cost, after an initial attempt to do this based on the different weight groups previously calculated. A costs estimation method based on existing price calculations from Barkmeijer Shipyards has been developed. After an explanation of how they established the price in the quotation for a cruise ship of comparable size, a cost function was written based on accommodation weight, installed power, steelweight, the ship's volume and the total building costs. Due to confidentiality reasons the exact numbers and factors used are not given but an overview of the structure of the price calculation is summarized. The building price is established out of the following items:

- *The steelwork*, this is based on the vessel's steelweight and takes into account both the used steelweight from the design as well as some scrap metal in the materials part. Based on the weight and the amount of work the costs are estimated. There is also an item for off-the-shelf components. This item is considered fixed for this size of vessels.
- *Paint work*, the costs of the paintwork is based on the amount of volume of the ship and a factor for the costs per volume.
- *Deck and Mooring equipment*, these costs are fixed as ships of roughly the same size all require about the same equipment.
- *Fire and Safety equipment*, is based on the ship's volume and a costs per volume factor.
- *Accommodation*, the costs of the accommodation are based on the weight of the accommodation system as determined by the weight calculation module and a costs per weight factor.
- *Ventilation and HVAC equipment*, the costs of the ventilation and HVAC equipment is a fixed price. Partly because the lack of information to make it variable and because the size of pumps, coolers and heaters is discrete as well. Therefore this is often kept similar for the same size of ships during the preliminary design phase.
- *The electrical installation*, costs are determined based on the electrical weight group from the weight calculation module and a price per weight factor.
- *Navigation and communication systems*, again a fixed price.
- *Propulsion equipment*, is based on a fixed general price existing of the auxiliary propulsion equipment and a discrete price for engines and propulsion pods obtained from the individual objects.
- *Machinery equipment*, similar to propulsion equipment the main engines have a discrete prices which can be imported from the individual objects and for the auxiliary machinery there is a price a based on the kW's installed power.
- *Secondary Object costs*, some systems or items in the model are defined as secondary object such as the lifeboats or the main engines. For these secondary objects the costs can be obtained from the object itself as the size of the object in these situation is often adapted from a database structure.
- I*nsurance, Financing and other*, these items are a fixed percentage of the building price.

The operating costs are determined based the thesis work of Epstein (2014). In his thesis he describes a method to estimate the operating costs in an early design stage. This method is based on a statistical study of existing cruise ships from the Royal Caribbean Cruise Line, Norwegian Cruise Line and Carnival Cruise Line brands. These ships are in the size range of 30000 - 225000 GT and thus bigger than the ships studied in this research. Economies of scale has a negative effect in this situation as the resulting factors in Epstein's thesis work are too low for the smaller vessels. The financial data is obtained from the financial year reports of these cruise companies. A note made is that the business model of these kind of mass-market ships differs significantly from the smaller, luxury or speciality market operators. Where half of the revenue in the mass-market segments is usually made with on board sales, the luxury or speciality segments often operate on basis of an all-inclusive price.

Nevertheless the methods are still considered useful as it proves the correlation between the ship's parameters and the costs. Based on data obtained from the financial statement of Lindblad expedition and the comparision with a cost breakdown found online the right coefficients are obtained to fit small cruise vessels, (National Geographic Lindblad, 2016; Wahlstrom, 2015). Because the costs are studied to understand the influences of modifications in the design, only those costs items are determined which are related to design parameters. Therefore the following cost items are included:

- Fuel costs
- Crew and payrolling costs
- Food and beverages
- Depreciation
- Interest
- Others such as maintenance and repair

The coefficients used in the formulas can be found in Table 4.6. To determine the fuel costs a similar formula was used as found in the original work. A third condition, dynamic positioning, was added to the original two conditions; at sea and in port. The ship was expected to do less port visits and do more frequently shore landings with the Zodiacs while keeping the ship at position with the dynamic positioning system. This condition is often seen in smaller cruise vessels and therefore considered necessary to enable. Within this condition it is assumed that 90% of P_{other} was used and 35% of P_{cruise}. Where P_{other} is the amount of power used for hotel functions and P_{cruise} is the power used to sail at cruising speed. In this way a more sophisticated operational profile could be used to better represent the 'real' condition. The actual division of the time within the different conditions depends on the ship developed and can be determined in the specific case, by default 60% at sea, 33% at Dynamic positioning and 7% in port condition. A margin of 25% is applied to account for uncertainties and price variations as well as to assure that there will be sufficient tank capacity. The fuel price as displayed in Table 4.6 is obtained from Ship and Bunker (2016).

The crew and payrolling costs are determined based on the number of crew and the costs per hour of a crew member. Note that the costs of an crew member have to include the employer's costs and are therefore not equal to the wage of a crew member.

For food and beverages different costs per day are used for crew and passengers. The costs of food on board a smaller ship are higher than the ships where the formula is obtained for and are corrected, by increasing the price per passenger, to better represent the data. Besides that the costs also differ for the different luxury levels as could be seen in Table 4.3.

The interest is also based on some assumptions. 70% of the ships building costs is taken as a loan and the duration of the loan is 15 years. To make the situation more representative the interest over the loan is averaged.

Finally the maintenance and other operating costs are determined. This is done based on the GT as described by Epstein, but increased by a factor four as the costs/GT are higher on smaller vessels. All above operating costs are based on very limited data and can therefore merely serve as an indication of the actual costs. As within this research they are used to compare the performance of different design, they are considered sufficiently representative.

Table 4.6: Table with coefficients used for determining the operating costs.

Coefficient	Value	Unit
Fuel price	430	€/ton
Crew member costs	72	€/day
Food costs passenger	65 - 75 -85	€/day
Food costs crew	7	€/day
Interest rate	5	%
Maintenance and repairs	2	€/GT

Besides the operational costs and the building price of the ship, to properly compare the different operational scenarios, the earnings of the ship have to be determined as well. Determining the earnings of a vessel is a rather complex process in case of a cruise ship. Part of the ship might be operated by third parties as for instance the Holland America Line outsources the casino operations, the onboard boutiques, and stores to third parties. Another factor increasing complexity are the different types of contracts used in the industry for hiring hotel staff and the nautical crew. Instead of building a full model to take this all into account, a simplification is done here by determining the earnings potential. Meaning that based on market prices obtained from ships currently in operation a price is determined. The prices as shown in Table 4.7 are based on prices from ships operated by National Geographic - Lindblad and Scenic cruises. The advertised prices are divided by the duration of the cruise in days to find the price for the eight days cruise. For the shorter and longer trips these prices are raised/lowered by €100 because the extra duration of the cruise comes from a lower transit speed and therefore the additional day does not bring in extra value in terms of sightseeing. Because the operational scenario will also exist of a transit from the one Polar region to the other prices for this transit phase have to be determined. The price levels are lowered by 25% during the trips sold while in transit.

Table 4.7: The earning potential based on ships currently in operation in €/*day*

Trip price	Luxury level		
Duration cruise[days]	Basic	Normal	Luxe
9	800	1020	1220
8	900	1120	1320
7	1000	1220	1420

4.6 Method validation

The methods used in the IECEM to determine weight, resistance and costs are mainly used to compare the designs produced by the IECEM with each other. A benchmark is made to compare the results of the methods used in the IECEM with a design project for a cruise ship at Conoship. This comparison will indicate the accuracy of the adopted methods and contribute to the acceptance of the results. To do so a SSM is built based on an existing general arrangement (GA). For this SSM a set of allowed variations is defined. Both these variations and the SSM are used in IECEM to generate designs and estimate the performance. The resulting designs and performances are then compared to existing calculations in the project to gain insight in the accuracy.

4.6.1 The Ship Synthesis Model

As the purpose of this test-case is to validate the estimation methods, a existing design project is used because this allows the comparison of the results from the IECEM based approach with the traditional method's results. The SSM is based on a concept GA, therefore the size of all spaces and systems in the GA are measured and translated to objects and OoO. Because the goal is to validate the methods and not to optimize the layout the model is mostly built with hard objects with a fixed size. This saves time in building the model and ensures that the dimensions of the spaces and systems in the SSM and the GA are consistent. Furthermore the subdivision of objects on decks is fixed as this ensures that the influence of the configuration on the Vertical Centre of Gravity (VCG) is minimized. This should result in better comparable results.

The resulting model exists of 43 OoO (including hull, decks and bulkheads) divided over 8 decks. Most OoO are modelled with hard objects, using the build in weight module, only the emergency generator, the lifeboats and the Zodiacs are modelled as an secondary object with an discrete weight. A last discrete weight object is the additional weight factor compensating for the increased structural weight due to the Polar Class notation. A resulting model can be seen in Figure 4.5.

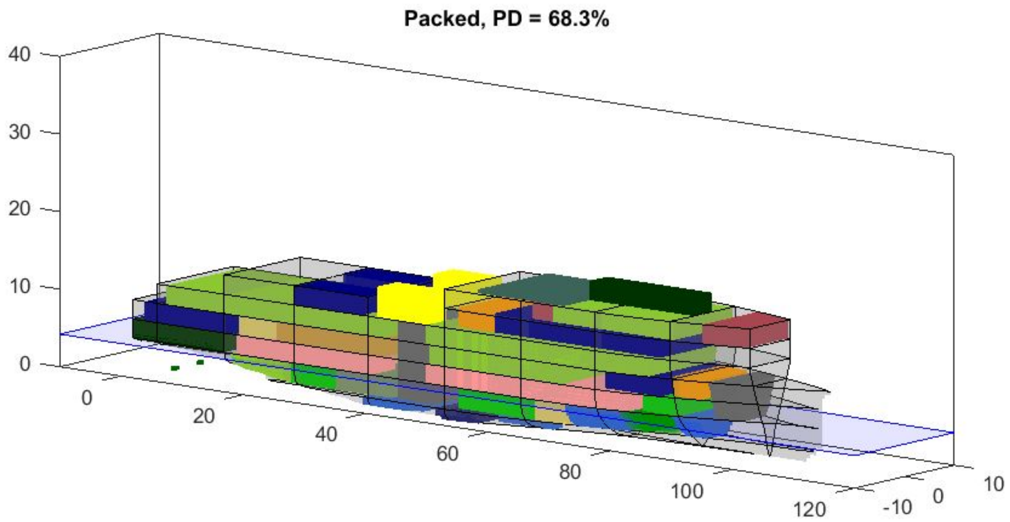


Figure 4.5: One of the resulting packing models

4.6.2 Variations

Usually when the IECEM is applied the goal is to study a range of variables, operational concepts or system configurations. In this case as the results should be comparable to that of the existing Conoship project, very limited variation is allowed. This study varies length, beam and draft to help the algorithm to find the desired configurations. An overview of the allowed variations can be found in Table 4.8. There are also variations in configuration which are only in horizontal direction as the deck on which an object is placed is fixed.

4.6.3 Results

The initial results of the model are displayed in Table 4.9. The main dimensions are slightly different, this has to do with the variations given to the IECEM. These variations were required in order to better find a configuration in which all systems fit. Noted should be here that the size of the systems and spaces were measured from the GA. Therefore they represent the provided size instead of the required size of spaces and systems one would usually provide in the SSM. This because the IECEM will create designs which still contain empty space and therefore allow you to increase the size in an successive design stage. This explains the slight increase in the main dimensions.

[2] Deck 2 is 3m in height, the other decks are 2.5m in height.

Table 4.8: Design variations for test case

Name	Variation(step)	Number
Length	98 - 110m (+0.5)	25
Beam	14 - 15.4m	Continuous
Draft	4 - 5m	Continuous
Decks in the hull	4-5 (+1)	2
Double bottom height	1.5m	Fixed
Deck height	2.5/3m[2]	Fixed
Name	Variation(step)	Number
Speed	12kn	Fixed
Range	2 000nm	Fixed

Table 4.9: A comparison between the existing dimensions and the ones determined with IECEM.

-	Project value	IECEM result	
Length	104.75	106.5	m
Beam	14.4	15.3	m
Draught	4.5	4.5	m
Lightweight	2 945	3 224.5	tons
Variable load	-	1 028	tons
VCG	6.93	7.52	m
Required Propulsion Power(P_D)	1470 (installed)	1351	kW
Required total power	2820	2 851	kW
Building costs	27.5	27.9	m€

4.6.4 Conclusion

Based on the results observed in Table 4.9 it can be concluded that the results match rather well. The results of IECEM are sufficient representative for a preliminary concept design.

4.7 Implementation of the requirements in a Ship Synthesis Model

The SSM, as described in Section 4.4, contains all the information of the ship's systems and spaces. The previous section gave an overview of the different systems and spaces of the model and why they are present. Within this section a more theoretical overview will be given of how the SSM is build. The first subsection will give the complete list of systems and spaces in the model, as well as discuss the variations made in the model. After that the second subsection will zoom in on some of the individual systems and spaces to explain how they are represented in the model.

