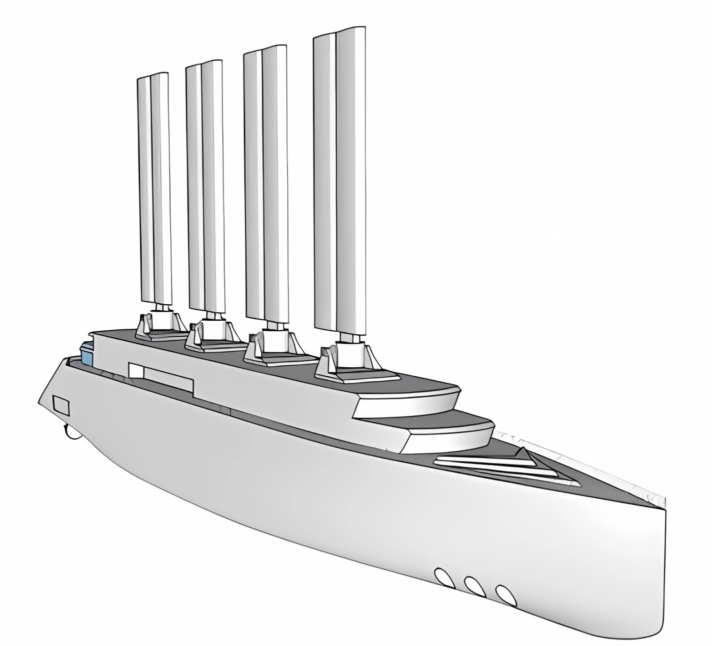
Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

Ida Solheim Eide
Magnus August Thorsrud Weidemann

Concept Development of a Sailing Cruise Ship Powered by Alternative Fuel

Bachelor's thesis in Ship Design
Supervisor: Lars Erik Nygård
Co-supervisor: Trond Sigurdsen
May 2023



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Preface

We would like to thank everyone who has helped us during our thesis. A big thank you to our co-supervisor Trond Sigurdsen from YSA Design, who has given a good introduction and knowledge about design and general arrangement for cruise ships. We are also grateful for the collaboration with AlfaWall Oceanbird, and especially to our contact persons Anton Dunström and Alfred Rapaport. They have shared valuable competence in sail theory and wing sails, and they have helped us with performance data for their concept. Furthermore, we thank Wärtsila for information about their Methanol engines, and Albert Devold from Sirius Design for knowledge about stability and tank arrangement for cruise ships. Finally, we thank our supervisor Lars Erik Nygård for follow-up and guidance when meeting challenges during the thesis.

Abstract

In this thesis, a concept for an environmentally friendly expedition cruise ship has been developed. The ship makes use of methanol as an alternative fuel to become CO_2-neutral. Wing sails were also implemented to reduce the emissions even more. Calculations have been preformed to find out the ship's stability. Permanent ballast was used to meet the requirements. Since the vessel is a passenger ship, safety regulations have been considered important to follow. Therefore, the development of the general arrangement and tank plan were affected by this. The hull shape was designed to be efficient for the ship's unpredictable operational profile. In addition, it is a luxury cruise ship and the focus has been on making an elegant and sleek hull.

Sammendrag

I denne oppgaven har et konsept for et miljøvennlig ekspedisjonscruiseskip blitt utviklet. Skipet tar i bruk metanol som alternativt drivstoff for å være CO_2-nøytralt. Seil blir også brukt for å kunne redusere utslippene enda mer. Beregninger har blitt utført for å bestemme skipets stabilitet, og permanent ballast har blitt brukt som en løsning for å møte kravene. Ettersom skipet er et passasjerskip, har sikkerhetskrav vært et viktig mål å følge. Dette har derfor påvirket utviklingen av blant annet generalarrangementet og tankplanet. Skrogutformingen har blitt designet for å være effektiv for den uforutsigbare operasjonsprofilen til skipet. I tillegg er skipet et luksus cruise skip og det har vært fokus på å lage et elegant og slankt skrog.

Project description

The assignment is delivered by YSA Design, an architectural firm located in Oslo. Their main area is buildings, but they have worked with solutions and general arrangement for several cruise ships and have expertise in the field. The respondent wants a concept that can be introduced to relevant shipping companies.

The assignment is to engineer and develop a concept for a cruise ship powered by alternative energy, in form of wind and alternative fuels. The cruise ship shall perform conventional journeys as well as expedition journeys to polar areas.

As the ship is powered by wind there should be no heeling when sailing. This is for ensuring safety and comfort for the passengers.

The given requirements for the vessel is:
- L = 170-185 m
- B = 20-24 m
- Cabins: 150-170
- Pax: 300-340
- Polar Classification
- Aesthetic appearance
- Lifeboats
- Pool
- Various public space
- Marina
- Modern sailing rigg
- Powered by alternative fuel

The delivery shall consist of:
- General arrangement
- Main propulsion system arrangement
- Performance data for wind assisted propulsion
- Tank plan
- Structural analysis

Abbreviations

- L_{LL} = Rule length
- Loa = length over all
- L_{pp} = Length between perpendiculars
- GT = Gross tonnage
- GM = Initial stability
- WAPS - Wind Assisted Propulsion System
- SOx - Sulfur oxides
- NOx - Nitrogen oxides
- GHG - Greenhouse gas
- LNG - Liquefied natural gas
- IMO - International Maritime Organization
- UN - United Nations
- MSC - Maritime Safety Committee
- MARPOL - International Convention for the Prevention of Pollution from Ships
- SOLAS - International Convention for the Safety of Life at Sea
- DNV - Det norske veritas
- SAC - Sectional area curve
- Cb - Block coefficient
- L_{WL}
- B_{WL}
- T - Draught
- CM - Midship coefficient
- SFC - Specific fuel consumption
- BSEC - Brake-specific energy consumption
- GA - General arrangement
- W - weight
- LCG - Longitudinal centre of gravity
- VCG - Vertcal centre of gravity
- LMOM - Longitudinal moment
- VMOM - Vertical moment
- GM - Metacentric height
- KM - distance from keel to metacentre
- CB - Central buoyancy
- CG - Central gravity
- CL - Centreline
- VCF - Vertical centre of flotation
- MOB - Man over board
- PC - Polar Class
- L.sum - sum of longitudinal stiffeners
- Trv.sum - sum of transverse stiffeners

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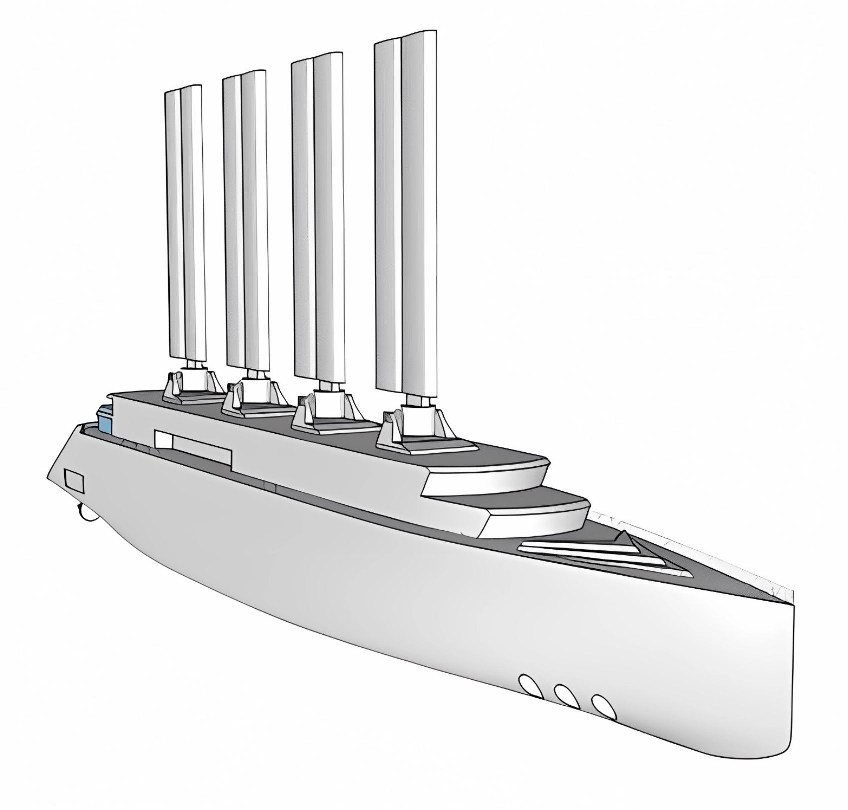
Summary of final concept



Main dimensions		
Lenght over all	180	m
Lenght b. perp	169.5	m
Beam	22	m
Draught	5.5	m
Number of decks	6	
Pax	284	
Crew	134	
Gross tonnage	15 017	GT

Propulsion system		
Design speed	17	kn
Max speed	21	kn
Wärtsila 9L32 Methanol	2 x 5 220	kW
Wärtsila 6L32 Methanol	2 x 3 480	kW
ABB DO 1100P Azipod	2 x 3470	kW
Oceanbird Wing Sail	4	
Range	3 500	NM

1 Introduction

Concept development and engineering of a cruise ships is a challenging task. As a passenger ship the safety on board is important to maintain. In addition, a passenger ship demands large areas for passenger spaces. This has to be balanced with the required space the ships systems, which are essential for a functional ship. When designing cruise ships, the focus is therefore on efficient infrastructure and area distribution.

Design work is demanding and challenging. The process is iterative, and several rounds of calculations must be done for each segment to find the best compromises. In ship design, the Design Spiral is a tool for how the design process can be carried out. The goal of the thesis was to get through the design spiral two times. Two rounds are not enough for a good result, but with limited time and manpower available, this is a sensible goal. Several rounds allow for improvements and adjustments, so that the final result can be as optimal as possible.

Due to the limited available time and capacity, limitations have been made in this thesis. This is to be able to go deeper on certain segments. The limitations will mean that assumptions and simplifications have been made in parts of the thesis. At these segments, more thorough work is required.

2 Background

The development of technology

Wind was for many centuries the only source of energy that ocean crafts could use. With the industrial revolution in the 1890s came the steam engine. The steam engine revolutionized energy production and made it possible for ships to sail without depending on favorable weather conditions. In the 1910s, diesel engines were put into use on ships. They were more efficient than the steam engine, as well as requiring a fraction of the volume that coal required. This allowed ships to be larger, carry more and sail faster than before [20] [13].

Today we see the consequences of burning fossil fuels and there is a great focus on finding alternative energy sources and carriers. Various alternative fuels are being researched and tested, but wind is also making a return as a promising means of propulsion. By creating efficient and modern sail rigging systems, Flettner rotors or kites, ships will be able to exploit the wind as they once did. Either the wind can account for 100 % of the propulsion, or it can be an additional system to reduce needed engine power.

Climate challenges

The shipping industry is facing major challenges for reducing emissions. In 2018 IMO set a goal to reduce greenhouse gas emissions by 50 % in 2050, compared to the level of emission in 2008. Today a large percent of the global fleet is still using fossil fuels as their energy source. Compared to other transport industries, the shipping industry has not come far in implementing more climate friendly solutions. The industry is forced to embrace new technologies and alternative fuels. The challenge is to find alternatives good enough to replace fossil fuels [36].

The cruise industry represent under 1 % of the global fleet, and on a global level they pollute a small share of the total CO_2 pollution. However, locally the emissions from the cruise ships are to large to ignore. It is a visible industry with destinations at both small and large cites all over the world. Cruise ships pollute a large amount of SO_X and NO_X compared to emissions from cars [18]. These vessels can be compared to a small village where the energy is provided by fossil fuels. Liquefied natural gas (LNG) as been introduced for larger cruise ships in recent years. Existing engines are being retrofitted for LNG, to reduce the SO_x and NO_x emissions. This is a step in the right direction, but will not give enough reduction in greenhouse gas emissions [37].

Prognoses for the cruise market

Globally the cruise industry has been a growing industry for many years. The cruise industry had an annual growth at 5-7 % before the pandemic, and it is expected to have a healthy growth in the coming years. With modern technology, expansions and innovations, cruise ships offer more activities and destinations than before, leading to an increase in popularity and demand.

The new segment, expedition cruises, has received an increased interest in the last couple of years. More cruises are being built for expeditions to arctic areas, and conventional cruises are showing interest in more polar destinations. The attractions for the cruise tourists are exciting wildlife and adventures which are not possible to get on a conventional cruise voyage [37].

3 Vessel Overview

The vessel type to be designed in this thesis is an expedition cruise ship with sails. It will offer cruises with a focus on proximity to the water and nature. With alternative fuels and the use of wind for propulsion, there should be an option to choose more environmentally friendly journeys.

3.1 Safety on board

As a passenger ship the safety on board is of utmost importance. Fire zones and escape routes needs be thought out to make sure evacuation can be carried out safe and efficient. Life boats and life rafts must have enough room for all people on board.

3.2 Ship movements

The ship is in the category of passenger vessel. It is therefore desirable to have as little movement as possible to take passenger and crew safety and comfort into account. Large movements can cause injuries and damages as loose objects in restaurants, kitchens, lounges and other spaces can fall and slide around. In addition, a lot of passengers might not be used to the sea and therefore get seasick. This affects the comfort and experience of the trip.

3.3 Static heeling

With sails as an additional propulsion system, there will be a risk of static heeling. This must be limited to maintain maneuverability, safety, and comfort. Static heeling of several degrees will lead to unfavorable working conditions for the crew, which may lead to weaker service for passengers. It will also affect the safety of the people on board.

3.4 Expedition cruise

Expedition cruises to exclusive destinations are becoming more and more popular in the cruise market. The ship will be able to take trips to polar regions. It must therefore meet the requirements for polar classification. Due to little infrastructure in polar areas, the vessel have to bring its own excursion equipment.

3.5 Marina

Cruise tourists are not only becoming more environmentally conscious, but also want to have a greater connection to the ocean than they have now. Therefore, it is important that the ship's layout facilitates passenger activities close to the water. Marinas are effective at getting passengers close to the water and are increasingly being implemented on luxury cruise ships. To meet demand, cruise ships can be designed with garages for small boats and water activity equipment.

3.6 Operational Profile

Since it has not been possible to obtain information about the operational profiles of sailing cruise ships, it has not been considered in this thesis. For sailing vessels, one factor to consider when making operational profile is the changing weather conditions. Modern technology have made weather predictions easier, but they can still be difficult to predict. This may cause variations in the operational profile, and to utilize optimal wind conditions, close weather monitoring and analysis are needed.

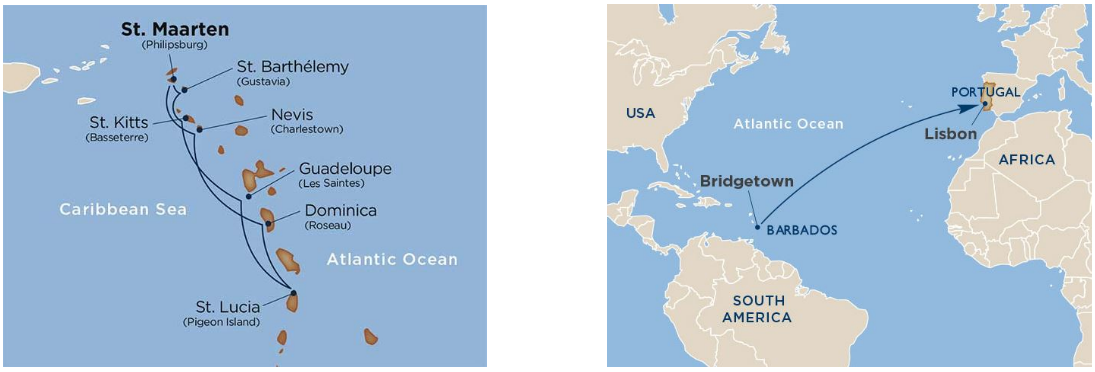
3.7 Operational region

As this is a concept development project, no destinations or operational areas have been given by a shipowner. Inspiration for potential routes have been taken from the shipping company Wind Star Cruises, who operates sailing cruise ships today. Three routes have been selected, one in the Mediterranean, see Figure 3.1, one in the Caribbean, see Figure 3.2a and one transatlantic crossing, see Figure 3.2b [12].

Source: www.windstarcruises.com

Figure 3.1: Example route for Mediterranean.

Figure 3.2: Example routes for operational region



Source: www.windstarcruises.com

(a) Example route for Caribbean.

Source: www.windstarcruises.com

(b) Example route for transatlantic crossing.

4 Rules and regulations

Humans have travelled and explored the oceans for centuries. For most of that time, the oceans were dangerous and unsafe. They have caused damage, injuries and lives, but as humans have obtained better knowledge and technology, the oceans have become much safer.

Climate change is a real problem which is causing irreversible damage to Earth. Human activities are polluting the atmosphere and causing increased greenhouse effect. This has catastrophic consequences when it comes to rising sea levels, irregular whether and droughts, more severe storms, food production and biodiversity loss [7].

To ensure safe and environmentally friendly shipping activities, it is essential that rules and regulations exist to enforce standards for design, construction and operation of vessels. If a ship is not built strong enough or has insufficient stability, the consequences can be tragic. The shipping industry is responsible for 3.5 % to 4 % of the global climate change emissions and other pollutants. Therefore, rules and regulations are created and enforced to help reduce this [46].

4.1 IMO

The International Maritime Organization (IMO) is the United Nations' (UN) specialized agency which develops and maintains rules and regulations for international shipping and maritime activities. The regulatory framework must be implemented by all member states and deals with maritime safety and security, environmental concerns and efficiency, legal matters and technical co-operation. IMO makes sure the international shipping is sustainable, energy efficient, safe and secure by making standards and guidelines. These guidelines concern everything form ship design, construction, equipment, manning, operation and disposal. IMO also provides technical assistance and support [26] [47].

4.2 MSC

The Maritime Safety Committee (MSC) is IMO's most senior technical committee and deals with IMO's responsibility for everything related to safety and security in the maritime sector. They cover passenger ships and all kinds of cargo vessels. Some of its tasks are to update SOLAS, STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers), related codes and modernize GMDSS (Global Maritime Distress and Safety System) [27] [42].

4.3 MARPOL

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention from IMO that covers prevention of pollution by ships from operational or accidental causes in the maritime environment [24].

4.4 SOLAS

International Convention for the Safety of Life at Sea (SOLAS) is an international treaty regarding safety of merchant ships and is often seen as the most important one. After its establishment in 1948, IMO has been responsible for developing and updating it [25].

4.5 DNV

Det Norske Veritas (DNV) is one of the world's largest ship classification societies and a global leader in quality assurance and risk management. They provide guidance and overlook development and construction in the maritime and energy industry to make sure mandatory rules and regulations are followed. When a project is finished, they provide the certificates. They also make sure that rules and regulations are enforced throughout the lifetime and disposal of a constriction by providing inspections [14] [38].

5 Hull Shape

The shape of the hull is essential when designing the right ship for the right mission. The hull is what is in contact with water and the shape determines how it behaves and how much resistance is created. There are a lot of different types of hull shapes, where the bow might be the most critical part of the design.

5.1 Bow design

All bow types try to solve the compromise between efficiency and usability. There are a lot of different bow designs used for cruise ships and they all have advantages and disadvantages.

5.1.1 Raked and flared bow

A bow that is forward leaning and has sides that widens out the higher you go, is raked and flared, see Figure 5.1. This has the advantage of providing extra buoyancy when meeting a wave. The ship rides over the wave, preventing the upper decks from being exposed to water. The flare also diverts away most green sea. Green sea is the terminology for a large amount of water washing up on the forward deck. This helps protect the superstructure, bridge and other exposed areas and equipment from getting wet or damaged by the water. The disadvantages are that the ship will quickly respond to larger waves, due to the extra buoyancy, and cause fast vertical accelerations. This feels unpleasant for the crew and passengers, and is one of the main causes for seasickness. The rake of the bow is trying to ease this effect, but is not effective with larger waves. A bow colliding with larger waves will cause the ship to lose a lot of forward momentum and making it less efficient. The bow wave formed is inefficient as it creates a great amount of hull resistance. This increases fuel consumption [34][10].

Source: www.wikipedia.org

Figure 5.1: A raked and flared bow. This ship has a bulb as it is unusual for ships not to.

5.1.2 Bulbous bow

A bulbous bow has the same rake and flare as the previously mentioned bow shape. To overcome the bow wave formed at the front and reduce the resistance, the underwater part protrudes out, see Figure 5.2. This protrusion creates another wave in front of the bow wave, and when designed correctly, the two waves will cancel each other out. The downside with a bulb is that it is designed for one speed, one draught, a specific waterline and calm water. This means it can generate greater resistance when not sailing in the optimal conditions. The bulb is mostly used for larger, slower moving ships with grater block coefficient, for example container ships, tankers and cruise ships. The bulbous bow is common for cruise ships, though new and more efficient bow shapes are starting to appear [33] [11] [5].

Source: www.maritime-executive.com

Figure 5.2: A bulbous bow.

5.1.3 Inverted bow

An inverted bow has the rake going backwards, see Figure 5.3. This means the waterline will be long and allows for smoother shoulders, which reduces water resistance. The inverted bow is sharp and cuts through waves. This helps to reduce resistance and mitigates the pitching motion in waves, causing a more pleasant sailing in bad weather. Though, with little form buoyancy, due to lack of hull displacement further up, it can become unpleasant as the hull will tend to dive if encountering larger waves. Water spray and green seas are not prevented, and the exposed decks need to be placed high above waterline. The X-bow, created by Ulstein, is an inverted bow design, but with larger displacement, see Fgure 5.4. It gets the benefits of a long and sharp hull while also providing more buoyancy in the bow area. As a result it is more efficient for smooth sailing through waves, making for a better experience [34] [10].

Source: www.boatinternational.com

Figure 5.3: An inverted bow

Source: www.frico.net

Figure 5.4: An X-bow

5.1.4 Straight bow

A straight, or plumb bow is a vertical bow, see Figure 5.5. This type of bow follow principals similar to the inverted bow. With a long waterline it cuts through water rather than trying to push it to the side. That is why it works with most drafts and speeds, making it in some cases more efficient than a bulbous bow. This can also help the ship sail smoother in rough seas, as the ship will not ride the waves and experience the vertical acceleration to the extent that normal bows do. With a long bow the shoulders can also be smooth, helping to reduce resistance even more. The negatives are that it will not have sufficient protection against green seas as there is not enough flare to redirect waves. The buoyancy in the front can be too little to hinder the bow from diving if exposed to large wave troughs. This creates a greater risk of green seas and can also cause vibrations and uncomfortable experiences [34] [10] [30].

Source: www.greenyard.no

Figure 5.5: A strait bow.

5.2 Stern design

The back part of a hull is the called the stern. The purpose with an efficient stern shape is to maximize the inflow of undisturbed water to the propellers. This will improve their efficiency as more of the energy from the propellers are transferred to the water, increasing the speed. It is important to design the aft to minimize the detachment area, as it causes turbulent water, increasing resistance [40].

5.3 Effective Hull Design

To create an efficient hull that reduces resistance, and therefore fuel consumption, a smooth hull without abrupt changes is optimal. A way to determent the smoothness of a hull is to look at the sectional area curve (SAC). It depicts the transverse underwater area along the length of the ship. The x-axis is the length of the ship, while the y-axis is the value of the area at the corresponding length. A smooth SAC curve indicates a hull with less resistance [44].

The mission of the ship will affect how the hull is designed. For larger cargo vessels, container ships, tankers and passenger ships, being able to carry as much as possible is essential to making the ships profitable. Therefore, these types of ships will often have a displacement hull. To determent a hulls fullness, the block coefficient (Cb) can be used. The equation for Cb is shown in formula 5.1, where ∇ is the volume displacement, $\mathrm{L_{WL}}$ is the waterline, $\mathrm{B_{WL}}$ is the waterline beam and T is the draught [19].

$$Cb = \frac{\nabla}{L_{WL} \cdot B_{WL} \cdot T} \tag{5.1}$$

A low value for Cb suggests a slim hull, while a high Cb value suggests a fuller hull [19].

5.4 Hull design for the sailing cruise ship

One of the requirements for the hull design was an efficient bow. With a vessel sailing with varying operational profile, the properties of straight bow was considered suitable. This is because the ship will generally try to use sails as much as possible, causing irregular speeds. If the ship falls behind schedule, it also has the potential of going faster, making up the lost time. In addition, the bow has an elegant and sleek visual, which gives the ship its wanted sailing yacht influence.

5.4.1 First variant

When the general look had been decided, a hull was made in the modelling program Maxsurf Modeler. The range of main dimensions where given in the project description, and the decided dimensions are presented in table 5.1. After concluding that most of the decks would have public areas at the aft, the deck height for the first three decks was decided to be 3.2 m. The 4th deck was given a height of 2.75 m, as this is common for decks with only staterooms. Note that the moulded depth is only the height of the main hull modeled in Maxsurf, and not the total height of all the decks combined.

Table 5.1: Main dimensions for first version

Main dimensions	
Length	180m
Beam	22m
Draught	5.5m
Moulded depth	17.85m
Number of decks	6

The shape was determined by the need for stability, as it was an important consideration from the beginning. Therefore, the model had a long midship section where the hull was relatively square. This was done, so the ship would have a large amount of form buoyancy when heeling occurs. In addition, the keel was brought almost all the way aft. This was to help create the most righting moment possible, without making the draft greater. Figure 5.6 shows hull lines from plan view, and Figure 5.7 shows the SAC curve for the first version.

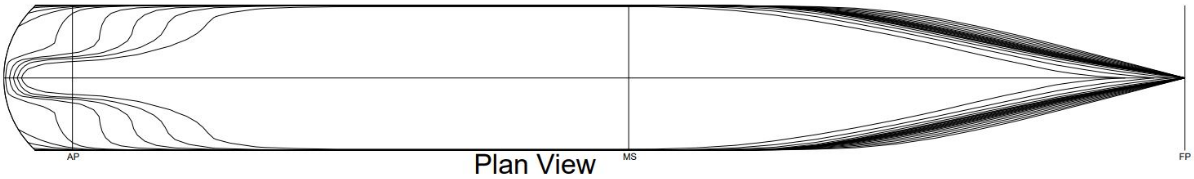


Figure 5.6: Plan line drawings first hull

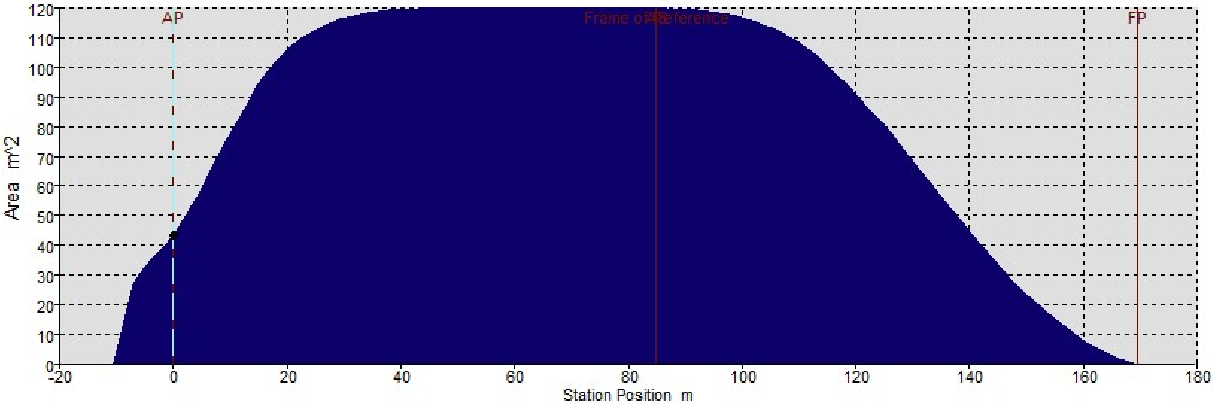


Figure 5.7: SAC curve for the first hull model

5.4.2 Second variant

The stability for the first version was found to be inadequate, and it was decided to remove a deck. The hull shoulders were smoothened out to create less resistance, making the ship more efficient. However, it decreased the midship coefficient (CM) and affecting the form stability. This was not seen as a problem after learning about different stability systems. After some discussion, it was determined that the lengthened keel was too large and would reduce the propellers efficiency by spoiling the azipods functions. One of the decks was at the same level as the waterline. This caused some problems when designing wing tanks. The tanks would not provide enough protect if the ship was to sail with grater draught then design draught. It also caused some problems for the marina platform at the aft.

Therefore, a second hull model was made. The tank top height was increased with one meter to solve the problems with the wing tanks and the marina platform. The overall height of the hull was reduced, as a deck was removed. The keel was shortened and made slimmer to facilitate the azipods better. The final main dimensions are shown in Table 5.2. See Figure 5.8 for final line drawings, and Figure 5.9 for final SAC curve.

Table 5.2: Final main dimensions

Final main dimensions	
Length	180m
Beam	22m
Draught	5.5m
Moulded depth	16.1m
Number of decks	5

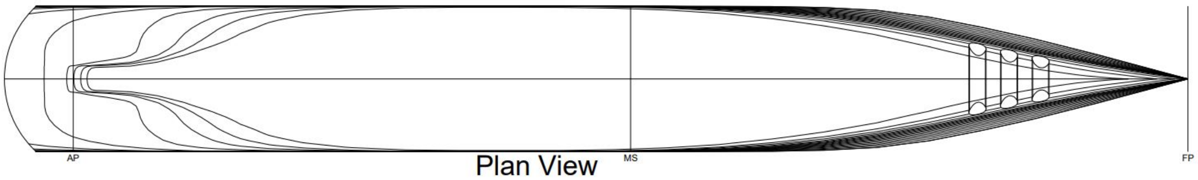


Figure 5.8: Plan line drawings second hull

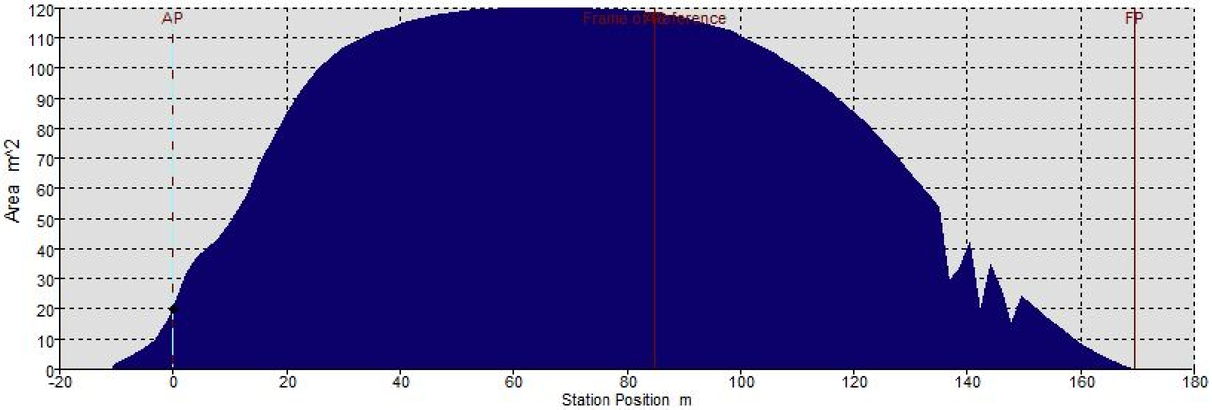


Figure 5.9: SAC curve for the second hull model. The cuts around 140 meters are because of the bow thrusters

6 Resistance

Towing resistance indicates how efficient a hull is, and is used for further dimensioning of propulsion system. Several methods and models have been developed to estimate the resistance of hulls, where the methods have different ship types they are best suited for.

6.1 Methods

In this thesis, two empirical methods have been considered, Holtrop & Mennen and Slender Body method, and the semi-empirical method towing tank test conducted. Empirical resistance models are useful in the development of hull shape and propulsion system.

6.1.1 Holtrop & Mennen

Holtrop & Mennen is a proven method for estimating hull resistance. The method is based on a large number of towing experiments carried out in the 1970s and 1980s, and based on the results of the experiments, an empirical model of towing resistance was created. It has proven to be a good method to use in the design phase and gives best results for displacement vessels [15].

6.1.2 Slender Body

The Slender body method is a theory-based method. The method gives the best results for slender hulls with a high L/B ratio. It is a more common method to use on multi-hulls, such as catamarans and trimarans, but can be used for monohulls. Using this empirical method, "perfect conditions" are assumed for the hull [17].

6.1.3 Towing tank test

Today's society is constantly evolving in the technological field, computer models and simulations are getting better and better. On the other hand, towing experiments are still recognized as the best method for estimating hull resistance. Towing experiments make it possible to physically experience how the hull behaves in different environments, both visually and with data measurements. A foundational argument for realistic results from a Towing Tank Test is geometric similarity. The method is a semi-empirical method, because the results is based on experiment and empirical equations. See Chapter x for execution and results from the towing tank test.

6.2 Prediction by empirical models

To estimate towing resistance, the computer program Maxsurf Resistance was used. The program handles the hull shape and runs resistance analysis. It was chosen to perform analysis with both the Holtrop & Mennen method and the Slender Body method, as the hull had some relevance for both methods. Before the analysis, values are required for the computer program to understand the design of the hull geometry. Some values were measured on the general arrangement, and various factors and coefficients assumptions were made. This is why the estimate from Maxsurf Resistance must be interpreted as an indication of the hull resistance. See Table 6.1 for input data in Maxsurf Resistance.

Table 6.1: Input values for Maxsurf Resistance. The appendage values are rough assumptions.

Maxsurf Resistance Input		
Frontal Area	334.6	m^2
Headwind	0	kts
Drag Coefficient	1	
Air Density	0.001	tonn
Appendage Area	200	m^2
Nominal App. lengt	51	m
Appendage Factor	2	

6.3 Results from empirical estimations

Table 6.2 presents the results from the two empirical hull resistance prediction methods mentioned above. It has been looked at seven different speeds, who are evenly distributed in the range of 11-23 kn and where the design speed is 17 kn. The reason for the range both above and below the design speed, is for investigating the needed power for maximum speed at 21 kn, and necessary power for lower speeds when sailing. The propulsion efficiency for Holtrop & Mennen and Slender Body method is assumed to be 0.7.

Table 6.2: Presents the results from the resistance estimations for the empirical methods, Holtrop & Mennen and Slender Body method.

Estimated Resistance				
	Holtrop & Mennen		***Slender Body***	
Speed [kn]	**Force [kN]**	**Power [kW]**	**Force [kN]**	**Power [kW]**
11	181	1 022	299	1 689
13	255	1 702	339	2 265
15	349	2 694	393	3 032
17	470	4 114	561	4 902
19	623	6 086	884	8 643
21	817	8 827	1 164	12 576
23	1064	12 590	2 066	24 440

The graphs in Figure 6.1 and Figure 6.2 presents the differences for the two methods Holtrop & Mennen and Slender Body.

Figure 6.1: Comparing hull resistance estimations from the Holtrop & Mennen method, the Slender Body method and the Towing Tank Test.

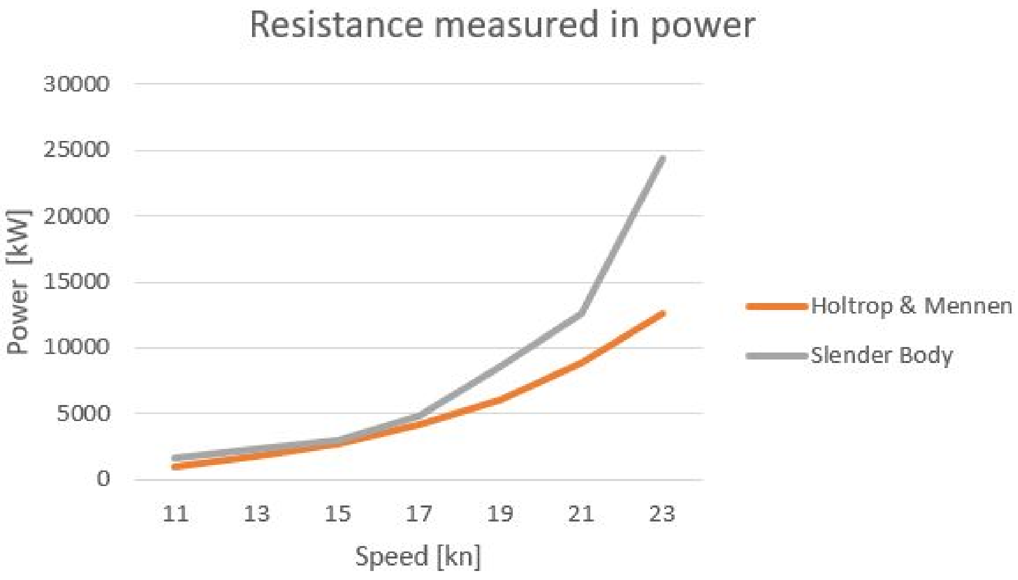


Figure 6.2: Comparing power estimations from the Holtrop & Mennen method, the Slender Body method and the Towing Tank Test.

To summarize, Slender Body will be a conservative chose of method, since it always shows higher values then Holtrop & Mennen. The differences between the results is small until 17 kn, then it increases drastically.

6.4 Choice of Empirical Method

It has been chosen to use the results from Holtrop & Mennen for further dimensioning of the propulsion system. This is based on the facts that Holtrop & Mennen is an experience-based method, and will therefore to a greater extent take account of irregularities that occur when a hull moves through the sea. Slender Body will not take this into account, as that method is theory-based and assumes "perfect conditions". In addition there was some uncertainty around the model validation for the Slender Body, since it gives best results for high L/B ratios. What a high ratio was considered as in this method, was challenging to find sources for and made the model validation difficult. Due to errors during the towing tank test, see discussion in Chapter 14, the credibility of the results from the towing tank test are not good, and it is chosen to not use them for further calculations.

7 Energy Carrier

In the last 100 years ships have used fuel oils have been used. Though they are reliable fuels, they pollute when burned and are therefore a cause for climate change. Different treaties and international organizations have plans and requirements to cut greenhouse gases. This includes the maritime sector and to reach IMO's goal of reducing greenhouse gas emissions. There are many solutions being tested out and implemented. These are amongst others optimizing hull hydrodynamics, make more efficient power and propulsion systems, better logistics and, probably the most impactful, using alternative fuels instead of fossil fuels. In this chapter the evaluation of energy carriers is from a ship engineering perspective [23].

