Aalto University School of Engineering
Department of Mechanical Engineering
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Khione

Final report

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Executive Summary

The purpose of this design project was to design a supply and research vessel for use in the arctic. The ship must be able to sail through 1.65 m thick ice at 3 knots, have 500 m^2 of space available for laboratories and offices and feature 2 medium size helicopters. The propulsion must be diesel electric with adjustable pitch propellers and provide a propulsive power of 26.6 MJ and the ship must be able to sail semi-autonomously. The semi-autonomous operation is what sets this ship apart from other vessels. There are autonomous ships under development, like the MV Yara Birkeland, but there are no (semi-) autonomous ships currently in operation. With this autonomy, crew size and with the cost of shipping can be decreased. It was also decided that the ship will use hydrogen as an auxiliary power source.

At the start of this project, the design requirements, parameters and limits were defined based on the ship's mission. With this information, the overall dimensions of the ship were determined using refence data and Normand's method, the results being an overall length of 133 m, a breadth of 22 m, a draft of 7 m and a displacement of 11896 tonnes. Given the overall dimensions, line drawings were created as well as a CAD model using Delftship. The structural design is based on regulations from the Polar Code

The financial analysis revealed that this ship will require government support in order to operate, as the cargo being carried is limited. This is however normal for a scientific vessel and the ship is in itself a prototype for semi-autonomous and hydrogen technology.

Future stages of the design will have to focus more detailed structural and hydrostatic design. Hopefully this project can function as a baseline for future special purpose icebreakers.

Project Team

Anniina Isokorpi
I am a novice in the field of marine technology. I do not have any experience or hardly any knowledge about naval architecture. For me, the biggest motivation to start studying marine technology was the different ways technology can be utilized to help the operative functions of the society (such as rescue operations, medevac, national security, etc.) – especially in demanding conditions. Considering the ship project on hand, I have work experience as a helicopter technician in an operative duty, thus I have knowledge on what requirements there are for the helicopter hangar onboard. In addition to both knowledge and interest about how to make the operative functions on a ship possible, I am also interested in fluid mechanics and stochastic processes. I did my minor in mathematics including statistical and stochastic methods and numerical analysis during the bachelor studies. I wish to be able to also use these strengths and skills to design a vessel that bears the extreme conditions of arctic seas.

Sanna Granqvist
I have gained experience in shipbuilding through my bachelor’s thesis and work at shipyard last 4 months. I wrote my bachelor’s thesis of future energy sources for merchant ships, which was a good start to get to know the shipbuilding industry. The summer at shipyard went by mostly studying alternative and possible resistance reduction devices/energy saving devices. So my experience in shipbuilding is mostly related to energy efficiency, which is a current topic in the industry so I think some of the experience can be used in the project. I’m also hoping to get a broader view of the industry through this course. My minor in bachelor studies was about computation and modelling in engineering which gave a glimpse of how both computation and modelling can be used in different fields.

Stephan van Reen

I gained a very basic knowledge of ship design during my minor, which sparked my interest in the maritime field. I realized that there is a lot of overlap between maritime engineering and my bachelor's in aerospace engineering. However, the bulk of my experience comes from a year long, full time student project to design and build a hydro-foiling solar boat that works. And so, my previous knowledge is into lightweight and efficient design and real-life experience.

My master is in Cold Climate Engineering and my goal to make ships and marine structures in the arctic more sustainable and eco-friendlier. I hope that this course can help me fill in the gaps in my knowledge as well as prepare me for the more advanced courses in naval architecture.

Oskar Veltheim
I am interested in arctic marine technology and especially in ice breaking ships. I have gained some knowledge about naval architecture by being active in LRK and working on shipyard about a year. My bachelor thesis was about methods to calculate ice loads on ships. When writing my bachelor thesis, I read and learned about ice rules and ice conditions. I have also orientated to ice rules in my work at shipyard. Working at shipyard has taught me the most about shipbuilding. I am looking forward getting better understanding of different areas of shipbuilding, such as hull form and structure, during this course.

Juhan Voutilainen

My prior knowledge according to marine technology is not very deep. However, I completed my bachelor's degree in mechanical engineering, so I have basic knowledge of the physical phenomena in the field of marine technology. My bachelor's thesis was about environmental regulations of ships operating in the area of the northern sea route. I have gained additional maritime knowledge especially about ice-going vessels by working in the company with focus in research and design of arctic vessels. I am sure knowledge about regulations that I obtained from doing my thesis and my work experience in the arctic maritime company will help our group in the project work.