4.7.1 The Ship Synthesis Model

The SSM exist of all the on board systems and spaces as listed below. The order of the list is not random, but actually represents the order of which they are implemented in the model, as described in Section 4.4. The number in brackets behind the items in the list below represent the quantity in which they are presents. So there are two generator rooms and four ballast water tanks. The individual systems are further explained in the next subsection. In Table 4.10 an overview is provided of the variations present in this model, the earlier named luxury and operational variations are repeated in Table 4.2 & 4.3.

1. The hull
2. The decks
3. The stabilizers
4. The bulkheads
5. Generator room (2)
6. The bowthruster
7. The Azimuth thrusters
8. The exhaust stacks of the generator room (2)
9. The exhaust piping from generator room to exhaust stack (2)
10. Stairs (5)
11. Central reception/hall
12. Bridge
13. Officers accommodation near bridge
14. The lifeboat
15. Emergency generator
16. Emergency control room
17. Hospital (primary)
18. Hospital (secondary)
19. Zodiac storage
20. Boarding station
21. Mudroom
22. Galleys (2)
23. Restaurant
24. Stores (4)
25. Laundry
26. Entertainment options (2)
27. Technical space/HVAC (3)
28. Accommodation passengers (20)
29. Accommodation crew (8)
30. Crew dayroom/mess
31. Fuel tanks (4)
32. Ballast tanks (4)

Table 4.10: Variations in hull parameters, passenger parameters and operational parameters

Name	Variation (step)	Number
Passengers	200 passengers	Fixed
Luxury Category	Basic - Normal - Luxurious	3
Operational Scenario	Slow transit - Normal - Fast	3
Endurance	4 - 6 weeks (+1week)	3
Name	Variation (step)	Number
Length	110 - 150 (+0.5)	81
Beam	17 - 22m	Continuous
Draft	3 - 7m	Continuous
Decks in the hull	4-5 (+1)	2
Double bottom height	1.5m	Fixed
Deck height	2.5 - 3m(+0.5)	2
Name	Variation (step)	Number
Zodiac solution	On deck or near the waterline	2
Stairs	2-5(+1)	4

The variations shown at the top of Table 4.10 are variations mainly effecting the cruise functionalities. Such as the luxury level of the ship, which puts it in a certain market segment. And the operational scenario the ship uses which might effect the type of passengers buying the cruise. The second part of the table names the variations in the ship's structure or platform. These variations will have their effect on the ship's nautical functioning, such as resistance and stability. The third part consists of different system solutions, in this case the Zodiac storage and related systems and the staircases. The Zodiacs are traditionally stored on stacks on the decks and launched by a small crane. This seems a simple and cost effective solution as it does not require additional structures on the ship. Newer vessels often show more yacht-like solutions where the Zodiacs are stored in dedicated stores or garages in the ship's hull. In terms of reliability and maintenance the later seems a better option, but also in terms of launching time as they are closer to the water and easier to prepare for operations while inside. If the storage location is chosen properly it can be combined with the boarding stations which will be more space effective.

The variation in the number of stairs is directly related to the MVZ as described in Subsection 4.5.4. Based on the length and beam of the ship the number of MVZs is determined and for each MVZ a staircase is fitted. Given the minimum and maximum length and beam of the ship five is the maximum and two the minimum.

4.7.2 The individual systems

The SSM exists of 32 unique OoO's. A description of the implementation of the different OoO will follow on order of the above mentioned list. For a complete and detailed oversight of the complete SSM a table can be found in appendix B.

The first item is the ship's hull, a system of the envelope type as it acts as the container in the packing problem (see Section 1.3 and Duchateau (2016)). The envelope system depends on six variables from the genetic algorithm. The first one allows variations in the hull type, in this test case there is only one hull type adopted from an earlier Conoship project and therefore this variable is fixed. Then there are length, draft and beam which are varied between the limits set in Table 3.1. The last two are shaping parameters for the bow and stern section.

The second OoO contains the decks. The decks are dependent on three variables, one defining the tanktop height, one the mean deck height, and the last one the bulkhead deck. From this an array with deck heights is constructed based on the simplification that besides the tanktop deck, every other deck has an equal deck height. This system also checks if the bulkhead deck is located high enough so that $the\_design\_draft + the\_freeboard <= bulkhead\_deck\_height$.

The stabilizers are the third Packing system and the last one before the bulkheads. The stabilizers are based on an example of Rolls-Royce. To optimize their function they are fitted near midship and in the keel radius. Furthermore there are two of them, placed symmetrically on each side of the ship.

The bulkheads again are a special type of object. The objects used here are of the type subdivision and are placed with a different placement function as the other objects. This system uses three variables from the genetic algorithm, one to determine the number of bulkheads, one to determine the position of the first bulkheads toward the stern of the vessel and one to determine the minimal distance.

The fifth and sixth OoO contain the generator room and main generators. There are two rooms total each having two generators with all four generators equal in size. As can be seen the generator rooms are only allowed on the tanktop deck and in the rear 75% of the ships length. This is done to speed up the configuration process as the forward 25% is often to narrow to place an generator room and the tanktop deck is best suited as the space more up in the ship is to valuable for other systems. This systems is built with three objects, one hard object being the generator set with the specific weight and dimension properties of the generator set. The third object is also a hard object and represents the space in which the object is located. The second object is a logical object, this object is used in a later stage to position the exhaust stack straight above the generator room.

The seventh Packing system in the SSM contains the bowthruster. To be effective the bowthruster should be placed as far to the bow as possible and as low as possible to ensure that it stays submerged. Therefore it has positioning constraints forcing it on the tanktop or deck above and in the forward most 20% of the ship. It uses two variables, for the x and the z position. The size of the bowthruster is determined with an estimation formula presented in Equation 4.2.

$$D_{Bowthruster} = 0.004 * A_{Lateral}/H_{Voxel} \tag{4.2}$$

Number eight is for the propulsion rooms, although there are two separate propulsion rooms, as they are completely symmetrical they can be modelled as one OoO. There are two objects, the room itself and the Azimuth thruster. The size of the room is fixed but the Azimuth's dimensions are acquired from a small database.

In a later stage during the initial analysis of the results it turned out that there was a conflict between the hull shape at the stern and the bigger thruster causing that no designs in operational scenario 3 where generated. To solve this the dimensions where fixed at 1 by 1 voxel for all thrusters. In the recommendations the issue of acquiring system dimensions from databases is further elaborated.

The exhaust system is assembled in multiple OoOs. First there is the exhaust stack and second there is the connection between the exhaust stack and the generator room. The exhaust stack systems is composed of four objects: one hard object representing the stack itself, two logical objects to arrange the stack in the same compartment and to locate it on top of a bulkhead and one free space object to block the space around the stack to improve air flow around it.

The eleventh and twelfth Packing system are the same but connect to generator room 2. Both the funnel systems are configured in a way that the connection copies the transverse position from the funnel. By doing this, the transverse position of the funnel can be made variable if desired, in this situation it is located in the middle, as the outside space is to valuable.

The next five objects are also a copy, all five contain staircases (systems 13 - 17). The number of staircases is initially depending on the number of MVZ's. The number of MVZ's is determined after the system definition, therefore on default five staircases are defined of the type 'object (ignore)'. After determining the number of MVZ's, the size and number of the zones is known and a number of stairs is switched from 'object (ignore)' to 'object'. Besides this the size of the MVZ is used to constrain the placement of the stairs so that every zone has its own stairs. The OoO's are defined with two objects: a hard object defining the stairs, and a logical object providing a local constraint to locate the stair cases close to a bulkhead.

Central in the ship and common on cruise ships is the central hall. This space contains the reception, sometimes small shops or the expedition office and is the first space you see onboard the ship. Together with the stairs it is essential for onboard logistics. In the SSM this is number 18 and exists of a simple hard object representing the space.

The nautical center of the ship, the bridge, is defined next in system 19. The most important property is the free sight demand as was discussed in Section 3.3. This is enforced with an free space object which blocks the space in front of the bridge all the way up and to the front as visualised by the pink object in Figure 4.6. The dark red object represents the bridge, and the bright red object a logical OR object. This logical objects places the bridge next to a bulkhead.

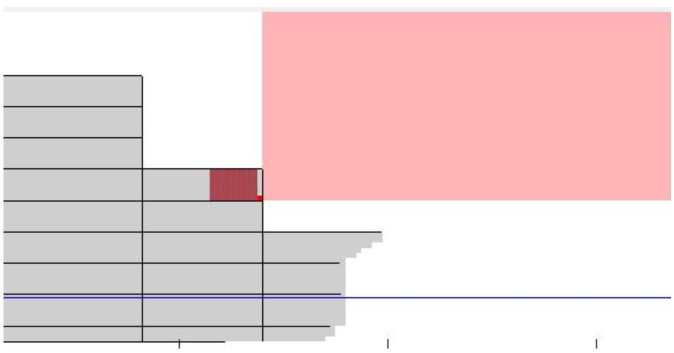


Figure 4.6: 2D representation of the bridge system

For safety reasons the captain and first officer usually has an accommodation close to the bridge. This is implemented in OoO 20. The soft object represents the accommodation, the exact shape does not matter much, with a soft object a minimum width can be assigned to ensure a bed fits in. The logical objects allows for a connection to the bridge, this is done by a so called adjacency function. This allows the system to be located adjacent to a specified system, in this case the bridge. Further more this officers accommodation is located on the starboard side of the ship.

For this size of cruise vessel, two lifeboats are sufficient. These are added to the SSM by system 21. The amount of lifesaving appliances is determined based on the number of people on board and made generic so that it is reusable if the same model is used for ships with more passengers. The capacity and dimensions are based on an example from Harding lifeboat systems. To ensure sufficient distance between the propulsion and the lifeboat when launched the location of the lifeboat is horizontal constrained to the forward 75%. To comply with the minimum and maximum distance to the water the lifeboats are either placed on the bulkhead deck or the deck immediately above the bulkhead deck.

All the other OoO basically have an identical structure as the ones described so far. Because of the system variations number 26 to 28 will be elaborated on. Information about the others can be found in the overview in appendix B. The Zodiac storage can either be in the hull or on deck, in case it is in the hull, the storage will also function as a boarding station and the mudroom will be located next to the storage. If the storage is on deck there will be a separate boarding station with the mudroom attached to it. This is captured in the OoO 26 to 28, 26 is the storage which has three variables from the genetic algorithm. The standard two variables for the x- and z-position and a third one placing the system on deck or in the hull. Based on this third parameter the shape of the hard object representing the Zodiacs is set and the transverse position switched to either 'middle' when it's on deck or 'sb' when it's in the hull. The boarding station is a hard object with fixed dimensions and by default present. The Mudroom, the third OoO, is built from a soft object reserving the required space and a logical object to connect this space to either the boarding station or the storage depending on the variable mentioned above. Besides determining its own location it also disables the boarding station if required.

With this the description of the individual systems is finished and the next chapter will deal with the search path and results.

Chapter 5. Results

5.1 Introduction

This chapter will use the method described in chapter 4 to find the most promising design. Therefore an exploration of the design space will be done in section 5.2. This exploration complies with the fourth step as displayed in the process diagram of Figure 4.2b. Based on the post-processing of the results of this exploration run, several steering runs are done to gain sufficient insight of the design space. These steering runs and the analysis of the results are visualised in the diagram with steps four to six and can be found in section 5.3. As a result of the exploratory and steering runs, limitations of the model and the design space will become clear. To be able to study the effect of those limitations on the set of results requires modifications of the SSM. Two specific situations are researched to study what was limiting the design. This process is presented in section 5.4. Finally, Section 5.5 will present the selection of the most promising design from the design population. This also demonstrates how the selected design can be further developed in a early stage concept design.

5.2 The Exploratory Run

The initial run, the exploratory run, is established with the basic problem setting given in Equation 5.1. The objective is set at the default objective of minimizing the negative packing density(PD) as adopted from (Duchateau, 2016). The constraints are mathematical versions of the earlier mentioned feasibility constraints of section 4.2.3. Each design that complies with the equality constrain h_1 does meet the space constraint and the reserve buoyancy constraint. When a design meets the draft constraint g_1, the speed constraint is also met as it is assumed that if the draft constraint is met, the resistance calculation and power prediction are valid. In this way the feasibility of a design is secured. The number of generations and the size of the population used by the genetic algorithm are set at 500 designs in each generation and 200 generations for the exploratory run. This leads to 100 500 design attempts during the exploratory search and is believed to provide sufficient information for an initial exploration of the design options.