7.1 Hydrogen

Hydrogen as a fuel will cut all pollution from "tank to wake". Though, not producing hydrogen with renewable energy will cause emissions. This is the case when hydrogen is produced from natural gas, called grey hydrogen. There is hydrogen being produced with renewable energy, green hydrogen, but the quantity is too small and expensive. Hydrogen is a gas. When stored as a gas, it requires a large volume because of its low mass density and energy to keep it pressurized. Hydrogen can also be stored as a liquid. This requires less volume, but large amount of energy is needed to liquefy it. Because hydrogen used as a fuel is a relatively new idea. Rules and regulations and infrastructure are not fully developed. Hydrogen is a dangerous gas and leakage is difficult to detect. The gas is highly explosive and flammable and the current rules require that hydrogen to be stored up on open deck [1]. The production is currently not enough to be considered a global marine fuel.

7.2 Ammonia

Ammonia is a gas and when used as a fuel, it does not produce CO_2. However, NO_x and N_2O slip emissions can happen. There is infrastructure for handling ammonia in a few ports, but the infrastructure for ammonia as a fuel is today not present. There are not enough ports to facilitate safe and efficient bunkering. Ammonia is highly toxic gas, and the technology and procedures required for safe storage on board are in early development. Ammonia combustion engines and fuel cell technologies are in early development as well as rules and regulations. There is currently not being produced enough ammonia, though it is expected that the production will increase. [49].

7.3 Biodiesel

Biodiesel as a fuel will emit CO_2, but when made from biomaterial and with renewable energy, it can be a net-zero emission fuel. It behaves somewhat like regular diesel, but changes to the engines and fuel systems are still required to optimize the performance [39].

7.4 Biogas

Biogas is produced from biomaterial and can be a net-zero emission fule if produced with renewable livestock and energy. The downside with biogas is the storage space needed. To reduce the space, the gas can be compressed and cooled down. The energy and cost required is higher than for LNG, as impurities make it more difficult to store [32].

7.5 Methanol

Methanol is an alcohol and produces CO_2 from “tank to wake”. Compared to diesel, methanol can reduce ”tank to wake” emissions by 7 %. Though, when using biomaterial and renewable energy for production, it is CO_2-neutral from “well to wake”. Production of renewable methanol can at the moment not meet the predicted demand, but production is expected to increase as more ships start using methanol as fuel. NO_x emissions can be managed with already existing technology. At ambient temperature and pressure methanol is a liquid and do not need to be stored under compression or cooled down. To have the required energy storage on board, the required volume is a little over two times waht it would be with marine diesel oil. It takes up a little over two times the volume of marine diesel The technology and equipment needed for handling and using methanol as a fuel is already available and located in over a 100 ports around the world [49] [43] [45].

7.6 Comparison of Energy Carriers

The mentioned pros and cons energy carriers above is summarized for overview and evaluation. Table 7.1 presents the positive and negative aspects, and was used for deciding fuel. The evaluation is based from a ship technical perspective. To gain a greater understanding of all aspects and properties of each fuel, life cycle analysis for each should be reviewed. This has not been done.

Table 7.1: Alternative fuel comparison

	Alternative fuel comparison	
	Pros	**Cons**
Hydrogen	-No pollution when prod used renewable	-Needs to be cooled and stored under pressure -Storing is difficult (leakage and on top deck) -Takes up large volume -Dangerous (explosive) -Rules and regulations are in development -Needs larger production to meet future demand -Required infrastructure is limited
Ammonia	-No pollution when produced renewable	-Needs to be cooled and stored under pressure -Highly toxic -Needs larger production to meet future demand -Required technology still under development -Rules and regulations are in development -Required infrastructure is limited
Biodiesel	-CO2 neutral when produced renewable -Safe and easy storage -Required technology available -Rules and regulations available	-A few changes required for engine and fuel systems -Needs larger production to meet future demand
Biogas	-CO2 neutral when produced renewable	-Needs to be cooled and stored under pressure -Needs larger production to meet future demand
Methanol	-CO2 neutral when produced renewable -One of the safest alternative fuels -Required technology available -Can be stored in outer hull under water -Required infrastructure is good and expected to increase -Rules and regulations available	-Needs larger production to meet future demand -Fumes are toxic, tanks and cofferdams need ventilation

7.7 Choice of fuel

After reviewing positive and negatives aspects of the alternative fuels mentioned above, methanol was chosen. It does require larger storage space, a little over two times the volume needed for conventional fuel, but it is one of the safest alternative fuels available. As the ship

carries passengers, this is vital, especially since the technology for ammonia as fuel is in early development.
safety easy storage infrastructure hvorfor ble andre utelukket

After choosing methanol as fuel, ports with methanol infrastructure were looked at to find routes that would match the operational routs presented in Chapter 3. A map over ports with methanol infrastructure was found and used to create similar routes, see Figure 7.1 [28].

There are a lot of ports with methanol infrastructure west in the Mediterranean Sea, so western Mediterranean routs were not looked into. For cruises in east Mediterranean and Greece, Damietta Port in Egypt and Constanza Port in Romania were the closest. For cruises in the Caribbean, the closest ports were Port Lisas in Trinidad and Tobago and Charleston, South Carolina and Savannah, Georgia in the US. For the transatlantic route, the closest ports are Sines in Portugal, Port Lisas and Charleston. Savannah is also close and can be an option.

For arctic expeditions the closest port is Bergen in Norway. Most Antarctic expeditions start in Ushuaia, Argentina, but the closest port with methanol infrastructure is Punta Arenas in Chile. This port is 250 km as the crow flies from Ushuaia.

By using Google Earth, simple measurements were done and and the longest route was found to be between Sines and Savannah, at a distance of almost 3 500 nautical miles. As this route is the longest, and also close to Western Caribbean, making it an attractive departure port for these routs, this distance became the dimensioning value for calculating necessary fuel storage.

Source: www.methanol.org

Figure 7.1: Map showing ports with existing methanol infrastructure.

As the ship is supposed to be sustainable, different alternative fuels were considered. These were hydrogen, ammonia, biodiesel and biogas. Factors that were taken into account when deciding fuel type were; how much CO_2 and other pollutants can be reduced, safety, availability and accessibility, infrastructure needed, rules and regulations and, because the ship is on the smaller side, how much space is needed to store the fuel.

8 Main Propulsion System

The effect from wing sails alone is too unpredictable and not enough to power the ship. Therefore, the ship needs a main propulsion system. This will provide reliable energy for propulsion and is also the only source of energy for the hotel consumption. By having two means of propulsion, will create redundancy.

8.1 Engine and propulsion system

After choosing methanol as fuel, Wärtsilä's 32 methanol engine was chosen, see Figure 8.1. Wärtsilä is a renowned company, and they are known for their expertise and innovative solutions. Their Wärtsilä 32 methanol engine-series has four dual fuel engines with different outputs. This means it is possible to create an engine arrangement that can provide the required power with most engines running on optimal load. Optimal load case is desirable since it saves fuel, which reduces pollution and costs. For the methanol engines optimal load is 75 % [Fredric Sunabacka, Product Manager W32/W34, Marine Power Solutions, Wärtsilä, 23.04.23]

Source: www.wartsila.com

Figure 8.1: Wärtsilä 32 methanol engine.

That the engine is dual fuel is also an advantage. It facilitates a possible conversion to using HFO, MDO or liquid biofuels should the availability, accessibility or economics of methanol not be profitable in the future. This is therefore an economic redundancy to the concept.

8.2 Engine arrangement

The resistance for the design speed of 17 knots was calculated to 470 kN. This is equivalent to 4 114 in kW. With a propeller efficiency 0f 0.7, a "mechanical to electric to mechanical" efficiency of 0.93 and an optimal engine load of 75 %, the total minimum effect needed for propuoltion was found to be 10 058 kW. The hotel load was set to be equal to 40 % [2] of the total installed power, meaning the propulsion power is 60 % of the total installed power. Based on this estimation, the total installed power needed was 16 763 kW. Using the same resistance, the calculated hotel load and the same efficiencies, the minimum required energy for design speed was found to be 13 677 kW. Table 8.1 shows the thought process. With the technical data from Wärtsilä, it was clear that the ship would need at least four engines. Therefore, two arrangements were made.

Blue boxes are input values.

Table 8.1: Minimum engine power required. The blue boxes have input values.

Minimum engine power required		
Speed	17	Knots
Required power	4 114	kW
Propeller efficiency	0.70	
Mechanical efficiency	0.93	
Optimal operational load	75	%
Required power to propellers	5 877	kW
Number of propellers	2	
Power per propeller	2 939	kW
Propeller model	ABB DO1100P	
Power needed to propeller	3 470	kW
Total power to propellers	6 940	kW
Total engine power at 75 %	7 543	kW
Total engine power at 100 %	10 058	kW
Hotel load as percentage of total installed power	40	%
Resulting hotel load	6 705	kW
Minimum required installed power	16 763	kW
Minimum power required for design speed	13 677	kW

8.3 Engine arrangement 1

The first arrangement has two sets with different engines. The first set is the main engines with a capacity of 5 220 kW. The second set is the auxiliary engine with a capacity of 3 480 kW. This has a total output of 17 400 kW. The ship only needs 6 300 kW, meaning the load is 61 %, which is not optimal. With the two auxiliary engines powering the hotel load, they run on a load of 91 %. This is not optimal either. Running the main engines on 75 %, they provide enough energy to power 100 % of the propulsion and the surplus of power can be used for the hotel, reducing the load on the auxiliary engines to 76 %. This means that the arrangement is optimal for the design speed of 17 knots and with full hotel load. Table 8.2 shows the engine arrangement and Table 8.3 shows the optimal power load for this arrangement.

Table 8.2: Engine arrangement 1

Engine arrangement 1		
Number of main engines	2	
Wärtsila Methanol 9L32	5 220	kW
Total power main engines	10 440	kW
Number of auxiliary engines	2	
Wärtsila Methanol 6L33	3 480	kW
Total power auxiliary engines	6 960	kW
Total installed power	17 400	kW

Table 8.3: *Optimal load case for engine arrangement 1*

Optimal load case for engine arrangement 1		
Resulting operational load main engines	61	%
Resulting operational load auxiliary	95	%
Optimal load main engines	75	%
Extra power from main engines	1 442	kW
Remaining hotel power required	5 264	kW
Resulting auxiliary engines load	76	%

8.4 Engine arrangement 2

The second arrangement consists of four of the same type of engine. With a minimum power per engine being 4 191 kW the 4 640 kW was chosen. Four of these have a total output of 18 560 kW. The propulsion needs 6 300 kW and the hotel load needs 6 700 kW meaning the engines run on a load of 75 %. This is optimal load for the designed condition, meaning the engines are operating most efficiently. Table 8.5 shows the engine arrangement and Table **??** shows the optimal power load for this arrangement.

Table 8.4: *Engine arrangement 2*

Engine arrangement 2		
Number of engines	4	
Minimum required power per engine	4 191	kW
Wärtsila Methanol 9L32	4 640	kW
Total installed power	18 560	kW

Table 8.5: *Optimal load case for engine arrangement 2*

Optimal load case for engine arrangement 2		
Required power for design speed	13 677	kW
Total installed power	18 560	kW
Resulting operational load	72	%

8.5 Engine arrangement decision

The pros for arrangement one are that it has a higher possibility of producing different amounts power, but with the most amount of engines running on optimal load. This increases efficiency and saves fuel and costs. The cons may be that the crew needs more training, because the two engines operate differently and require different maintenance, or that spare parts are different between the two types, which will increase cost.

The pros for arrangement two are that the crew needs less training and spare parts are the same. The cons are that it has less option to run different power output with the most amount of engines running on optimal load.

After looking at the pros and cons of the two arrangements, arrangement one was picked, as the two different types of engines are actually the same, just with different numbers of cylinders.

Therefore, the extra training and extra cost of spare parts are not valid, making the benefit of having engines with different power output decisive.

8.6 Fuel Consumption

First estimation of required fuel storage took the total power installed, maximum wanted speed, distance and efficiency to calculate the energy needed. See Table 8.6. After that, the specific fuel consumption (SFC) for regular marine diesel engines and the density of diesel were used to calculate the volume of diesel needed. See Table 8.7 for result. Methanol takes up over two times the required volume of diesel, so with a factor of 2.1, the estimated methanol storage capacity was 1012 m^3. To see how accurate this estimation is, the volume needed for storing marine diesel oil and heavy fuel oil are shown in Table 8.8.

Table 8.6: Required energy to sail 3500 nautical miles in 21 knots

Required energy		
Range	3 500	NM
Speed	21	kn
Time	167	h
Hull power estimate	8 827	kW
Required power from engines	13 707	kW
Required energy from engines	2 284	kW

Table 8.7: Required volume of methanol

Methanol volume		
BSEC	7 871	kJ/kWh
Calorific value	19 900	kJ/kg
SFC	0.396	kg/kWh
Mass	903 551	kg
Density	790	kg/m^3
Required volume	1 143	m^3
Safety margin	10	%
Total volume	1 258	m^3

LFO volume		
SFC	0.187	kg/kWh
Mass	426 273	kg
Density	790	kg/m3
Required volume	540	m3
Safety margin	10	%
Total volume	594	m3

HFO volume		
SFC	0.188	kg/kWh
Mass	429 471	kg
Density	790	kg/m3
Required volume	544	m3
Safety margin	10	%
Total volume	598	m3

Table 8.8: Required volume of MDO and HFO.

To accurately calculate the fuel storage needed, Wärtsilä was contacted. They provided the break specific energy consumption (BSEC) for the methanol engine and with a calorific value of 19 900 kJ/kg for methanol the specific fuel consumption could be found. Using the energy from the previous estimation, the SFC and the density of methanol, the required volume was calculated. This came out to be 1 285 m^3, which was 273 m^3 off our original estimate.

8.7 Propulsion system

It was early on decided that the ship would be using two azimuth thrusters for main propulsion, as they give the ship maximum maneuverability. This is a great advantage as it allows the ship to travel in more difficult areas where propellers on fixed shafts would have had trouble maneuvering. The ship will then be able to offer more destinations.
To find the right azimuth thrusters, the total power needed to the propellers was divided by two, which gave the minimum power each azimuth thruster needed. The minimum power was 3 000 kW, and after looking at different azimuth thrusters, the closest was ABB's Azipod® DO1100P, see Figure 8.2. It has a power requirement of 3 470 kW and was chosen for the main propulsion system.

Source: www.maritimepropulsion.com

Figure 8.2: ABB's Azipod D series

Propellers should can have a load of 350 kW/m^2 on their projected area, as higher values will start to affect their performance. To dimension the propellers the power was divided by 350 and the diameter was found from the area, see Table 8.9.

Table 8.9: Propeller diameter calculation

Propeller diameter		
Power to propeller	3 470	kW
Maximum load on propeller	350	kW/m^2
Propeller	9.91	m^2
Diameter	3.55	m
Chosen diameter	3.60	m

9 WAPS - Wind Assisted Propulsion Systems

Harnessing wind for propulsion is technology that has been around for millennia. This technology has evolved over the years, and especially in recent times, new solutions, materials, automation, and sensor technology have led wind to become a viable option as additional propulsion on ships. Advantages of wind as an energy source are that it is free and it can be found all over the world. There are different solutions for exploiting the wind, and in this project three different types of solutions have been considered, traditional sails, rotor sails and wing sails.

9.1 WAPS for reducing emissions

The shipping industry is facing major challenges in reducing greenhouse gas emissions, and the industry has in recent years rediscovered WAPS as a solution. WAPS reduce emissions by providing power that is harnessed without creating pollution, therefore lowering emissions and the carbon-footprint. With the rising fuel prices, carbon taxation, and tight goals for decarbonization, the interest in WAPS has increased. According to an article from DNV, some technologies are proven to reduce environmental emissions by 8 %, others are expected in the range 20-45 %, depending on hull optimization, regulations and operational improvements [22].

9.2 Performance prediction factors

Choosing WAPS as a solution have some essential performance factors to be aware of. When operating with wind, there will be unexpected influences caused by environment and nature. For example, unsteady wind and air pressure affects how much power the wings can produce. The wings will experience turbulence and the air flow will be disturbed. The level of turbulence is hard to predict. The amount of wind in the operating region is crucial and should be large enough to produce sufficient power. For optimizing power production from the WAPS, weather routing is the key for best results [A. Dunström, Trainee at AlfaWall, A. Rapaport, Performance engineer at AlfaWall, 20.02.2023, Presentation].

Another consideration is the system limitations and handling. The sails will have operational limits, which affects the ease of use. This can be upper or lower limits for wind speed. Most of the WAPS technologies these days are automated and controlled by sensors. For optimal efficiency, the sails are constantly trimming and adjusting themselves. The nature can change fast and make it challenging for the system to keep up. But, it is not impossible for the system to handle weather [A. Dunström, Trainee at AlfaWall, A. Rapaport, Performance engineer at AlfaWall, 20.02.2023, Presentation].

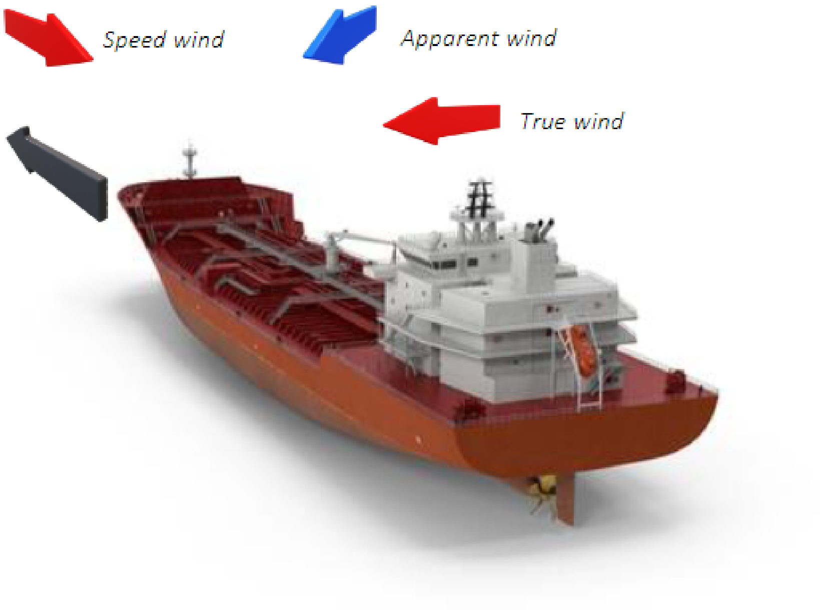
For achieving results with WAPS as power source, a good interaction between the ship and the sails is important. This includes coursekeeping, leeway, stability and displacement. The sails can not cause the ship to deviate from the course. Ships has a mission to complete, often on a time schedule. Deviation from the course can cause unnecessary increase in fuel consumption. The displacement of the ship affects the efficiency by defining the amount of water to move. To maintain the stability of the ship, the wind forces and the heeling effect has to be taken into consideration [A. Dunström, Trainee at AlfaWall, A. Rapaport, Performance engineer at AlfaWall, 20.02.2023, Presentation].

The type of ship is a factor for success, because some ship types are more suitable for wind assisted propulsion than others. WAPS often use a lot of deck space, and for some types of ships deck space is important to keep clear. It is strongly recommended to do ha hazard identification study to make sure the ships planned operations will not be limited by the WAPS. Masts and sails must clear bridges and other obstacles along the route. The WAPS will affect the safety of the ship, by influencing the handling and operational of the vessel and the line of sight [22].

9.3 The Physics of sailing

The physics behind how forces occur in the sail can be explained by Bernoulli's principle. When the wind hits a curved surface, the wind moving on the outside of the arc must go over a greater distance than the wind on the inside of the arc. This means that the wind on the outside is accelerated and has greater speed compared to the wind on the inside. According to Bernoulli's principle, accelerated winds lead to reduced static pressure and vice versa. A low pressure and a high pressure will be formed, and this pressure difference will create a lift force standing perpendicular to the wind direction. In addition, a counteracting force, the drag force, is also made. The drag force is parallel to the direction of the wind [48].

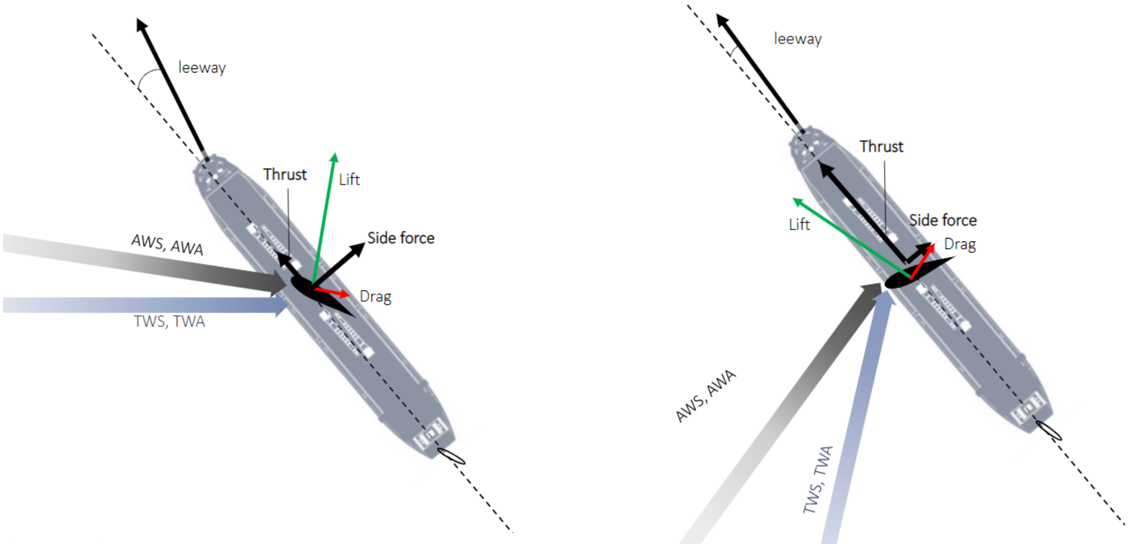
When a moving ship is sailing, a speed wind, with opposite direction to the thrust direction, will form over the vessel. Combining this wind with the real wind, the true wind, you will get the apparent wind, see Figure 9.1. This is the wind used by the sails for generating thrust. The speed and angle of the apparent wind effects how much thrust the sails manage to generate.



Source: Oceanbird by AlfaWall

Figure 9.1: Wind directions affecting the ship, and resulting apparent wind

The thrust and side force are given by the force components of the lift and drag force. The thrust force is given by the components in the ships x-axis. Figure 9.2 show how decisive the wind direction is for the resulting thrust force. To create propulsion, the resulting thrust force must point in a positive ship direction. The figure shows two scenarios, Figure 9.2a for large resulting side force, and Figure 9.2b for large resulting thrust force.



Source: Oceanbird by AlfaWall

(a) Apparent wind generating large side force

Source: Oceanbird by AlfaWall

(b) Apparent wind generating large thrust force

Figure 9.2: Different scenarios for apparent wind and resulting forces

The power components of the lift and drag force across the ship are added together and are called side force. If this side force becomes too large, it will cause heeling and leeway. To counteract heeling, sailboats have a large keel. The keel creates a lateral force opposed to the lateral force from the sail, and the heeling is reduced. The keel will also minimize leeway by working as an lifting surface generating a counteracting side force. On larger ships, it is less practical to have a large keel. The solution then is to use stabilization systems such as ballast tanks, fins, single keels, and gyroscopes to counteract the inclination.

9.4 Traditional Sail

As mentioned, there are currently several types of solutions for creating propulsion using wind. One of the solutions is traditional sails. Traditional sails are constantly evolving when it comes to materials, automation and functionality. The sails are made of flexible fabric and the wind largely determines the efficiency. Today there are automatic soft sails. This makes it easier to manoeuvre the sails, less extensive training is needed, and there is no need for extra crew to handle the sails [29].

The advantages of soft sails are that they can operate with most wind directions as the sails can be positioned and trimmed to crate the optimal arc and thus produce the most power. They can also be packed together and will not pose much air resistance when not in use. Traditional sails can visually have a finer aesthetic look, and are therefore often a desired solution in, for example, the sail yacht industry. In a study that examines the economic and ecological aspects of various solutions for wind propulsion, a disadvantage of soft sails is that they have greater life cycle costs compared to wing sails [29].

9.5 Wing Sail

Wing sails are vertically standing aerodynamic wings. The wings are similar to an airplane wing. This solution is effective because the foil is usually symmetrical and can thus produce power with both sides and most wind directions. This is useful as a stiff wing foil can not crate arcs, and a stiff arc would only be useful with some wind directions. A disadvantage is that it can not achieve the maximum power produced compared to a sail with an arc. Therefore, having a wing sail consisting of a main wing and a wing flap, one can recreate the arc of the classic sails and increase the effect even more [29].

The sails are made of a rigid material, and many solutions have the possibility of folding down. It is a positive trait, as it avoids extra resistance for the ship. Other advantages of wing sails are that they are easy to handle as much of its operation is automated. This will reduce the need for additional crew. They are easy to install and maintain, but are an expensive investment. Another disadvantage is that they take up a relatively large amount of deck space and are not beneficial for ships that need deck space [29].

The physics behind the thrust force from wing sails and soft sails is the same for both. What separates them is the design and operation.

9.6 Rotor Sail

Rotor sails, often called Flettner rotors, are vertical cylinders that rotate and create lift force with the help of the Magnus effect. The Magnus effect occurs when wind meets the spinning rotor. The air flow will be accelerated on one side and decelerated on the other side. This creates a pressure difference that provides a lifting force that stands perpendicular to the wind direction. The power output from the Flettner rotors depends on the wind direction and speed. As the lifting force is perpendicular to the wind direction, the wind must come across the ship to get the greatest effect [16].

The advantage of rotor sails is that they do not take up much deck space. They require no additional crew and are easy to handle with automated systems. A negative side of rotor sails is that they require energy to rotate the cylinders. The rotation will also cause vibrations and noise that can cause damage to the structure of the ship. The sails are less efficient at high speeds [29].

9.7 Choice of sail type

When choosing a solution, the focus is on efficiency, aesthetics and flexibility.

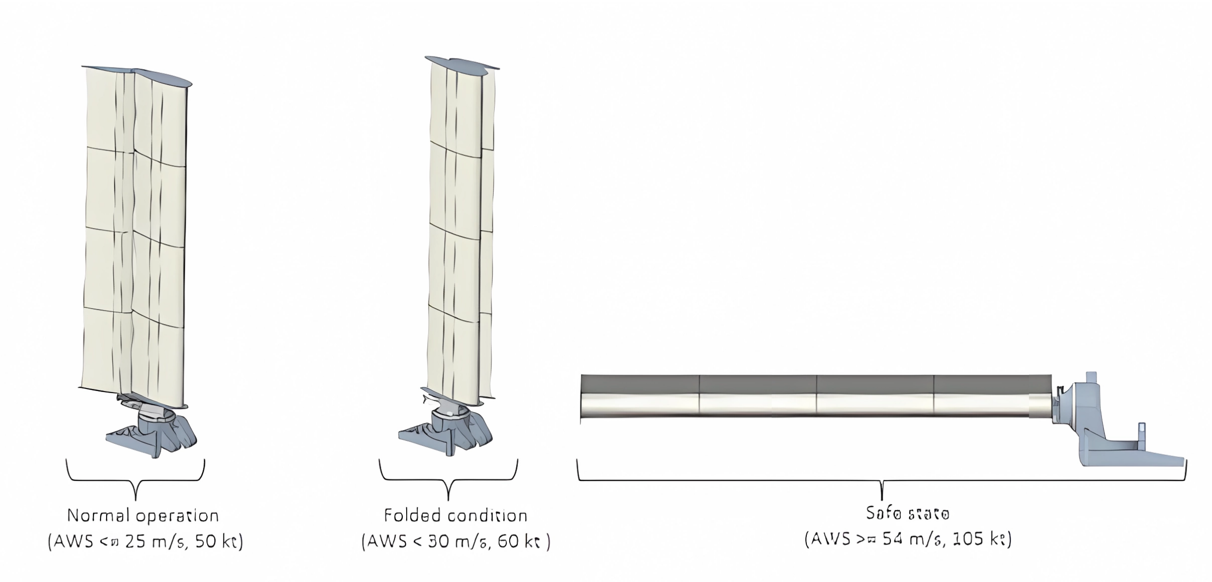
An important aspect of the vessel is that it should be aesthetically beautiful, therefore the Flettner rotors were not chosen. In addition, flexibility in relation to wind direction was important. It gives the ship more opportunities for using the WAPS, which will lead to fuel savings and reduced emissions. Most traditional sails do not have the possibility of folding down the masts. This creates restrictions on access to certain places and will limit opportunities for routes and locations to visit.

The choice fell on wing sails because they offer aerodynamically efficient wings with aesthetic expression that coincides with the layout of the ship. They are automated which makes them easy to handle for crew, and the possibility of folding them down is beneficial for resistance when not sailing, as well as increasing the navigability of the ship. When choosing a solution, price is not considered.

9.8 Oceanbird Wing Sail

For this project a wing sail concept developed by Swedish AlfaWall Oceanbird was chosen. It was established contact with the company, and they have provided valuable information and data. AlfaWall Oceanbird is a joint project of two companies called Alfa Laval and Wallenius. The concept is called Oceanbird Wing Sails, and the project is in the testing phase. The first full scale prototype is expected to be built by the end of 2023 [35].

The wing consists of two aerodynamic wings, one as the main sail and one as a flap for optimizing the aerodynamic forces. The sail can also rotate around its own z-axis and its control system is automated. This will help to extract the most energy from the current wind conditions. The wing wing sails can also be folded together and laid down for ease of use in regards to different weather conditions and obstacles along routes. The different conditions for the sail operation are shown in Figure 9.3.



Source: Oceanbird by AlfaWall

Figure 9.3: Different conditions and wind limitations for the Oceanbird Wing Sail. These limits are for the prototype and can change in the future.

The limitation for the wing is when apparent wind speed is at 50 knots in normal operation, 60 knots in folded condition, and 105 knots in safe state, laid down. It is important to specify that these values are for the prototype and can be changed in the future. Oceanbird provided the measurements of the wing, see table 9.1[A. Dunström, Trainee at AlfaWall, A. Rapaport, Performance engineer at AlfaWall, 20.02.2023, Presentation].

Table 9.1: Oceabird Wing Sail measurements

	Wing	**Foundation**
Height [m]	40	6
Chord [m]	14	8
Beam [m]	-	8.7
Weight [t]	Σ 168	
VCG [m]	Σ 11.2	

9.9 Performance estimation of the Oceanbird Wing Sail

Oceanbird provided performance data for one wing sail for the requested routes, see Appendix D. The data contained an estimation for the average power delivered in different ship speeds. Oceanbird used a propulsion efficiency of 0.7 in their estimate. An interference factor was also used and assumed to be 0.8. This factor is a made up factor for this thesis and takes into account the wind disturbance between the sails.

Figure 9.4, 9.5, and 9.6 present the percentage of the hull resistance powered by wind for the three chosen routes. The percentage is given by Formula 9.1, where $P_{Holtrop}$ is the estimated resistance and P_{Sail} is the data given from Oceanbird.

$$Percentage = \frac{P_{Sail}}{P_{Holtrop}} \cdot 100 \tag{9.1}$$

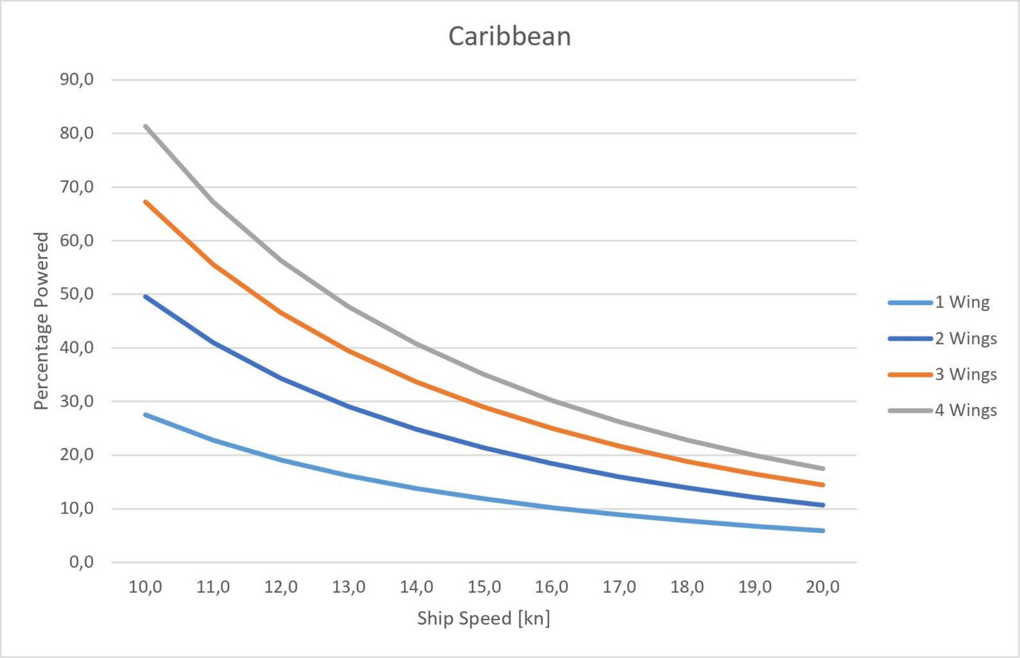


Figure 9.4: The wing performance for different ship speeds for the Caribbean.

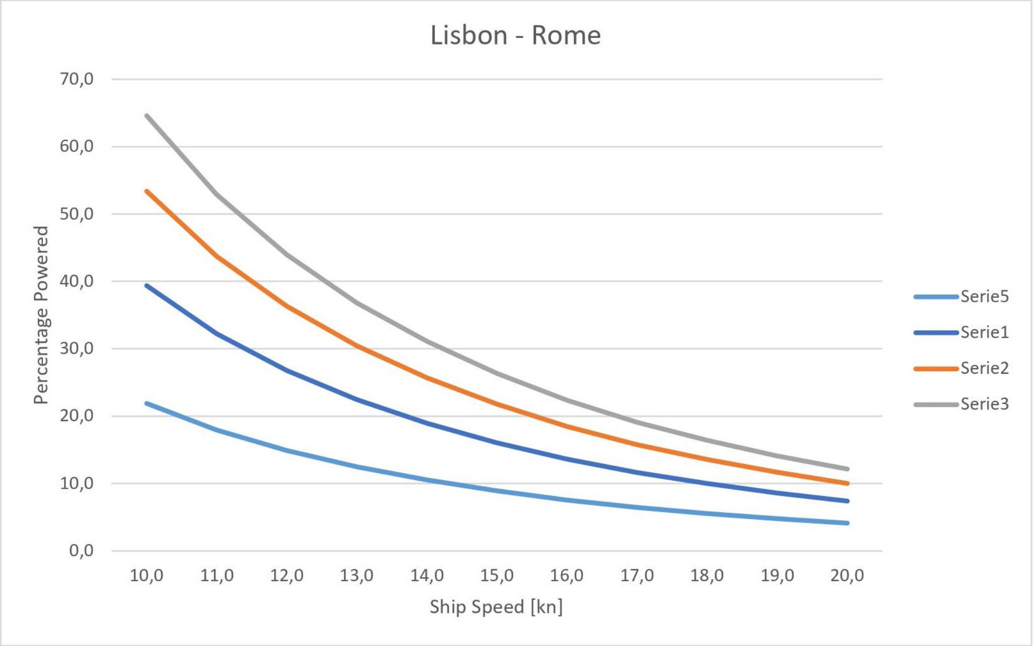


Figure 9.5: The wing performance for different ship speeds for the Mediterranean route

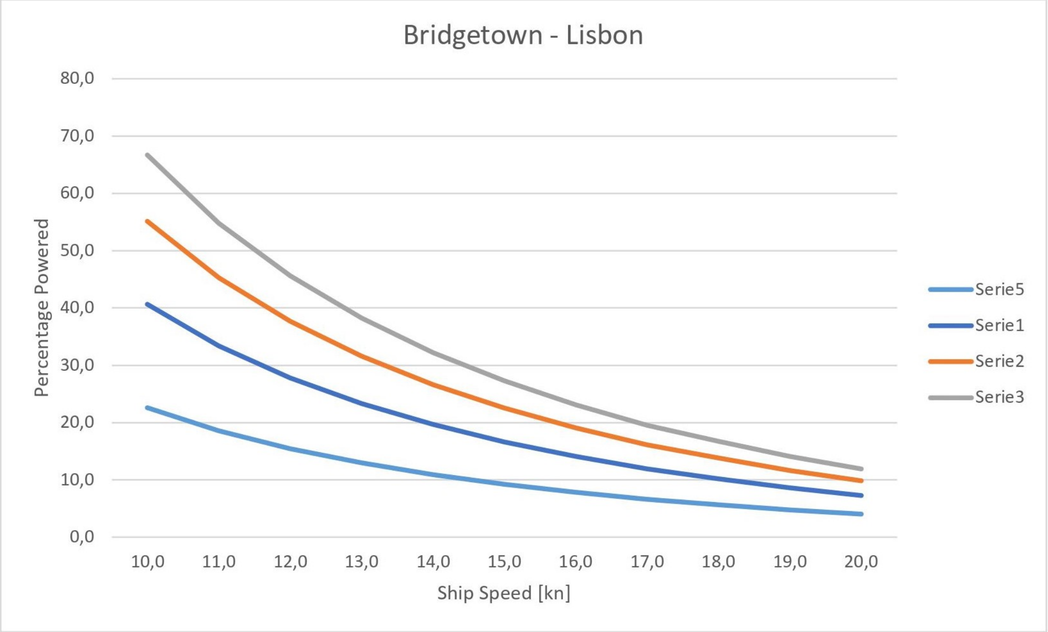


Figure 9.6: The wing performance for different ship speeds for the transatlantic crossing.

Table 9.2 summarizes the performance and estimated savings for the chosen operating regions. The performances applies for the vessels design speed and when four wings are installed. As the result shows the goal for 10-20 % of propulsion being delivered by wind power is reached. For the Caribbean route, over 25 % of the ships propulsion can be provided by wind power with four wings installed. For lower ship speeds the percentage of savings is considerably greater. As the results presents, the route and wing arrangement affects the estimated engine savings. As the graphs in Figure 9.4, Figure 9.5 and Figure 9.6 presentes, the wings relatively propulsion contribution decreases the higher speed. This is because the hull resistance increases exponentially with the speed. The difference between the performance of different numbers of sails decreases when the ship speed increases.

Table 9.2: Estimated engine savings when four wings installed. The values applies for design speed at 17 kn.

Estimated engine savings for four wings		
Route/Region	**Power savings**	**Savings in percentage**
Caribbean	1654	26.2
Bridgetown-Lisbon	1235	19.5
Lisbon-Rome	1205	19.1

9.10 Discussion

A sail can not produce the maximum achievable thrust when the air flowing over the wing is disturbed. In this thesis this is taken into account with the interference factor. This phenomena is well known and the reason racing sail boats try to find lanes with undisturbed air in sailing competitions. There is currently not much research done about how sails affect each other with disturbed air, reducing the efficiency. Therefore, it has been assumed that a sail only receives 80 % usable air form the sail in front of it. This means the first sail gets 100 % usable air flow, the second sail receives 80 % usable air flow from the first sail, the third receives 80 % usable air flow from the second sail and so on.

The hull shape is not optimized for the performance of the wing sails, as they only provide a secondary proportion power. During the development of the hull shape, the goal instead was to make it as stable as possible. This affects the resistance and increase drag, which reduces the overall effect from the sails. The hull was later made more efficient, but it is believed that the hull shape is till not optimal for sail usage. There has not been done any analysis and comparison between different hull shapes to find out which shape is the most efficient for sail usage.

When choosing the routes for the ship, weather data was not considered. The routes was chosen from a market perspective, and was inspired from the shipping company Wind Star Cruises. Though the routes were inspired by routes for existing cruise ships with sails as additional propulsion, there has not been done any weather data analysis on the routes. It is therefore unclear whether or not these routes are the most beneficial for sail operations. For increasing the wing performance, a weather data analysis should be conducted, and then the routes can be planned. To obtain position in the cruise market, the goal should be to find the balance between market request and beneficial weather data.

10 General Arrangement

A general arrangement (GA) is an overview drawing of the general structure of the ship and provides information about the layout of each deck from plan, profile and body plan view. It shows for example zone divisions and bulkheads, room distribution, stairs and elevator lobbies, machinery and other important elements. The GA is the most important tool for communicating the ship, and is the basis for all class drawings, 3D models and construction drawings.

In the development phase, there will always be changes to the GA as a greater understanding of the vessel is achieved through calculations, estimations and testing. The general arrangement is usually a basis for a lot of these processes. As results are collected and interpreted, changes are made to meet requirements and optimize space distribution to increase the vessels functionality.

10.1 Method

The method used to create the general arrangement in this thesis was to first choose a passenger cabin width and frame spacing, which for this concept were set to 3.2 m for the cabin and 800 mm for the frame spacing. It is common for cruise ships to have a cabin width that is the same as the web distance, or opposite. This is to keep the structural integrity of the ship. After discussing what type of spaces each deck will most likely have, the deck heights were decided. For cruise ships, it is common that cabin decks are 2 750mm from steel to steel and decks with public spaces are 3 200mm. Then, line drawings for each deck were exported from the hull model in Maxsurf and imported into AutoCAD.

The first priority when starting to draw the GA was to place fire bulkheads. There are rules for how long and large each fire zone can be, see Appendix A. The fire zones with passenger cabins were sized to match with the length of the number of cabins. Cabins are usually mirrored so bathrooms are next to each other. This means that vertical infrastructure, like pipes, can be placed in a space between the bathrooms, serving both and saving space. To make the most efficient design, the number of cabins should therefore be an even number. As cabins are prefabricated, space on each side of the fire bulkheads were taken into account to make sure no cabins would collide with the ship's structural elements when installed. To make sure the bulkheads are placed on a frame without shortening the frame spacing, those frames are made wider equal to the added width of the bulkheads.

There are rules for escape routes concerning staircases, muster stations and exit points. The most common arrangement is that each zone has a staircase. This takes up a lot of space. This vessel is on the smaller side and space is important. Therefore, the rule that a staircase placed next to a fire bulkhead can be utilized by both zones, was used to save space. The promenade deck is where the lifeboats were going to be placed, and it was early on decided that the promenade deck would have public spaces, like restaurants and lounges. These public rooms can be used as muster stations. Muster stations are where passenger groups gather in an emergency to receive information and everyone can be accounted for.

Further, watertight bulkheads, machine rooms and tanks were drawn. A machine room must always have a watertight bulkhead in front and behind. If the ship has multiple machine rooms, it is practical to separate them with a fire safe and watertight bulkhead. This is to create redundancy, should one of the engine rooms stop working. Casings for the exhaust and air intake is placed over the engine rooms and run vertically through the ship ending in a funnel at the top deck. To make sure the necessary tank volumes were met, the tanks were made in the calculation program Maxsurf Stability.

There is often a main galley on ships, and as cruise ships have multiple restaurants, it is important that the galley is close to vertical communication, like service stairs and elevators. This is to make sure the galley can serve these areas.

Next was to place passenger and crew cabins. There is usually a requirement of how many cabins the client wants and creating a solution that fits all of them can be a challenge. The most common arrangement is to have multiple cabin decks in the middle of the ship, and then have public decks over and under these. This solution maximizes the number of cabins that can have balconies or ocean view, but also creates a very tall ship. This arrangement is therefore most common with larger cruise ships, as they have the stability needed. Another solution is to divide public and cabin spaces vertically. This is a better solution for smaller ships because the few decks on board are divided into vertical fire zones and the stair and elevator lobbies can serve both areas, saving space.

Thereafter, the remaining areas were divided into different public spaces. It is important to place those areas that need food and other provisions close to vertical communication for easy transport. The space is in addition divided into storage, housekeeping, toilets, crew areas, and AC systems. AC systems require 6 % of the usable area in each vertical zone [Trond Sigurdsen, Senior Architect, Partner, Head of Sustainability and Technology at YSA Design]. There are suggestions on where to put AC systems, but no calculations have been done to see if the required percentage have been achieved. The empty areas left, were occupy by some of the remaining systems and infrastructure needed for a cruise ship. For example battery room, water treatment, mooring and anchoring. No rules, regulations or area requirements for these spaces have been checked.

10.2 Top deck

The result for the top deck is shown in Figure 10.1. The foundation of the sails are placed on the top deck, as the sails need to be on the uppermost part of the ship to get access to the air. The funnels are also on this deck, but can not be taller than 6 meters, as that will cause them to collide with the sails. Aft there is a glass section functioning as a glass roof and gives natural light to the atrium staircase.

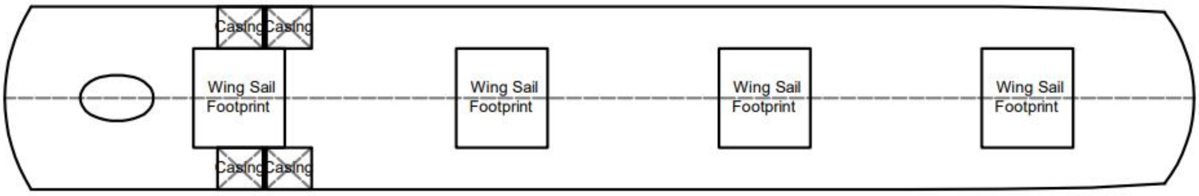


Figure 10.1: Top Deck

10.3 Deck 5

Deck 5, see Figure 10.2, is the upper most deck with inside area. This is where the bridge, offices, cabins for the officers are located forward. There are also passenger suites in the middle and a bar and a lounge at the aft. Because the forward stairs and elevator lobby only serves crew, no passenger stairs or elevator go to this deck. The aft lobby though, has passenger stairs and elevators that serve all passenger decks.

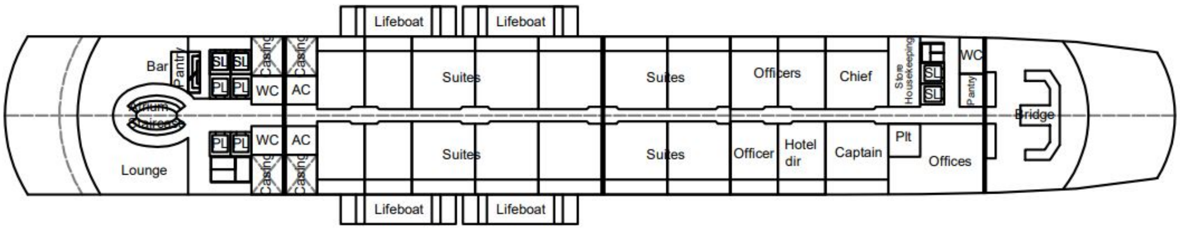


Figure 10.2: Deck 5

10.4 Deck 4

Deck 4 has the most public spaces. These are a forward lounge with a bar, salon, spa and treatment, barber, shops, library and lounge, coffee bar and an à la carte restaurant with show kitchen, wine cave and the possibility to sit outside on the promenade deck. The passenger would, in an emergency, embark the lifeboats on this deck as they are placed there. There are two lifeboats on each side. The wave breaker, which also serves as an entrance to the forward most crew staircase, is places forward on the promenade deck. See Figure 10.3 for result.

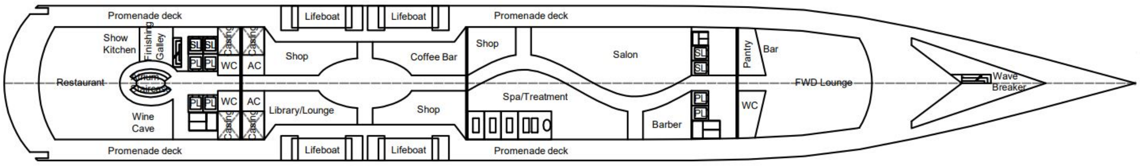


Figure 10.3: Deck 4

Early in the design process there was a wish to let the passenger have the opportunity to walk the length of the ship outside. This gives the passengers the experience of following scenery and animals from the bow to the stern without being forced to go inside. The choice of a rap around promenade deck with outside stairs to the lower aft decks made this possible.

The lifeboat type chosen is the VIKING Norsafe JYN-85 MKI. It can carry 80 people and the ship has two of these on each side. That is equivalent to a lifeboat capacity of 160 people on each side, which is 38 % of all 418 passenger and crew. This meets the lifeboat capacity regulation. The davit system chosen is the VIKING Norsafe LHD-150 MKI Hydraulic Luffing Lifeboat davit. These stand on the deck and make the volume taken up by lifeboat and davit systems minimal, which is preferable on this ship.

10.5 Deck 3

Most of the area of deck 3 is taken up by passenger staterooms, where the majority of them have a balcony and the rest have ocean view. The mooring and anchoring system is place forward on this deck. At the aft, there is the second deck of the atrium, the fitness area and outside deck with whirlpools. See Figure 10.4 for result.

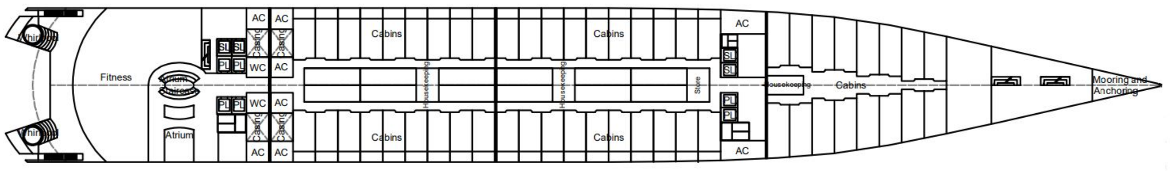


Figure 10.4: Deck 3

10.6 Deck 2

Deck 2, see Figure 10.5, is mostly cabins, but for both passenger and crew. These cabins are both ocean view and inside, as the space between the ocean view cabins have been used for cabins as well. Forward on this deck is the anchor storage and a day room for crew. At the aft, there is the first floor of the atrium, which is also where embarkation is. The pool restaurant is a buffet restaurant. Passengers have the opportunity to sit inside or outside on the pool deck, where the infinity pool is located. The aft mooring is also located on this deck.

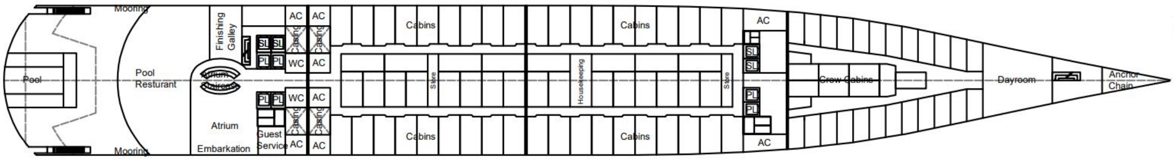


Figure 10.5: Deck 2

10.7 Deck 1

On deck 1 are the last crew cabins and a day room forward. In the middle section, there is a crew mess, storage and the second floors of the engine rooms. The second floors have cut outs to make room for the engines. Aft is the main galley, a crew mess, more storage, a garage, pool equipment room and propulsion room. The garage is for small boats, kayaks and other water activity equipment for excursions, exhibitions and passenger enjoyment. The garage has two doors on each side where boats and equipment can be launched from. On the outside deck is the marina with a platform. The platform can be lowered when the ship is not in transit. This provides extra deck space close to the water. The marina has two floating platforms connected to it, which can be used for easy embarkation to the boats and kayaks. Deck 1 is the bulkhead deck, meaning all watertight bulkheads terminate here. See Figure 10.6 for result.

10.8 Tank Top

In the front is the bow truster room. The engine rooms are place midships with machinery control room forward and workshop aft. Aft is a battery room and water treatment system. In the wing tanks are anti-heeling tanks, ballast tanks and methanol tanks. On the inside are

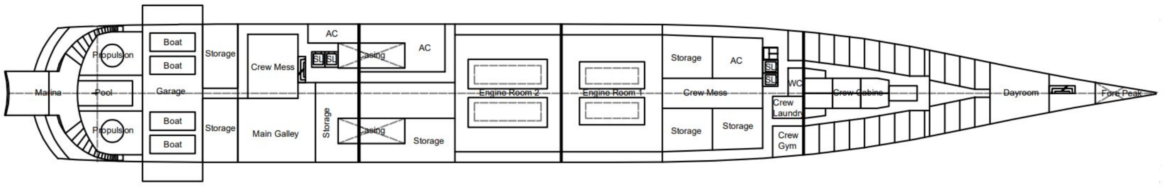


Figure 10.6: Deck 1

a lubricant oil tank,sewage and grey water tanks, fresh water tanks and four more methanol tanks. These methanol tanks follow Clean (Design) principals for fuel oil and can therefore be converted if needed. See Figure 10.7 for the result.

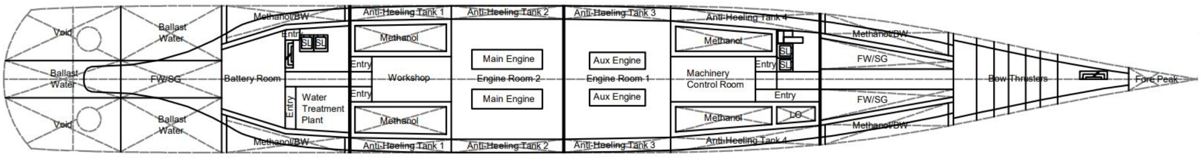


Figure 10.7: Tank Top

10.9 Double Bottom

In the double bottom are ballast water tanks and permanent ballast. The anti-heeling systems, such as pipes between the tanks and pumps are placed in the voids, to save space on tank top. See Figure 10.8.

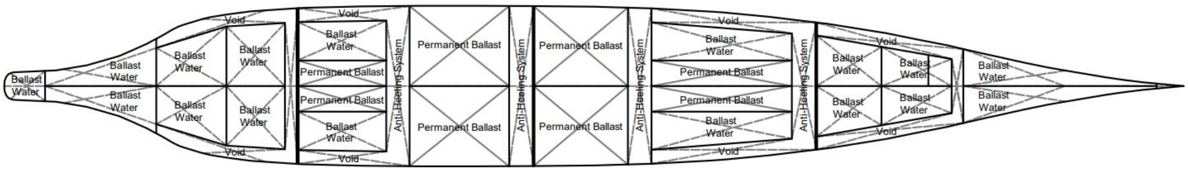


Figure 10.8: Double Bottom

10.10 Tank arrangement

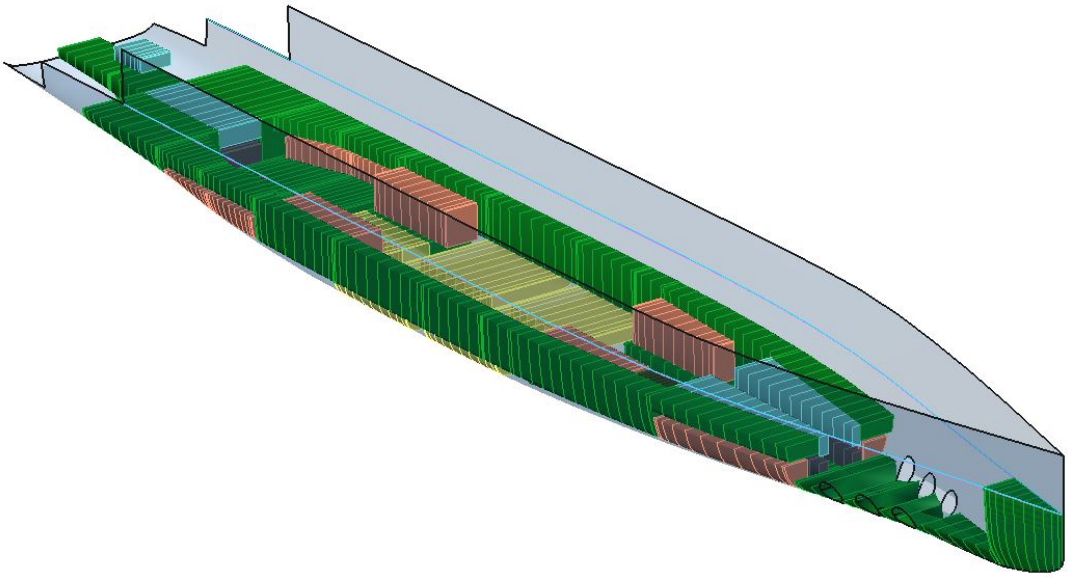


Figure 10.9: 3D moadel of the hull with defined tanks from Maxsurf Stability

Figure 10.9 shows a 3D view of the tank arrangement. Green tanks are ballast water, orange is methanol, light blue is fresh water, dark grey is sewage and grey water and dark brown is lubricant oil. For more details about the tank arrangement, see Appendix F.

10.11 Summery and comparison

After the general arrangement was finished the total number of passenger staterooms and crew cabins were found. The area of public and crew spaces were also found and have been compared to the area estimation from Kai Levander's "System Based Ship Design" [31]. The values used are for similar spaces and are for car ferries. The vessel in this thesis is a luxury cruise ship. It is expected that the areas on board, at least for passengers, are bigger compared to on a ferry. The ares found using Levander's values are therefore the minimum area wanted for these spaces. See Table 10.1 for area comparison.

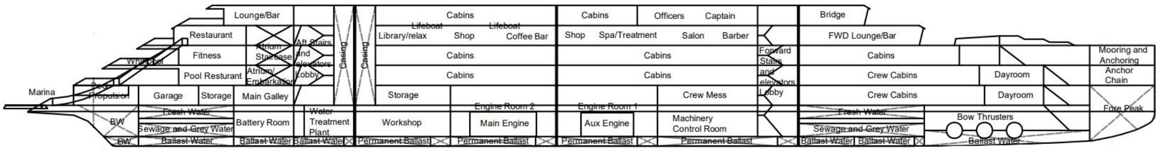


Figure 10.10: Profile view of the ship arragnement

Table 10.1: General arrangement area comparison

Area comparison [m^2]		
	Estimated	**Actual**
Pool restaurant	227	230
Fitness		268
A la Carte restaurant	77	230
Lounges	113	345
Cafe	85	55
Library		55
Shops	142	145
Entrence and atrium	85	133
Public toilets	14	100
Spa	85	176
Salong		176
Barber		35
Crew mess and dayroom	300	325
Crew recreation (Gym)	20	23
Crew laundry	13	16
Galley	84	133
Central store	20	23
Provision and shop store	42	54
Housekeeping and store	63	132
Engine rooms	511	590

From Maxsurf Stability, tank volumes were found. Volumes for lubricant oil, sewage and grey water and fresh water was also estimated with Levander's values. The results are summarized in Table 10.2. Kai Levander's System Based Ship Design, [31], was used to determent the minimum required area for different spaces and the minimum required volume for sewage, grey water and freshwater. The values used were based on values for RoPax ferries, as it was the closest category to cruise ship. If a box is empty, it was because Levander's publication did not have a similar space.

Table 10.2: Tank voulme comparison

Tank volume comparison [m^3]		
	Estimated	**Actual**
Methanol external tanks	600	455
Methanol internal tanks	658	808
Lubricant oil	51	54
Sewage and grey water	401	402
Fresh water	401	407
Anti-heeling tanks (one side)	730	737

All rules and regulations used for the development of the GA and tank arrangement are summarized in a list in Appendix A.

10.12 Changes and further development

There are a lot of rules and regulations not considered during this concept development. These were for example the requirements of tanks for bilge water, sludge, spills and other hazards liquids. The required space for AC systems, which shall take up 6 % of the deck area in each vertical zone, has not been checked, though suggestions to locations have been made. There is a lifeboat arrangement that fulfils the "37.5 % passenger capacity on each side" requirement, but the location is not ideal and mean the staterooms located nearby would have to be fireproof as the area around lifeboats should be fire resistant. According to Oceanbird, the foundation does not take up any space on the deck underneath, but there still needs to be extra structure. Therefore, it is likely that staterooms can still be located under the foundations, as long as the support structure is properly integrated in the design. A better vertical dividing could have helped solve these problems and made the layout more optimal.

The required number of cabins have not been met. This is due to one deck being removed. To increase the number of cabins, making the ship more profitable, a lot of inside cabins were created. As this is a luxury cruise ship, there is a need for better cabins, like balcony and ocean view. There was discussions about adding the deck back, but as it was too far into the developed, there was no time left to make the changes.

11 Weight estimate

11.1 Theory

To do stability calculations, a weight estimate is needed. A weight estimate is a summary of all mass and their positions that makes the lightweight of the ship. To do the weight estimations, one can use computer programs or do it manually. It is important that the data gathered is as correct as possible, as it will result in the most accurate stability calculations.

11.2 Method

The method used for the weight estimation in this thesis was a manual one. Using a SketchUp model, data about the area of the hull, decks, bulkheads etc., their centre of gravity and their location was found. This data was then placed in an excel spreadsheet. Data was gathered about all the major systems and larger equipment on board, which too were entered into the spreadsheet. With the weight (W), the longitudinal centre of gravity (LCG) and vertical centre of gravity (VCG), longitudinal moments (LMOM) and vertical moments (VMOM) were found. To find the VCG for the lightship, the sum of VMOMs was divided by the total weight. For the LCG, the sum of LMOMs was used instead. Some safety margins were added, and the resulting VCG was found.

11.3 First estimation

To obtain stability the VCG must be smaller than the distance from keel to the metacentre (KM). The KM value, given in the hydrostatics, was 10.8m. When the first estimate was finished the resulting VCG was 12.7m. Subtracting this value from the KM gave a negative metacentric height (GM), which means the vessel had no stability. In addition, the hydrostatics provided the weight displacement at 14 200 tonnes. The estimated lightship weight was considered to be too large, as the remaining displacement would not have been sufficient to carry the required fuel, provisions and people. Table 11.1 presents the results for the first estimate.

Table 11.1: First weight estimation

	Estimate
LCG	67.758 [m]
VCG	12.653 [m]
GM	-1.852 [m]
W	12 615.25 [t]

11.4 Second estimation

After investigating what could be the cause, with no results, our supervisor was consulted. A few flaws were brought to attention, and some suggestions for improving the stability was provided. An example was the value used for the weight of accommodation, which was set to 250 kg/m^2. This value is often used as the load to dimensioning support structures, but is not the real weight. Changing it to the more realistic value of 50 kg/m^2 lowered the VCG value. However, the VCG was still too high.

To help lower the VCG even more, and for visual reasons, one decks was removed. The mistakes of the values and formulas used in the first estimation were addressed. After that the spreadsheet was updated to have all the correct values for the ship hull and its systems. The results of the second estimation indicated that the mistakes had been corrected. Though, the VCG was still slightly above KM, meaning poor stability.

The reason the VCG was high was the sails. They are heavy and placed high up, increasing the overall VCG. Removing them reduced the VCG to 8.3 m, which means the ship is stable enough without them. One of the major attractions of the ship is the sails and as there were not any steel or systems missing in the calculations, the suggestion to use permanent ballast was implemented. The spreadsheet was updated to include permanent ballast, and tanks in the double bottom were filled with concrete. This gave the final estimations shown in table 11.2.

Table 11.2: Second weight estimation

	Estimate
LCG	72.689 [m]
VCG	7.632 [m]
GM	3.507 [m]
W	11 907 [t]

11.5 Third estimation

As there had been changes to the general arrangement because of misunderstandings with some rules regarding tank locations, a new tank arrangement was made. The stability was found to be too great. To reduce it, stability calculations were run with weight and centre of gravity values from the second weight estimation. The weight of the permanent ballast was reduced until the limit of where the stability criteria would pass for lightship, was reached. The minimum VCG required was around 8.6 m, and the value of the permanent ballast was around 2 500 tonnes. The new tank arrangement was design to have tanks large enough for this weight and spread over a longer length of the ship to help distribute the load. The volume made for the permanent ballast correspond to a weight of 2 656 tonnes of concrete. The final values of the weight estimation for lightship condition are given in table 11.3.

Table 11.3: Third weight estimation

	Estimate
LCG	73.400 [m]
VCG	8.209 [m]
GM	3.180 [m]
W	11 306 [t]

Figure 11.1 shows what percentage of the total weight each "item" contributes.

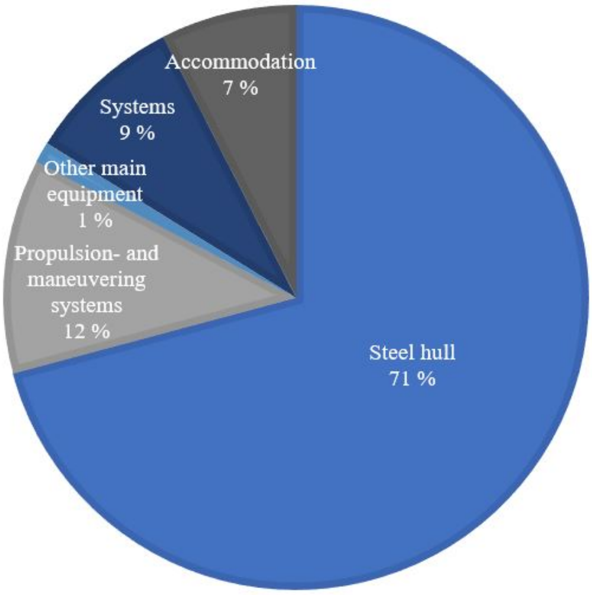


Figure 11.1: Pie chart showing the weight distribution of lightship by percentage

Because of time limitations, the weight estimation of the steel and placement was not changed to fit the new tank arrangement. This is a source of error when it comes to the stability calculations, but the values from the previous weight estimation are regarded as close enough to give an appropriate indication.

12 Stability

An important aspect to consider when designing a ship is to make sure the it is stable enough. The stability affects the safety of the vessel and the people on board. The sailing cruise ship in thesis is slim. This means it has less form stability, which will create smaller righting moments, making the possibility of capsizing grater.

12.1 Theory

To determent a ships stability, one uses its metacentric height. The metacentric height is the distance between the VCG and the metacentre of the ship. Metacentre is the point where a vertical line from the centre of buoyancy (CB), meets the line that goes through the centre of gravity (CG), parallel to the centreline (CL) of the ship. If the GM value is positive, the ship has stability. With a negative GM value, the CG is above M, the ship is unstable. The formula for metacentric height is shown in [4].

As mentioned, making sure a ship is stable is critical. Though, a ship that is excessively stable, has a too high GM value, can be experienced as unpleasant for the passengers and even cause injuries and damage. This is because the ship will rapidly respond to changes in the sea. It will roll with a short period and high amplitude, resulting in high angular accelerations and making the ship feel “stiff”. Therefore, the minimum initial GM value is 0.15 m, see Appendix A, and a GM value between 1.5 and 2.2 is often considered both safe and comfortable for passenger ships [3].

12.2 Static stability

To provide stability against static heeling caused by the wind load on the wing sails, it was concluded that anti-heeling tanks were the best solution. To find the necessary volume of water needed to withstand the heel from a certain wind speed, a simple moment calculation was done. The force of the wind acting on the ship side, including the sails, was multiplied with the distance from the vertical centre of flotation (VCF) of the ship to the centre of the projected area. The moment found was then divided by the distance form VCF to the CG of the anti-heeling tanks to get a force. The water required to create the same force was the amount needed for the anti-heeling system. The process and result are shown in Tabel 12.1

After the third weight estimations was done, tanks were made in Maxsurf Stability. After that, two loadcases were created, Departure Port and Arrival Port. In the Departure Port condition, all tanks with necessary liquids were filled to 100 %. The ship has anti-heeling tanks which were filled to 50 % on both sides. All others tanks were left empty. An equilibrium analysis was run where the draft and trim were found.

To get close to the upright hydrostatic, the designed condition for the ship and shown in Table 12.2, some ballast tanks were filled. There was an effort made to fill them evenly as not to exaggerate the shear force and momentum experienced in the hull. The Longitudinal Strength graph and the degree of tank filling for both conditions are provided in Appendix H.

The same method was used for the Arrival Port condition, but initial fillings were 10 % for tanks with necessary liquids and 100 % for sewage and greywater. The results of the hydrostatics for the two conditions are shown in Table 12.3

Table 12.1: Anti-Heeling volume calculation

Anti-Heeling volume		
Projected area	4 877	m^2
Air density	1.225	kg/m^3
Speed	50	Knop
Speed	25.7	m/s
VCF	5.47	m
VCA	21.25	m
z wind	15.78	m
Drag coeff. (Cd)	2	
Force caused by wind	3 952 809	N
Moment caused by wind	62 383 230	Nm
z anti-heeling tanks	8.5	m
g	9.81	m/s^2
Force from water	7 339 203	N
Mass water	748 135	kg
Density salt water	1025	kg/m^3
Required volume	730	m^3

Table 12.2: Upright hydrostatics for design condition

Upright hydrostatics		
Displacement	14 299	t
Draft at FP	5.5	m
Draft at AP	5.5	m
WL Length	180	m
Beam	22	m
Block coeff. (Cb)	0.641	
LCB	72.668	m
LCF	65.965	m
KB	2.977	m
VCG	5.5	m
BM	7.918	m
GM	5.394	m
KM	10.894	m

GZ is the righting leaver at heeling angles and is directly related to the GM value, se Formula 12.1. GZ curve is a graph where the GZ value is plotted for different heeling angels.

$$GZ = GM \cdot \sin \phi \tag{12.1}$$

When optimal equilibrium was found, a Large Angle Stability analysis was run for both conditions. The Large Angle Stability analysis analyzes the GZ curve against rules and regulations to make sure the stability is adequate. All requirements were passed for both conditions, and the GZ curves are provided in Appendix H.

Table 12.3: Equilibrium for Departure Port and Arrival Port conditions

Equilibrium hydrostatics			
	Departure port	**Arrival port**	
Displacement	14 056	14 098	t
Draft at FP	5.426	5.438	m
Draft at AP	5.426	5.438	m
Draft at LCF	5.426	5.438	m
Trim	0	0	m
WL Length	180	180	m
Beam	22	22	m
Block coeff. (Cb)	0.638	0.639	
LCB	72.782	72.762	m
LCF	66.168	66.127	m
KB	2.934	2.941	m
VCG	7.400	7.386	m
BM	7.998	7.984	m
GM	3.532	3.540	m
KM	10.932	10.926	m

Figure 12.1 shows the vertical moment distribution, and it is clear that the propulsion and maneuvering systems is a large contributor. This is in contrast to the weight distribution seen in Figure 11.1, where propulsion and maneuvering systems makes up a smaller percentage. The reason being that the sails are heavey and placed on top of the ship.

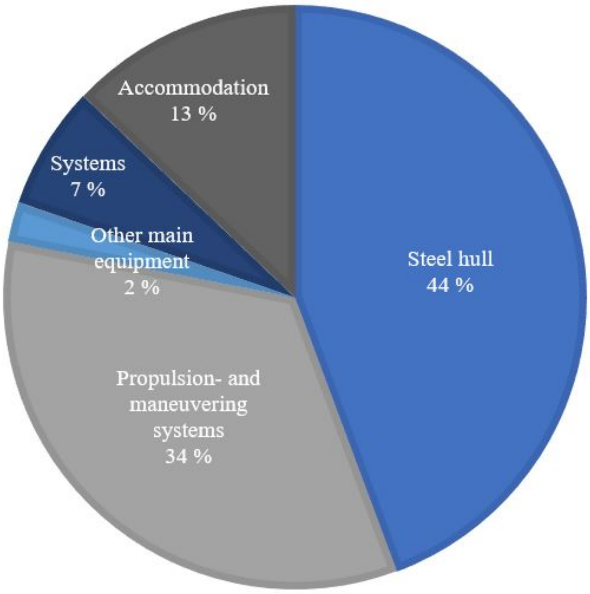


Figure 12.1: Pie chart showing the vertical moment distribution of lightship by percentage

12.2.1 Dynamic stability

The dynamic stability was not analysed in this thesis, but it is likely that stabilizer fins will be necessary to reduce rolling.

12.3 Damage stability

Damage stability was not analysed, as it is a more demanding analysis and there was not enough time. When calculating damage stability, the ship's stability will be analysed with different compartments and spaces filled with water, causing them to lose their buoyancy. This will reduce the overall stability of the ship.

Though, when using the Departure Port condition and only filling ballast tanks on one side and all anti-heeling tanks to 100 %, the ship's stability still passes on all criteria. The tank arrangement is designed such that there is always a void or a wing or a double bottom tank between the shell plating and inner compartment of the ship. This means there is argument that the ship might have good enough damage stability, as the possibility of a whole compartment flooding is small.

13 Structural Arrangement

The structural arrangement is an important part of the ship, because it affects the strength and performance. The strength of the ship is important for the vessel's functionality and safety. The purpose of the structural arrangement is to absorb stresses and forces from different loads. They are caused by weight from deck loads, wave impacts, sea and wind pressure.

This chapter is about the structural analysis done of the vessel. Focus areas during the analysis were to dimension an arrangement strong enough to withstand the loads from the surroundings, but at the same time be cost effective. In addition, the vessel shall fulfill the requirements for a suitable polar class. The structural arrangement is designed in Nauticus Hull and 3D-Beam after DNV standards. Stiffeners and plates are dimensioned in Nauticus Hull, while girders are dimensioned in 3D-Beam.

13.1 Topology

Plates, stiffeners and girders are the ones to withstand the impact from the surroundings. Pressure from the surroundings will effect the plate, further will this result in line load on the stiffeners, and in the end, the line loads will result in point loads on the girders.

Ships with a length over 70 m are typically longitudinally stiffened, but this is taken under consideration in each case [41]. Since the vessel in this project has a length at 180 m, it would be intuitive to choose longitudinal stiffeners. However, the requirements related to polar classification made the longitudinal stiffeners not sufficient. Therefore, transverse stiffeners were chosen from the ice belt and down. See Figure 13.1.

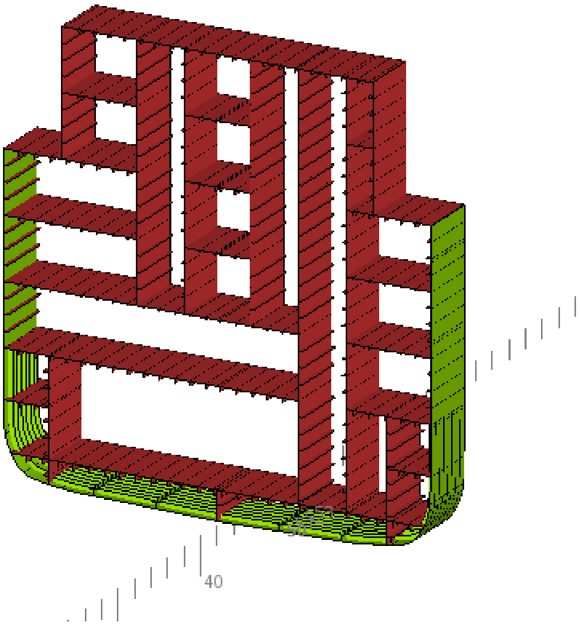


Figure 13.1: 3D-model from section #44 showing the topology. Red colour means VL-NS steel, green colour means VL-36 steel.

13.2 Polar Classification

Ships who want to operate in polar areas have to be certified. There are many different grades of classification, and the ship owner and ship designers have to select the certificate most appropriate for the ship's mission and requirements. In polar classification (PC) there are 7 levels of classifications, were they evaluate time of year, ice thickness and ice age. In structural arrangement this has an impact regarding the strength capability required. Pressures used for calculations will increase because of ice. This will affect the amount of steel needed. Different types of steel will be considered, since some steel types are stronger than others.

After taking the ships intended mission and operating profile into consideration, the PC 6 met the requirements for the ship. The description for Polar Class 6 is defined as: "Summer/autumn operation in medium first-year ice which may include old ice inclusions" [6]. For Nauticus to include the extra pressure and forces, the required input in Nauticus was plotted. The input included selecting the correct Polar Class and defining the frames for when the hull angle are shifting from zero for both the aft and forward part of the hull. In addition, defining the frame for where the hull angle is 10°. The angles where defined from plan view. The part between the 10°angle and the forward end was divided evenly in to four sections. The angles for each section was measured and plotted in Nauticus. This was for securing the bow strength for the ice loads, since the bow is highly exposed. As a last input, the upper ice water line and the lower ice water line was defined.

13.3 Section Scantlings in Nauticus Hull

The critical section is defined were there is a continuous vertical opening. On a cruise vessel this is a staircase or an elevator shaft. Therefore, when defining the vertical communication there was focus on not drawing the elevators and staircases in or close to midships, because that is were the global moment is largest. The section scantlings in Nauticus Hull is based on the general arrangement. The geometry for a specific frame is drawn. The geometry is essential for how Nauticus reads the section and then calculate.