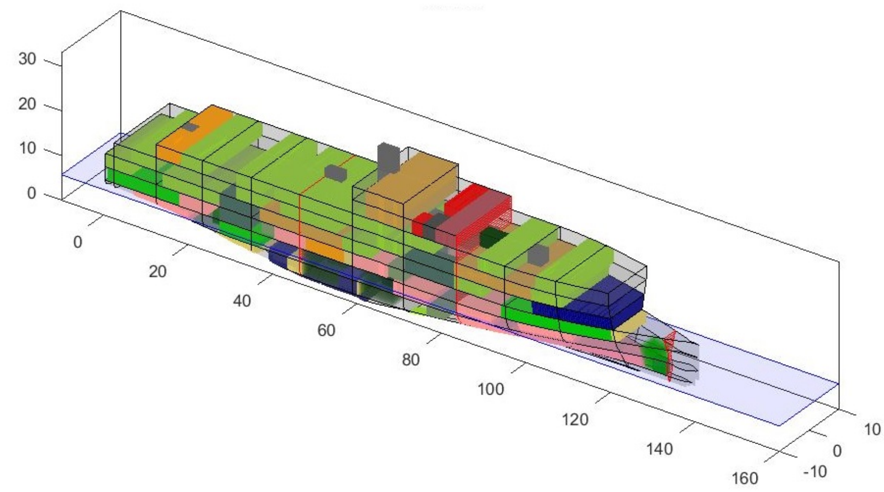
$$\begin{aligned}
\min_x \quad & f \quad && \text{-PD(x)} \\
\text{s.t.} \quad & h_1 && systems_{placed}(x) = systems_{total}(x) \\
& g_1 && T(x) \leq T_{design}(x) \\
& g_2 && |LCB(x) - LCG(x)| \leq \delta_{required} \\
& g_3 && GM_{min} \leq GM(x) \leq GM_{max}
\end{aligned} \tag{5.1}$$

The exploratory run resulted in 17 825 feasible designs as can be seen in Table 5.1. The results in the table are presented as the number of feasible designs for the different luxury levels and operational scenarios.

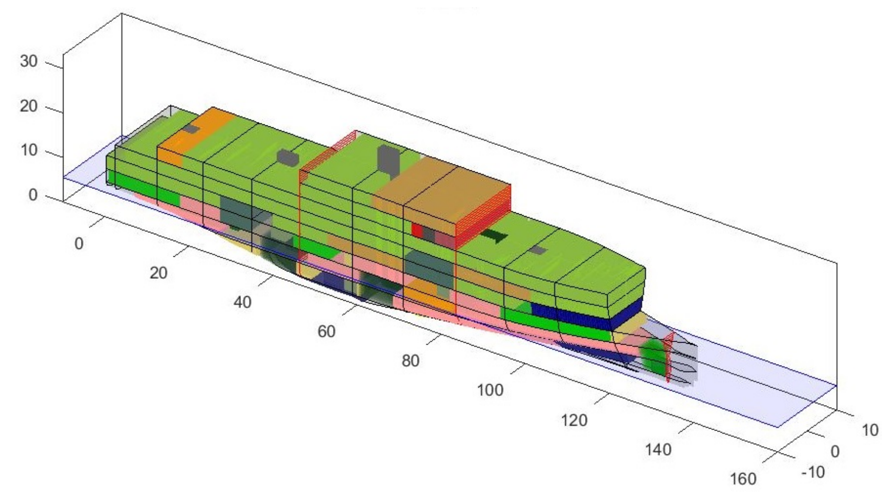
Table 5.1: The number of feasible designs of the exploratory run.

		Luxury Category			
		Basic	Normal	Luxe	Total
Operational scenario	Slow transit speed	238	3 779	13 757	17 774
	Medium	7	37	7	51
	Fast	0	0	0	0
	Total	245	3 816	13 764	17 825

The initial run is done with the objective given in Equation 5.1. While analysing the resulting designs it is important to consider that maximizing the PD is not equal to selecting the option with the least amount of volume. Therefore the peak in the number of designs in luxury level Luxe can explained by the fact that the larger accommodations in the higher luxury level make it easier to fill in the gaps in the ship's arrangement. Figure 5.1 shows two vessels, the top one is a luxury level Basic vessel with a PD of 64%, the highest PD for luxury level Basic. The lower design, Figure 5.1b, is a luxury level Luxe design with an PD of 84%. Both have roughly the same length and the arrangement of systems and spaces on board also shows similarities. The Basic luxury vessel has a less efficient arrangement as the PD is lower even though it is the design with the highest density. This behaviour is unexpected as it would be logical that the ship becomes shorter when the luxury level and thereby the size of spaces decreases. Instead the length stays the same and the PD decreases for designs with a lower luxury level. Therefore steering run four will be used to search for shorter designs to better understand this length limitation.



(a) An example design for the Basic luxury level with the highest PD of 64%



(b) An example design for the Luxe luxury level with the highest PD of 84%

Figure 5.1: Two example designs from the exploratory run indicating that a higher luxury level design can be denser arranged.

Furthermore the peak in feasible designs for the Slow operational scenario is at the Luxe luxury level, where for the Medium operational scenario the peak of feasible designs is at the Normal luxury level. While there are not that many designs available for the Medium operational scenario, it appears that given an increasing speed the lower luxury levels are easier to arrange in a design. A possible explanation for this phenomena is given by Zandstra (2014) where he describes the limitations of the genetic algorithm with respect to finding a set of solutions representing the entire solutions space. He indicates that the genetic algorithm prefers the easier to configure set of requirements. This is partly because the objective only tries to find the design with the highest PD and therefore does not require mulptiple designs for the nine different combinations of variations. Duchateau (2016) also states that maintaining diversity in the results of the exploratory run requires more attention. Within this thesis research this is solved by doing steering runs to make sure that the resulting set of designs contains sufficient alternatives to make a good comparison for the different luxury levels and operational scenarios. On top of the steering runs discussed previously, two steering runs are conducted to expand the solution space for the Medium and Fast operational scenario and lastly one steering run is used to search for cheaper designs. Of all designs the most expensive is at € 68.7 million and the cheapest is at € 45.6 million. Searching for the design with the highest PD does not guarantee that the cheaper designs are present in the set. To explore the solution space for these different options a series of steering runs is performed focussing on those area.

5.3 The Steering Runs

Steering runs are used in this study to further explore the solution space for design solutions missing in the exploratory run's results. For this case four steering runs are used, the first one to look for Medium and Fast operational scenarios and the second one focusing on Fast operational scenarios. The third steering run adds more cheaper designs to the set of designs and the fourth steering run looks for shorter designs. The results of the steering runs are discussed in subsection 5.3.5 and an in depth analysis of limitations is presented in section 5.4.

5.3.1 Medium and Fast Operational Scenario

The problem definition is kept the same for the different steering runs but the objective function is extended. Besides the first objective of maximizing the PD, a second objective is added which benefits designs complying with the operational scenario requirement. The resulting objective function is presented in Equation 5.2.

$$\begin{array}{lll} \min_x & f_1 & \text{-PD(x)} \\ & f_2 & \text{Operational Scenario} \geq \text{Medium} \end{array} \tag{5.2}$$

In the first steering run 362 feasible designs were found out of 10 500 attempts, a population size of 500 and 20 generations. The composition of the resulting set of solutions is presented in Table 5.2. From the feasible designs 253 designs also complied with the added objective for the operational scenario Medium and only one with Fast. The yield (feasible designs/design attempts) was only 3.4% compared to the 17.7% of the exploratory run.

Table 5.2: The total number of feasible designs for the different categories resulting from the first steering run.

		Luxury Levels			
		Basic	Normal	Luxe	Total
Operational scenario	Slow transit speed	244	3 815	13 823	17 882
	Medium	30	180	94	304
	Fast	0	1	0	1
	Total	274	3 996	13 917	18 187

The low yield is partly due to the low number of generations. As the genetic algorithm suffers from a start-up effect, meaning that it takes some time(generations) to find feasible designs and therefore will perform worse. To overcome this issue the next steering runs will be done with 40 generations. Increasing the number of generations will effect the number of solutions found in a certain search direction, not the direction itself. As the next steering run is used to search for more Fast operational scenario ships, the lack of results in this steering run will be compensated. The IECEM uses elite designs, designs from the current set of solutions that comply with the added objective, to create a first generation for the genetic algorithm. The elite designs and the more limited search allow for less generation compared to the exploratory run.

5.3.2 More Fast Operational Scenarios

The second steering run will be more focused on generating Fast operational scenario designs. A second objective f_2 is added to the objective function in Equation 5.3.

$$\begin{aligned} \min_x \quad & f_1 \quad \text{-PD(x)} \\ & f_2 \quad \text{Operational Scenario == Fast} \end{aligned} \tag{5.3}$$

To increase the yield the number of generations is increased from 20 to 40 with a population size of 500 designs. From the total 20 500 designs, 2 034 were feasible which is a yield of 9.9%. A total of 70 designs in the Fast operational scenario were found and an additional 232 Medium operational scenario designs. The resulting set of feasible designs of the exploratory and first two steering runs can be found in table 5.3.

Table 5.3: The results of the second steering run.

		Luxury Levels			
		Basic	Normal	Luxe	Total
Operational scenario	Slow transit speed	247	3 894	15 473	19 614
	Medium	30	221	285	536
	Fast	1	67	3	71
	Total	278	4 182	15 761	20 221

The first thing that stands out is that the peak in number of feasible designs for the Medium operational scenario has shifted from Normal to Luxe luxury level. While for the Fast operational scenario the peak is at the Normal luxury level similar to the Medium operational scenario in the first two runs. This indicates that the genetic algorithm prefers densely packed design for a higher luxury level. Figure 5.2 supports this claim as it shows that the PD is higher for the higher luxury levels already in the exploratory run. Thus most designs are found in the higher luxury level, Luxe and Normal. The hypothesis about the shift in peak is that for the Normal luxury level it is less complex to generate designs as it exists of less systems. Only in the Luxe luxury level the auditorium is a separate space. Because of that it will first generate Normal designs and then make the step to Luxe to further increase the PD. To confirm this hypothesis additional research is required.

The second thing is the limited amount of designs available for the Fast operational scenario. One of the reasons less Fast operational scenario designs are generated by the IECEM has to do with the generator and generator room size. The engines required for the faster operational scenario are huge and hardly fit in the defined generator rooms as can be seen in Figure 5.3. The generator rooms in this model are Packed after the bulkheads are placed. With the bigger engines resulting from the Fast operational scenario it is harder to fit them between the bulkheads. In an attempt to solve this the number of generators is increased to six and a new exploratory run is conducted. This will be further elaborated on in Subsection 5.4.1.

5.3.3 Cheaper Designs

Figure 5.4 shows the operational expenditure versus the building costs of the feasible designs generated in the exploratory and first two steering runs with blue crosses. Because of the original objective of maximizing the PD there is a good reason to believe that cheaper designs are possible. The building costs is one of the MoPs used in section 5.5 to select the best combination of luxury

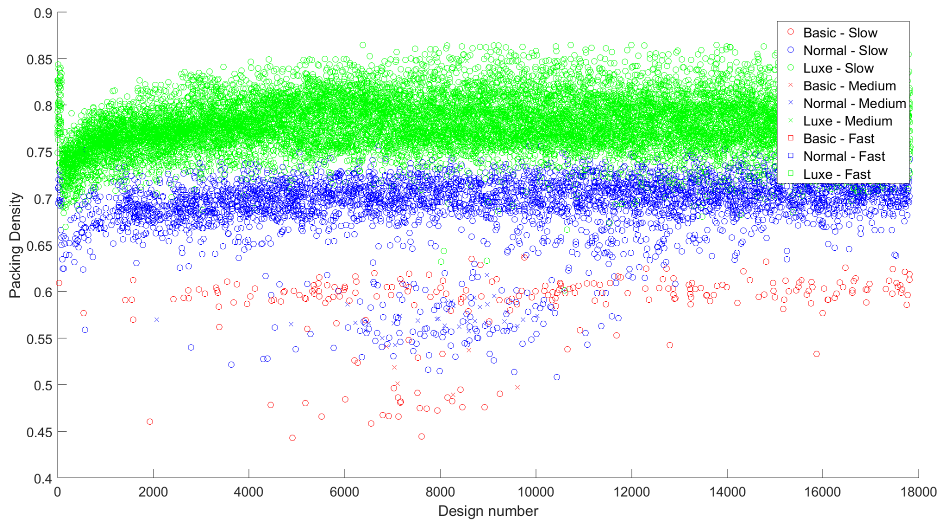


Figure 5.2: The development of the PD for the different luxury levels during the exploratory run.

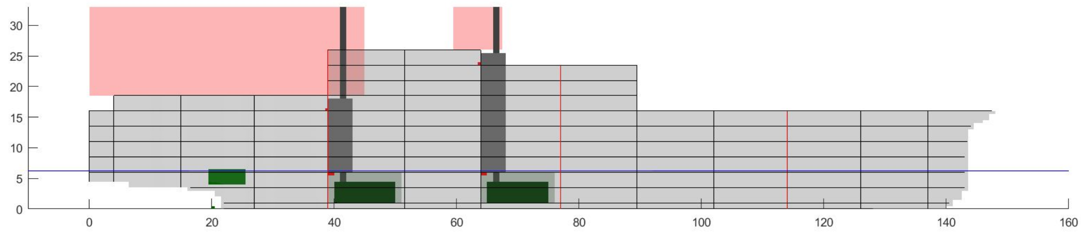


Figure 5.3: The huge engines hardly fit the generator room

level and operational scenario. To investigate this claim the third steering run is used to search for cheaper designs. The objective function is complemented with objective f_2 to stimulate the search for cheaper designs as can be seen in Equation 5.4.