The vessel have two continuous vertical openings, the aft and forward elevators shafts. It was therefore decided to draw both these transverse sections, since these sections are defined as critical. In addition, a section was drawn amidship because of the large global moment. For polar classification, four sections where drawn in the front of the ship. The overview for positions for the section scantlings is presented in Table 13.1.

Table 13.1: Overview for frames scantled in Nauticus and where they are located at the ship.

Frame	**Location**
#44	Aft Staircase
#99	Midship
#134	Fwd Staircase
#159	Polar Class - 1st Section
#174	Polar Class - 2nd Section
#189	Polar Class - 3rd Section
#205	Polar Class - 4th Section

The plates were assigned positions for more precises calculations. This is because some locations have lower requirements than others. For example, an accommodation deck does not need to be dimensioned for loads as large as for example the strength deck or the tank top. Figure 13.2 shows the assigned position codes.

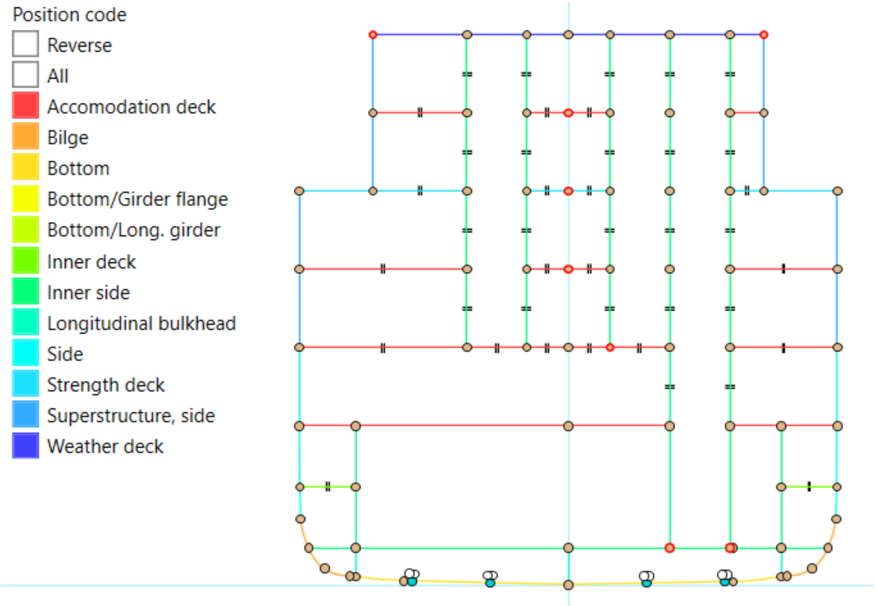


Figure 13.2: Assigned positions in geometry module in Nauticus Hull for #44.

After defining position codes, plates and stiffeners were added. Figure 13.3 is an example for how a finished section scantling can look like. In this project the spacing between stiffeners are 800 mm, and the ice belt is defined from z = 3.5 m to z = 6.5 m for #44, #99 and #134. For the remaining scantlings, the ice belt is defined from z = 3.5 m to z = 7.5 m, due to high pressure exposure for the bow. Plate thicknesses with square brackets are of VL-36 steel quality, which is high strength steel. Plate thicknesses without square brackets are of VL-NS, which is normal construction steel. Due to buckling in the transverse stiffeners, longitudinal girders were implemented. The distance between these was set to 3 200 mm. In Figure 13.3 girders are drawn. Notice that those are not dimensioned at all, and their purpose is to store the transverse stiffeners and making the span shorter.

For the transverse stiffeners at the section scantlings #44, #99 and #134 the spacing is set to 400 mm. For #159 the spacing is 300 mm, and for the three remaining scantlings the transverse stiffener spacing is set to 200 mm. Shorter spacing gives smaller plate field, and more steel to absorb forces. Decreasing the transverse stiffener spacing for the forward section scantlings is done to be able to choose smaller stiffener profiles, and will lover the required plate thickness.

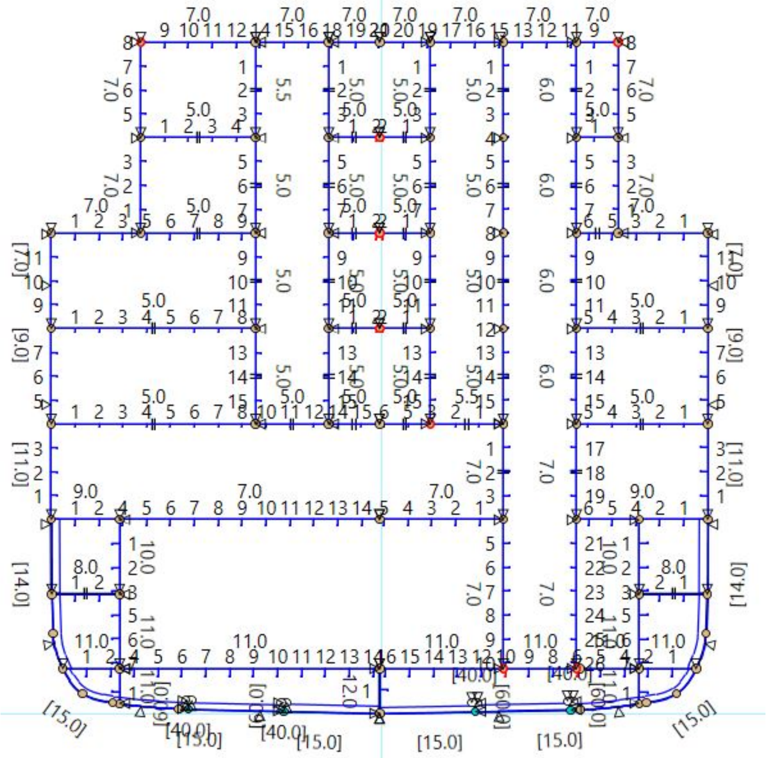


Figure 13.3: Section scantling in Nauticus Hull. Present the arrangement for stiffeners, and the plate thicknesses.

13.4 Dimensioning Girders

The girders are part of the basic structure of a ship. It should store stiffeners and define the plate fields together with the stiffeners. The dimensioning of the girders was done in 3D-Beam. A simplification was made when drawing the system, as only the hull beam was designed and not the superstructure. For the double bottom, the height of the web was defined as the double-bottom height, and for the wing tanks, the height of the web was defined as the width of the side tanks. For the remaining sides and decks, an assumption was first made about the dimensions of the girders. Then the dimensions were adjusted according to the results of the analysis in 3D-Beam. Two pillars were added to support the girders in the decks, limiting the span and decreasing buckling. See Figure 13.4 for the arrangement.

The loads for dimensioning the girders is calculated with the formulas 13.1 and 13.2.

Formula 13.1 gives the sea pressure affecting the hull. It is given by the draft, the acceleration of gravity and the mass density of seawater.

$$P = T \cdot g \cdot \rho \tag{13.1}$$

The sea pressure is used to find the line load to which the carrier system is dimensioned. The formula for line load is given by Formula 13.2. The line load is the product of the sea pressure, the carrier distance, a hydrodynamic additional factor and an additional factor for ice classification. The hydrodynamic additional factor is assumed to be 1.2, and takes account of dynamic loads such as waves hitting the hull. The additional factor for ice classification is here set to 1.5, and

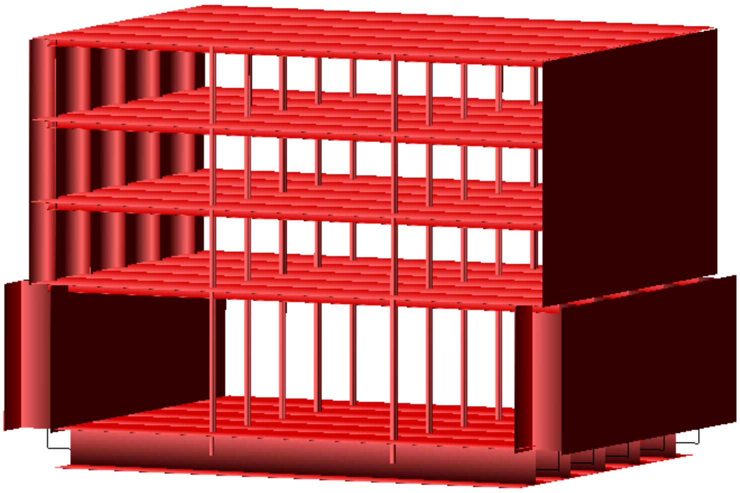


Figure 13.4: The arrangement for the girders drawn in 3D-Beam.

is an assumption. It takes into account the additional pressures due to ice classification. Figure 13.5 presents the resulting load case for the girder dimensioning.

$$q = P \cdot s \cdot 1.2 \cdot 1.5 \tag{13.2}$$

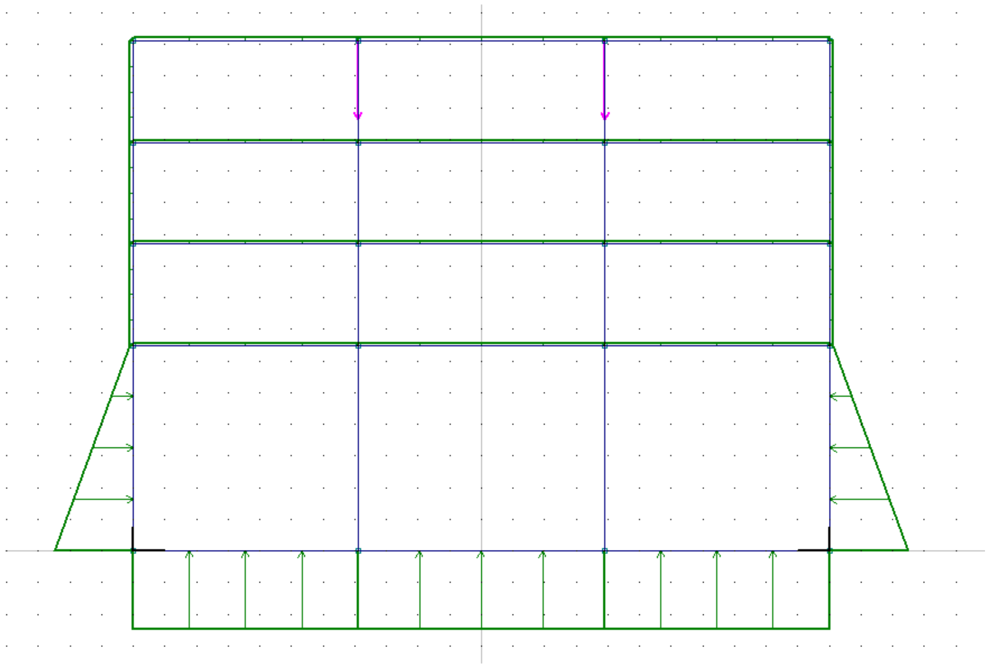


Figure 13.5: Load case for when dimensioning girders.

13.5 Global Moment

Global bending moments are used to validate the hull girder strength. Cruise ships have often naturally good longitudinal strength, due to the number of decks and few large deck openings. This means there are large amount of steel throughout the ship both horizontally and vertically to store forces.

Permissible bending moments are obtained from Nauticus Hull and are in accordance with DNV standard. All the sections are within the requirements for the control moments, and as Table 13.2 shows, the two critical sections meet the requirement for resistance moments by a good margin.

Table 13.2: Checking the Hull girder strength for the three sections most susceptible to bending moment.

Hull Girder Strength						
	Hog/Sag	**Min Msw [kNm]**	**Min Mw [kNm]**	**Z req [m^3]**	**Z act [m^3]**	**Yes/No?**
#44	Sagging	-309 403	-536 586	5.37	18.03	Yes
	Hogging	474 439	446 288	5.84	18.03	Yes
#99	Sagging	-438 805	-930 713	7.83	18.30	Yes
	Hogging	672 864	774 091	8.27	18.30	Yes
#134	Sagging	-438 805	-930 713	5.63	17.21	Yes
	Hogging	672 864	774 091	5.95	17.21	Yes

13.6 Local strength

In this project, no calculations have been made on local strength. It was decided early on that this should not be done, due to time and capacity limitations. Local strength is a topic that should bee look at in further work, as an essential part of the concept is the sails. The sails are of the foil type, and with their 168 tonnes, the sails will contribute to a significant vertical load. There will be a need for a support structure around the foundation to manage the forces.

13.7 Stiffeneres, plates and girders results

Values from the dimensioning of plates and stiffeners from Nauticus Hull and 3D-Beam are given in Table 13.3. The values are not exact for every point in the ship, but are an average. In the bow, plate thicknesses, stiffener spacing and size of stiffener profiles will increase due to the polar class.

See appendix I for more exact values.

Table 13.3: Summary of structural arrangement

Summary Structure			
Component	**Location**	**Dimension [mm]**	**Type**
Plates	Deck 2 Deck 3	5	-
	Deck 5	6	-
	Deck 4 (Strength deck) Elevators	7	-
	Deck 1 Superstructure	9	-
	Inner bottom Side tanks	11	-
	Skin above ice belt	12	-
	Skin below ice belt	15	-
Stiffeners	Deck 2 Deck 3	100 x 8	HP Bulb, Longitudinal
	Superstructure Elevators	180 x 10	HP Bulb, Longitudinal
	Deck 1 Deck 4 Deck 5 Skin above ice belt	220 x 10	HP Bulb, Longitudinal
	Inner bottom Side tanks	280 x 12	HP Bulb, Longitudinal
	Skin below ice belt (bottom)	280 x 12	HP Bulb, Transverse
	Skin below ice belt (side)	340 x 16	HP Bulb, Transverse
Girders	Double bottom	1 500 x 15	Web
	Side tanks	2 000 x 10	Web
	Sides Inner decks Deck 4 (Strength deck)	400 x 12 200 x 12	Web Flange
	Pillars	200x6 200x8	Web Flange

Each plate and stiffener in the cross sections was checked for stress, yielding and buckling. The results are given in Table 13.4. The cross sections is checked against DNV standards.

Table 13.4: Scantlings controlled in Nauticus Hull.

Structural Arrangement Check		
	Location	**Ok/ Not ok**
#44	After Staircase	Ok
#99	Midship	Ok
#134	Forward Staircase	Ok
#159	Polar - 1st section	Ok
#174	Polar - 2nd section	Ok
#189	Polar - 3rd section	Ok
#204	Polar - 4th section	Ok

13.8 Steel Weight Summary

Nauticus Hull calculated the steel weight for each cross section. See Table 13.5 for results. The plates and longitudinal stiffeners was given in the unit tonnes per meter, and the transverse stiffeners were given in tonnes. "L. Plates & Stiffeners" represent the total sum of the to steel types, VL-NS and VL-36. The transverse stiffeners are in the steel type VL-36. An average steel weight for all the cross section was calculated. For the longitudinals the total sum (L.Sum) in tonnes was found by multiplying the average weight with the ship length. The total sum for the transverse stiffeners (Trv.Sum) was found by multiplying the average weight with the number of girder frames. The girder distance is 3 200 mm. The overall total steel weight for the ship was calculated by adding the L.Sum and Trv.Sum, and the result is a steel weight at 2 776 tonnes.

Table 13.5: Estimated weight for the steel structure in scantlings with values from Nauticus Hull.

Weight Summary - Nauticus Hull		
	L. Plates & Stiffeners [t/m]	**Trv.Stiffeners [t]**
#44	23.07	0.87
#99	21.13	0.89
#134	22.93	1.13
#159	15.60	1.28
#174	11.22	1.52
#189	7.79	1.31
#204	3.70	1.02
Average	15.06	1.15
L.Sum [t]	2 711	
Trv.Sum [t]	64	
Total [t]	**2 776**	

The steel weight sum was used for comparison with the manual weight estimate. Table 13.6 present the steel weight, when only incluiding the equivalent structure designed in Nauticus Hull. For manual weight estimate values, see Appendix G. The total steel weight using weight estimate values is 2 773 tonnes.

Table 13.6: Estimated weight for steel structure in section scantlings with values from the Weight Estimate, see Appendix G for Weight Estimate values.

Weight Summary - Weight Estimate	
Aft	329 t
Midship	668 t
Forward	235 t
Superstructure	518 t
Skin	939 t
Tank Arrangement	84 t
Total	**2 773 t**

Comparing the results from Table 13.5 and Table 13.6 the difference for the total steel weights is three tonnes, and indicates that the weight estimate is good regarding plate thicknesses and stiffeners factors. The total steel weights represent the foundational steel structure and do not include all steel structure. For the manual steel weight estimate, see Appendix G.

13.9 Discussion

The polar classification work done in this project is not sufficient for realistic classification. The only additional work done is the ice class module in Nauticus Hull. This is not a sufficient calculation for polar classification, but for this project it was decided that the Nauticus module was sufficient enough. The goal was to get indications of the amount of additional structure and steel.

For dimensioning girders, it is used assumptions and simplifications. The loads are based on a simplified formula and assumed hydrodynamic factor and ice load factor. In addition, the scantling done in 3D-Beam is a simplified scantling, where only the hull beam is included. The super structure is included as a load, where the load is calculated with steel weight values from the manual weight estimate.

14 Model test

The model experiment was carried out in the towing tank at NTNU Ålesund. The purpose of the model experiment was to to obtain numbers on resistance data to use in comparison with results from empirical methods. In addition, this visualized how the hull moves through water.

14.1 Model preparation

An important prerequisite for towing tank tests is that there is geometric similarity between model and full scale. This is the foundation for the theory behind these tests.

The model was milled in foam material, and further processed with sanding and carving of cargo compartment. See Figure 14.1 and Figure 14.2. In the hold, the bracket attached to the load cell was to be mounted.

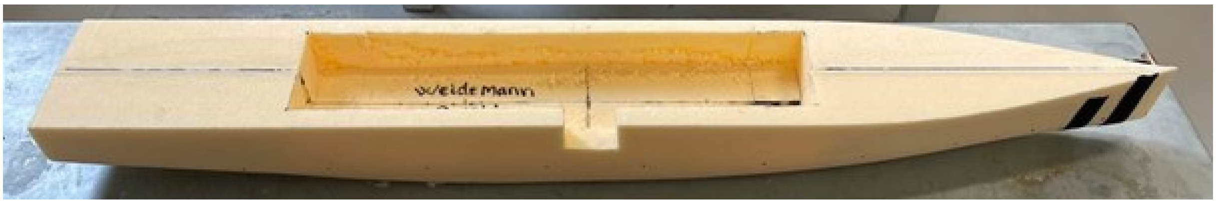


Figure 14.1: Model preparations. Top view.

Figure 14.2: Model preparations. Bottom.

At 14 cm in width, the model is relatively narrow compared to other models. This created challenges relating to load cell mounting. The load cell was too wide, and a piece had to be cut out at the top of the model for it to fit. See Figure 14.3.

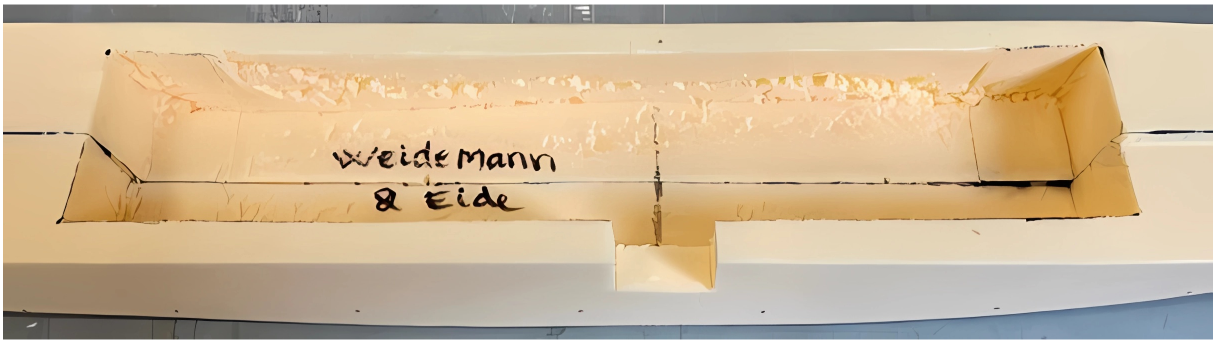


Figure 14.3: Cargo space and cut out for fitting the load cell.

In order for the model to get the right draught, weights were placed in the load compartment. This led to a new challenge as the model showed signs of instability. It made sense that the model did not have intact stability, as the VCG in the model was not correct compared to the VCG for the full-scale hull. The cargo hold was not made deep enough, and the center of gravity was too high. The solution was to remove the degree of freedom rolling with use of tape.

14.2 Execution of the test

In model experiments, turbulent flow is desirable in order to make the conditions as similar as possible to real conditions. This can be achieved by increasing the friction resistance of the model, increasing the hull roughness.

Before the experiment started, a test run was conducted to check the flow around the hull and that the setup worked. Here it was discovered that the hull had laminar flow and it was decided to attach anti-slip tape at the bow to increase the coefficient of friction. See Figure 14.4.

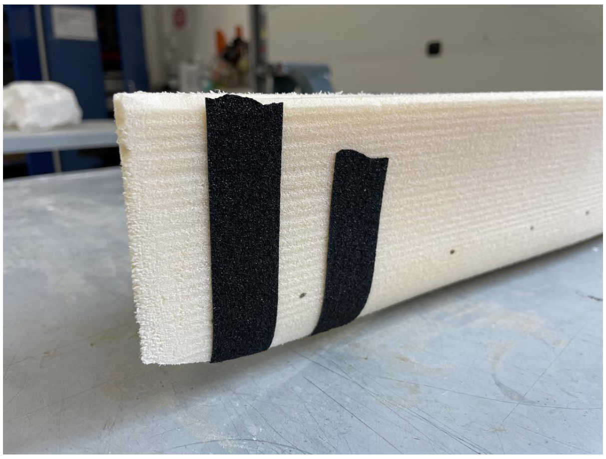


Figure 14.4: Strips in the bow for generating turbulence flow.

The test was conducted by running a series of laps with every other speed between 11-23 knots. Each speed were run four times. An important aspect of the execution was to wait until the water calmed down between each run. This was to remove factors that would affect the result. In Figure 14.5 and Figure 14.6 visualize the model during the test. The Figures are for represents different speeds.

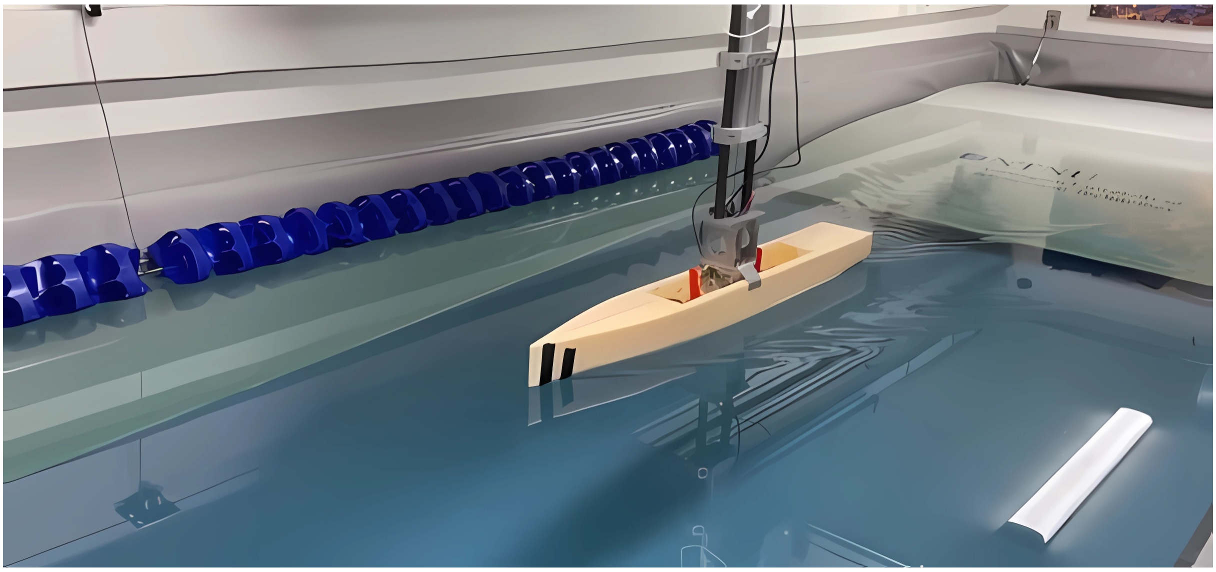


Figure 14.5: Towing tank test in 11 knots.

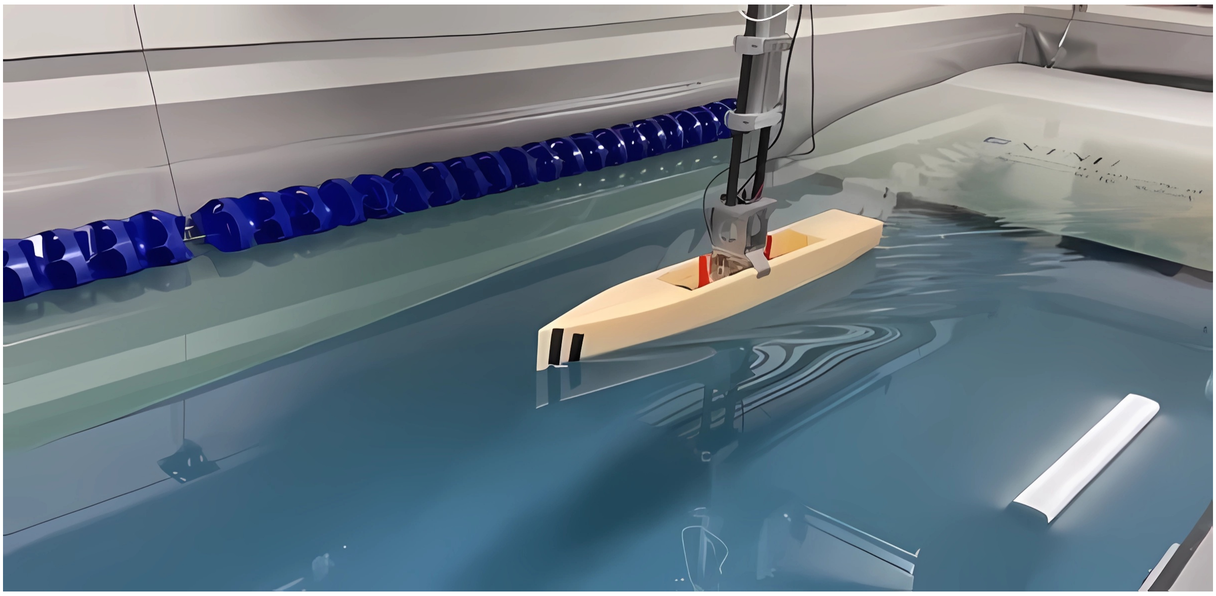


Figure 14.6: Towing tank test in 17 knots. Making some larger wave pattern.

14.3 Processing data

The desired data in relation to the towing resistance was when the model had a constant speed. This was found by averaging only this area in the data set.

An average was calculated for each data set, and an assessment of deviations was made. Deviations that were considered too large were not included in further calculations. Furthermore, the resistance value for each velocity was found by taking the average of all four series as shown in Table 14.1.

The values from the towing tank are resistance values for the model, and must be scaled up to full scale. The model scaling procedure is shown in Appendix J.

Table 14.1: Results from the towing tank test in model scale. Cells coloured in red are not included in calculations due to deviation.

Model - Resistance in Newtons							
	11 kn	**13 kn**	**15 kn**	**17 kn**	**19 kn**	**21 kn**	**23 kn**
Serie 1	0.132	0.203	0.280	0.348	0.408	0.538	0.663
Serie 2	0.147	0.174	0.281	0.351	0.435	0.574	0.661
Serie 3	0.138	0.204	0.245	0.357	0.412	0.532	0.672
Serie 4	0.133	0.217	0.264	0.366	0.434	0.530	0.665
Average	**0.138**	**0.208**	**0.275**	**0.355**	**0.422**	**0.533**	**0.665**

14.4 Results

The test results were scaled up to full scale resistance by ITTC procedure. See Appendix J for procedure. Table 14.2 shows the results from the towing tank test.

Table 14.2: The result from the Towing Tank Test in model scale and full scale.

Resistance				
	Froude number	**Model [N]**	**Full Scale Resistance [kN]**	**Full Scale Power [kW]**
11 kn	0.135	0.138	331	1 872
13 kn	0.159	0.208	552	3 689
15 kn	0.184	0.275	744	5 738
17 kn	0.208	0.355	985	8 613
19 kn	0.233	0.422	1 156	11 297
21 kn	0.257	0.533	1 513	16 346
23 kn	0.282	0.665	1 953	23 108

The results from the towing tank test was compared with the results from the empirical methods. See Table 14.3.

Table 14.3: Summary of the results for the three methods for resistance estimation.

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Summary Resistance Data						
	Towing Tank Test		***Holtrop & Mennen***		***Slender Body***	
Speed [kn]	**Force [kN]**	**Power [kW]**	**Force [kN]**	**Power [kW]**	**Force [kN]**	**Power [kW]**
11	331	1 872	181	1 022	299	1 689
13	552	3 689	255	1 702	339	2 265
15	744	5 738	349	2 694	393	3 032
17	985	8 613	470	4 114	561	4 902
19	1 156	11 297	623	6 086	884	8 643
21	1 513	16 346	817	8 827	1 164	12 576
23	1 953	23 108	1 064	12 590	2 066	24 440

The graph in Figure 14.7 visualize the differences for the three methods for the hull resistance given in kilo newton.

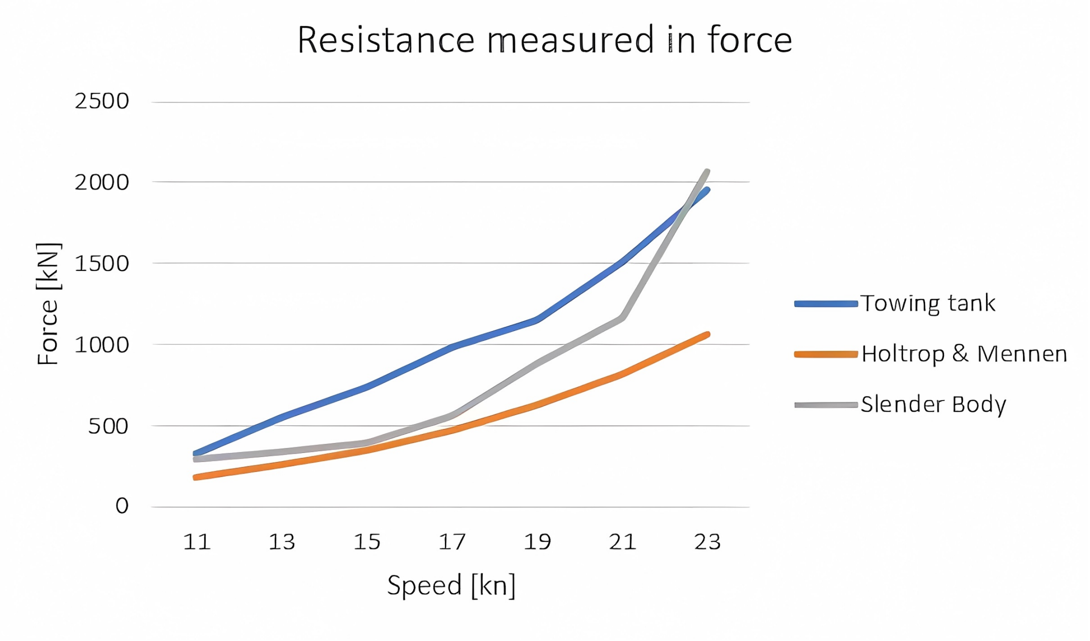

Figure 14.7: Resistance results from the Towing Tank Test in full scale compared to Holtrop & Mennen and Slender Body method.

The graph in Figure 14.8 visualize the differences for the three methods for the needed power given in kilowatt.

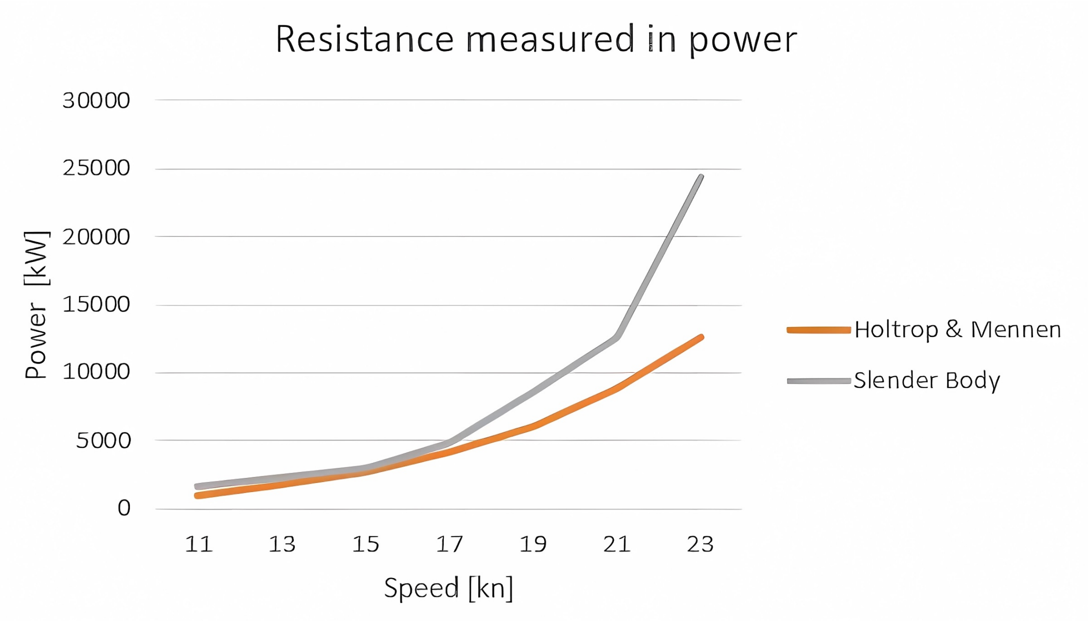

Figure 14.8: Power results from the Towing Tank Test in full scale compared to Holtrop & Mennen and Slender Body method.

The difference between the towing tank test and Holtrop & Mennen method is increasing with the speed increase, and the numbers from the towing tank is about twice as large as the values from Holtrop. Comparing the Slender body method and the Holtrop & Mennen method, the Holtrop method is showing lower results, but at 15 kn the differences is less than 50 kN. For high speeds the towing tank test and Slender Body method are more close with their results.

14.5 Sources of errors

During the experiment, vibrations were observed in the forward part of the hull. The vibrations probably affected the load cell, which led to higher resistance values. This is seen as an important source of error in this towing attempt. The vibration is most likely due to the hull design. With a long and slim hull and a long and narrow bow section, there was too much stress for the forward part of the hull. A more processed model would potentially lead to higher quality of the experiment and results.

Another factor is that it is not checked whether the correct level of turbulent flow was achieved. The measure to provoke turbulent flow was to mount pieces of tape on the bow. If two pieces of tape were sufficient is based on assumption and observation of flow. This is therefore an uncertainty with the test.

A possible source of high values is measurement errors in the load cell. This is based on a study comapring hte towing tank at NTNU Ålesund with the facilities at SINTEF. The study detected significant noise in the signals from the load cell. The source of the noise can come from vibrations in the arm and carrier of the carriage [21].

The tank size can have an impact in that waves from the model are reflected in the wall and hit the model in return. The effect of this is influenced by the relationship between tank width and length of the model, and the likelihood is that this has affected the results. This is for when finite tank volume is a reality [21].

14.6 Conclusion for Towing Tank Test

The results from the towing tank test is considered to have lack of credibility on the basis of a model not adapted well enough for the test facilities. With values twice the Holtrop & Mennen method and the errors occurring during the test, there is reason to believe that the test failed. It should have been executed a new test for investigating the quality of the first results, but there was no time for this.

15 Visualizing and 3D-model

SketchUp is a 3D modeling program used in this thesis. A model of the ship was created in SketchUp to help visualize the concept in the best way possible. Looks were an impotent aspect of this task. Because the ship is a luxury cruise ship, the visuals should therefore be elegant and sleek. It was also a desire to have a sailing yacht influence. Therefore, the aft was designed within a curved form that leaned forward and the bow is sharp and long. The two top decks are further back, which also helps to make an elegant visual. The 3D model is presented in the figures 15.1, 15.2, 15.3 and 15.4.

Another advantage of SketchUp is that areas can be provided and with simple measurements, one can find the area centre. This is useful when doing weight estimations, as the geometry can easily be modeled and then area and centre is found.

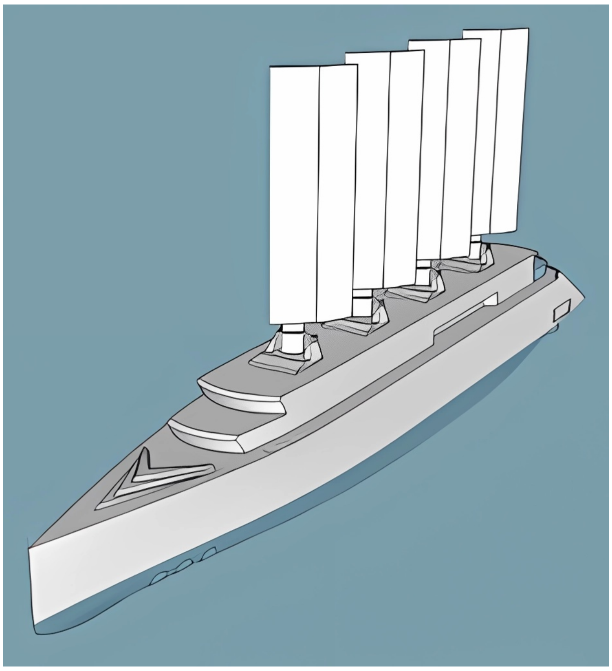

Figure 15.1: SketchUp model of the ship shown from above and back

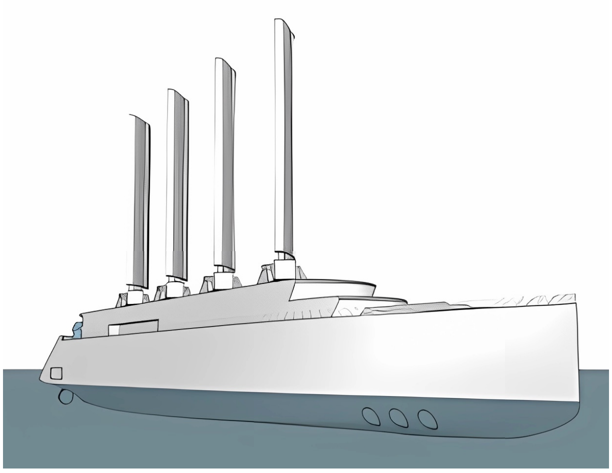

Figure 15.2: SketchUp model of the ship shown from below and back

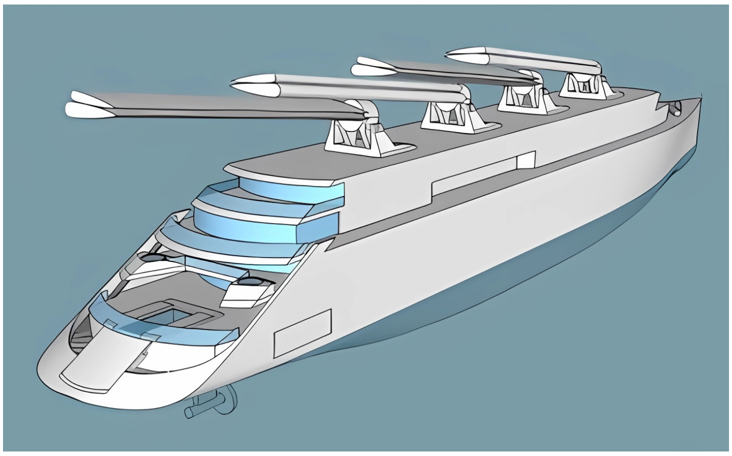

Figure 15.3: SketchUp model of the ship shown from above and froward

The way the Oceanbird wing sails lay down is at an angle close to the deck. If this solution was used for this ship, the wings would protrude outside the side of the ship, which would ruin the elegant look. Therefore, a solution made in this thesis was to lay the sails on top of another. Currently, this is not possible, as Oceanbird does not provide this solution. However, they were not opposed to it being a solution in the future.

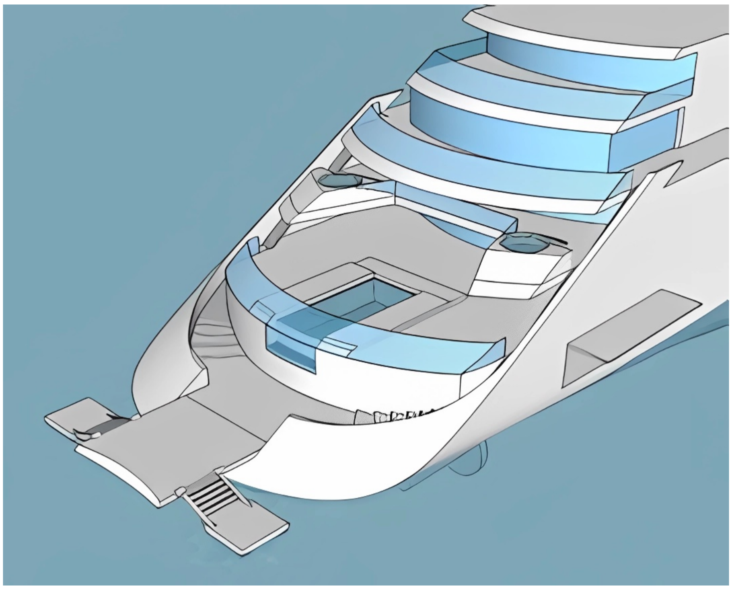

Figure 15.4: SketchUp model of aft area and the marina, with the platform lowered and garage door open

16 Discussion

Wind Assisted Propulsion System

One of the segments for this task was to implement modern technology for WAPS on a cruise ship. The WAPS would account for 10-20 % of the power required for propulsion and would lead to lower carbon emissions. Sails from Oceanbird of the aerodynamic foil type were chosen. This type of WAPS is seen as an effective solution. The performance results shows good values in relation to the goal of the task. For this ship, the Oceanbird wings can contribute a relatively large percentage of power, depending on the ship's speed. The power of the sails is based on average weather data for an area, and when assessing sails for propulsion, investigations must be made on their profitability. A decision must be made on the area of operation and associated wind conditions, as well as the operational profile and assignment for the ship. When choosing routes for the vessel, optimal weather data has not been prioritized.

When calculating the power contribution from several sails, a factor has been used to take the height for an interference effect that will occur between the sails. The factor is assumed based on guesstimate, as there were lack of knowledge and experience. By setting the factor to 0.8, the goal was to be conservative. This is based on the theory of this effect which states that it is possible to achieve a factor above 1 in some cases. No verification has been done to make sure the assumed factor is conservative.

The sails from Oceanbird are still in the development phase, and the wing used in this thesis is therefore a prototype. By using a prototype, there numbers used for calculations are still in development and the possibility of changes in properties are present. This can further affect the performance and must be considered when assessing the success of implementing these wings. However, the concept development of the ship is in an early phase, and a prototype is sufficient for indicating the effect of a wind assisted propulsion system.

In the final concept of this thesis, four wings are installed. In further work, it can be seen whether it is more beneficial to install three wings rather than four. From an investment perspective, choosing three wings will cost less. In contrast, by choosing four wings, it is possible to achieve greater fuel savings. Another aspect of assessing the number of wings is their area requirements. The wings occupy a relatively large space on the top deck, especially in lowered condition. Taking safety into consideration, this can cause restrictions for passenger use on the top deck.

Environmentally friendly ship

The energy solution chosen for propulsion is methanol and wind power. This is a solution that helps lower greenhouse gas emissions. Methanol is an alternative fuel and is being implemented as a marine fuel to make shipping more environmentally friendly. However, methanol is only carbon neutral provided that the production is supplied with renewable energy and bio material. The extent to which the ship is climate-friendly is therefore defined by the origin of the methanol. Regardless of the origin of the methanol, wind-assisted propulsion systems will contribute to a more climate-friendly ship. The reason being that wind is a renewable energy source and causes no emission when used as a power source.

Methanol as a fuel was chosen based on an engineering viewpoint. To design the most environmentally friendly ship, life cycles analysis should be conducted for all alternative fuels

available. There where not looked at any life cycles analysis in this thesis. A life cycles cost analysis should also be performed to decide which alternative fuels would be most cost effective. This should also be done for the sails to find out the optimal number that produces the most thrust at the lowest cost.
After looking at different bow shapes the strait bow was concluded to be the most efficient. If there had been more time, a more in dept look at and test of the different types could have been carried out.

Stability

At a point in the process, it was decided to remove a deck. The reason for this was the challenge of achieving sufficient stability. The intention of removing a deck was to achieve a decent VCG without having to install permanent ballast. This was seen as better solution since using only ballast water for adjusting draught gives more flexibility. By installing permanent ballast in double bottom, the ship is tied to constantly carry weight. When removing the deck, the vertical centre of gravity decreased. However, the improvement was not enough, and the solution was to use permanent ballast in double bottom.

As mentioned permanent ballast was implemented for securing sufficient stability. Around 3 500 tonnes with concrete was used in double bottom. This was necessary for the stability of the ship, making it safe and functional. However, it turned out that 3 500 tonnes was to much, causing a rather high GM value. A high GM value will make the ship stiff and uncomfortable in rough seas. Making a ship comfortable for passengers is one of the essentials when designing passenger ships. To decrease the GM value, the weight of the permanent ballast was reduced to around 2 600 tonnes. This resulting GM value is still high at around 3.5 m, but the margins for passing the severe wind criteria are smaller. Therefore, the ship might need to be a bit uncomfortable in rough seas to be able to have sails.

Rules and regulations

The general arrangement in this thesis has been made to follow as many rules and regulations as seen viable with the available time and manpower. As this concept is a cruise ship that is going to carry passengers, rules for safety and stability were prioritized. More knowledge of these rules and regulations has been achieved. A greater understating on how to incorporate them with a functioning and useful layout have been learned, and multiple iterations were made to optimize the design. Still there are flaws in the GA and as most rules and regulations for maritime shipping have not been looked at, some systems and equipment were placed on board without checking to see if they comply.

Space usage

A target set was that the values from using Levander's estimations would be the minimum space requirements. This has been achieved for most of the spaces, except for the coffee bar. It was close to the goal, but after having to place lifeboats on the promenade deck, the area was reduced. Though, passengers have multiple options of spaces where they can relax, and beverages are served. In addition, most spaces are over the minimum or much larger. This is beneficial, as passengers traveling on luxury cruises will demand greater space than what is provide on car ferries. It has not been checked to see if some spaces are too large and should be divided to make more efficient use of the space.

Marina concept

The marina concept developed works great in theory. It is flush with the deck when lowered, maximizing usable area. From the marina, two floatable platforms can be lowered onto the water. They will serve as embarkation platforms to watercrafts like small boats and kayaks. When the ship needs to move or bad weather occurs, the marina can easily be folded together and rotated back to resting position. This will make the decision to lower it down easier for the crew, increasing the time passenger can use it. There has not been performed any strength calculations for the marina to make sure the current dimensions are large enough to handle the forces that will act on it. The marina is a concept and the folding together and rest position are just theoretical. Therefore, it is not certain that the concept will be easier to handle than a regular marina.

Boat and equipment garage

Cruise ships travel to more remote areas around the world as demand for remote destinations increases. This ship is also going to remote destinations, meaning it must be self-reliant. To be able to offer excursions on these locations the ship needs to carry its own equipment. Therefor the ship has a garage for at least four small boats and enough storage for other water activity equipment to increase the options available for the passengers. The boats can easily be launched from two openings in the side of the ship and, when not in use, the doors are locked and protect the boats and equipment.

Outside viewing possibility

Another request was for the ship to have an undisturbed route outside on the deck from bow to stern. This is to be able to follow wildlife activity and exciting scenery as the ship is sailing by. Having to go inside would obscure the view and ruin the experience. This was made by having a promenade deck on Deck 4 and outside stairs at the aft to lower decks. The view will be undisturbed for most of the distance, but the lifeboats and the hull side at the aft decks will be major obstructions. Solutions for another lifeboat arrangement and openings in the hull to view from must be considered in further work.

Lifeboats

With the four lifeboat chosen, there are enough seats for 37.5 % of the total capacity on each side, meaning requirements. Though, the location and design of the lifeboat and davit system has not been checked to see if it would be approved in accordance with rules and regulations. It is most likely not, as the solution for the lifeboat and davit system was made late in the development. The process of designing a lifeboat arrangement was started earlier, but when a deck was removed and a new hull made, the process had to wait until the final capacity was known.

An alternative lifeboat arrangement was made. Two lifeboats, one on each side, of Fassmer's PLT-EVO 170, would meet requirements. This would reduce the length the lifeboats and davits would occupy on deck, but it would require a taller space. This alternative would affect fewer staterooms, though it would block most of the view for the affected cabins. These cabins are suites, and it is therefore not a preferable alternative. No suitable davit system was found ether and the alternative was therefore disregarded. A solution to the problem would be to place the lifeboats close to the casing, as this will make it easier to fireproof the area. This was not possible, because the casing was placed too far out to the side and could not be moved.

Cabins

Because of a stability issue and for visual purpose, on deck was removed. This removed valuable area, causing the final design not to meet one of its requirements. The ship was to have 150 to 170 passenger cabins. The first version of the concept had four decks where cabins were going to be placed. This would have made meeting the minimum target relatively easy and every cabin after would be a bonus. When the deck was removed, at least 40 potential cabins were lost. The final number of cabins were 142 and with the additional 40, it would make a total of 182 cabins. This is exceeding requirements and means between 12 and 32 cabins could have been removed. This would have been beneficial as 25 % of the current cabins are inside cabins. For a luxury cruise ship the maximum number of balcony and ocean view cabins is wanted

Visuals

Using SketchUp to create a 3D model of the ship helped visualise it. Decisions affecting its visual appearance were easier to do when having the ability to make multiple options and viewing them from different perspectives. It was also useful as SketchUp provides area data and easy measurements can be done to find the area centre. Even though most of the external ship have been modelled, some areas are not completed. These are the bridge and the funnels. If designs had been discussed and finalized, they could have been modelled and provided a more complete look of the cruise ship.

The final look meets requirements of having an elegant design. The strait bow contributes to this look. The uppermost decks are shorter and removing a deck gave the bow an even sleeker visual. The aft is designed within a curved form that leans forward. This is influenced by sail yacht and makes the vessel look exclusive and luxurious.

17 Conclusion

The product of this thesis is an environmentally friendly expedition cruise ship fulfilling the given requirements in the assigned project description. The ship is equipped with sails and an alternative propulsion system. Calculations have been carried out to determent the ship's stability, and solutions as permanent ballast was implemented for passing the requirements. With methanol as fuel the ship can be CO_2-neutral. Safety has been considered when developing the general arrangement and rules have been followed. The hull is efficient and has an aesthetic look with a strait and sleek bow.

With limited time there as not been time for investigating different solutions, and the result is not optimized. The general arrangement is not efficient and has to be looked more into. More calculation on permanent ballast will give more optimal stability.

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A Rules and Regulations

DNV, Rules for Classification: Ships

- Part 3: Hull, Chapter 1: General principles
  - Section 4: Symbols and Definitions: 3.1.1 and 3.1.2 are about rule length (L) and freeboard length (LLL).
- Part 3: Hull, Chapter 2: General arrangement design
  - Section 2: Subdivision arrangement: 1.1.1, 1.1.4, 1.1.5, 4.1.1 and 4.1.2 are about bulkheads.
  - Section 3: Compartment arrangement: 1.2.1, 2.2 and 2.3 are about cofferdams and double bottom.
- Part 3: Hull, Chapter 15: Stability
  - Section 1: Stability: 4.1.1 is about minimum initial metacentric height.
- Part 6: Additional class notations, Chapter 2: Propulsion, power generation and auxiliary systems
  - Section 6: Low flashpoint liquid fuelled engines - LFL fuelled and gasoline refuelling and storage installations - gasoline inst: 3.2.1.1, 3.2.1.3, 3.2.1.4, 3.2.1.5, 3.2.2.1, 3.4.1.1 and 3.4.1.5 are about fuel tanks, where they can be located and their protection.
- Part 6 Additional class notations, Chapter 7: Environmental protection and pollution control
  - Section 2: Environmental class - Clean: 1.4.3, 3.3.8.1 and 3.3.8.2 are about Clean (Design) requirements.
- Alternative Fuels for Containerships (a publication)
  - 4.4.1 is about where low-flashpoint liquid fuel tanks can not be located.

International Convention for the Prevention of Pollution from Ships

- Annex I- Regulations for the Prevention of Pollution by Oil
  - Appendix 2 - Interim recommendation for a unified interpretation of regulations 18.12 to 18.15 “Protective location of segregated ballast spaces” 2 is about the width of the wing tanks.

International Convention for the Safety of Life at Sea

- Chapter II-2 - Construction - Fire protection, fire detection and fire extinction
  - Part C - Suppression of fire, Regulation 9 - Containment of fire: 2.2.1.2 is about fire bulkheads and main vertical zones size and divisions.
  - Interpretations of SOLAS Chapter II-2, As Amended by Resolution MSC.27(61)
    - 2 Regulation II-2/24 - Main vertical zones and horizontal zones. It is about stairway location. The solution of Figure 3 in that appendix is used for this concept.
  - Chapter III - Life-saving appliances and arrangements
    - Part B - Requirements for ships and life-saving appliances, Regulation 21 - Survival craft and rescue boats, 1 Survival craft. 1.1 and 1.1.1 are about lifeboat capacity.

MSC.267(85) Code on Intact Stability, Part A - Mandatory Criteria

- 267(85) Ch2 - General Criteria
  - 2.3: IMO roll back angle: All of the criteria under 2.3 in Maxsurf Resistance Criteria was used and for "Severe wind and rolling", the following values and setup were used:
    - Area centroid height (from zero point): h = 21.525 m
    - Total area A = 4 877 m2
    - Additional area A = 0 m2
    - H = mean draft / 2 was chosen instead of "H = vert. centre of projected lat. u'water area"

System Based Ship Design, Kai Levander, SeaKey Naval Architecture, 2012 (publication)

- 6. Ferry design
  - 6.8 System based design of RoPax ferries This publication has average values for areas and volumes for types of spaces and items on different ship types. Values for RoPax ferries were used in this thesis.

B Line drawings

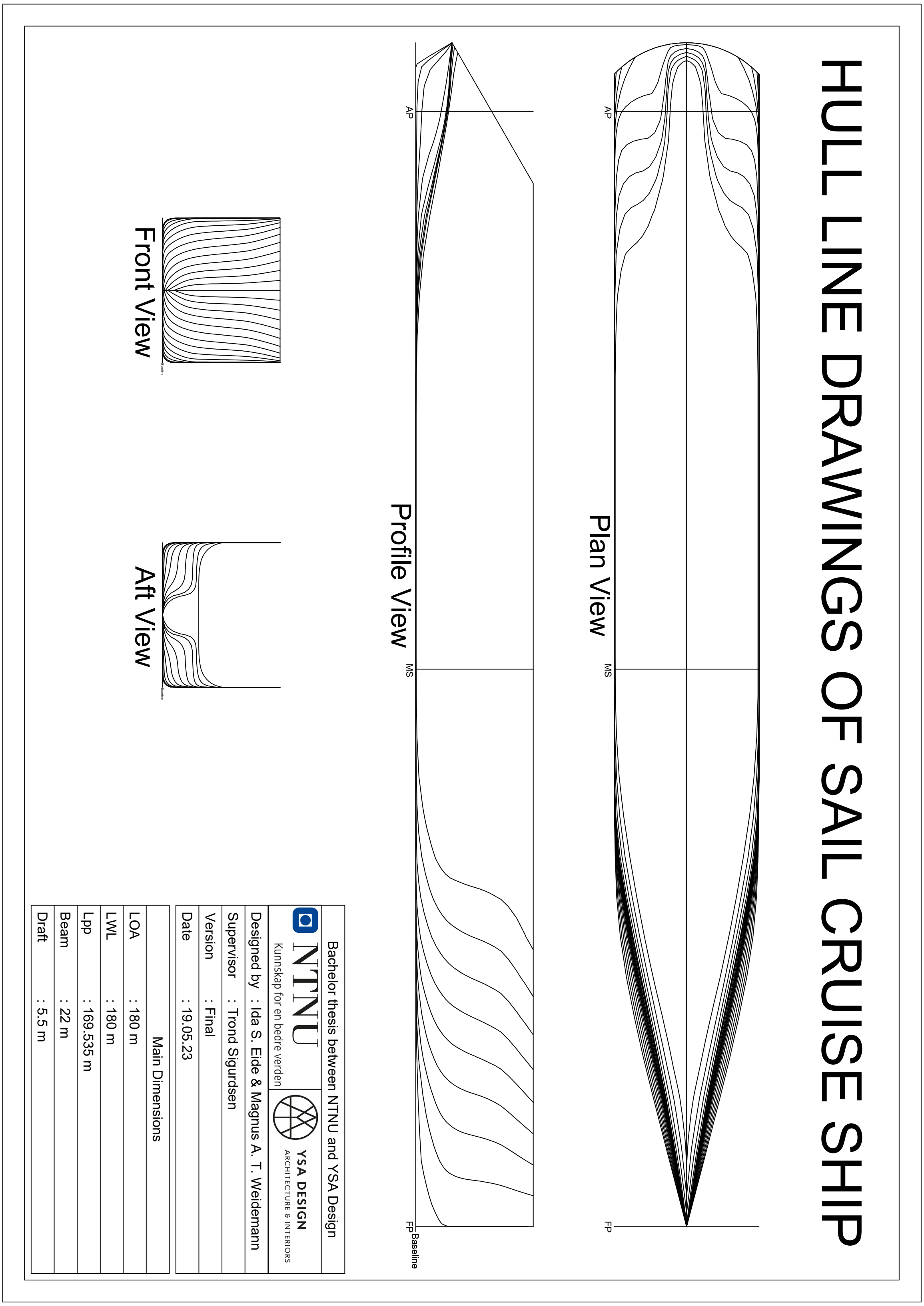


Figure B.1: Line drawings of the first hull design.

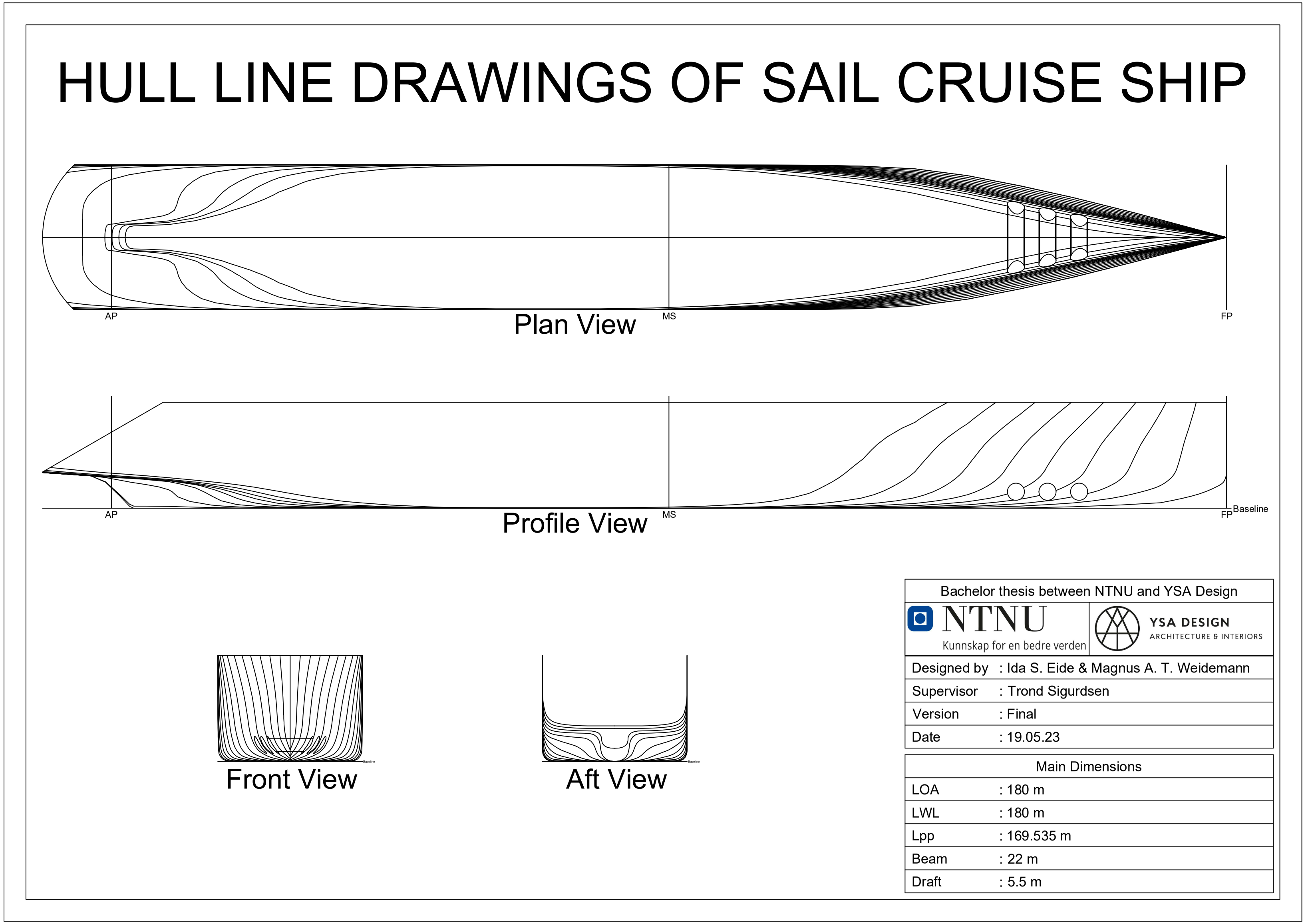


Figure B.2: Line drwaings for final hull design.

C Singel line diagram

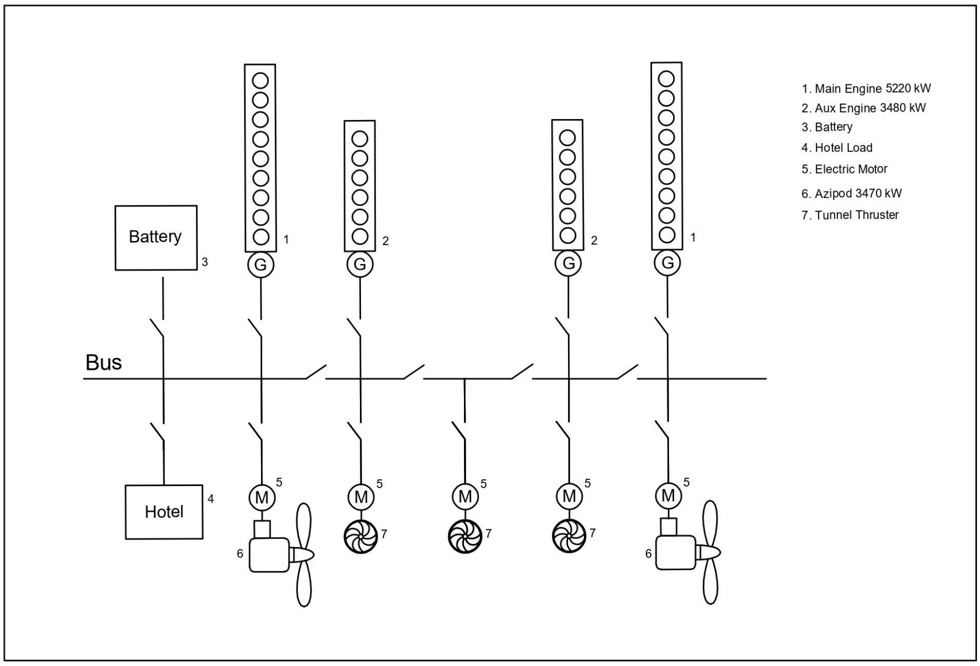


Figure C.1: Simplified Singel Line Diagram for engine arrangement 1.

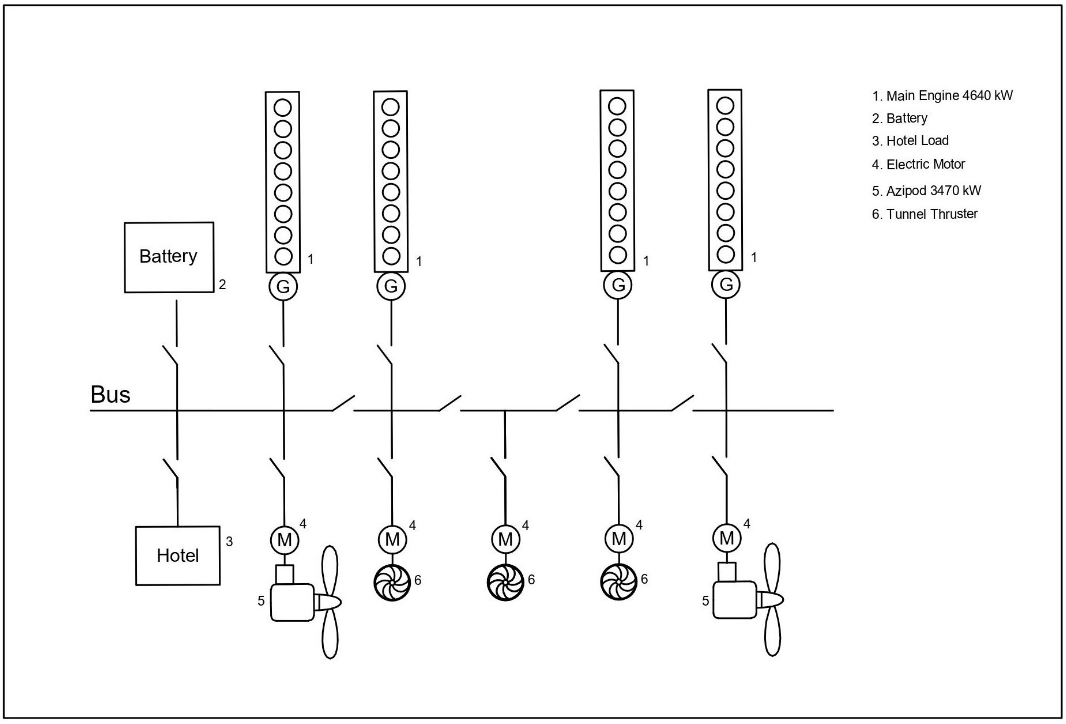
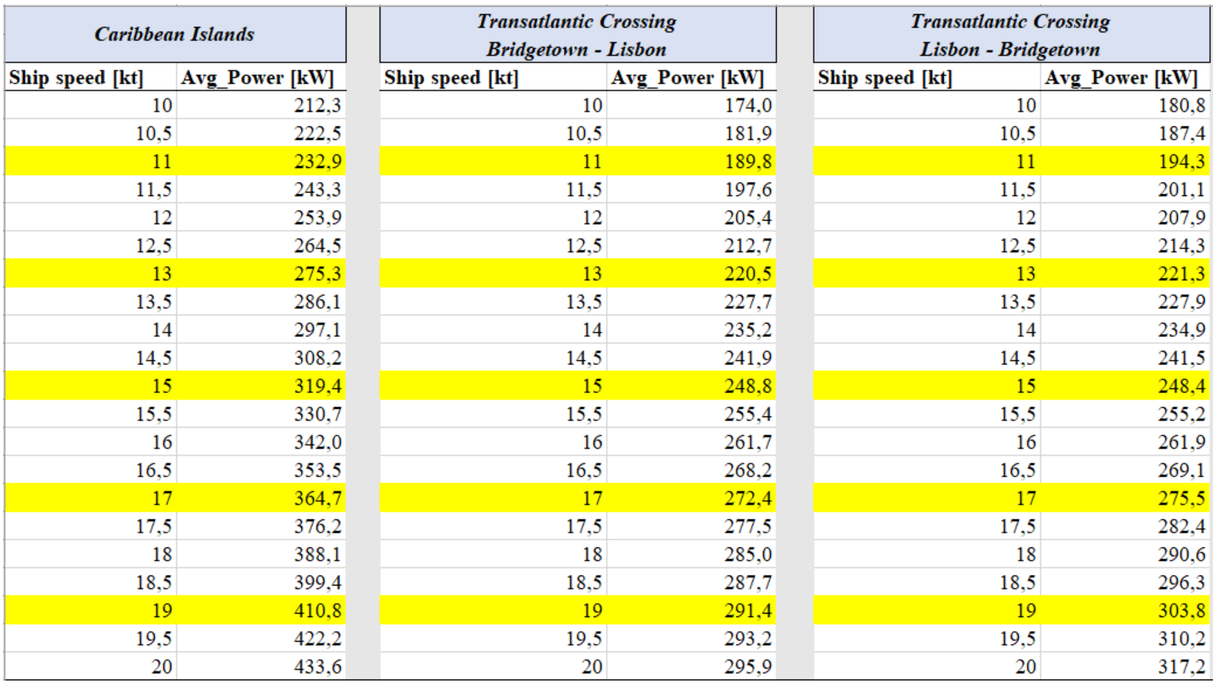


Figure C.2: Simplified Singel Line Diagram for engine arrangement 2.

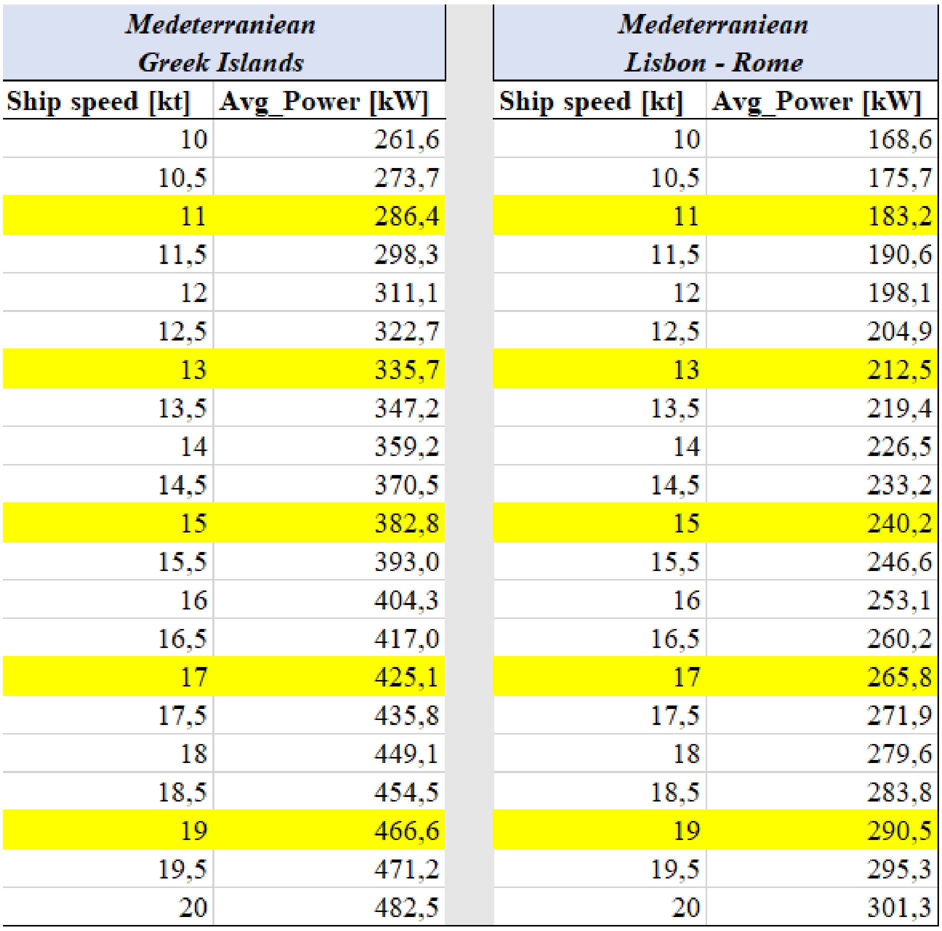
D Oceanbird Wing Sails

Performance data delivered by Oceanbird



Caribbean Islands		*Transatlantic Crossing Bridgetown - Lisbon*		*Transatlantic Crossing Lisbon - Bridgetown*	
Ship speed [kt]	**Avg_Power [kW]**	**Ship speed [kt]**	**Avg_Power [kW]**	**Ship speed [kt]**	**Avg_Power [kW]**
10	212,3	10	174,0	10	180,8
10,5	222,5	10,5	181,9	10,5	187,4
11	232,9	11	189,8	11	194,3
11,5	243,3	11,5	197,6	11,5	201,1
12	253,9	12	205,4	12	207,9
12,5	264,5	12,5	212,7	12,5	214,3
13	275,3	13	220,5	13	221,3
13,5	286,1	13,5	227,7	13,5	227,9
14	297,1	14	235,2	14	234,9
14,5	308,2	14,5	241,9	14,5	241,5
15	319,4	15	248,8	15	248,4
15,5	330,7	15,5	255,4	15,5	255,2
16	342,0	16	261,7	16	261,9
16,5	353,5	16,5	268,2	16,5	269,1
17	364,7	17	272,4	17	275,5
17,5	376,2	17,5	277,5	17,5	282,4
18	388,1	18	285,0	18	290,6
18,5	399,4	18,5	287,7	18,5	296,3
19	410,8	19	291,4	19	303,8
19,5	422,2	19,5	293,2	19,5	310,2
20	433,6	20	295,9	20	317,2

Figure D.1: Performance data for one Wing Sail provided by Oceanbird.



Medeterranieean Greek Islands			*Medeterranieean Lisbon - Rome*	
Ship speed [kt]	**Avg_Power [kW]**		**Ship speed [kt]**	**Avg_Power [kW]**
10	261,6		10	168,6
10,5	273,7		10,5	175,7
11	286,4		11	183,2
11,5	298,3		11,5	190,6
12	311,1		12	198,1
12,5	322,7		12,5	204,9
13	335,7		13	212,5
13,5	347,2		13,5	219,4
14	359,2		14	226,5
14,5	370,5		14,5	233,2
15	382,8		15	240,2
15,5	393,0		15,5	246,6
16	404,3		16	253,1
16,5	417,0		16,5	260,2
17	425,1		17	265,8
17,5	435,8		17,5	271,9
18	449,1		18	279,6
18,5	454,5		18,5	283,8
19	466,6		19	290,5
19,5	471,2		19,5	295,3
20	482,5		20	301,3

Figure D.2: Performance data for one Wing Sail provided by Oceanbird.