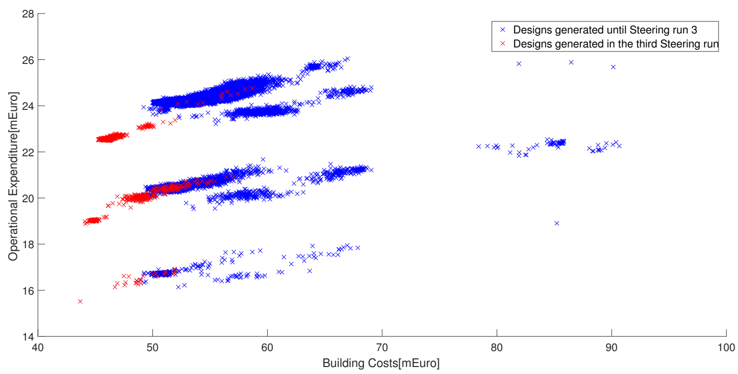


Figure 5.4: The building costs in million Euro versus the operational expenditure in million Euro with the red crosses indicating the new cheaper designs.

$$\begin{array}{lll} \min_x & f_1 & \text{-PD(x)} \\ & f_2 & \text{Building costs} \leq €49 Million \end{array} \tag{5.4}$$

The results of the third steering run can be found in table 5.4 again 40 generations have been used with 500 design attempts each generation. The 749 resulting feasible designs all are operational scenario Slow which is understandable as the slower scenario requires smaller engines and less fuel capacity esulting in smaller and cheaper vessels. For the different luxury levels the building costs of the cheapest designs are: 43.7, 44.1 and 45.3 million Euro for Basic, Normal and Luxury levels respectively. These designs are all generated in the third steering run indicating that the lower limit on the building costs was not yet reached. These results can also be seen in Figure 5.4 where the third steering run is highlighted by the red crosses.

Table 5.4: The results of the third steering run.

		Luxury Levels			
		Basic	Normal	Luxe	Total
Operational scenario	Slow transit speed	273	4 157	15 933	20 363
	Medium	30	221	285	536
	Fast	1	67	3	71
	Total	304	4 445	16 221	20 970

5.3.4 Shorter Designs

Table 3.1 shows that the lower limit on the ship's length is 110m. The smallest value for length found in the dataset yet is 133m and represented by only one ship. Therefore a fourth steering run is conducted to find shorter designs with an adjusted objective f_2 in Equation 5.5.

$$\begin{array}{lll} \min_x & f_1 & \text{-PD(x)} \\ & f_2 & \text{Length} \leq 132\text{m} \end{array} \tag{5.5}$$

Although the designs generated in steering run four tend to have lower operational costs as can be seen in Figure 5.5, the difference is very small. The shortest design now is 128m, only 5m shorter, indicating that the minimum length of a design from this model is limited.

Table 5.5 show the statistics of the fourth steering run, with the 40 generations and a population size of 500. Another 1 301 feasible designs where generated.

Table 5.5: The results of the fourth steering run.

		Luxury Levels			
		Basic	Normal	Luxe	Total
Operational scenario	Slow transit speed	279	4 952	16 433	21 664
	Medium	30	221	285	536
	Fast	1	67	3	71
	Total	310	5 240	16 721	22 271

5.3.5 Conclusions on Steering Runs

A final dataset of over 22 000 designs is acquired with designs available for the nine different options of luxury levels and operational scenarios. Besides having designs for the different luxury levels and operational scenarios, additional steering runs have been used to extend the solution set to include the cheaper and shorter designs. During steering run three where shorter designs were searched the shortest length resulting was still 128 meters long where the hard limit is at 110 meters. To find out what aspects are driving length in this solution set additional analysis are discussed in the next section.

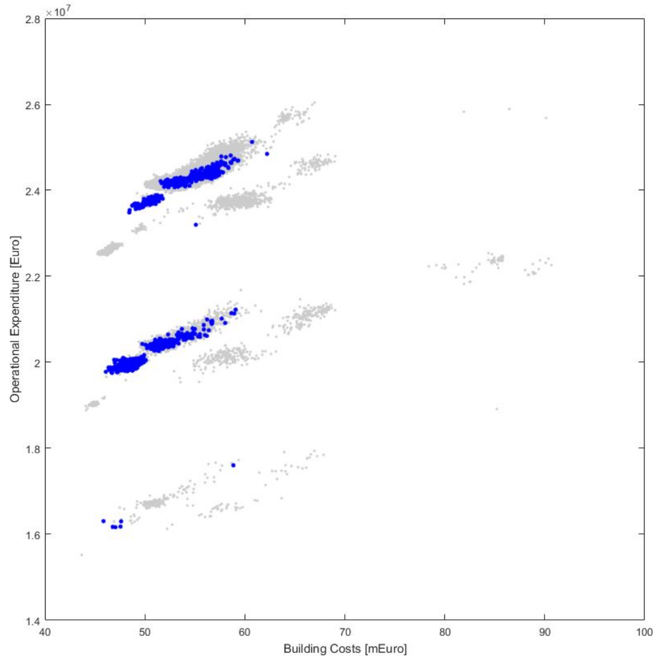


Figure 5.5: The short designs of steering run four (blue) compared to the other designs (grey).

5.4 Analysing the Results

During the steering runs it turned out that certain design aspects were influencing the generation of specific design solutions. To better understand these design drivers additional analysis have been conducted. Initially it was checked if the algorithm attempts shorter designs, this was done by a separate test generating 10 000 designs based on random values. From these attempts the length was normally distributed between the minimum and maximum value, concluding that it is possible to generate the shorter designs. From this random test it also became clear that a lot of the designs failed on the generator room system. This will be further discussed in subsection 5.4.1. From earlier discussions it already showed that the bulkhead spacing based on the floodable length calculation proves difficult. Therefore subsection 5.4.2 will elaborate on the influence of this floodable length check on the design's minimal length.

5.4.1 The Six Generator Model

After the second steering run it appeared that generating faster operational scenario designs is difficult. Clearly something is limiting the model from generating these solutions and it was suggested that the generator size might play a role in that. To reduce the size of the generators and still have sufficient power the number of generators has been increased to a total of six. This solution is demonstrated as the model has been adapted and a new exploratory run has been executed. For this new exploratory run the same problem definition and objective function of Equation 5.1 have been used and the six generators have been used instead of four. Although the results of the new exploratory run showed a significant increase in operational profile Medium results, no Fast results were generated. To further study this, the variation in operational scenario has been fixed on Fast only, not as before by modifying the objective function but by fixing the option in the model. This led to the generation of operational scenario Fast designs proving that the model is capable of generating them.

Figure 5.6 shows the results of a set of randomly generated designs. For this test 20 500 designs are generated based on a random generated vector with variables. This vector is used by the packing algorithm to attempt to generate a design. In this situation the genetic algorithm is not used but mimicked by the random generated values. The results of this test give a good indication of the more difficult systems and objects in the model. Figure 5.6 shows the failure rate of the packing algorithm on specific systems. For example 12% of the design attempts fail on placing the generator system. For the original four generator model the generator system, the exhaust stack, the first stairs and the mudroom cause the most failures. As only the generator room is dependent on the operational scenario, this is further studied. The small bar at the utmost right of the plot does not give a failure rate, but the number of designs which where successfully packed. They are included to present the complete results and not only the failing part.

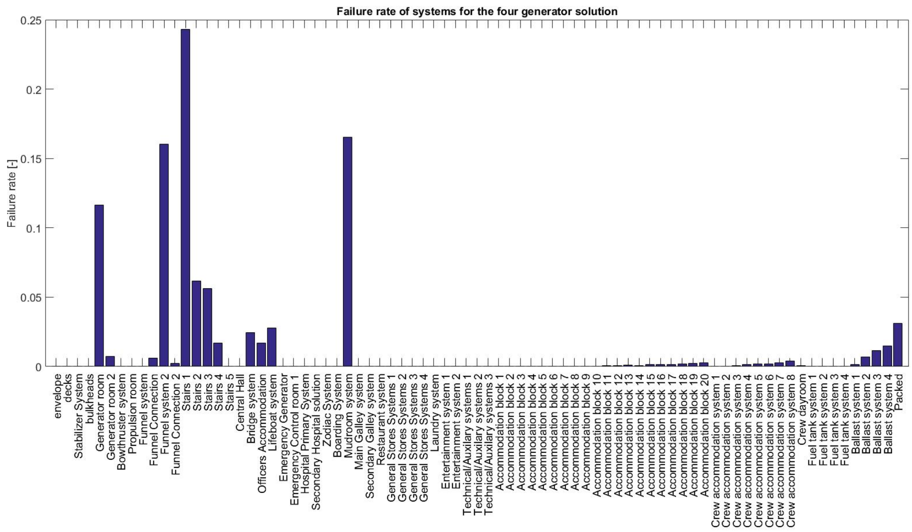


Figure 5.6: The failure rate of the packing algorithm for the different systems in case of the four generator model.

The six generator model has been tested the same way and a similar bar plot has been composed as can be found in Figure 5.7. The six generator model still has the exhaust stack, the first stairs and the mudroom causing most of the failures but the issue with the generator room is solved.

Concluded can be that the six generator room option makes it easier to place the generator room and generate Medium operational scenario ships. This partly solves the issue of the lack of faster designs in the solutions set. It has been shown that the generation of Fast operational scenario designs is possible but during a normal exploratory run it does not occur. One of the possible causes can be the objective function as maximising the PD might not be the right incentive to produce also the Fast operational scenario.

5.4.2 Floodable Length

The bulkhead placement is done based on a floodable length curve where the bulkheads are placed and it is checked whether they comply or not. Instead of only checking if the current set of bulkhead complies to this deterministic damage stability constraint, it has also been tried in the past to optimize the compartment size or bulkhead spacing in order to have bigger compartments which easier house larger systems. In the third steering run shorter designs have been found. Although the shortest length of a design in the solution set is 128 meters it is hypothesized that shorter designs should be possible. This because of the void spaces still available in designs as well because of the beam and draft limitations which have not been reached yet. The length of the model is expected to be driven by the floodable length calculation and the bulkhead spacing. This is studied by placing the bulkheads without performing the floodable length calculation.

This claim has been tested by doing a new exploratory run with the same problem definition, objective function, and population size and number of generations as the original exploratory

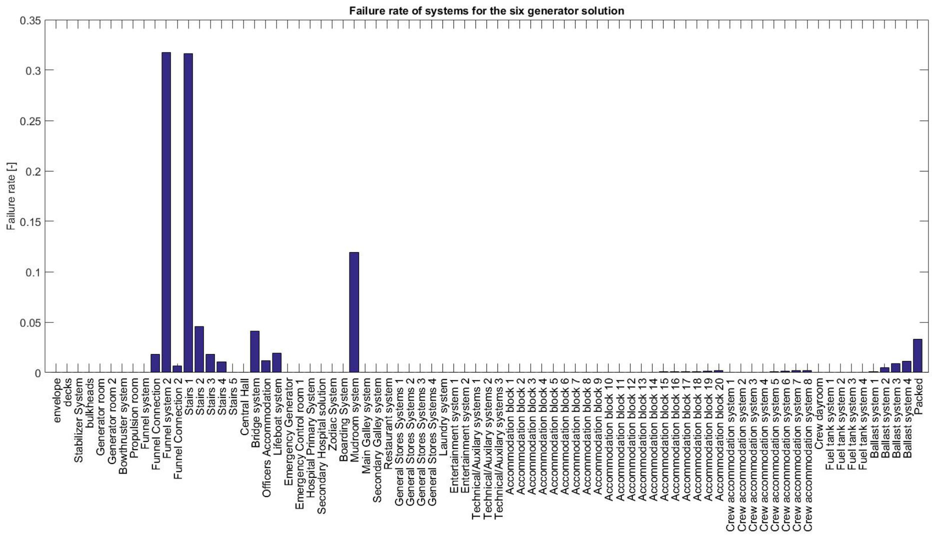


Figure 5.7: The failure rate of the packing algorithm for the different systems in case of the six generator model.

run. The floodable length calculation was switched off and the bulkheads are now placed without checking whether their location makes sense from the deterministic damage stability perspective. The resulting population contained shorter designs with the shortest available now at 120 meters. Besides shorter designs, the PD also had a new maximum value at 88%. Both observations indicate that the floodable length is strongly influencing the length and PD of the generated designs. Switching the floodable length calculation off is not a solution to the issue but by doing this analysis more insight was gained in the influence of the issue. Further research is recommended in the combination of the damage stability, freeboard height and bulkhead deck position. As there is a strong relation between these three aspects of the ship design which cause difficulties as the one described above.