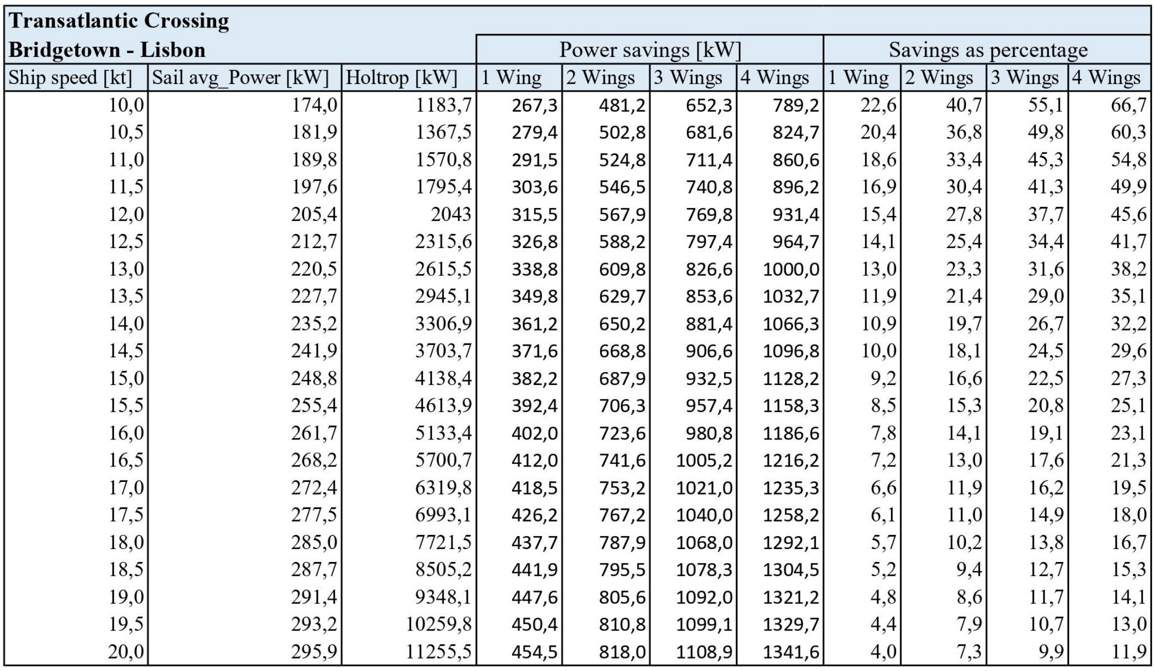
Processed Performance Data

Caribbean										
			Power savings [kW]				Savings as percentage			
Ship speed [kt]	Sail avg_Power [kW]	Holtrop [kW]	1 Wing	2 Wings	3 Wings	4 Wings	1 Wing	2 Wings	3 Wings	4 Wings
10,0	212,3	1183,7	326,1	586,9	795,6	962,6	27,5	49,6	67,2	81,3
10,5	222,5	1367,5	341,8	615,3	834,0	1009,1	25,0	45,0	61,0	73,8
11,0	232,9	1570,8	357,7	643,9	872,9	1056,1	22,8	41,0	55,6	67,2
11,5	243,3	1795,4	373,8	672,8	912,1	1103,5	20,8	37,5	50,8	61,5
12,0	253,9	2043	389,9	701,9	951,5	1151,1	19,1	34,4	46,6	56,3
12,5	264,5	2315,6	406,2	731,2	991,2	1199,2	17,5	31,6	42,8	51,8
13,0	275,3	2615,5	422,8	761,1	1031,7	1248,2	16,2	29,1	39,4	47,7
13,5	286,1	2945,1	439,5	791,1	1072,4	1297,5	14,9	26,9	36,4	44,1
14,0	297,1	3306,9	456,4	821,4	1113,5	1347,1	13,8	24,8	33,7	40,7
14,5	308,2	3703,7	473,4	852,1	1155,0	1397,4	12,8	23,0	31,2	37,7
15,0	319,4	4138,4	490,6	883,1	1197,1	1448,2	11,9	21,3	28,9	35,0
15,5	330,7	4613,9	508,0	914,4	1239,6	1499,7	11,0	19,8	26,9	32,5
16,0	342,0	5133,4	525,4	945,8	1282,0	1551,0	10,2	18,4	25,0	30,2
16,5	353,5	5700,7	543,0	977,4	1324,9	1602,9	9,5	17,1	23,2	28,1
17,0	364,7	6319,8	560,2	1008,4	1367,0	1653,8	8,9	16,0	21,6	26,2
17,5	376,2	6993,1	577,9	1040,2	1410,0	1705,9	8,3	14,9	20,2	24,4
18,0	388,1	7721,5	596,2	1073,2	1454,7	1760,0	7,7	13,9	18,8	22,8
18,5	399,4	8505,2	613,5	1104,2	1496,8	1810,9	7,2	13,0	17,6	21,3
19,0	410,8	9348,1	631,0	1135,8	1539,6	1862,7	6,8	12,2	16,5	19,9
19,5	422,2	10259,8	648,5	1167,4	1582,4	1914,5	6,3	11,4	15,4	18,7
20,0	433,6	11255,5	666,0	1198,8	1625,0	1966,0	5,9	10,7	14,4	17,5

Figure D.3: Estimated engine savings for different ship speeds in the Caribbean region.

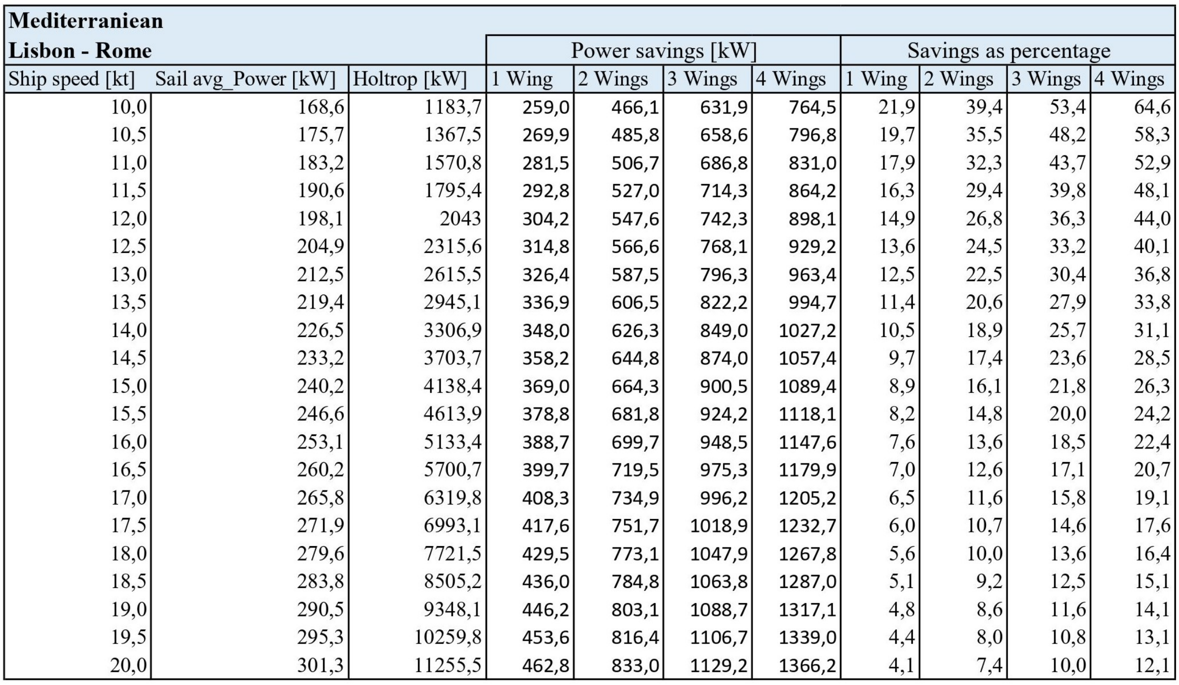
Transatlantic Crossing										
Lisbon - Bridgetown			Power savings [kW]				Savings as percentage			
Ship speed [kt]	Sail avg_Power [kW]	Holtrop [kW]	1 Wing	2 Wings	3 Wings	4 Wings	1 Wing	2 Wings	3 Wings	4 Wings
10,0	180,8	1183,7	277,8	500,0	677,8	820,0	23,5	42,2	57,3	69,3
10,5	187,4	1367,5	287,9	518,2	702,5	849,9	21,1	37,9	51,4	62,1
11,0	194,3	1570,8	298,4	537,1	728,1	880,9	19,0	34,2	46,4	56,1
11,5	201,1	1795,4	308,9	556,0	753,7	911,8	17,2	31,0	42,0	50,8
12,0	207,9	2043	319,3	574,8	779,2	942,7	15,6	28,1	38,1	46,1
12,5	214,3	2315,6	329,2	592,6	803,4	971,9	14,2	25,6	34,7	42,0
13,0	221,3	2615,5	340,0	612,0	829,6	1003,6	13,0	23,4	31,7	38,4
13,5	227,9	2945,1	350,1	630,1	854,1	1033,4	11,9	21,4	29,0	35,1
14,0	234,9	3306,9	360,9	649,5	880,5	1065,2	10,9	19,6	26,6	32,2
14,5	241,5	3703,7	371,0	667,8	905,3	1095,2	10,0	18,0	24,4	29,6
15,0	248,4	4138,4	381,6	687,0	931,2	1126,6	9,2	16,6	22,5	27,2
15,5	255,2	4613,9	392,0	705,5	956,4	1157,1	8,5	15,3	20,7	25,1
16,0	261,9	5133,4	402,3	724,1	981,5	1187,5	7,8	14,1	19,1	23,1
16,5	269,1	5700,7	413,4	744,1	1008,7	1220,3	7,3	13,1	17,7	21,4
17,0	275,5	6319,8	423,1	761,7	1032,5	1249,1	6,7	12,1	16,3	19,8
17,5	282,4	6993,1	433,7	780,7	1058,3	1280,4	6,2	11,2	15,1	18,3
18,0	290,6	7721,5	446,4	803,4	1089,1	1317,6	5,8	10,4	14,1	17,1
18,5	296,3	8505,2	455,2	819,3	1110,6	1343,6	5,4	9,6	13,1	15,8
19,0	303,8	9348,1	466,6	839,9	1138,5	1377,4	5,0	9,0	12,2	14,7
19,5	310,2	10259,8	476,5	857,6	1162,5	1406,5	4,6	8,4	11,3	13,7
20,0	317,2	11255,5	487,2	877,0	1188,8	1438,2	4,3	7,8	10,6	12,8

Figure D.4: Estimated engine savings for different ship speeds for the route Lisbon - Bridgetown.



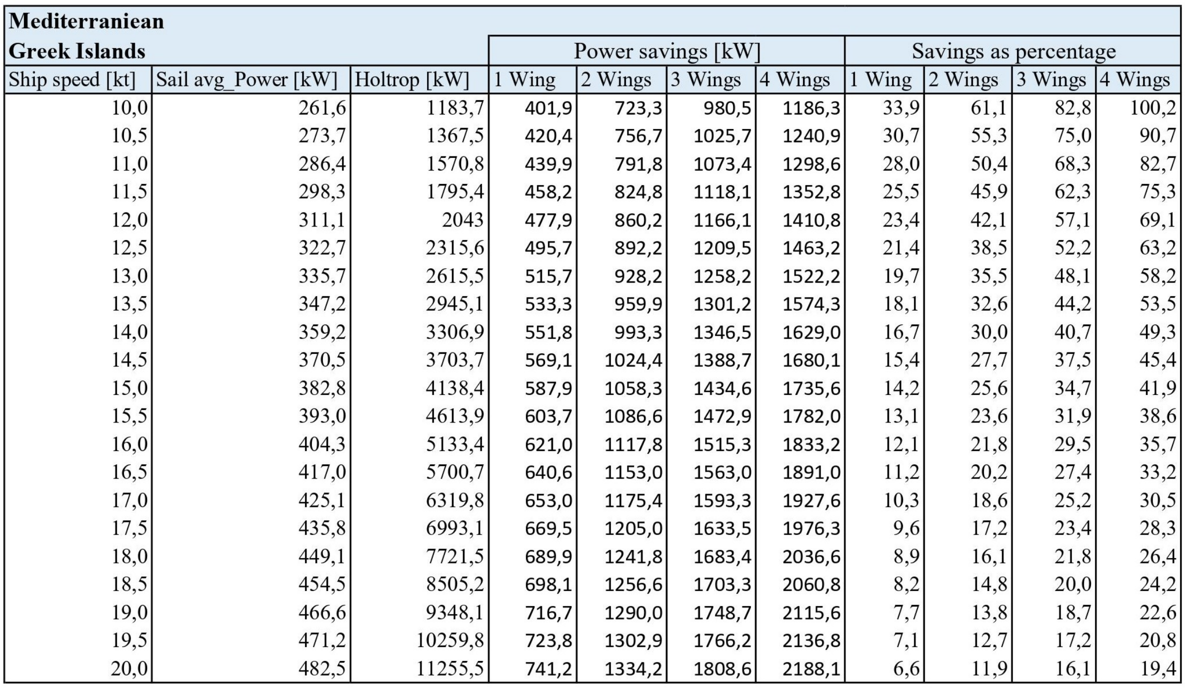
Transatlantic Crossing **Bridgetown - Lisbon**			Power savings [kW]				Savings as percentage			
Ship speed [kt]	Sail avg_Power [kW]	Holtrop [kW]	1 Wing	2 Wings	3 Wings	4 Wings	1 Wing	2 Wings	3 Wings	4 Wings
10,0	174,0	1183,7	267,3	481,2	652,3	789,2	22,6	40,7	55,1	66,7
10,5	181,9	1367,5	279,4	502,8	681,6	824,7	20,4	36,8	49,8	60,3
11,0	189,8	1570,8	291,5	524,8	711,4	860,6	18,6	33,4	45,3	54,8
11,5	197,6	1795,4	303,6	546,5	740,8	896,2	16,9	30,4	41,3	49,9
12,0	205,4	2043	315,5	567,9	769,8	931,4	15,4	27,8	37,7	45,6
12,5	212,7	2315,6	326,8	588,2	797,4	964,7	14,1	25,4	34,4	41,7
13,0	220,5	2615,5	338,8	609,8	826,6	1000,0	13,0	23,3	31,6	38,2
13,5	227,7	2945,1	349,8	629,7	853,6	1032,7	11,9	21,4	29,0	35,1
14,0	235,2	3306,9	361,2	650,2	881,4	1066,3	10,9	19,7	26,7	32,2
14,5	241,9	3703,7	371,6	668,8	906,6	1096,8	10,0	18,1	24,5	29,6
15,0	248,8	4138,4	382,2	687,9	932,5	1128,2	9,2	16,6	22,5	27,3
15,5	255,4	4613,9	392,4	706,3	957,4	1158,3	8,5	15,3	20,8	25,1
16,0	261,7	5133,4	402,0	723,6	980,8	1186,6	7,8	14,1	19,1	23,1
16,5	268,2	5700,7	412,0	741,6	1005,2	1216,2	7,2	13,0	17,6	21,3
17,0	272,4	6319,8	418,5	753,2	1021,0	1235,3	6,6	11,9	16,2	19,5
17,5	277,5	6993,1	426,2	767,2	1040,0	1258,2	6,1	11,0	14,9	18,0
18,0	285,0	7721,5	437,7	787,9	1068,0	1292,1	5,7	10,2	13,8	16,7
18,5	287,7	8505,2	441,9	795,5	1078,3	1304,5	5,2	9,4	12,7	15,3
19,0	291,4	9348,1	447,6	805,6	1092,0	1321,2	4,8	8,6	11,7	14,1
19,5	293,2	10259,8	450,4	810,8	1099,1	1329,7	4,4	7,9	10,7	13,0
20,0	295,9	11255,5	454,5	818,0	1108,9	1341,6	4,0	7,3	9,9	11,9

Figure D.5: Estimated engine savings for different ship speeds for the route Bridgetown - Lisbon.



Mediterraniean **Lisbon - Rome**			Power savings [kW]				Savings as percentage			
Ship speed [kt]	Sail avg_Power [kW]	Holtrop [kW]	1 Wing	2 Wings	3 Wings	4 Wings	1 Wing	2 Wings	3 Wings	4 Wings
10,0	168,6	1183,7	259,0	466,1	631,9	764,5	21,9	39,4	53,4	64,6
10,5	175,7	1367,5	269,9	485,8	658,6	796,8	19,7	35,5	48,2	58,3
11,0	183,2	1570,8	281,5	506,7	686,8	831,0	17,9	32,3	43,7	52,9
11,5	190,6	1795,4	292,8	527,0	714,3	864,2	16,3	29,4	39,8	48,1
12,0	198,1	2043	304,2	547,6	742,3	898,1	14,9	26,8	36,3	44,0
12,5	204,9	2315,6	314,8	566,6	768,1	929,2	13,6	24,5	33,2	40,1
13,0	212,5	2615,5	326,4	587,5	796,3	963,4	12,5	22,5	30,4	36,8
13,5	219,4	2945,1	336,9	606,5	822,2	994,7	11,4	20,6	27,9	33,8
14,0	226,5	3306,9	348,0	626,3	849,0	1027,2	10,5	18,9	25,7	31,1
14,5	233,2	3703,7	358,2	644,8	874,0	1057,4	9,7	17,4	23,6	28,5
15,0	240,2	4138,4	369,0	664,3	900,5	1089,4	8,9	16,1	21,8	26,3
15,5	246,6	4613,9	378,8	681,8	924,2	1118,1	8,2	14,8	20,0	24,2
16,0	253,1	5133,4	388,7	699,7	948,5	1147,6	7,6	13,6	18,5	22,4
16,5	260,2	5700,7	399,7	719,5	975,3	1179,9	7,0	12,6	17,1	20,7
17,0	265,8	6319,8	408,3	734,9	996,2	1205,2	6,5	11,6	15,8	19,1
17,5	271,9	6993,1	417,6	751,7	1018,9	1232,7	6,0	10,7	14,6	17,6
18,0	279,6	7721,5	429,5	773,1	1047,9	1267,8	5,6	10,0	13,6	16,4
18,5	283,8	8505,2	436,0	784,8	1063,8	1287,0	5,1	9,2	12,5	15,1
19,0	290,5	9348,1	446,2	803,1	1088,7	1317,1	4,8	8,6	11,6	14,1
19,5	295,3	10259,8	453,6	816,4	1106,7	1339,0	4,4	8,0	10,8	13,1
20,0	301,3	11255,5	462,8	833,0	1129,2	1366,2	4,1	7,4	10,0	12,1

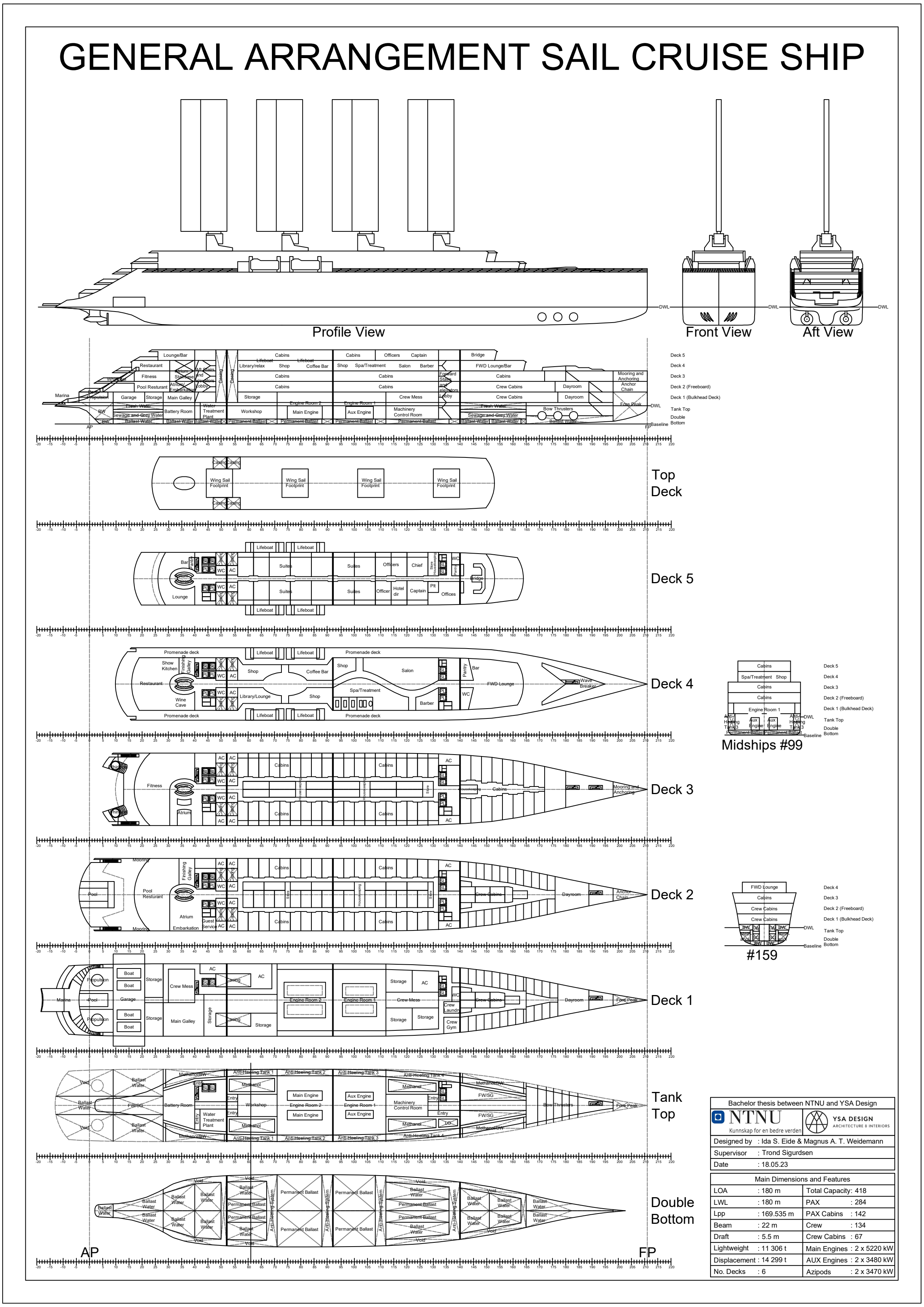
Figure D.6: Estimated engine savings for different ship speeds for the Mediterranean route Lisbon - Rome.



Mediterraniean Greek Islands			Power savings [kW]				Savings as percentage			
Ship speed [kt]	Sail avg_Power [kW]	Holtrop [kW]	1 Wing	2 Wings	3 Wings	4 Wings	1 Wing	2 Wings	3 Wings	4 Wings
10,0	261,6	1183,7	401,9	723,3	980,5	1186,3	33,9	61,1	82,8	100,2
10,5	273,7	1367,5	420,4	756,7	1025,7	1240,9	30,7	55,3	75,0	90,7
11,0	286,4	1570,8	439,9	791,8	1073,4	1298,6	28,0	50,4	68,3	82,7
11,5	298,3	1795,4	458,2	824,8	1118,1	1352,8	25,5	45,9	62,3	75,3
12,0	311,1	2043	477,9	860,2	1166,1	1410,8	23,4	42,1	57,1	69,1
12,5	322,7	2315,6	495,7	892,2	1209,5	1463,2	21,4	38,5	52,2	63,2
13,0	335,7	2615,5	515,7	928,2	1258,2	1522,2	19,7	35,5	48,1	58,2
13,5	347,2	2945,1	533,3	959,9	1301,2	1574,3	18,1	32,6	44,2	53,5
14,0	359,2	3306,9	551,8	993,3	1346,5	1629,0	16,7	30,0	40,7	49,3
14,5	370,5	3703,7	569,1	1024,4	1388,7	1680,1	15,4	27,7	37,5	45,4
15,0	382,8	4138,4	587,9	1058,3	1434,6	1735,6	14,2	25,6	34,7	41,9
15,5	393,0	4613,9	603,7	1086,6	1472,9	1782,0	13,1	23,6	31,9	38,6
16,0	404,3	5133,4	621,0	1117,8	1515,3	1833,2	12,1	21,8	29,5	35,7
16,5	417,0	5700,7	640,6	1153,0	1563,0	1891,0	11,2	20,2	27,4	33,2
17,0	425,1	6319,8	653,0	1175,4	1593,3	1927,6	10,3	18,6	25,2	30,5
17,5	435,8	6993,1	669,5	1205,0	1633,5	1976,3	9,6	17,2	23,4	28,3
18,0	449,1	7721,5	689,9	1241,8	1683,4	2036,6	8,9	16,1	21,8	26,4
18,5	454,5	8505,2	698,1	1256,6	1703,3	2060,8	8,2	14,8	20,0	24,2
19,0	466,6	9348,1	716,7	1290,0	1748,7	2115,6	7,7	13,8	18,7	22,6
19,5	471,2	10259,8	723,8	1302,9	1766,2	2136,8	7,1	12,7	17,2	20,8
20,0	482,5	11255,5	741,2	1334,2	1808,6	2188,1	6,6	11,9	16,1	19,4

Figure D.7: Estimated engine savings for different ship speeds the region of the Greek Islands.

E General Arrangement



Bachelor thesis between NTNU and YSA Design

NTNU
Kunnskap for en bedre verden

YSA DESIGN
ARCHITECTURE & INTERIORS

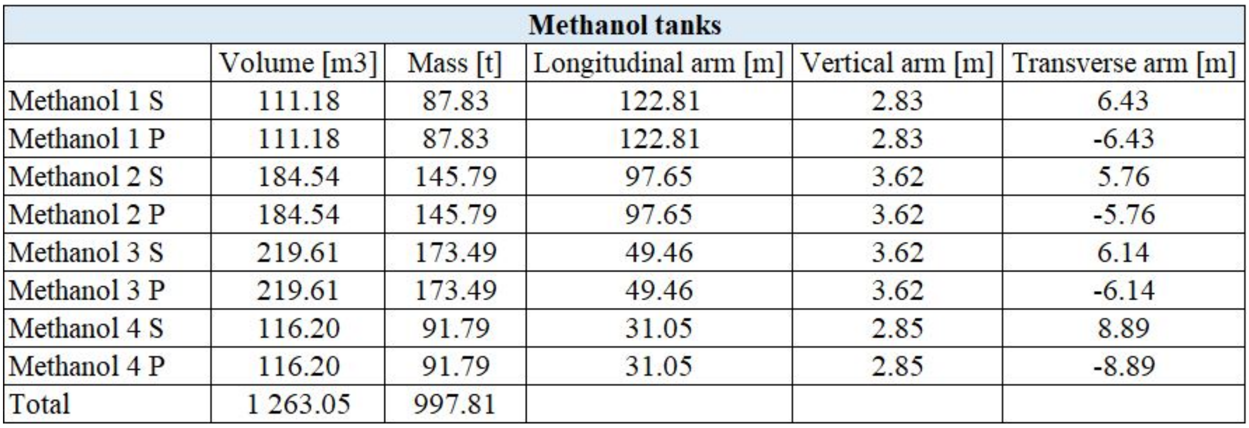
Designed by : Ida S. Eide & Magnus A. T. Weidemann
Supervisor : Trond Sigurdsen
Date : 18.05.23

Main Dimensions and Features

LOA	: 180 m	Total Capacity	: 418
LWL	: 180 m	PAX	: 284
Lpp	: 169.535 m	PAX Cabins	: 142
Beam	: 22 m	Crew	: 134
Draft	: 5.5 m	Crew Cabins	: 67
Lightweight	: 11 306 t	Main Engines	: 2 x 5220 kW
Displacement	: 14 299 t	AUX Engines	: 2 x 3480 kW
No. Decks	: 6	Azipods	: 2 x 3470 kW

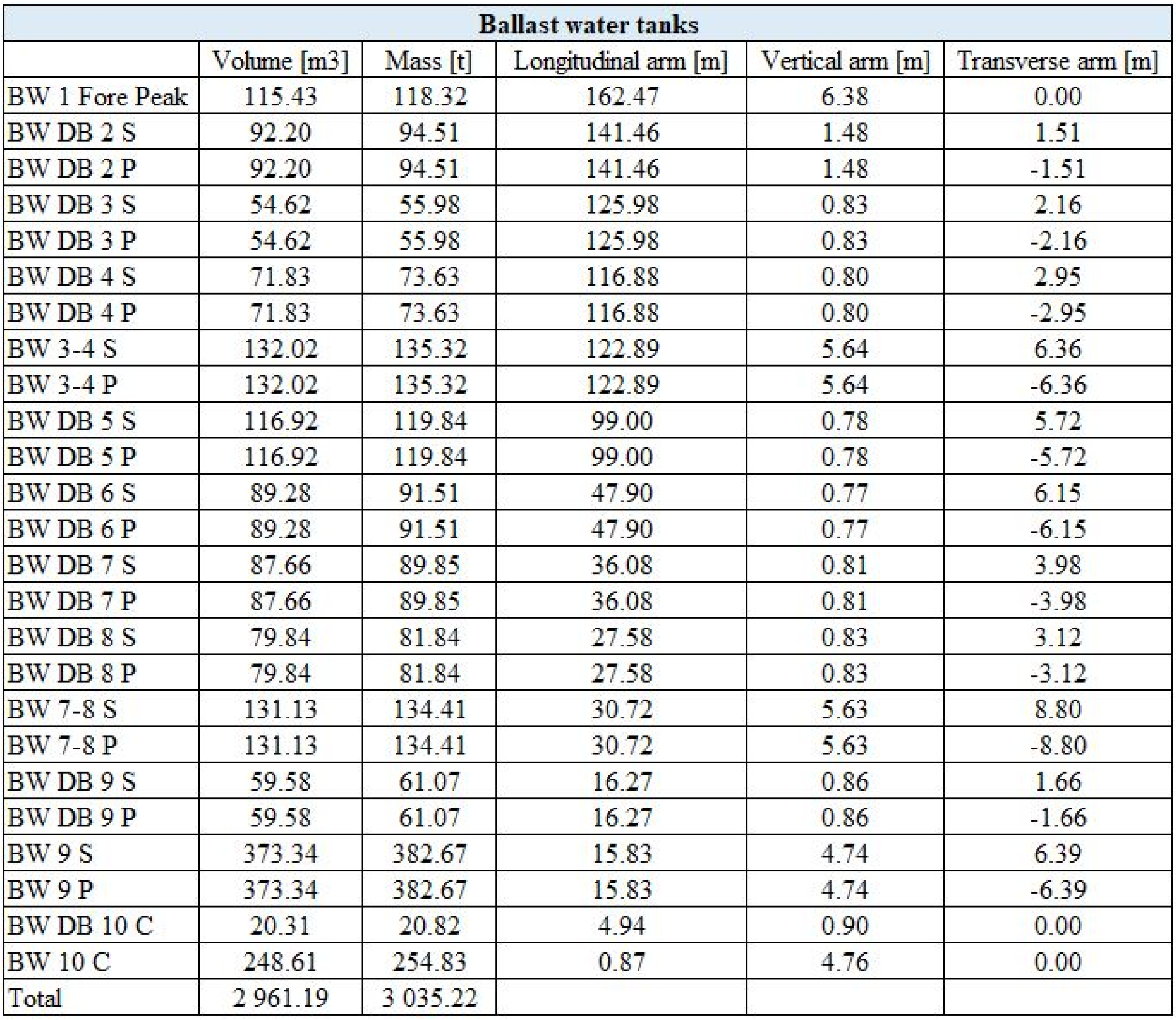
Figure E.1: The final general arrangement

F Tank Arrangement



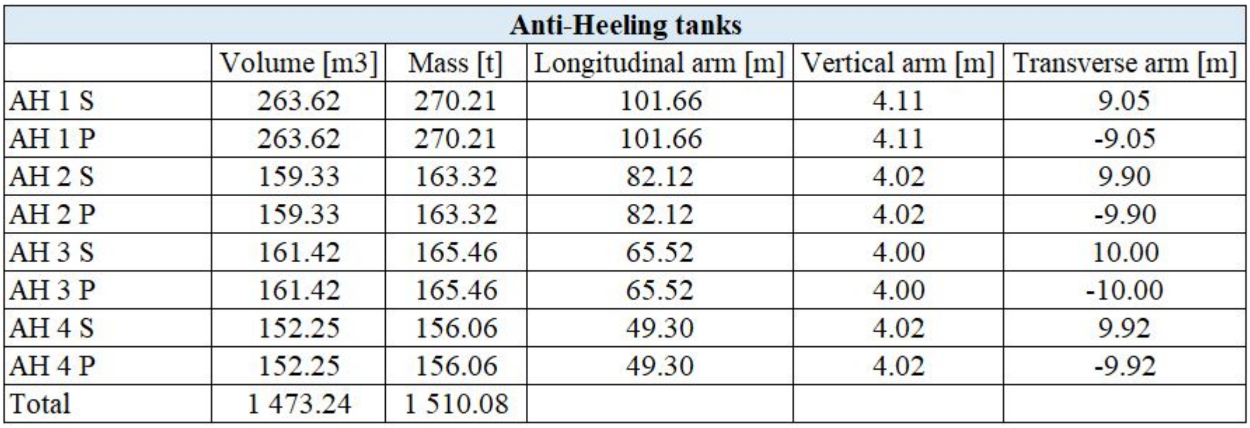
Methanol tanks					
	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
Methanol 1 S	111.18	87.83	122.81	2.83	6.43
Methanol 1 P	111.18	87.83	122.81	2.83	-6.43
Methanol 2 S	184.54	145.79	97.65	3.62	5.76
Methanol 2 P	184.54	145.79	97.65	3.62	-5.76
Methanol 3 S	219.61	173.49	49.46	3.62	6.14
Methanol 3 P	219.61	173.49	49.46	3.62	-6.14
Methanol 4 S	116.20	91.79	31.05	2.85	8.89
Methanol 4 P	116.20	91.79	31.05	2.85	-8.89
Total	1 263.05	997.81			

Figure F.1: Methanol fuel tanks capacity



Ballast water tanks					
	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
BW 1 Fore Peak	115.43	118.32	162.47	6.38	0.00
BW DB 2 S	92.20	94.51	141.46	1.48	1.51
BW DB 2 P	92.20	94.51	141.46	1.48	-1.51
BW DB 3 S	54.62	55.98	125.98	0.83	2.16
BW DB 3 P	54.62	55.98	125.98	0.83	-2.16
BW DB 4 S	71.83	73.63	116.88	0.80	2.95
BW DB 4 P	71.83	73.63	116.88	0.80	-2.95
BW 3-4 S	132.02	135.32	122.89	5.64	6.36
BW 3-4 P	132.02	135.32	122.89	5.64	-6.36
BW DB 5 S	116.92	119.84	99.00	0.78	5.72
BW DB 5 P	116.92	119.84	99.00	0.78	-5.72
BW DB 6 S	89.28	91.51	47.90	0.77	6.15
BW DB 6 P	89.28	91.51	47.90	0.77	-6.15
BW DB 7 S	87.66	89.85	36.08	0.81	3.98
BW DB 7 P	87.66	89.85	36.08	0.81	-3.98
BW DB 8 S	79.84	81.84	27.58	0.83	3.12
BW DB 8 P	79.84	81.84	27.58	0.83	-3.12
BW 7-8 S	131.13	134.41	30.72	5.63	8.80
BW 7-8 P	131.13	134.41	30.72	5.63	-8.80
BW DB 9 S	59.58	61.07	16.27	0.86	1.66
BW DB 9 P	59.58	61.07	16.27	0.86	-1.66
BW 9 S	373.34	382.67	15.83	4.74	6.39
BW 9 P	373.34	382.67	15.83	4.74	-6.39
BW DB 10 C	20.31	20.82	4.94	0.90	0.00
BW 10 C	248.61	254.83	0.87	4.76	0.00
Total	2 961.19	3 035.22			

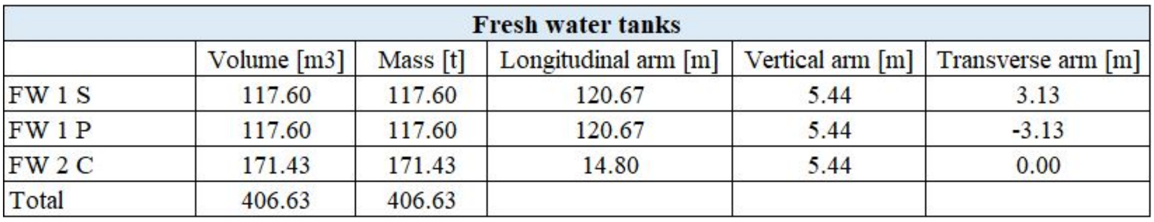
Figure F.2: Ballast water tanks capacity



Anti-Heeling tanks

	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
AH 1 S	263.62	270.21	101.66	4.11	9.05
AH 1 P	263.62	270.21	101.66	4.11	-9.05
AH 2 S	159.33	163.32	82.12	4.02	9.90
AH 2 P	159.33	163.32	82.12	4.02	-9.90
AH 3 S	161.42	165.46	65.52	4.00	10.00
AH 3 P	161.42	165.46	65.52	4.00	-10.00
AH 4 S	152.25	156.06	49.30	4.02	9.92
AH 4 P	152.25	156.06	49.30	4.02	-9.92
Total	1 473.24	1 510.08			

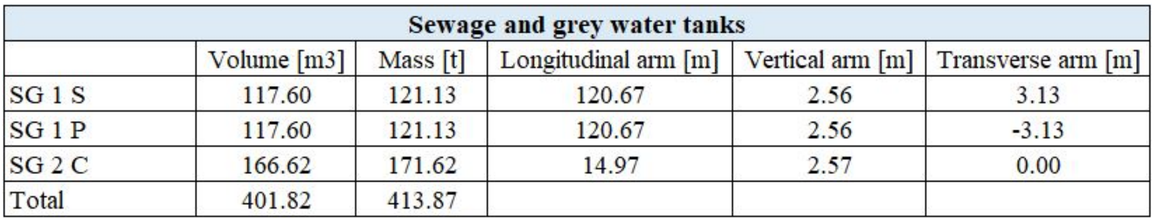
Figure F.3: Anti-Heeling tanks capacity



Fresh water tanks

	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
FW 1 S	117.60	117.60	120.67	5.44	3.13
FW 1 P	117.60	117.60	120.67	5.44	-3.13
FW 2 C	171.43	171.43	14.80	5.44	0.00
Total	406.63	406.63			

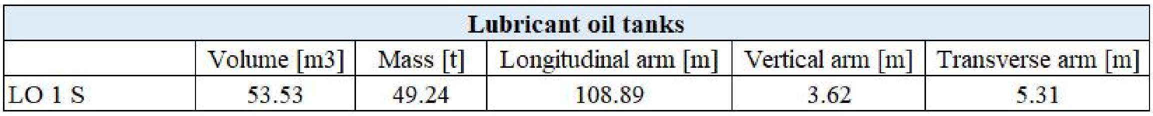
Figure F.4: Fresh water tanks capacity



Sewage and grey water tanks

	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
SG 1 S	117.60	121.13	120.67	2.56	3.13
SG 1 P	117.60	121.13	120.67	2.56	-3.13
SG 2 C	166.62	171.62	14.97	2.57	0.00
Total	401.82	413.87			

Figure F.5: Sewage and Grey water tanks capacity



Lubricant oil tanks

	Volume [m3]	Mass [t]	Longitudinal arm [m]	Vertical arm [m]	Transverse arm [m]
LO 1 S	53.53	49.24	108.89	3.62	5.31

Figure F.6: Lubricant oil tank capacity

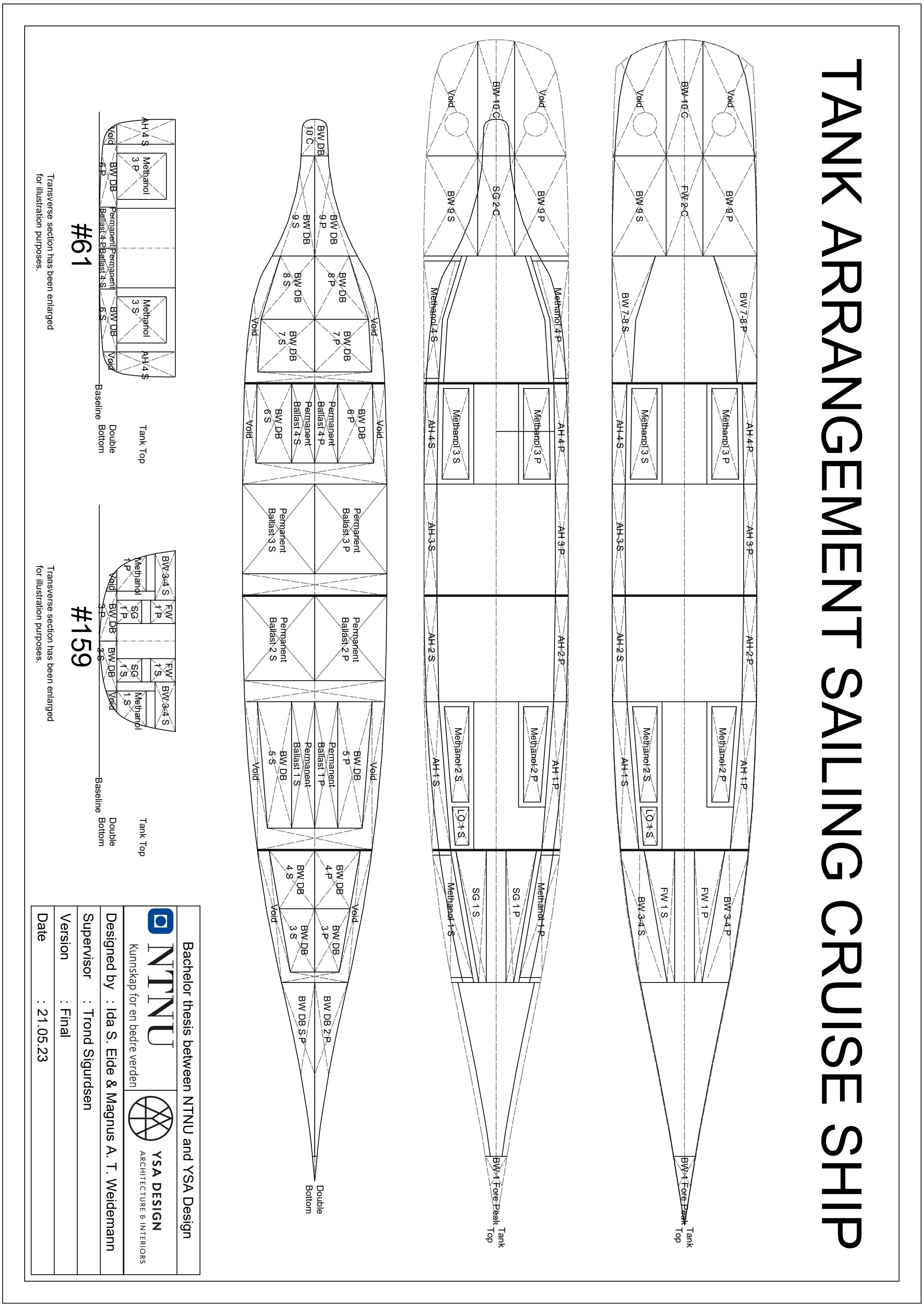
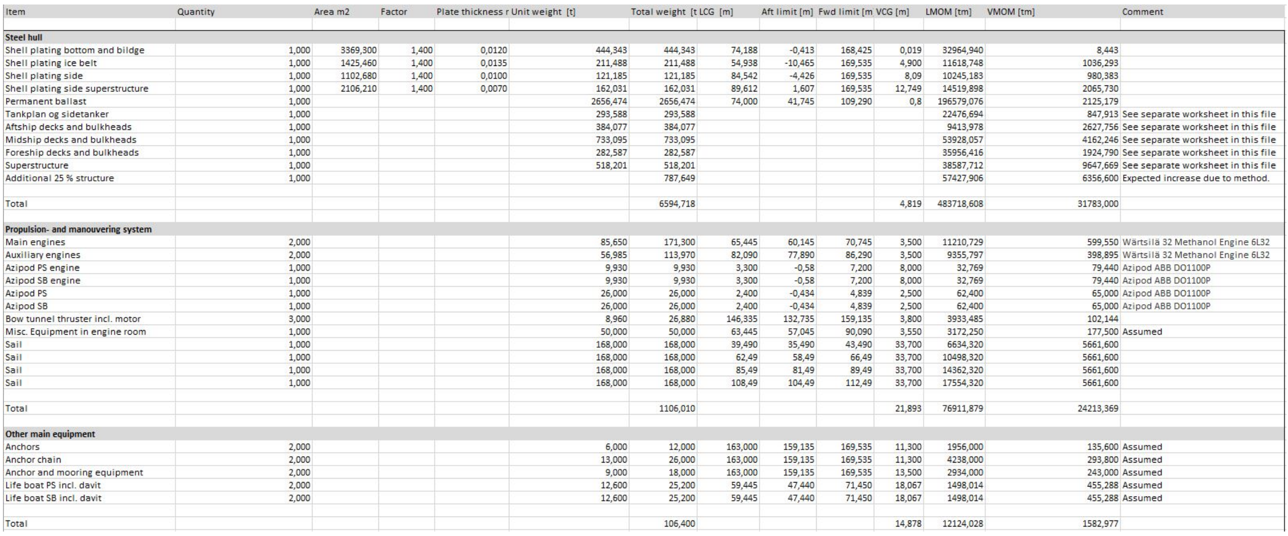


Figure F.7: Tank arrangement. The transverse sections have been scaled up.

G Weight estimate

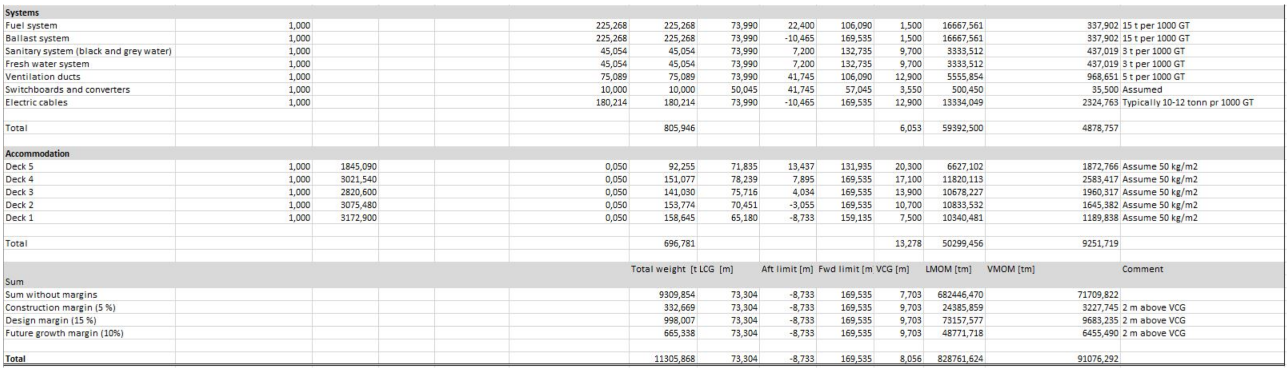
Figure G.1 shows the weight estimation calculations done in Excel:



Item	Quantity	Area m2	Factor	Plate thickness r	Unit weight [t]	Total weight [t	LCG [m]	Aft limit [m]	Fwd limit [m	VCG [m]	LMOM [tm]	VMOM [tm]	Comment
Steel hull													
Shell plating bottom and bildge	1,000	3369,300	1,400	0,0120	444,343	444,343	74,188	-0,413	168,425	0,019	32964,940	8,443	
Shell plating ice belt	1,000	1425,460	1,400	0,0135	211,488	211,488	54,938	-10,465	169,535	4,900	11618,748	1036,293	
Shell plating side	1,000	1102,680	1,400	0,0100	121,185	121,185	84,542	-4,426	169,535	8,09	10245,183	980,383	
Shell plating side superstructure	1,000	2106,210	1,400	0,0070	162,031	162,031	89,612	1,607	169,535	12,749	14519,898	2065,730	
Permanent ballast	1,000				2656,474	2656,474	74,000	41,745	109,290	0,8	196579,076	2125,179	
Tankplan og sidetanker	1,000				293,588	293,588					22476,694	847,913	See separate worksheet in this file
Aftship decks and bulkheads	1,000				384,077	384,077					9413,978	2627,756	See separate worksheet in this file
Midship decks and bulkheads	1,000				733,095	733,095					53928,057	4162,246	See separate worksheet in this file
Foreship decks and bulkheads	1,000				282,587	282,587					35956,416	1924,790	See separate worksheet in this file
Superstructure	1,000				518,201	518,201					38587,712	9647,669	See separate worksheet in this file
Additional 25 % structure	1,000					787,649					57427,906	6356,600	Expected increase due to method.
Total						6594,718				4,819	483718,608	31783,000	
Propulsion- and manouvering system													
Main engines	2,000				85,650	171,300	65,445	60,145	70,745	3,500	11210,729	599,550	Wärtsilä 32 Methanol Engine 6L32
Auxiliary engines	2,000				56,985	113,970	82,090	77,890	86,290	3,500	9355,797	398,895	Wärtsilä 32 Methanol Engine 6L32
Azipod PS engine	1,000				9,930	9,930	3,300	-0,58	7,200	8,000	32,769	79,440	Azipod ABB DO1100P
Azipod SB engine	1,000				9,930	9,930	3,300	-0,58	7,200	8,000	32,769	79,440	Azipod ABB DO1100P
Azipod PS	1,000				26,000	26,000	2,400	-0,434	4,839	2,500	62,400	65,000	Azipod ABB DO1100P
Azipod SB	1,000				26,000	26,000	2,400	-0,434	4,839	2,500	62,400	65,000	Azipod ABB DO1100P
Bow tunnel thruster incl. motor	3,000				8,960	26,880	146,335	132,735	159,135	3,800	3933,485	102,144	
Misc. Equipment in engine room	1,000				50,000	50,000	63,445	57,045	90,090	3,550	3172,250	177,500	Assumed
Sail	1,000				168,000	168,000	39,490	35,490	43,490	33,700	6634,320	5661,600	
Sail	1,000				168,000	168,000	62,49	58,49	66,49	33,700	10498,320	5661,600	
Sail	1,000				168,000	168,000	85,49	81,49	89,49	33,700	14362,320	5661,600	
Sail	1,000				168,000	168,000	108,49	104,49	112,49	33,700	17554,320	5661,600	
Total						1106,010				21,893	76911,879	24213,369	
Other main equipment													
Anchors	2,000				6,000	12,000	163,000	159,135	169,535	11,300	1956,000	135,600	Assumed
Anchor chain	2,000				13,000	26,000	163,000	159,135	169,535	11,300	4238,000	293,800	Assumed
Anchor and mooring equipment	2,000				9,000	18,000	163,000	159,135	169,535	13,500	2934,000	243,000	Assumed
Life boat PS incl. davit	2,000				12,600	25,200	59,445	47,440	71,450	18,067	1498,014	455,288	Assumed
Life boat SB incl. davit	2,000				12,600	25,200	59,445	47,440	71,450	18,067	1498,014	455,288	Assumed
Total						106,400				14,878	12124,028	1582,977	

Figure G.1: Excel spreadsheet of final weight estimation

Figure G.2 shows the rest of the weight estimation calculations done in Excel:



Systems													
Fuel system	1,000				225,268	225,268	73,990	22,400	106,090	1,500	16667,561	337,902	15 t per 1000 GT
Ballast system	1,000				225,268	225,268	73,990	-10,465	169,535	1,500	16667,561	337,902	15 t per 1000 GT
Sanitary system (black and grey water)	1,000				45,054	45,054	73,990	7,200	132,735	9,700	3333,512	437,019	3 t per 1000 GT
Fresh water system	1,000				45,054	45,054	73,990	7,200	132,735	9,700	3333,512	437,019	3 t per 1000 GT
Ventilation ducts	1,000				75,089	75,089	73,990	41,745	106,090	12,900	5555,854	968,651	5 t per 1000 GT
Switchboards and converters	1,000				10,000	10,000	50,045	41,745	57,045	3,550	500,450	35,500	Assumed
Electric cables	1,000				180,214	180,214	73,990	-10,465	169,535	12,900	13334,049	2324,763	Typically 10-12 tonn pr 1000 GT
Total						805,946				6,053	59392,500	4878,757	
Accommodation													
Deck 5	1,000	1845,090			0,050	92,255	71,835	13,437	131,935	20,300	6627,102	1872,766	Assume 50 kg/m2
Deck 4	1,000	3021,540			0,050	151,077	78,239	7,895	169,535	17,100	11820,113	2583,417	Assume 50 kg/m2
Deck 3	1,000	2820,600			0,050	141,030	75,716	4,034	169,535	13,900	10678,227	1960,317	Assume 50 kg/m2
Deck 2	1,000	3075,480			0,050	153,774	70,451	-3,055	169,535	10,700	10833,532	1645,382	Assume 50 kg/m2
Deck 1	1,000	3172,900			0,050	158,645	65,180	-8,733	159,135	7,500	10340,481	1189,838	Assume 50 kg/m2
Total						696,781				13,278	50299,456	9251,719	
						Total weight [t	LCG [m]	Aft limit [m]	Fwd limit [m	VCG [m]	LMOM [tm]	VMOM [tm]	Comment
Sum													
Sum without margins						9309,854	73,304	-8,733	169,535	7,703	682446,470	71709,822	
Construction margin (5 %)						332,669	73,304	-8,733	169,535	9,703	24385,859	3227,745	2 m above VCG
Design margin (15 %)						998,007	73,304	-8,733	169,535	9,703	73157,577	9683,235	2 m above VCG
Future growth margin (10%)						665,338	73,304	-8,733	169,535	9,703	48771,718	6455,490	2 m above VCG
Total						11305,868	73,304	-8,733	169,535	8,056	828761,624	91076,292	

Figure G.2: Excel spreadsheet of final weight estimation

The weight was found by multiplying the volume of steel with the density of steel, set to 7.85 t/m^3.

Gross tonnage of the ship was found with this formula:

$$GT = V \cdot K_1 \tag{G.1}$$

where V is the enclosed volume of the ship and K_1 is a volume factor.

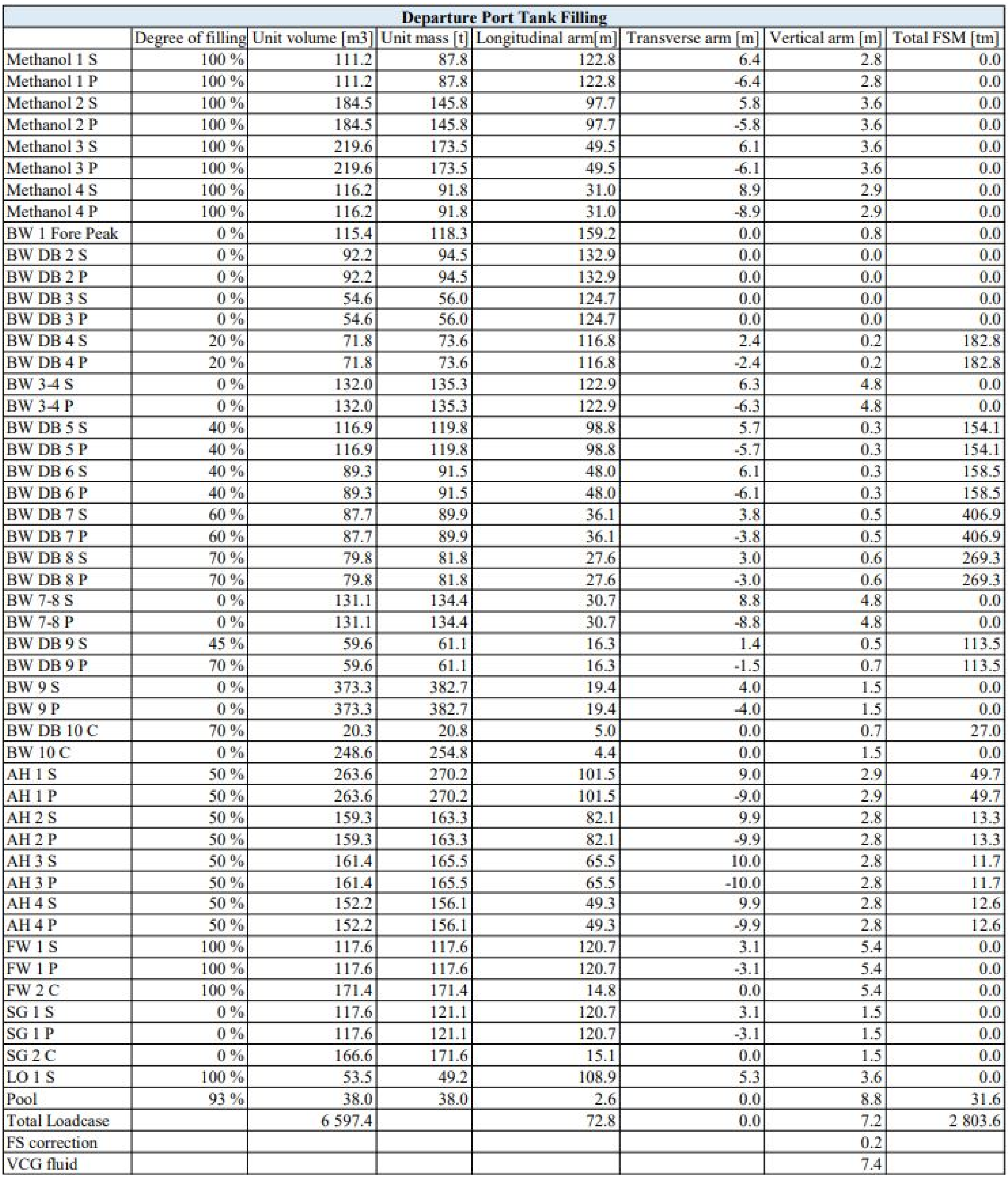
To find K_1, this formual is used:

$$K_1 = 0.2 + 0.02 \cdot Log_{10}(V) \tag{G.2}$$

Using a volume of $V = 51053.26m^3$ gave a $K_1 = 0.29$. This gave a gross tonnage of $GT = 15017.85$.

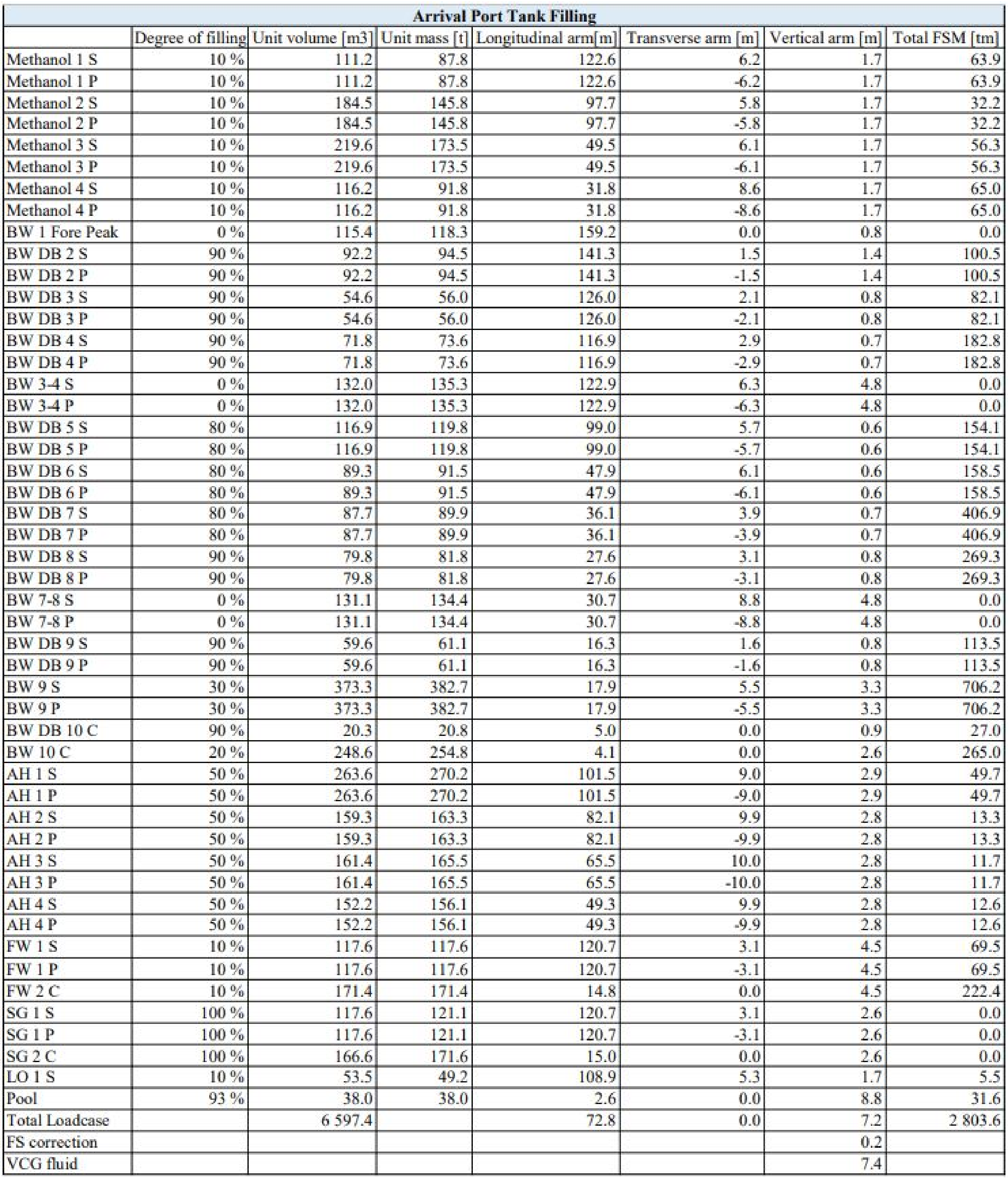
H Stability

Stability conditions and results



Departure Port Tank Filling							
	Degree of filling	Unit volume [m3]	Unit mass [t]	Longitudinal arm[m]	Transverse arm [m]	Vertical arm [m]	Total FSM [tm]
Methanol 1 S	100 %	111.2	87.8	122.8	6.4	2.8	0.0
Methanol 1 P	100 %	111.2	87.8	122.8	-6.4	2.8	0.0
Methanol 2 S	100 %	184.5	145.8	97.7	5.8	3.6	0.0
Methanol 2 P	100 %	184.5	145.8	97.7	-5.8	3.6	0.0
Methanol 3 S	100 %	219.6	173.5	49.5	6.1	3.6	0.0
Methanol 3 P	100 %	219.6	173.5	49.5	-6.1	3.6	0.0
Methanol 4 S	100 %	116.2	91.8	31.0	8.9	2.9	0.0
Methanol 4 P	100 %	116.2	91.8	31.0	-8.9	2.9	0.0
BW 1 Fore Peak	0 %	115.4	118.3	159.2	0.0	0.8	0.0
BW DB 2 S	0 %	92.2	94.5	132.9	0.0	0.0	0.0
BW DB 2 P	0 %	92.2	94.5	132.9	0.0	0.0	0.0
BW DB 3 S	0 %	54.6	56.0	124.7	0.0	0.0	0.0
BW DB 3 P	0 %	54.6	56.0	124.7	0.0	0.0	0.0
BW DB 4 S	20 %	71.8	73.6	116.8	2.4	0.2	182.8
BW DB 4 P	20 %	71.8	73.6	116.8	-2.4	0.2	182.8
BW 3-4 S	0 %	132.0	135.3	122.9	6.3	4.8	0.0
BW 3-4 P	0 %	132.0	135.3	122.9	-6.3	4.8	0.0
BW DB 5 S	40 %	116.9	119.8	98.8	5.7	0.3	154.1
BW DB 5 P	40 %	116.9	119.8	98.8	-5.7	0.3	154.1
BW DB 6 S	40 %	89.3	91.5	48.0	6.1	0.3	158.5
BW DB 6 P	40 %	89.3	91.5	48.0	-6.1	0.3	158.5
BW DB 7 S	60 %	87.7	89.9	36.1	3.8	0.5	406.9
BW DB 7 P	60 %	87.7	89.9	36.1	-3.8	0.5	406.9
BW DB 8 S	70 %	79.8	81.8	27.6	3.0	0.6	269.3
BW DB 8 P	70 %	79.8	81.8	27.6	-3.0	0.6	269.3
BW 7-8 S	0 %	131.1	134.4	30.7	8.8	4.8	0.0
BW 7-8 P	0 %	131.1	134.4	30.7	-8.8	4.8	0.0
BW DB 9 S	45 %	59.6	61.1	16.3	1.4	0.5	113.5
BW DB 9 P	70 %	59.6	61.1	16.3	-1.5	0.7	113.5
BW 9 S	0 %	373.3	382.7	19.4	4.0	1.5	0.0
BW 9 P	0 %	373.3	382.7	19.4	-4.0	1.5	0.0
BW DB 10 C	70 %	20.3	20.8	5.0	0.0	0.7	27.0
BW 10 C	0 %	248.6	254.8	4.4	0.0	1.5	0.0
AH 1 S	50 %	263.6	270.2	101.5	9.0	2.9	49.7
AH 1 P	50 %	263.6	270.2	101.5	-9.0	2.9	49.7
AH 2 S	50 %	159.3	163.3	82.1	9.9	2.8	13.3
AH 2 P	50 %	159.3	163.3	82.1	-9.9	2.8	13.3
AH 3 S	50 %	161.4	165.5	65.5	10.0	2.8	11.7
AH 3 P	50 %	161.4	165.5	65.5	-10.0	2.8	11.7
AH 4 S	50 %	152.2	156.1	49.3	9.9	2.8	12.6
AH 4 P	50 %	152.2	156.1	49.3	-9.9	2.8	12.6
FW 1 S	100 %	117.6	117.6	120.7	3.1	5.4	0.0
FW 1 P	100 %	117.6	117.6	120.7	-3.1	5.4	0.0
FW 2 C	100 %	171.4	171.4	14.8	0.0	5.4	0.0
SG 1 S	0 %	117.6	121.1	120.7	3.1	1.5	0.0
SG 1 P	0 %	117.6	121.1	120.7	-3.1	1.5	0.0
SG 2 C	0 %	166.6	171.6	15.1	0.0	1.5	0.0
LO 1 S	100 %	53.5	49.2	108.9	5.3	3.6	0.0
Pool	93 %	38.0	38.0	2.6	0.0	8.8	31.6
Total Loadcase		6 597.4		72.8	0.0	7.2	2 803.6
FS correction						0.2	
VCG fluid						7.4	

Figure H.1: Filling condition of tanks for Departure Port for optimal hydrostatics



Arrival Port Tank Filling							
	Degree of filling	Unit volume [m3]	Unit mass [t]	Longitudinal arm[m]	Transverse arm [m]	Vertical arm [m]	Total FSM [tm]
Methanol 1 S	10 %	111.2	87.8	122.6	6.2	1.7	63.9
Methanol 1 P	10 %	111.2	87.8	122.6	-6.2	1.7	63.9
Methanol 2 S	10 %	184.5	145.8	97.7	5.8	1.7	32.2
Methanol 2 P	10 %	184.5	145.8	97.7	-5.8	1.7	32.2
Methanol 3 S	10 %	219.6	173.5	49.5	6.1	1.7	56.3
Methanol 3 P	10 %	219.6	173.5	49.5	-6.1	1.7	56.3
Methanol 4 S	10 %	116.2	91.8	31.8	8.6	1.7	65.0
Methanol 4 P	10 %	116.2	91.8	31.8	-8.6	1.7	65.0
BW 1 Fore Peak	0 %	115.4	118.3	159.2	0.0	0.8	0.0
BW DB 2 S	90 %	92.2	94.5	141.3	1.5	1.4	100.5
BW DB 2 P	90 %	92.2	94.5	141.3	-1.5	1.4	100.5
BW DB 3 S	90 %	54.6	56.0	126.0	2.1	0.8	82.1
BW DB 3 P	90 %	54.6	56.0	126.0	-2.1	0.8	82.1
BW DB 4 S	90 %	71.8	73.6	116.9	2.9	0.7	182.8
BW DB 4 P	90 %	71.8	73.6	116.9	-2.9	0.7	182.8
BW 3-4 S	0 %	132.0	135.3	122.9	6.3	4.8	0.0
BW 3-4 P	0 %	132.0	135.3	122.9	-6.3	4.8	0.0
BW DB 5 S	80 %	116.9	119.8	99.0	5.7	0.6	154.1
BW DB 5 P	80 %	116.9	119.8	99.0	-5.7	0.6	154.1
BW DB 6 S	80 %	89.3	91.5	47.9	6.1	0.6	158.5
BW DB 6 P	80 %	89.3	91.5	47.9	-6.1	0.6	158.5
BW DB 7 S	80 %	87.7	89.9	36.1	3.9	0.7	406.9
BW DB 7 P	80 %	87.7	89.9	36.1	-3.9	0.7	406.9
BW DB 8 S	90 %	79.8	81.8	27.6	3.1	0.8	269.3
BW DB 8 P	90 %	79.8	81.8	27.6	-3.1	0.8	269.3
BW 7-8 S	0 %	131.1	134.4	30.7	8.8	4.8	0.0
BW 7-8 P	0 %	131.1	134.4	30.7	-8.8	4.8	0.0
BW DB 9 S	90 %	59.6	61.1	16.3	1.6	0.8	113.5
BW DB 9 P	90 %	59.6	61.1	16.3	-1.6	0.8	113.5
BW 9 S	30 %	373.3	382.7	17.9	5.5	3.3	706.2
BW 9 P	30 %	373.3	382.7	17.9	-5.5	3.3	706.2
BW DB 10 C	90 %	20.3	20.8	5.0	0.0	0.9	27.0
BW 10 C	20 %	248.6	254.8	4.1	0.0	2.6	265.0
AH 1 S	50 %	263.6	270.2	101.5	9.0	2.9	49.7
AH 1 P	50 %	263.6	270.2	101.5	-9.0	2.9	49.7
AH 2 S	50 %	159.3	163.3	82.1	9.9	2.8	13.3
AH 2 P	50 %	159.3	163.3	82.1	-9.9	2.8	13.3
AH 3 S	50 %	161.4	165.5	65.5	10.0	2.8	11.7
AH 3 P	50 %	161.4	165.5	65.5	-10.0	2.8	11.7
AH 4 S	50 %	152.2	156.1	49.3	9.9	2.8	12.6
AH 4 P	50 %	152.2	156.1	49.3	-9.9	2.8	12.6
FW 1 S	10 %	117.6	117.6	120.7	3.1	4.5	69.5
FW 1 P	10 %	117.6	117.6	120.7	-3.1	4.5	69.5
FW 2 C	10 %	171.4	171.4	14.8	0.0	4.5	222.4
SG 1 S	100 %	117.6	121.1	120.7	3.1	2.6	0.0
SG 1 P	100 %	117.6	121.1	120.7	-3.1	2.6	0.0
SG 2 C	100 %	166.6	171.6	15.0	0.0	2.6	0.0
LO 1 S	10 %	53.5	49.2	108.9	5.3	1.7	5.5
Pool	93 %	38.0	38.0	2.6	0.0	8.8	31.6
Total Loadcase		6 597.4		72.8	0.0	7.2	2 803.6
FS correction						0.2	
VCG fluid						7.4	