5.5 The Most Promising Design

In the previous sections a solution set is created during the exploratory run and extended during several steering runs to give a good representation of the possible solutions. Within this section this set of solutions will be used to select a basis for a concept design. First, the most promising design will be selected from the solution set based on the economical MoPs defined in subsection 2.2.2. After that the selected design will be elaborated on. Finally, subsection 5.5.3 will demonstrate how the selected design can be further developed.

5.5.1 Selecting the Most Promising Design

Figure 5.8 shows the designs with the gross cashflow in million Euro on the y-axis and the gross tonnage on the x-axis. The different colors, red, blue and green indicate the different luxury levels Basic, Normal and Luxe respectively. The small circles correspond to the Slow, the crosses to the Medium and the squares to the Fast operational scenario.

The figure shows that more luxurious ships have a higher earning potential, the same goes for faster operational profiles. It also shows that the potential earnings are rather high if one considers that the gross (bruto) cashflow is determined by subtracting the operational expenditure and the capital expenditure from the estimated earnings. Given this condition, it still allows for good comparison as the mistake is absolute and not relative. When it is decided to

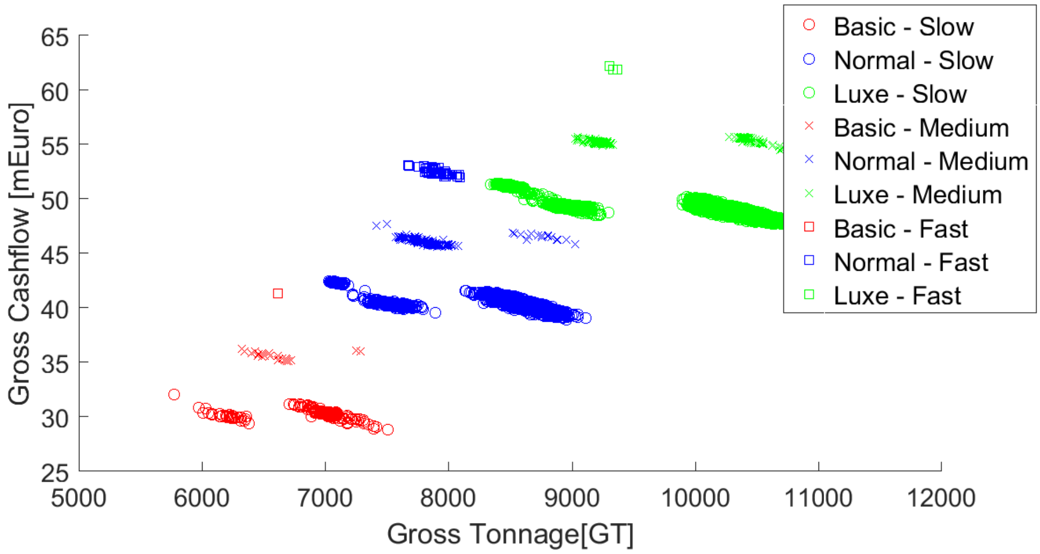


Figure 5.8: The different colors, red, blue and green indicate the different luxury levels Basic, Normal and Luxe respectively. The small circles correspond to the Slow, the crosses to the Medium and the squares to the Fast Operational Scenario.

continue with a resulting design the earnings should be recalculated. Furthermore it can be seen that a higher luxury level also means a bigger ship as the gross tonnage increases whereas more speed does not effect the gross tonnage significantly. The slow operational concept for the Luxe luxury level clearly shows two distinct groups of data, one between 8 000 and 9 500 GT and one between 10 000 and 11 000 GT. This difference comes from the discrete variation in deck height where the deck height is either 2.5 or 3 meters.

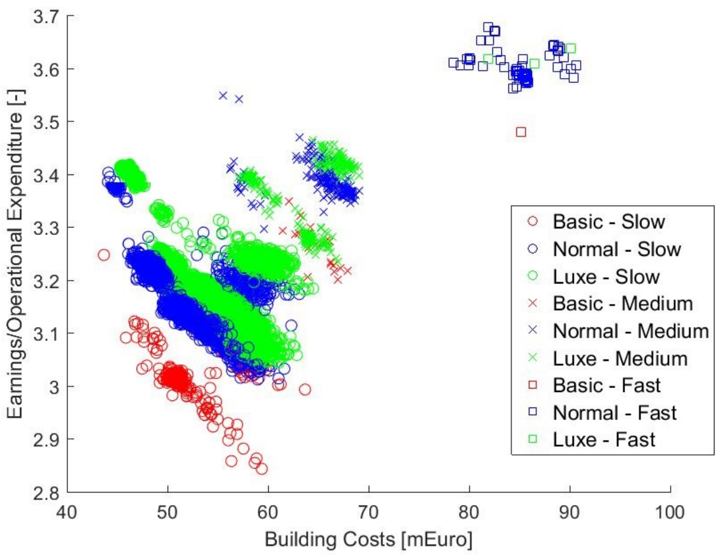


Figure 5.9: The building costs of the resulting population versus the earnings divided by the operational expenditure.

In section 4.5.5 the economical MoPs where defined as they are should provide the best insight in the desirability of a design. Figure 5.9 shows the building costs in million Euro on the x-axis against the earnings divided by the operational expenditure on the y-axis. Desirable designs in this graph are located in the left upper corner as that would give the cheapest ship which earns the most for what it costs to run. Figure 5.10 is almost identical to the previous figure except that now the capital expenditure is included and the y-axis therefore gives the earnings divided by the total expenditure. The cluster of operational scenario Fast designs in the right upper corner of the figure perform worse now as they have considerable higher capital expenditures as the building costs are higher.

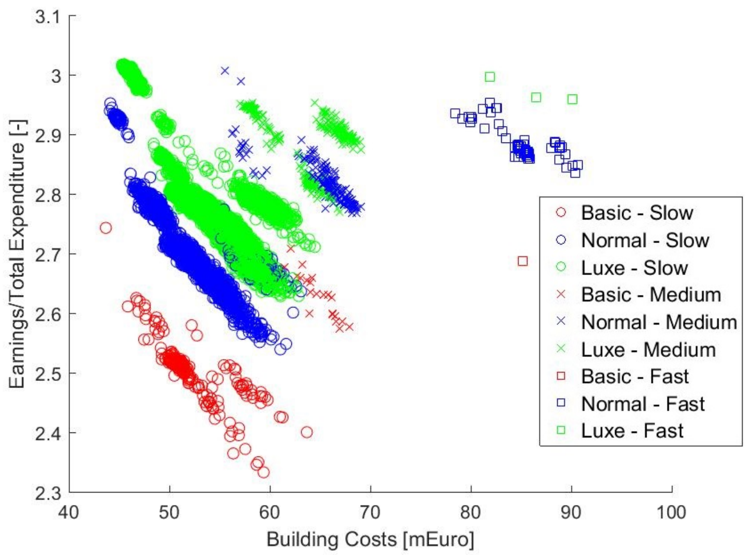


Figure 5.10: The building costs of the resulting population versus the earnings divided by the total expenditure.

Based on the above presented figures the Slow operational scenario seems the most attractive one combined with either luxury level Normal or Luxe. These smaller clusters of designs in the left upper corner have four instead of five decks in the hull and are slightly longer. This reduces their resistance hence a decrease in required propulsion power. Eventually this results in cheaper engines and less fuel consumption. From this small cluster one design is selected based on the lowest building costs and higher ratio. Figure 5.11 shows the selected example design which can form the basis for a concept design in the next phase, more about the selected design will follow in the next subsection. It is deliberately called an example design as most designs in this smaller cluster show numerous similarities. Therefore more information about the design aspects of other designs in this cluster is provided together with the resulting design.

5.5.2 The Resulting Design

The resulting design was selected from the small cluster of designs of which a detail graph is presented in Figure 5.12. From this figure it can be seen that a luxury level Luxe ship could be justified. Because the additional investments required for such an ship are limited and the earnings over total expenses ratio improves.

The figure also indicates that multiple other designs are available which show similarities to the chosen design. In Figure 5.13 the length, beam and draft of the designs in the selected area are presented. Although there is some spread in the length and beam of the different designs the draft is highly concentrated around 5 meters. The selection for the current design is based on it's economical performance but as will be shown later on much more information is available for each design such as hydrostatic reports, a breakdown of the estimated building costs and the weight estimation. Considering all this information for the over 460 design available in this selected

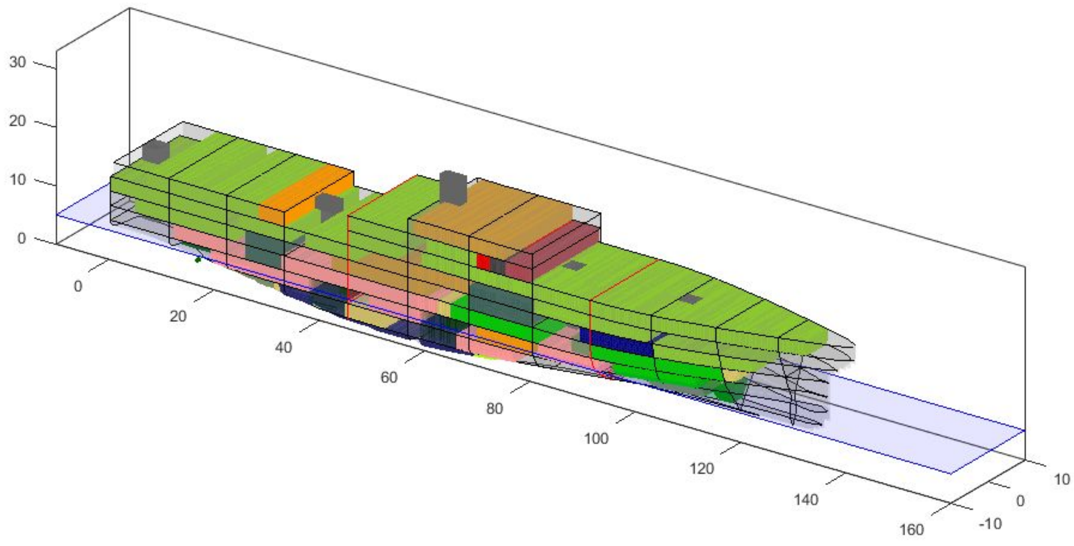


Figure 5.11: The resulting design serving as a basis for a concept design.

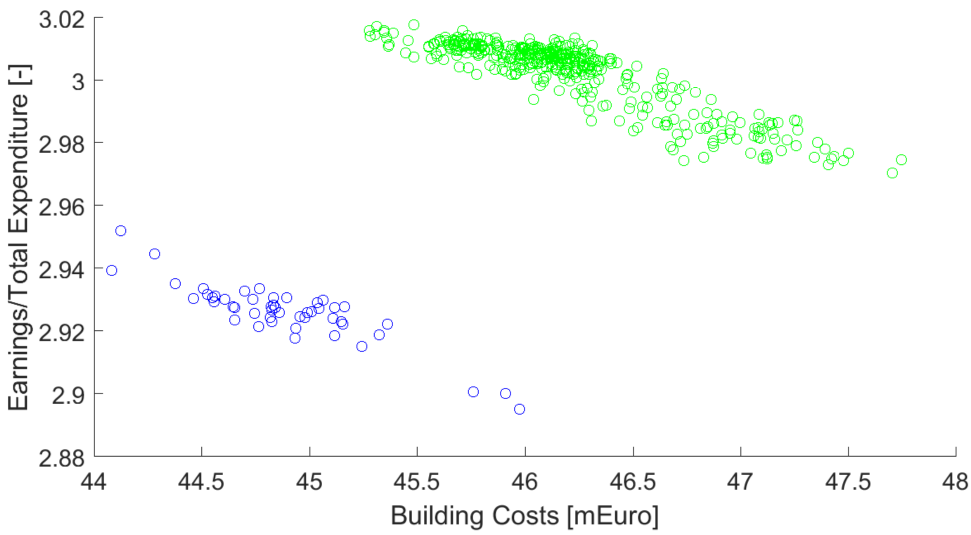


Figure 5.12: The potential earnings divided by the total expenses versus the building costs for the selected area. Selected design is coloured pink.

area of the design space in a selection process is not possible. At the moment the right tools or procedure to do so are not yet available. Also some design may have a better layout compared to others but now the only way to compare this is by manually checking all the different designs.

The main dimensions of the selected design are presented in table 5.6. Additional design information such as a breakdown of the building costs or a resistance curve can be found in appendix C. The selected design has the Slow operational scenario and Normal luxury level. A 2D visualisation of the resulting design from the IECEM method is given in Figure 5.14, where the different decks and a side view are given of the selected design. This 2D visualisation will serve as a basis for the next step in this early stage concept design process. This next step will be touched upon in the next subsection.

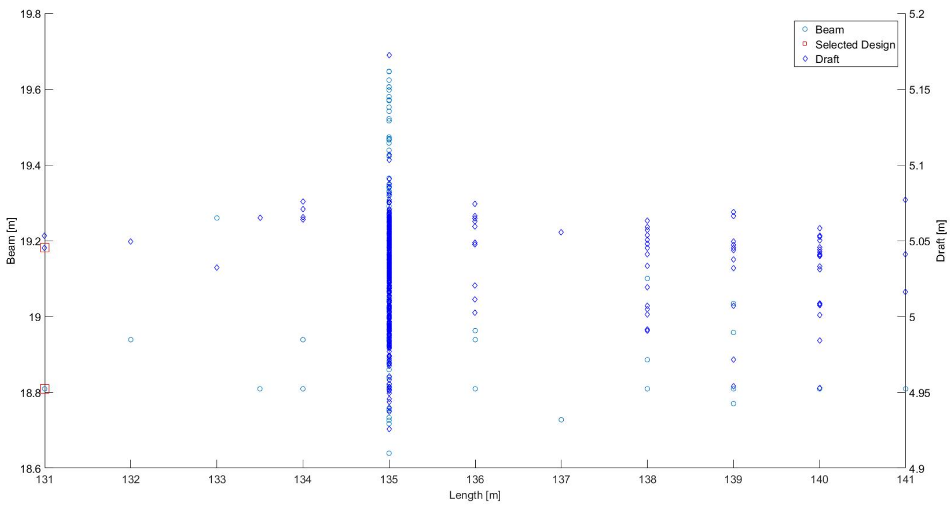


Figure 5.13: The beam and draft versus the length of the ships in the selected area.

Table 5.6: Main particulars of the resulting design of figure 5.11

Main Particulars	
Length	139m
Beam	18.8m
Draft	5.03m
Displacement	$7034m^3$
Lightweight	5538 tons
VCG	9.04m
GMt	2.77m
Installed Power	$4 * 1360kW$
Costs	44.55 m€

5.5.3 Continue concept development

The 2D visualisation of the layout of the resulting most promising design is unclear and it is hard to recognize the different spaces of a cruise ship. Therefore this next step is taken where the 2D drawing is made more clear and names are added to the different spaces. No significant changes are conducted to the location of spaces because this would require to redo all the MoP calculations and that is not the goal of this exercise. With this step human engineering judgement continues to develop the design. Meaning that minor changes to the layout are made to improve the quality of the layout and form a basis to develop a general arrangement from are done by an engineer and not the algorithm.

The drawings of Figure 5.15, 5.16 & 5.17 provide better insight in the layout of systems and spaces. The IECEM approach has not been used before to study the layout of spaces inside a ship. Because of this the layout presented in the drawings contains interesting characteristics. For instance the clustering of the passengers accommodation on decks 6 and 7 which is not hard coded as a constraint in the program but is very common practice in cruise ship design as it has benefits with building and retrofitting the ship. An even more interesting characteristic is the location of the lounge on deck 9, although this location is again not forced by a constraint it provides the vessel with a special features as the lounge now has a 360 degree view, something very nice on board an expedition vessel. This is not (often) seen in cruise ship design and therefore considered as a new feature. Another characteristic to point out is the location of the bridge. This bridge was constrained to be placed on one of the higher decks and with free sight forward and upwards. As can be seen with its location on deck 8 it fulfils both constrains and is therefore placed as desired. Another item where this can clearly be seen are the staircases; each Main Vertical Zone is separated by a fire bulkhead, coloured red in the drawings, and needs to have its own main staircase. However there are some clear characteristics that are undesirable about the layout, such as the emergency generator. It is located in between the passenger accommodation where it will cause noise complaints and vibration issues. Another example is the location of the primary hospital. In order to comply with the SRtP regulation the ship needs a secondary hospital. In the selected design the primary and secondary hospital are placed next to each other. These systems were not constrained sufficiently and are now placed at undesirable locations. When the preliminary concept design is further developed these need to be moved. Both spaces could benefit from an additional constraint preventing this behaviour. The hospital would require a separation constraint to make sure it is not in the same MVZ. The emergency generator should be moved to an higher deck such as the bridge deck where the sound and ventilation do not cause problems.

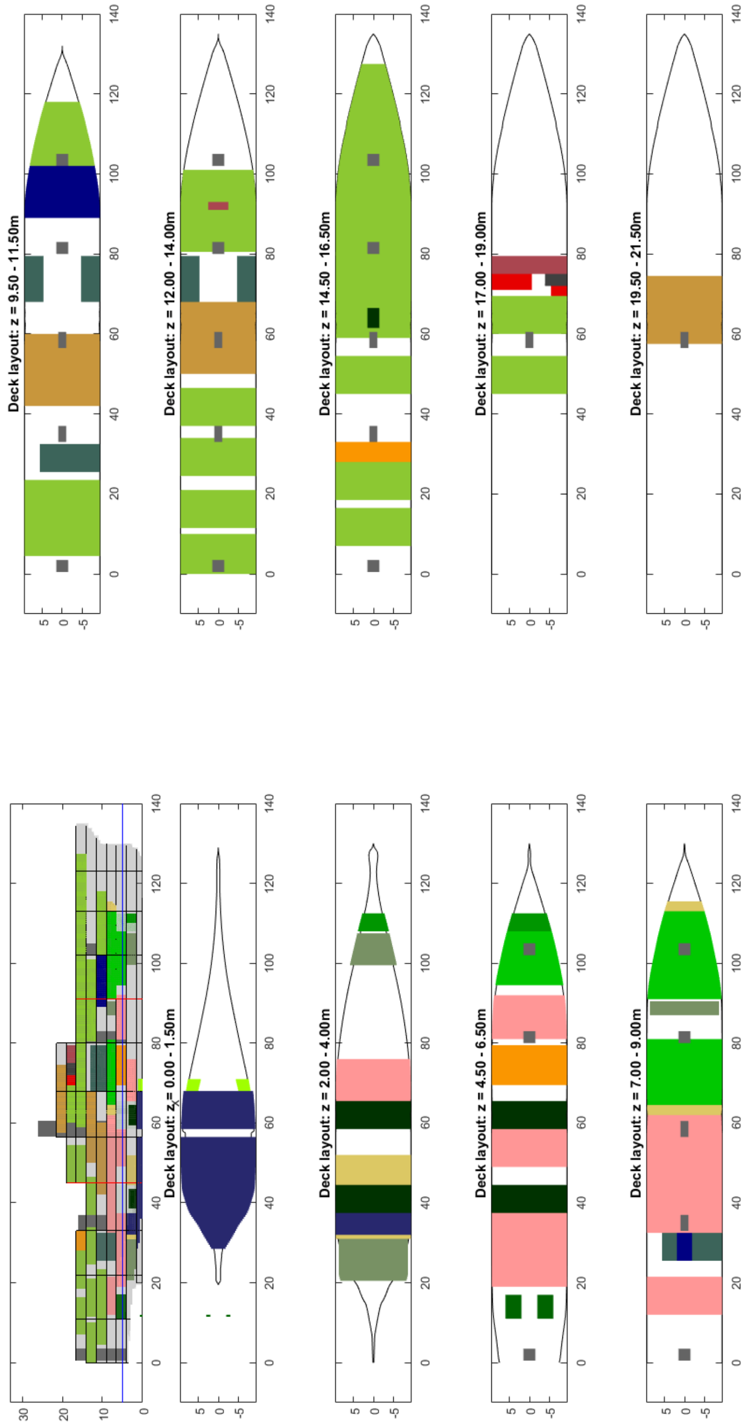


Figure 5.14: The layout of the resulting design as produced by the IECEM.