Figure H.2: Filling condition of tanks for Arrival Port for optimal hydrostatics

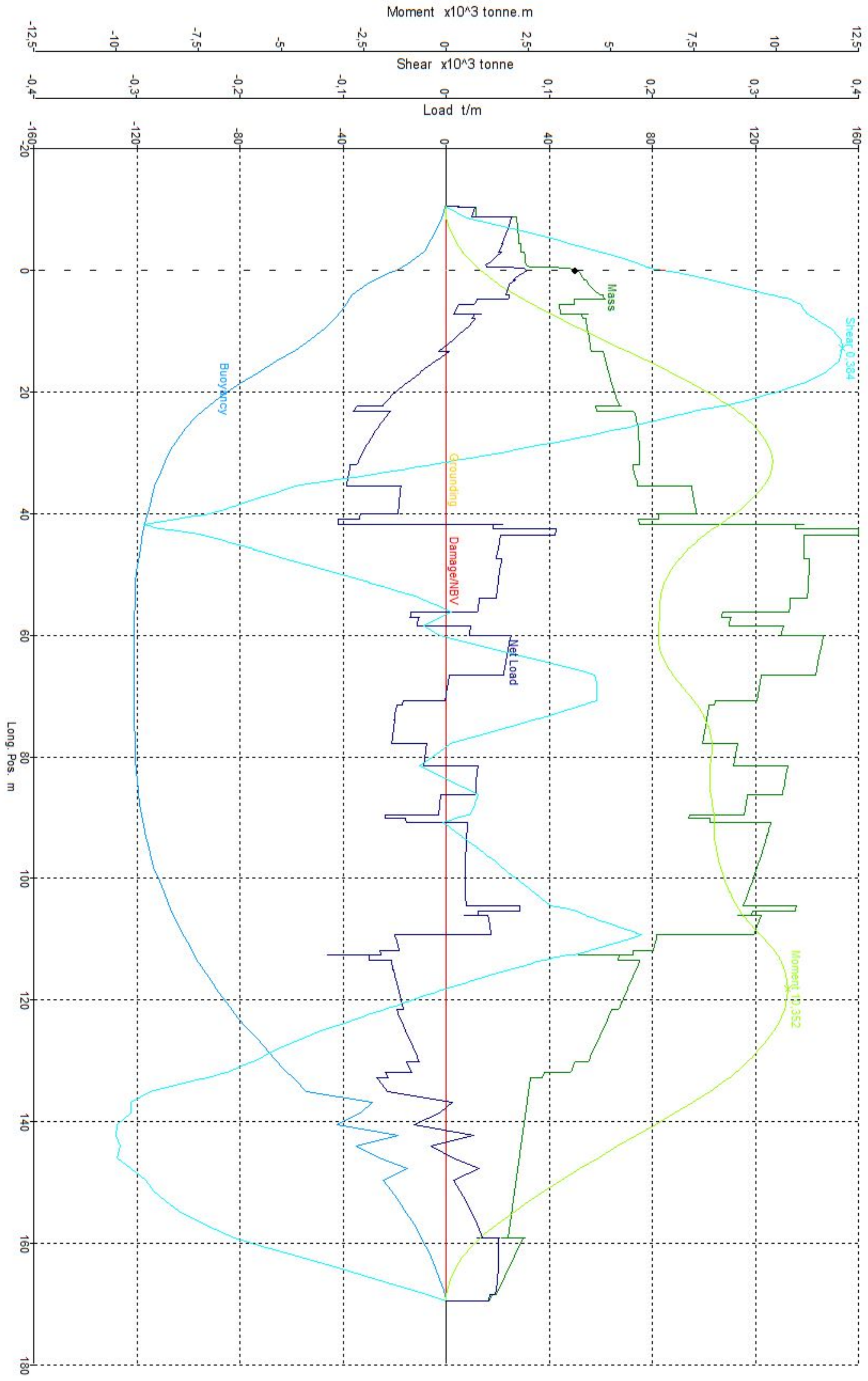


Figure H.3: Longitudinal Strength graph for Departure Port condition

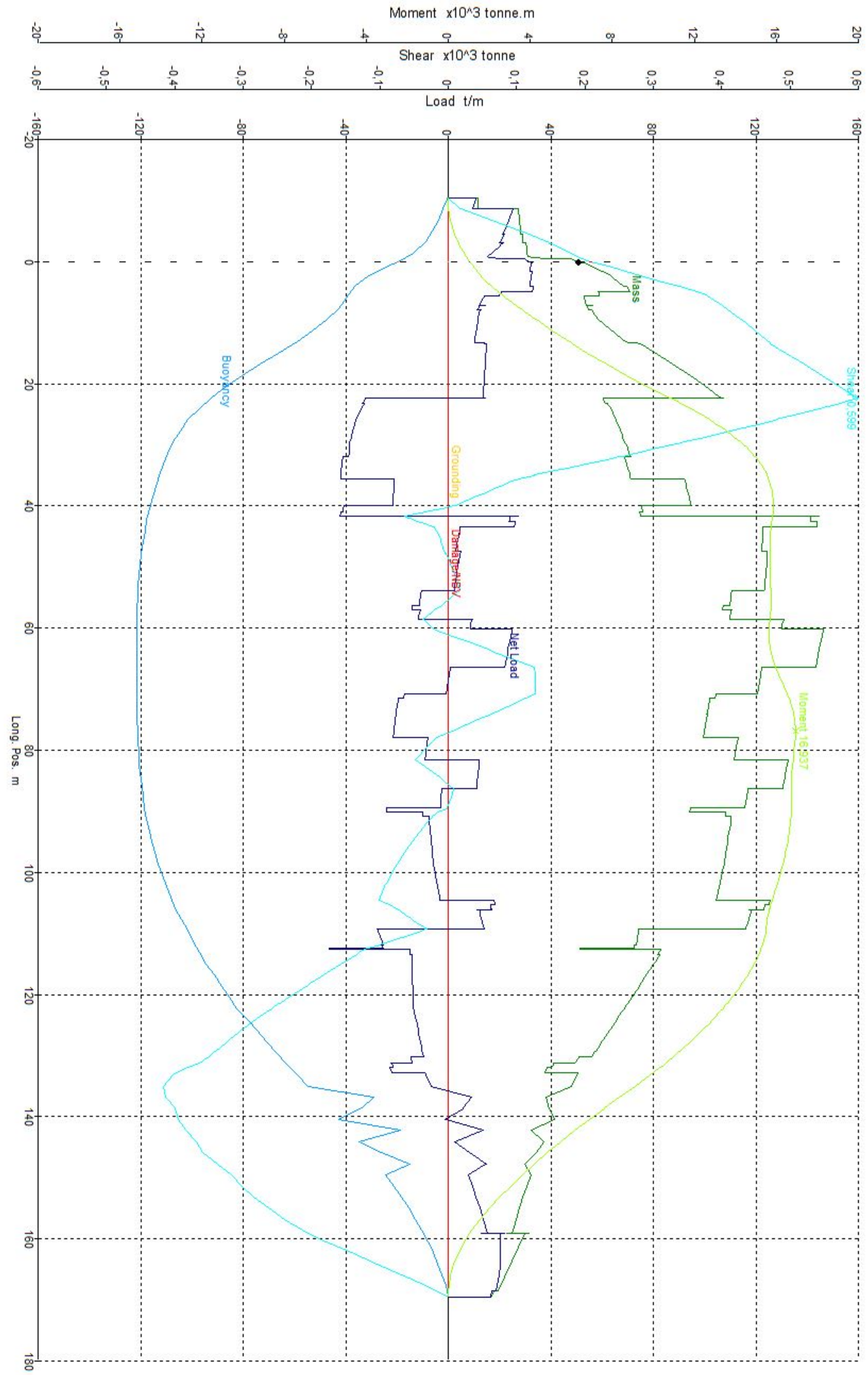


Figure H.4: Longitudinal Strength graph for Arrival Port condition

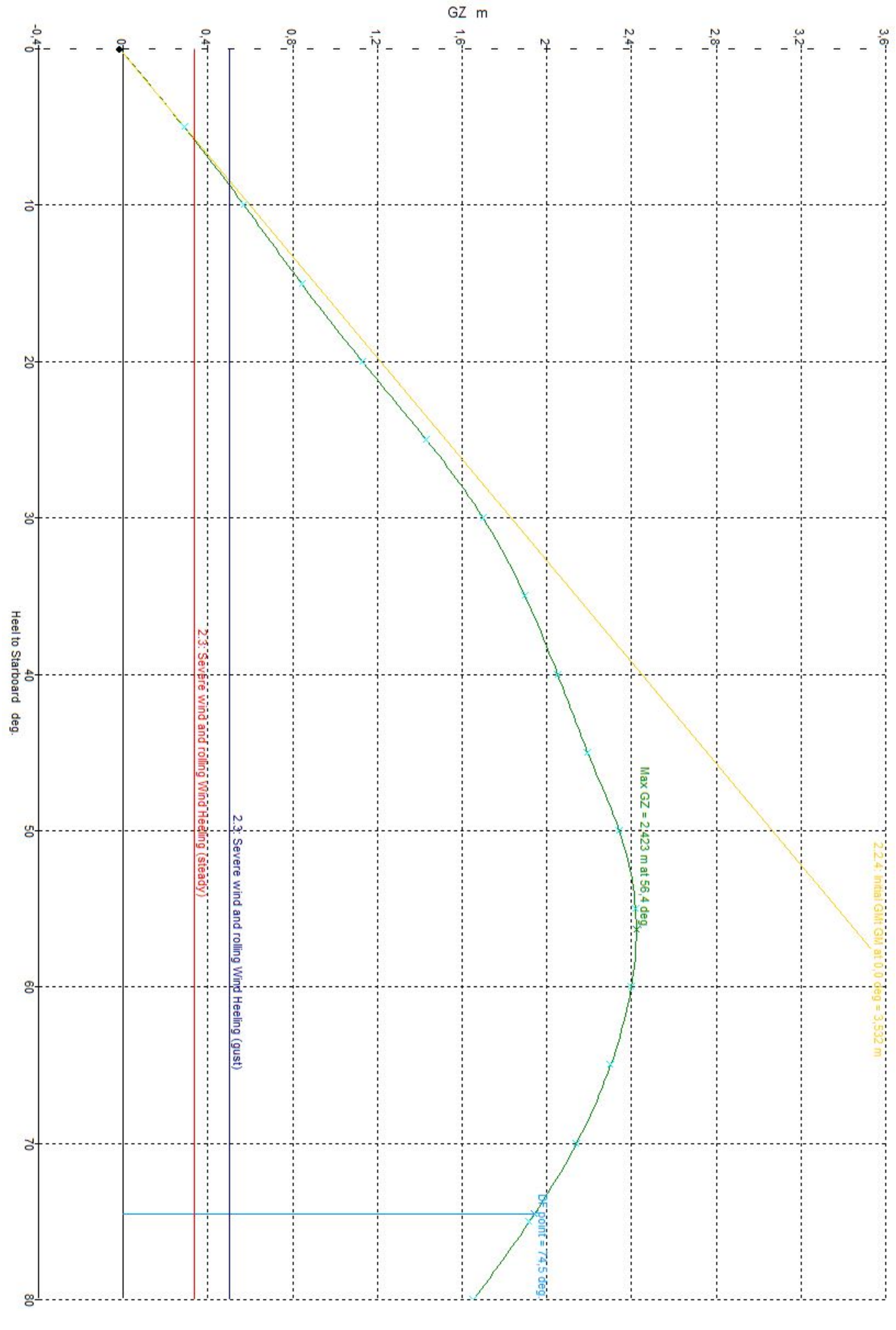


Figure H.5: GZ curve for Departure Port condition

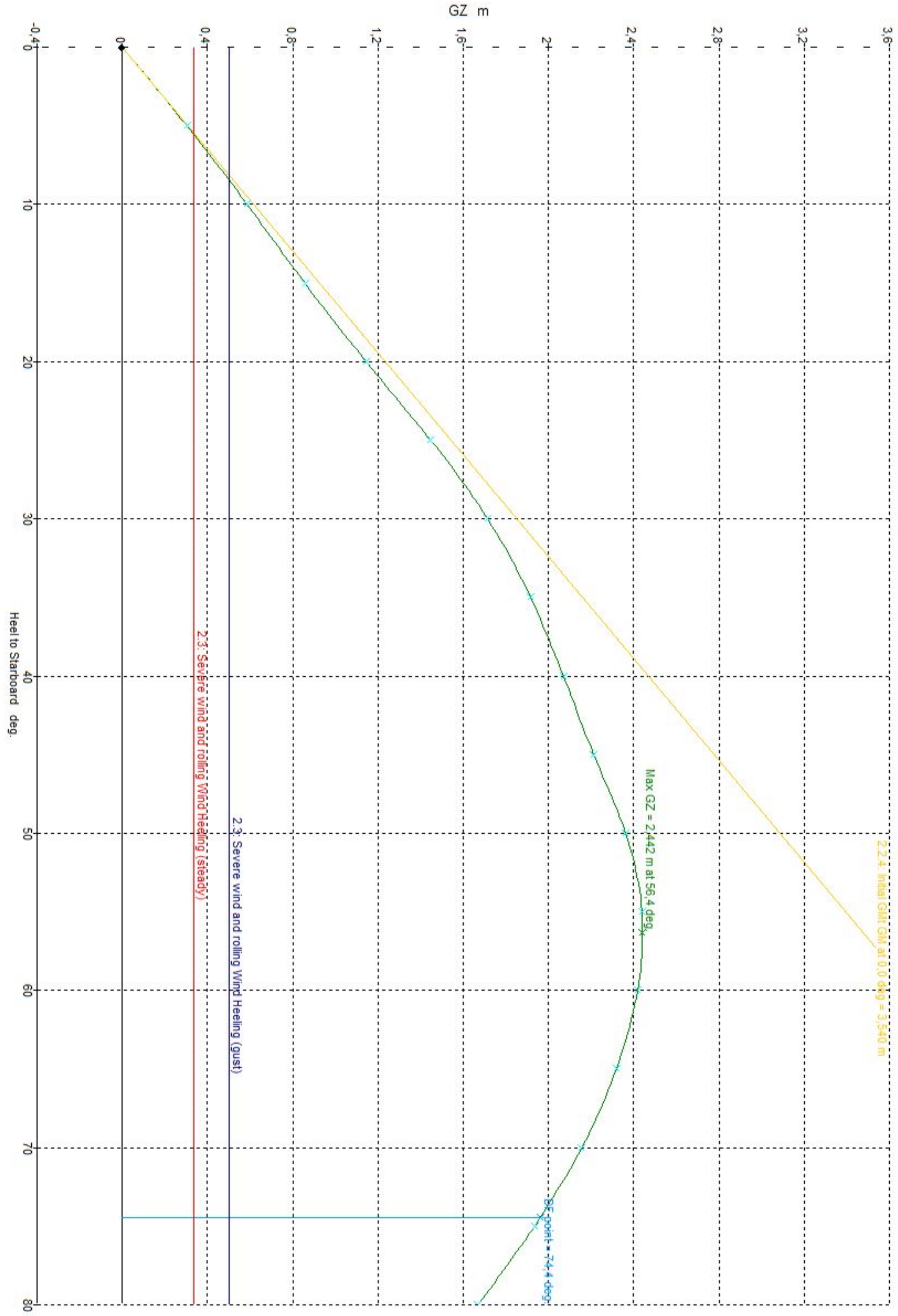


Figure H.6: GZ curve for Arrival Port condition

I Structure

Finished Section Scantlings

Below all seven section scantlings is presented. Notice in the bottom of figures I.1, I.2, I.3 and I.4 girders are drawn. The girders is not correctly dimensioned, but is only there to simulate girders limit the span and prevent buckling for the transverse stiffeners. For the other sections this is fixed by the function for regulating the span of the girders. The span is set to 3200mm, the same as the web frame. The cross sections present the plate thickness and steel type. Values with square brackets is steel type VL-36, which represent high strength steel. The rest is ordinary construction steel.

Figure I.1 presents the arrangement for section scantling #44:

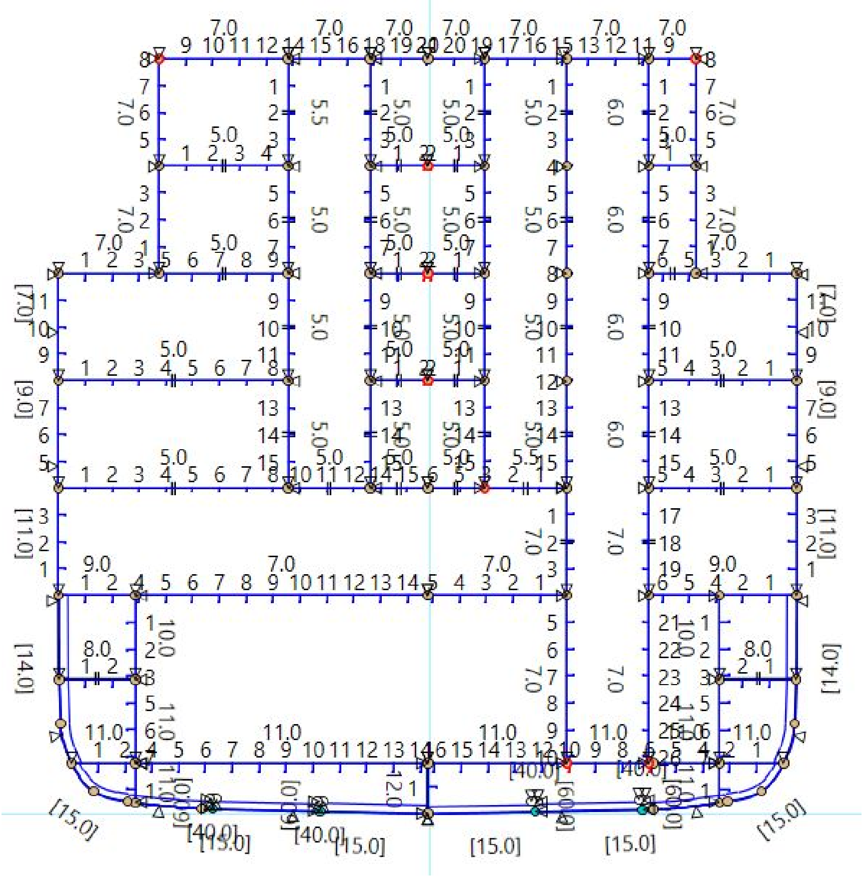


Figure I.1: Result for section scantling #44.

Figure I.2 presents the arrangement for section scantling #99:

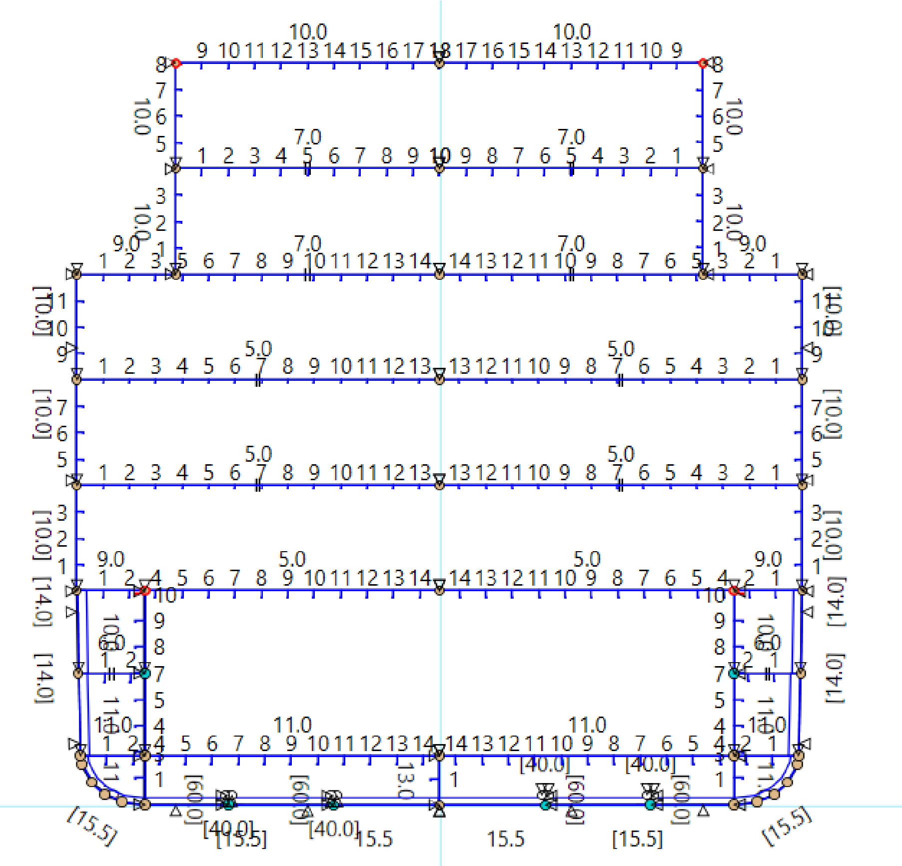


Figure I.2: Result for section scantling #99.

Figure I.3 presents the arrangement for section scantling #134:

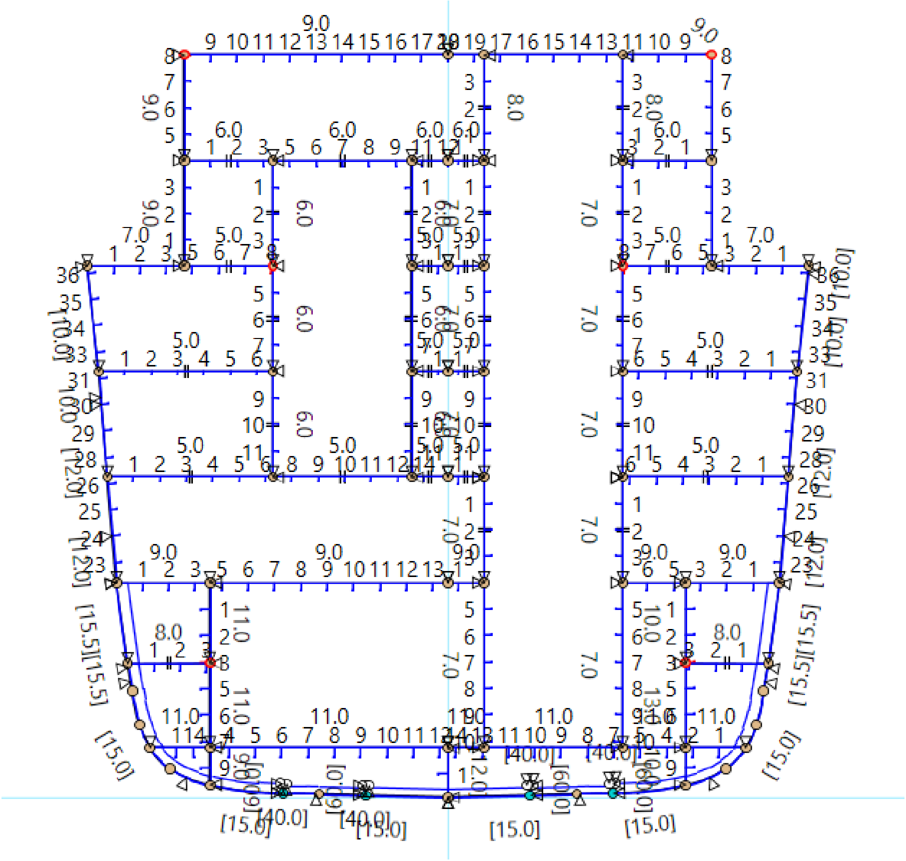


Figure I.3: Result for section scantling #134.

Figure I.4 presents the arrangement for section scantling #159:

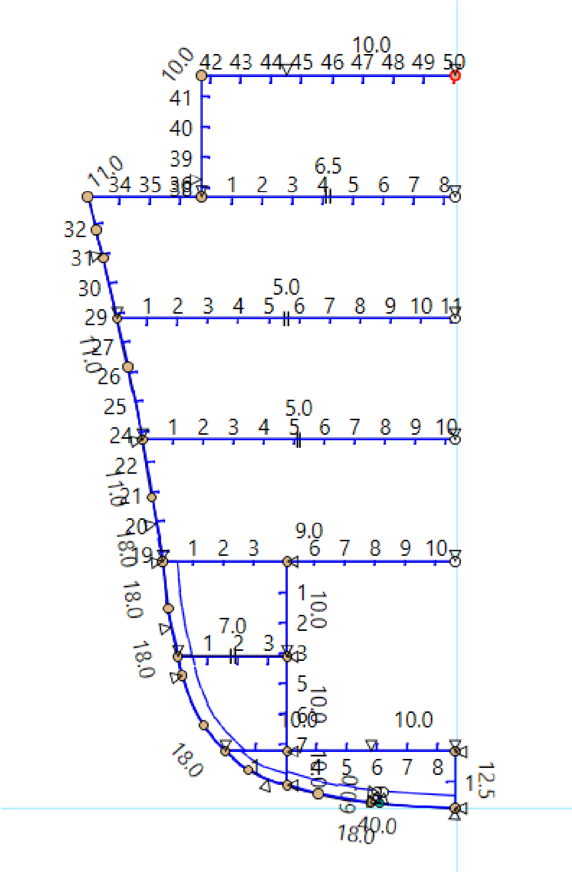


Figure I.4: Result for section scantling #159.

Figure I.5 presents the arrangement for section scantling #174:

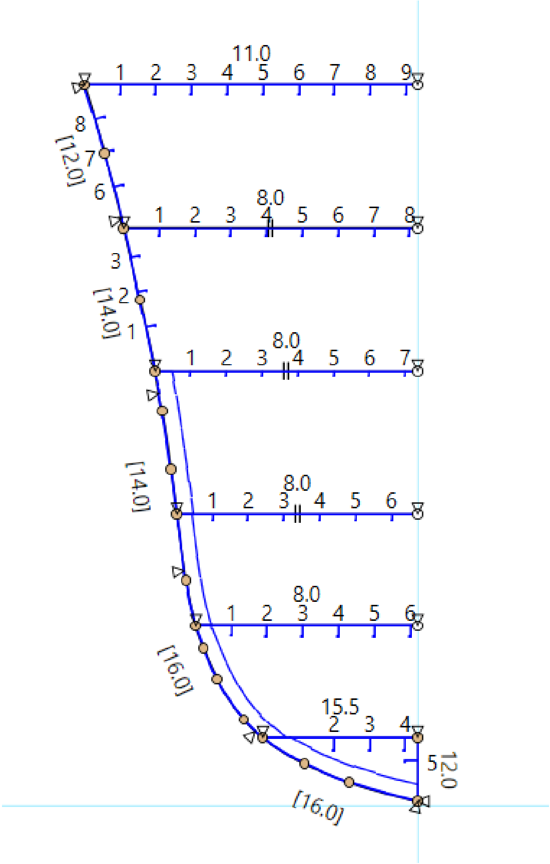


Figure I.5: Result for section scantling #174.

Figure I.6 presents the arrangement for section scantling #189:

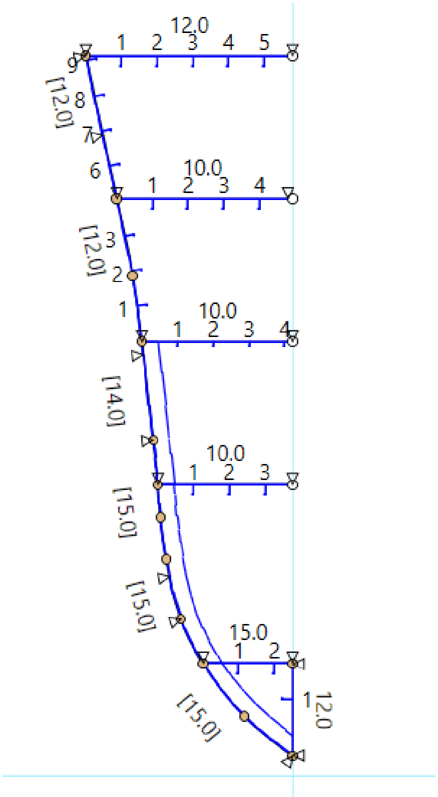


Figure I.6: Result for section scantling #189.

Figure I.7 presents the arrangement for section scantling #204:

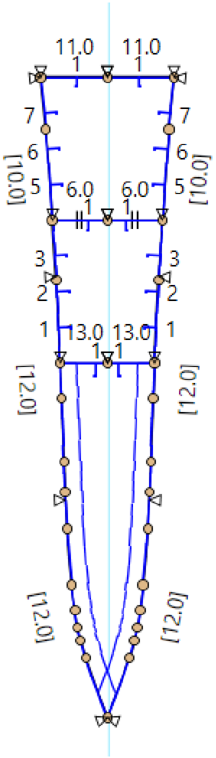


Figure I.7: Result for section scantling #204.

Stiffeners Summary

Table I.1 presents all the different stiffener profiles used in the structural arrangement. In general, the smaller profiles for longitudinal stiffeners are used in accommodation decks and superstructure. The larger profiles are used in lower decks and hull skin. For the transverse stiffeners, the two smaller profiles are used scantling #44, #99 and #134. The larger profiles are used in the four Polar Class scantlings, #159, #174, #189, #204.

Table I.1: Summary of stiffener profiles used the sections scantlings.

HP Bulb Stiffeners	
Longitudinal	**Transverse**
100x8	220x10
180x10	280x12
200x10	340x16
220x10	370x16
280x12	

Cross Sections Weight Summary

Table 13.5 presents the weight summary for the cross sections in Nauticus Hull. For calculating $L.Sum$ the average for longitudinal stiffeners was multiplied with the ship length, Loa. For calculating the $Trv.Sum$ the average for transverse stiffeners was multiplied with the Loa and divided on the web frame at 3200mm.

J Model test

Procedure for model scaling

Scaling the speeds for the model test:

$$Froudenumber = \frac{V_S}{\sqrt{g \cdot L_S}} = \frac{V_M}{\sqrt{g \cdot L_M}} \tag{J.1}$$

$$V_M = Froudenumber \cdot \sqrt{g \cdot L_M} \tag{J.2}$$

Froude scaling used for finding the parameters in formulas below.
Wet surface:

$$S_M = \frac{S_S}{\lambda^2} \tag{J.3}$$

Procedure used for model scaling is the ITTC PROCEDURE 7.5-02-02-01.
1. Total resistance coefficient for model is calculated with formula:

$$C_{TM} = \frac{R_{TM}}{\frac{1}{2} \cdot \rho_M \cdot V_M^2 \cdot S_M} \tag{J.4}$$

where $\mathrm{R_{TM}}$ is the measured resistance in the towing tank and $\mathrm{V_M}$ is the speed of the model in m/s.

2. Coefficient for residual resistance is calculated:

$$C_{RM} = C_{TM} - (1+k) \cdot C_{FM} - C_{AAM} - C_{BDM} \tag{J.5}$$

where

The friction resistance coefficient is given by the ITTC 1957 formula[9]:

$$C_{FM} = \frac{0.075}{(logRe_M - 2)^2} \tag{J.6}$$

$$Re = \frac{V \cdot L_{WL}}{\nu} \tag{J.7}$$

The air resistance coefficient is:

$$C_{AAM} = \frac{\rho_a \cdot C_{DM} \cdot A_{TM}}{\rho_{FW} \cdot S_M} \tag{J.8}$$

The resistance coefficient for transom stern is:

$$C_{BDM} = \frac{0.029 \cdot (S_{BM}/S_M)^{3/2}}{(C_{FM})^{1/2}} \tag{J.9}$$

The form factor is calculated with MARINTEKs formula:

$$k = 0.6\phi + 145\phi^{3.5} \tag{J.10}$$

where

$$\phi = \frac{C_B}{L_{WL}} \cdot \sqrt{(T_{AP} + T_{FP}) \cdot B} \tag{J.11}$$

3.The residual resistance coefficient is equal for model and full scale.

$$C_{RM} = C_{RS} = C_R \tag{J.12}$$

4. The total resistance coefficient for full scale is calculated:

$$C_{TS} = C_R + (1+k) \cdot (C_{FS} + \Delta C_F) + C_{AAS} + C_{BDS} + C_A \tag{J.13}$$

where

The friction coeffisient in full scale is calculated:

$$C_{FS} = \frac{0.075}{(log R_{nS} - 2)^2} \tag{J.14}$$

The full scale air resistance is:

$$C_{AAS} = \frac{\rho_a \cdot C_{DS} \cdot A_{TS}}{\rho_{SW} \cdot S_S} \tag{J.15}$$

The resistance coefficient for transom stern inn full scale is:

$$C_{BDS} = \frac{0.029 \cdot (S_{BS}/S_S)^{3/2}}{(C_{FS})^{1/2}} \tag{J.16}$$

The roughness allowance for the hull shape is:

$$\Delta C_F = 0.044 \left[\left(\frac{k_s}{L_{WL}}) \right)^{\frac{1}{3}} - 10 \cdot Re^{-\frac{1}{3}} \right] + 0.000125 \tag{J.17}$$

where k_s indicates the roughness of the hull. When there is no measured data for k_s, standard value is 150'10^{-6}[8].

Following the recommendations from ITTC [8], when using the roughness allowance above, this formula for correlation allowance is used:

$$C_A = (5.68 - 0.6 log Re) \cdot 10^{-3} \tag{J.18}$$

5. The total hull resistance in full scale is calculated with formula:

$$R_{TS} = C_{TS} \cdot \left(\frac{1}{2} \cdot \rho_{SW} \cdot V_S^2 \cdot S_S \right) \tag{J.19}$$

Further, the hull efficienty is given by

$$P_E = R_{TS} \cdot V_S \tag{J.20}$$

K First Sketches

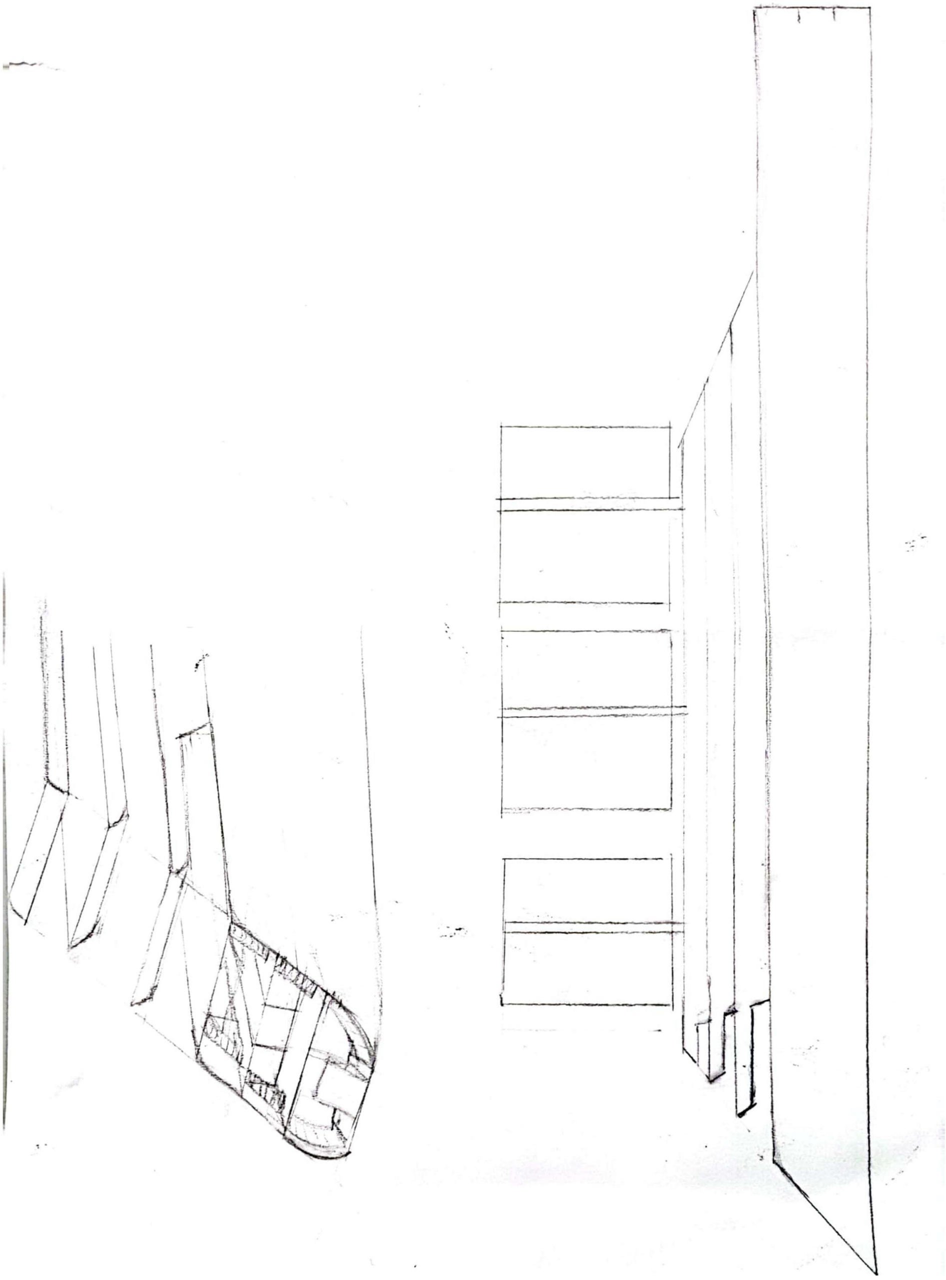


Figure K.1: First sketches

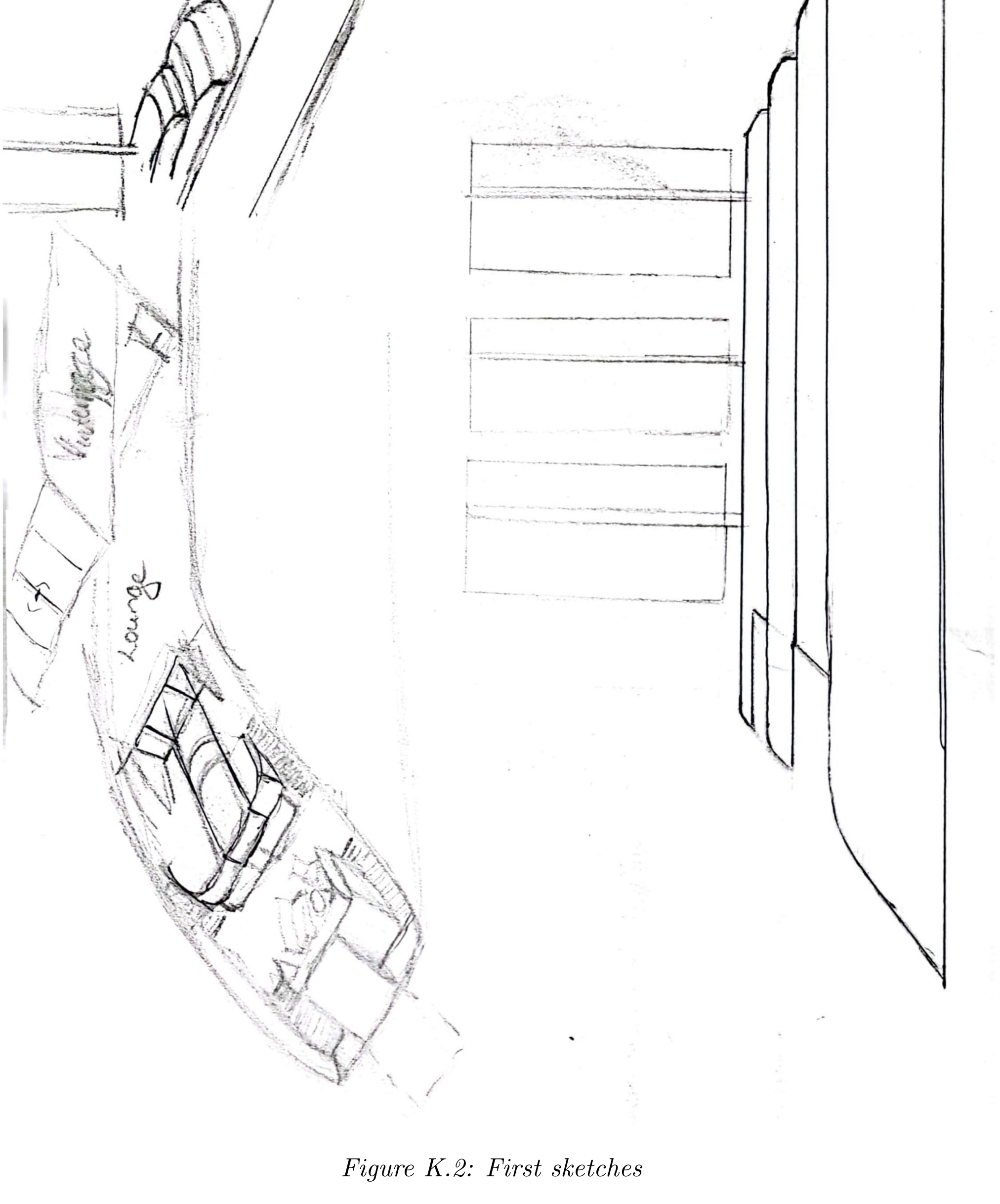


Figure K.2: First sketches

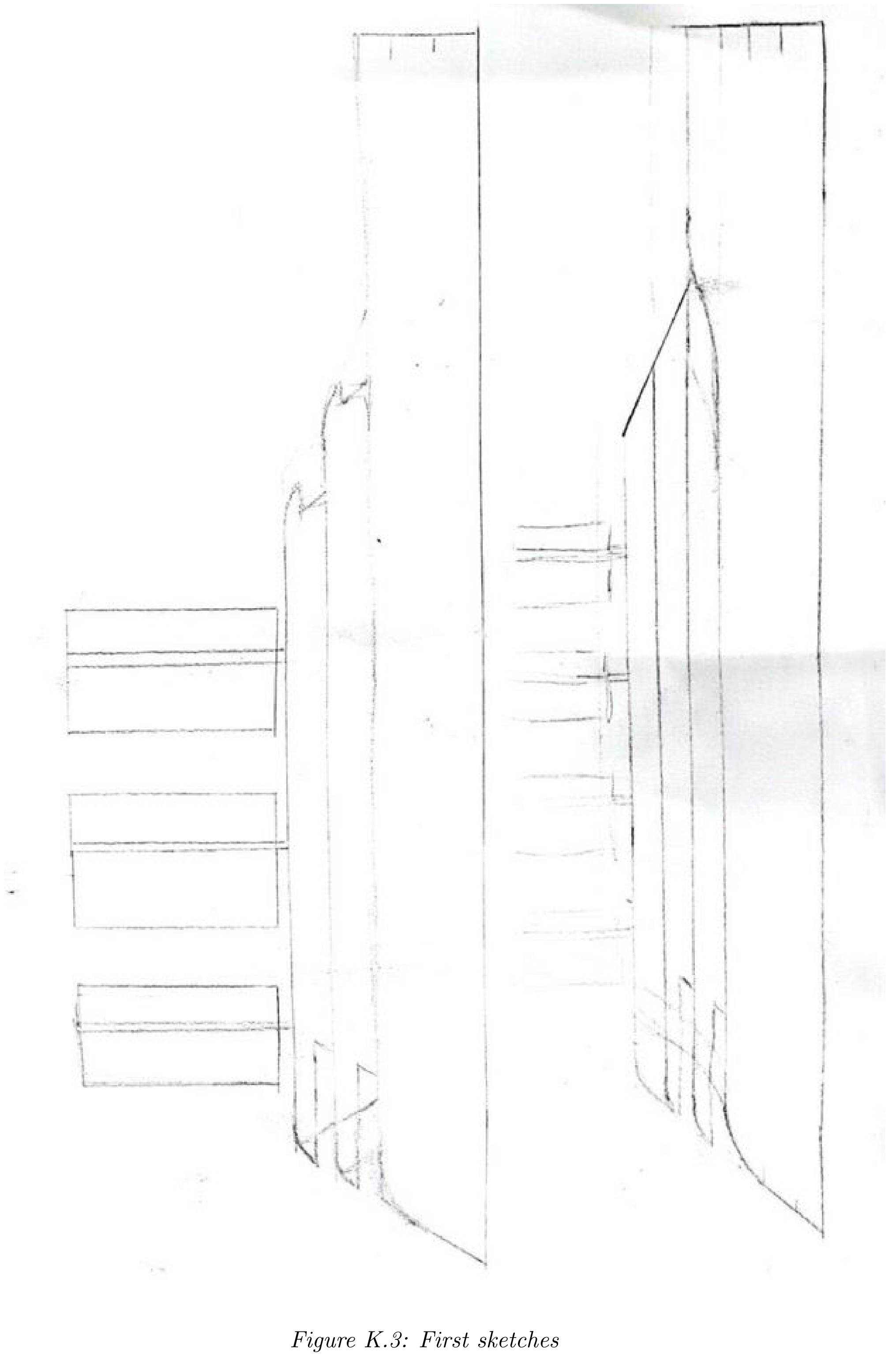


Figure K.3: First sketches

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