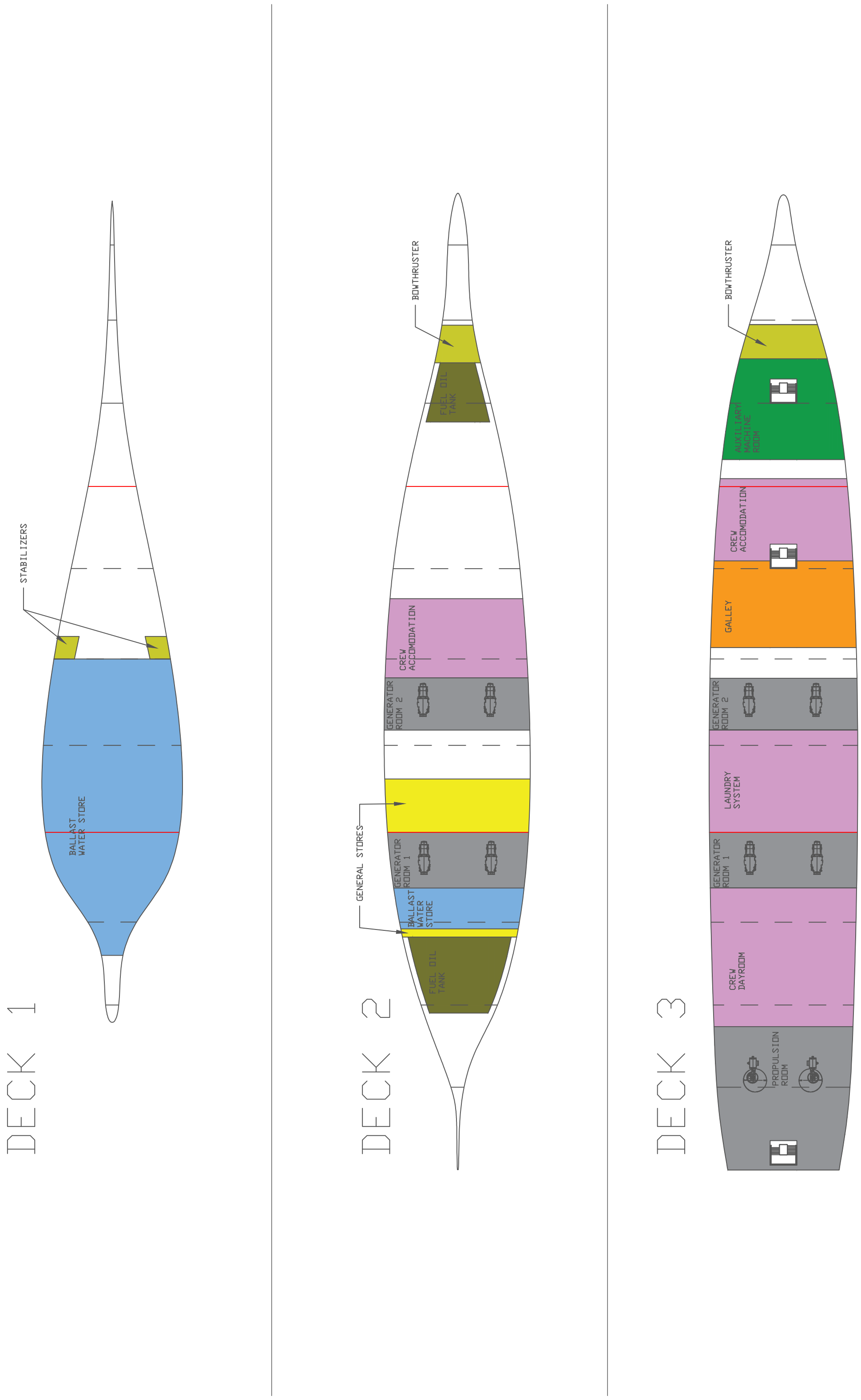


Figure 5.15: The layout of decks 1 to 3 of the resulting most promising design

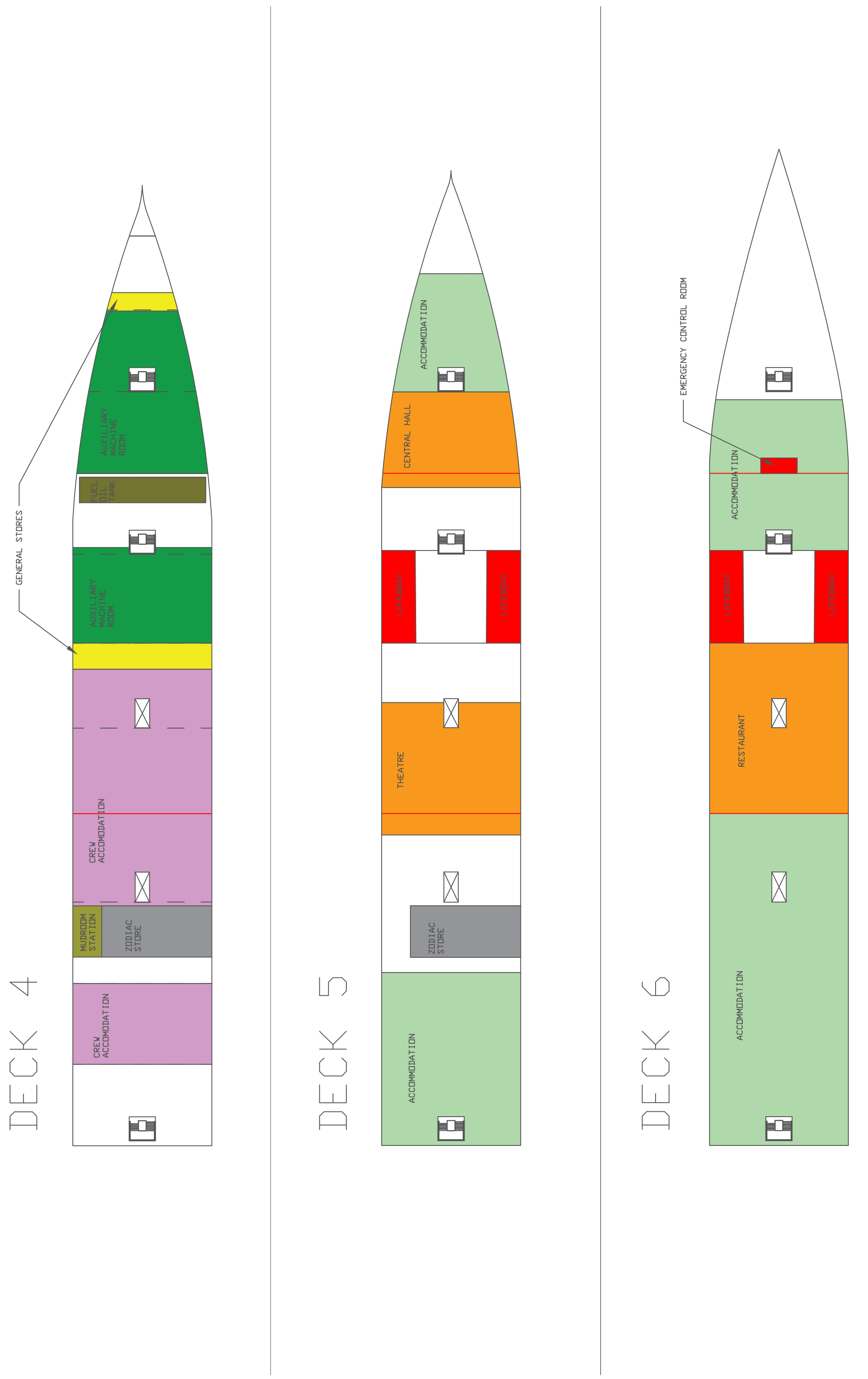


Figure 5.16: The layout of decks 4 to 6 of the resulting most promising design

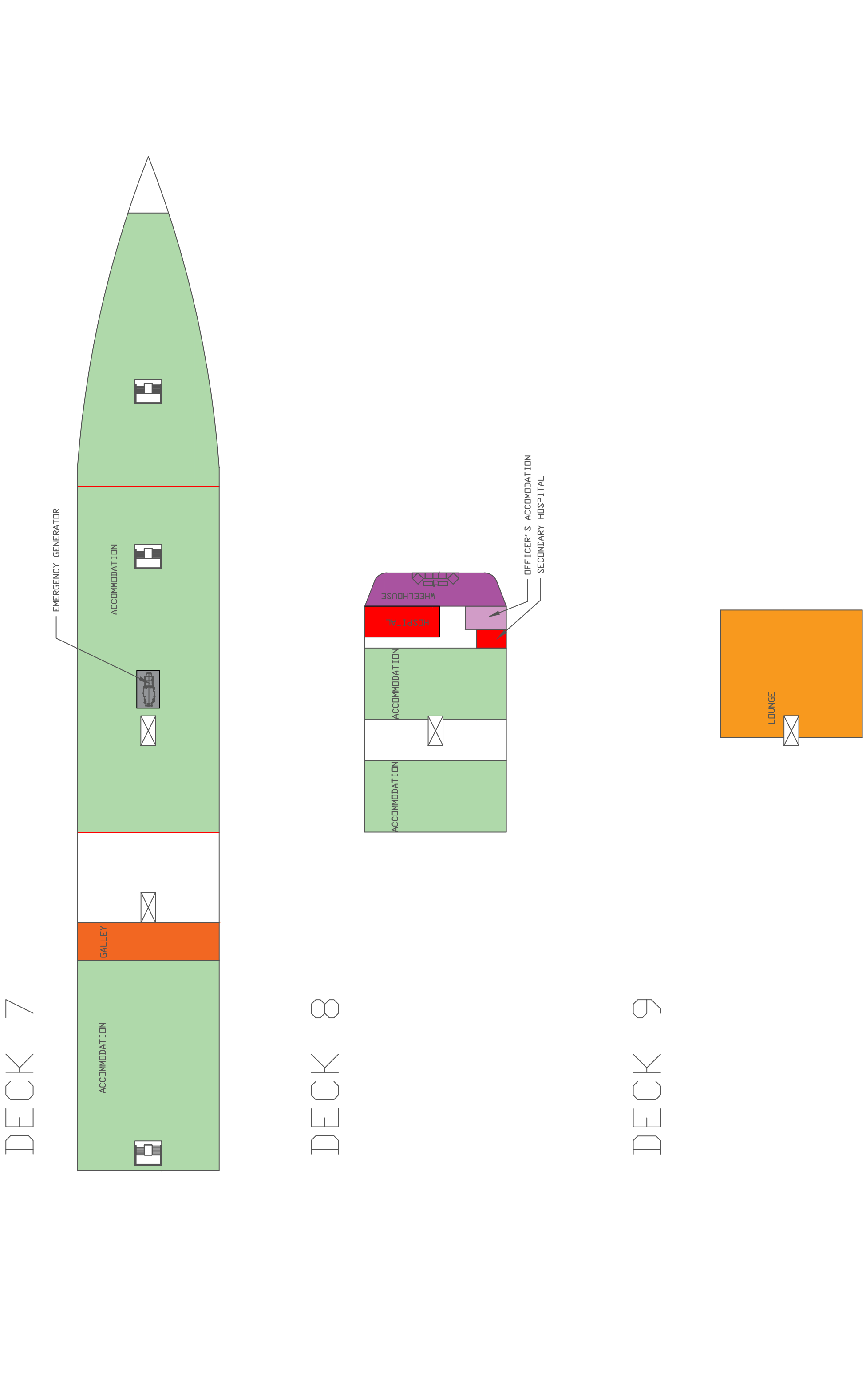


Figure 5.17: The layout of decks 7 to 9 of the resulting most promising design

Chapter 6. Conclusions and Recommendations

6.1 Conclusions

This section presents the conclusions of this research by answering the research questions. First the sub-questions will be answered and secondly the answer to the main research question will be presented.

6.1.1 The Sub-questions

At the start of the research four sub-questions were formulated to help answering the main question. Within this subsection each sub-question is repeated and the answer to the question is formulated.

Which niche-market in the current market for small cruise ships is interesting for Conoship to design for?

In chapter 2 a brief overview of the general cruise market is given and the selection of the expedition cruise market is discussed. Due to seasonality multiple different locations will be served in a combination of the North and South polar regions with coastal cruises during the transit from North to South and vice versa. Thus, the Polar regions were selected as a promising niche-market deserving further study as the amount of people interested in a Polar cruise is growing and the current vessels are old. Because of the older cruise vessels and all the new regulation a new vessel in this market will provide an operator with a competitive advantage.

What regulations, requirements and conditions limit the design space for the cruise vessel?

Chapter 3 describes the most important regulations, but also names characteristic requirements resulting from this niche-market. An example is the need to be able to transfer people from the ship to the shore where there is no quay available. This can for instance be done by the use of a helicopter or smaller zodiacs, in this case two options are selected both using zodiacs but with different facilities and storage options. In terms of regulations in early stage the Safe Return to Port regulation stands out as it has severe demands on the redundancy of certain systems and spaces in particular the hospital, generator rooms and galleys. Other regulations are the Polar Code with tank locations, the ban on HFO, and zero discharge regulations. Lastly also the IMO Fire Safety Systems Code with the Main Vertical Zones has a strong influence on the ship's subdivision.

How to develop a design process for a cruise ship which integrates the IECEM to obtain the expected benefits of the IECEM?

Section 4.3 presents a design process which uses the quantitative qualities of the IECEM to study variations in design requirements. In this case multiple luxury levels and operational scenarios are defined and the IECEM is used to create large series of example designs for the different combinations of luxury level and operational scenario. Methods to determine the building costs, operational expenses and capital expenses as well as the ship's weight, resistance and stability are implemented to measure the performance of the individual design. In this way the IECEM based ship concept design process supports the designer with large quantities of designs and their performance to select the best set of variations to create a concept design with.

What is the most promising cruise ship concept design for Conoship to enter the defined niche-market?

The most promising cruise ship design for Conoship has been selected based on its economical performances: earnings, expenses and building costs. Chapter 5 elaborates on the set of designs that has been generated and ends with the selection of the most promising design. Based on the earnings divided by the expenses and the building costs a example design is selected with a Slow operational scenario and the Normal luxury level.

6.1.2 The Main Question

The main research question stated at the start of this research is:

How could the Interactive Evolutionary Concept Exploration Methodology (IECEM) contribute to the design of an unique cruise vessel for Conoship to position itself in the market of small cruise vessels?

The answer to this question needs to cover three aspects: the contributions of the IECEM to the design process, an resulting unique cruise vessel design, and how this design helps in positioning Conoship in the cruise ship design industry.

Firstly the IECEM contributed to the design process by generating large series of designs. These large series enabled the analysis of the effect of the different variations in operational scenarios and luxury levels on the financial performance of the design. Besides the analysis of these variations it also provided different solutions for the designs in terms of principle dimensions such as the length, beam or the number of decks.

Secondly the resulting design contains unique cruise vessel design features such as the 360 deg view lounge on the top deck. Also, the selected yacht-like solution of storing the tenders in a dedicated tender storage is hardly seen in existing cruise ships. Although the resulting design is still in a preliminary design phase and the level of detail in the arrangement is very limited, the design already contains an initial division of the MVZs which is rather unique in this stage of the process.

Lastly to position itself in the market of small cruise vessels a specific niche-market is selected. The Polar expedition cruise market provides good conditions for new vessels but also suits the company given its previously experience in different kinds of offshore vessels. In order to present it to the market additional 2D general layout drawings have been developed which provide more insight in the specific design. This supports the design with enough knowledge and information to present it to the market.

6.2 Contribution

The contributions made with this thesis research are as follows:

1. First application of the IECEM in a commercial design and engineering office.
    - I created a cruise ship model containing most characteristic items of an small expedition cruise ships.
    - I developed a method to estimate the building costs of a cruise ship for the use in the IECEM software.
    - I extended the software to determine the positions of the Main Vertical Zones according to the IMO Fire Code.
2. Contributions to the development of the Conoship Cruise vessel.
    - I identified the Polar expedition cruise market as a growing and interesting niche-market.

- I explored different operational scenarios and luxury levels to identify their financial performance and select the best combination.

3. Development of new methods to present the designs and select a design.

   - I developed numerical representations of the found feasible designs for the different variations studied.
   - I derived an initial layout based on the generated 3D visualisation. This initial layout provides more insight in the arrangements of spaces onboard and thereby lays the foundation for further studies on the ship designs.

6.3 Recommendations

Although the main research question is answered and a resulting design is presented as a result of the research there are possible points of improvement and ideas for future work.

During the analysis of the results it was already discussed that within the solution set multiple designs were closely related as there dimensions and layout were almost identical. Grouping those designs would decrease the number of solutions to only the unique set of designs. This would reduce the effort required to filter through an enormous data set and select the one single design to proceed with. Besides reducing the absolute number of solutions it also allows to more thoroughly analyse the layout of the different solutions. Both the means to group the designs as well to analyse the layout of a design are topics of further research.

The second recommendation is about the selection of the one design. Where grouping together the similar design will already improve the selection process, it still needs more attention as selecting the one design out of a large set is a complex process. While a lot of information about the different designs is available, taking all into account when searching for the one design is hard. Besides this it might also occur that changing parameters may shift the optimal point. To properly address this part of the IECEM design process a dedicated study into the selection process is required.

The focus during analysing the different designs has mainly been on their performance. While for complex service ships the layout of spaces has a huge influence on the performance of the vessel. Therefore a conceptual arrangement drawing is created based on the resulting design from the IECEM. This conceptual arrangement shows that the most important components are already located at the right positions but meanwhile also highlights that certain aspects go wrong. To properly overcome this additional research to the layout of spaces and there relation to other spaces needs to be researched. These relations will help to position the spaces in the design in a way which improves the conceptual arrangement of spaces.

The final recommendation concerns the ranking of the designs. The NSGA uses the values obtained for the objective functions to rank the designs and as a feedback on improving the information used to generate designs from with the packing algorithm. Currently this feedback is only generated for feasible designs. All designs that are not feasible but do get packed and all design which fail to get packed are given the same objective value. To improve the quality and the yield of the NSGA a possible improvement can be created by returning an objective value to the NSGA for the non-feasible designs.

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Appendix A. Deployement Lindblad-National Geographic ships 2016-2017

2016/17 EXPEDITION CALENDAR

	PAGES	# OF DAYS	SHIP	2016								2017											
				MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
EXPLORE THE WORLD'S CAPITALS OF WILDNESS																							
Antarctica	10	14	NG Explorer & NG Orion							■	■	■	■									■	■
Antarctica, South Georgia and the Falklands	12	24	NG Explorer & NG Orion							■		■	■									■	
South Georgia and the Falklands	14	18	NG Explorer & NG Orion						■					■							■		
Land of the Ice Bears	16	11	NG Explorer		■											■	■				■		
Exploring Alaska's Coastal Wilderness	18	8	NG Sea Lion & NG Quest	■	■	■	■									■							
Alaska Wild Escape	20	6	NG Sea Bird													■	■	■	■				
Big Picture Alaska	22	11	NG Sea Bird														■	■	■				
Treasures of the Inside Passage: Alaska and British Columbia	24	14	NG Quest														■			■			
Baja California and the Sea of Cortez	26	8	NG Sea Bird									■	■	■									
Whales & Wildness: Spring in the Sea of Cortez	28	8	NG Sea Bird																				
Upper Amazon	30	10	Delfin II					■		■	■	■	■	■	■	■	■	■	■		■	■	■
Galápagos	32	10	NG Endeavour/Endeavour II* & NG Islander	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Costa Rica and the Panama Canal	34	8	NG Sea Lion							■	■												
Rounding the Cape: Chilean Patagonia and Argentina's Staten Island	36	20	NG Explorer						■												■		
Best of Chilean Patagonia: From Torres Del Paine to Cape Horn	38	16	NG Explorer & NG Orion						■												■		
Patagonia: Chilean Fjords and Argentina's Staten Island	40	12	NG Explorer & NG Orion						■												■		
TRACING THE EDGE OF EUROPE'S AGE OLD COASTLINES																							
Culture and Cuisine from Oporto to Basque Country	44	8	NG Orion	■											■					■			
Bordeaux to London: The French Atlantic Coast	46	8	NG Orion	■				■								■							
Wild and Windswept: Exploring the Coasts of England and Wales	48	8	NG Orion		■															■			
Norway and Scotland: Fjordlands and the Inner Hebrides	50	8	NG Orion		■														■				
Scandinavia by Sea: Denmark, Sweden, and Norway	52	8	NG Orion			■											■						
The North Sea: Copenhagen to London	54	8	NG Orion					■								■							
Portugal and Spain: From the Algarve to Catalonia	56	8	NG Orion												■								
Circumnavigating the Baltic Sea	58	14	NG Orion													■	■						
46° TO 80° NORTH—CHANGES IN LATITUDE, CHANGES IN ATTITUDE																							
A Remarkable Journey to Alaska, British Columbia & Haida Gwaii	62	15	NG Sea Bird & NG Sea Lion	■				■							■	■				■			
Norway's Fjords and Arctic Svalbard	64	17	NG Explorer & NG Orion			■										■							
Svalbard, Iceland & Greenland's East Coast	66	17	NG Explorer														■						
Nordic Passages: Shetlands, Orkney, Faroes, and Iceland	68	14	NG Orion														■		■				
A Circumnavigation of Iceland	70	10	NG Orion															■					
Iceland's Wild West Coast to Greenland	72	10	NG Orion																■				
Iceland & Greenland: Viking Legends and Wild Fjords	74	16	NG Explorer				■											■					
Epic 80°N: Exploring Greenland, Baffin & Ellesmere Islands	76	24	NG Explorer				■												■				
Exploring Greenland and the Canadian High Arctic	78	15	NG Explorer															■					
The Canadian Maritimes	80	8	NG Explorer					■												■			
CULTURE & NATURAL HISTORY ROOTED IN GEOGRAPHY																							
Machu Picchu & Peru's Land of the Inca	84	8	Land Program	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Galápagos + Machu Picchu & Peru's Land of the Inca	86	16	NG Endeavour/Endeavour II* & NG Islander + Land Program	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Upper Amazon + Galápagos	88	20	NG Endeavour/Endeavour II*/Islander/Delfin II	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
Upper Amazon + Machu Picchu & Peru's Land of the Inca	89	17	Delfin II + Land Program	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
Costa Rica to Panama Plus Monteverde Cloud Forest	90	11	NG Sea Lion							■	■	■	■	■									
Panama to Coast Rica Plus Monteverde, Arenal Volcano And Tortuguero	91	15	NG Sea Lion								■												
Exploring Costa Rica: Cloud Forest to the Caribbean	92	9	Land Program								■												
Columbia & Snake Rivers Journey: Harvest, History & Landscapes	93	7	NG Sea Bird & NG Sea Lion					■	■														
Sailing the Caribbean	96	8	Sea Cloud										■										
Sailing the Greek Isles	98	9	Sea Cloud		■	■	■	■									■	■	■	■			
Under Sail: Greece to the Dalmatian Coast	100	12	Sea Cloud		■		■									■	■		■	■			
England, Ireland, Scotland & Wales: A Circumnavigation	102	19	NG Explorer												■								
Vietnam & Cambodia	104	14	Jahan									■	■										
Scotland's Highlands & Islands	105	9	Lord of the Glens			■	■										■	■	■				
Baja California: A Remarkable Journey	105	15	NG Sea Bird																				
Wild Islands & Treasures of Baja California	105	8	NG Sea Bird								■												

*National Geographic Endeavour *will be replaced by* National Geographic Endeavour II *in January 2017. See pgs 120-123 for details on each ship.*

Appendix B. SSM description

Number	System	Type	NumObj	NumNVObj
1	envelope	envelope	0	0
2	decks	decks	0	0
3	Stabilizer System	object	1	0
4	bulkheads	bulkheads	1	0
5	Generator room	object	3	0
6	Generator room 2	object	3	0
7	Bowthruster system	object	2	0
8	Propulsion room	object	2	0
9	Funnel system	object	4	0
10	Funnel Connection	object	1	1
11	Funnel system 2	object	4	0
12	Funnel Connection 2	object	1	1
13	Stairs 1	object (ignore)	2	0
14	Stairs 2	object (ignore)	2	0
15	Stairs 3	object (ignore)	2	0
16	Stairs 4	object (ignore)	2	0
17	Stairs 5	object (ignore)	2	0
18	Central Hall	object	1	0
19	Bridge system	object	3	0
20	Officers Accommodation	object	1	1
21	Lifeboat system	object	1	0
22	Emergency Generator	object	2	0
23	Emergency Control room 1	object	1	0
24	Hospital Primary System	object	1	0
25	Secondary Hospital solution	object	1	1
26	Zodiac Store, launch and recover system	object	1	0
27	Boarding System	object (ignore)	1	0
28	Mudroom system	object	1	1
29	Main Galley system	object	1	0
30	Secondary Galley system	object	1	0
31	Restaurant system	object	1	0
32	General Stores Systems 1	object	1	0
33	General Stores Systems 2	object	1	0
34	General Stores Systems 3	object	1	0
35	General Stores Systems 4	object	1	0
36	Laundry system	object	1	0
37	Entertainment system 1	object	1	0
38	Entertainment system 2	object	1	0
39	Technical/Auxilary systems 1	object	1	0
40	Technical/Auxilary systems 2	object	1	0
41	Technical/Auxilary systems 3	object	1	0
42	Accommodation block 1	object	1	0
43	Accommodation block 2	object	1	0
44	Accommodation block 3	object	1	0
45	Accommodation block 4	object	1	0
46	Accommodation block 5	object	1	0
47	Accommodation block 6	object	1	0
48	Accommodation block 7	object	1	0
49	Accommodation block 8	object	1	0
50	Accommodation block 9	object	1	0

51	Accommodation block 10	object	1	0
52	Accommodation block 11	object	1	0
53	Accommodation block 12	object	1	0
54	Accommodation block 13	object	1	0
55	Accommodation block 14	object	1	0
56	Accommodation block 15	object	1	0
57	Accommodation block 16	object	1	0
58	Accommodation block 17	object	1	0
59	Accommodation block 18	object	1	0
60	Accommodation block 19	object	1	0
61	Accommodation block 20	object	1	0
62	Crew accommodation system 1	object	1	0
63	Crew accommodation system 2	object	1	0
64	Crew accommodation system 3	object	1	0
65	Crew accommodation system 4	object	1	0
66	Crew accommodation system 5	object	1	0
67	Crew accommodation system 6	object	1	0
68	Crew accommodation system 7	object	1	0
69	Crew accommodation system 8	object	1	0
70	Crew dayroom	object	1	0
71	Fuel tank system 1	object	1	0
72	Fuel tank system 2	object	1	0
73	Fuel tank system 3	object	1	0
74	Fuel tank system 4	object	1	0
75	Ballast system 1	object	1	0
76	Ballast system 2	object	1	0
77	Ballast system 3	object	1	0
78	Ballast system 4	object	1	0

Appendix C. Additional Information on the Most Promising Design

Table C.1: Building Cost calculation

Building Costs		
Steel fabrication costs	10.82	[mEuro]
Steel material costs	4.44	[mEuro]
Steel prebuild costs	0.70	[mEuro]
Paint costs	1.04	[mEuro]
Deck & Mooring costs	0.42	[mEuro]
Fire and Safety costs	1.09	[mEuro]
Accomodation costs	8.43	[mEuro]
HVAC costs	2.10	[mEuro]
Electrical instal. costs	6.06	[mEuro]
Nav./Com. elec. costs	0.50	[mEuro]
Propulsion system costs	0.13	[mEuro]
Machinery equipment costs	4.08	[mEuro]
Secondary object costs	1.50	[mEuro]
Margins costs	2.82	[mEuro]
Building costs	44.13	[mEuro]

Table C.2: The Expenses and Earnings calculation

Earnings and Expenses calculation		
Potential Earnings	64.26	[mEuro]
Potential Earnings Polar Region	51.41	[mEuro]
Operational Expenditure	18.89	[mEuro]
Capital Expenditure	2.88	[mEuro]
Total Expenses	21.77	[mEuro]
Total expenses per passenger day	299.01	[Euro]
Gross Cashflow a year	42.49	[mEuro]
Fuel Expenses a passenger day	43.95	[Euro]

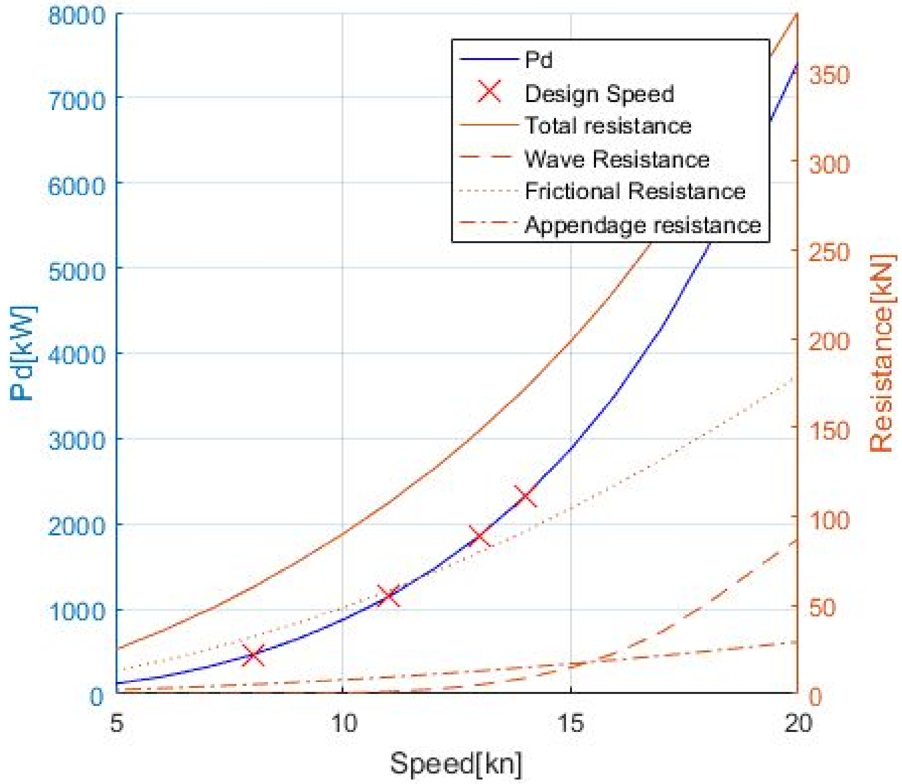

Figure C.1: The speed power curve of the Most Promising Design