Project Schedule

Week	start	ready
37	Starting PNA project	
38	Studying Reference ship data	Starting PNA project
39	Deciding main Dimensions	Studying Reference ship data
40	making Hull form	Deciding main Dimensions
41	learning Hydrostatics	
42	making GA	making Hull form
43		
44	calculating Ship structures	making GA
45	planning machinery	calculating Ship structures
46	calculating weight and stability	planning machinery
47	Planning economics	calculating weight and stability
48		Planning economics
49	finishing up	finishing up
50	exam	exam

Contents

Nomenclature

Abbreviations	
AB	Arctic Bridge
AUV	Autonomous Underwater Vehicles
DWT	Dead Weight Tonnes
DWTC	Cargo Weight
DWTC&E	Weight of crew and their effects
DWTH	Hydrogen weight
DWTPR	Weight of provisions
EN	Equipment number
HFO	Heavy Fuel Oil
MDO	Marine Diesel Oil
MHS	Required number of Man Hours
NPV	Net Present Value
NWP	North West Passage
NSR	Northern Sea Route
PC4	Polar Class 4
PSV	Platform Supply Vessel
ROV	Remotely Operated Underwater Vehicles
SAR	Search and Rescue
SFI	
SOLAS	International Convention for the Safety of Life at Sea
TSR	Transpolar Sea Route
WPA	Water plate area

Symbols	
A	Area of profile view of the hull
B	Greatest breadth
C_B	Block Coefficient
C_M	Midship section area coefficient
C_P	Prismatic coefficient
C_{ST}	Hull structure cost
D	Depth
H	Height from the summer load waterline to the top of the uppermost deckhouse
K_{MAN}	Man hour cost
K_{STEEL}	Cost of steel per ton
L_{PP}	Length between perpendiculars
P	Power
T	Draft
t_{net}	Shell thickness
W_E	Lightship Weight
W_M	Machinery Weight
W_O	Outfitting weight
W_S	Structural Weight
Δ	Displacement
μ	Mean value
ρ	Density

1 Design Context and Mission

1.1 Design Mission and Objectives

The mission of the team is to design a safe, reliable, and efficient research and re-supply vessel for use in Arctic waters. The ship will operate independently in extreme conditions and will provide supplies for people who completely rely on it. Thus, the reliability and safety of the ship are highly prioritised in this project.

The efficiency of the research and re-supply operations will be guaranteed by providing top level laboratories, underwater research capability, helicopter hangars and most importantly by making ship capable of operating in thick ice. Additionally, ship will be designed to have capability for semi-autonomous operation. Our ambition is to create innovative designs which will bring new solutions to the industry and show the way for future ships performing operations in ice-covered waters.

1.2 Design Variables, Innovations and Boundaries

The vessel must be able to operate in arctic conditions. The route that the vessel will travel may vary, but it will be in the Arctic. The extreme environment sets requirements for the vessel such as icebreaking capability up to 1.65 m thick ice while maintaining the sailing speed of 3 knots. The propulsion system should be able to produce a propulsive power of 26,600 kW, divided over two diesel electric propellers with controllable pitch. Furthermore, the ship should feature both bow and stern thrusters. The advantage of diesel-electric propulsion over a diesel engine is that diesel-electric propulsion can provide maximum torque at all speeds (Wärtsilä, 2016), which is ideal for an icebreaker. Icebreakers generally sail at slow speeds, but they still need to apply a lot of force to get through the ice.

On the vessel, there must be science laboratories and offices, which are 500 m^2 in area combined. About half of this space (250 m^2) will be offices, each office being 10 square meters, shared by 2 people. There will be 80 researchers. As for the crew, an average crew size is 25 people (Deloitte, 2011), but because this ship will be semi-autonomous, the ship crew is expected to only be 20 people, 6 of which are licensed helicopter pilots, 3 helicopter mechanics and 12 perform the ship's operations. Every 2 crew members share one 10 m^2 room, with the captain having his/her own room.

Research Onboard
The laboratory will have the latest technology that is needed for high-quality research on biological, chemical, or physical oceanography as well as paleoceanography. For underwater research, there will be different sensor arrangements for hydrographic survey and oceanographic research. The vessel will have both multibeam and single beam echosounders for determining the water depth and mapping the seabed. There will also be a towed side scan sonar, i.e. a towed vehicle that is equipped with a sonar system that can create an image of the sea floor from a large area at once. There will be a CTD system to measure the conductivity, temperature, and pressure of the seawater. The vessel also has supporting technology for remotely operated underwater vehicles (ROV's) and autonomous underwater vehicles (AUV's). The vessel will have ultra-short baseline, an acoustic positioning system, that can communicate with subsea transponders on the sea floor or on a ROV. For the AUVs, the vessel will also have an inverted ultra-short baseline, which will make it possible for AUVs to autonomously dock or track the vessel.

Resupply Operations
As a resupply vessel, the two main innovations are also the helicopter hangar and the supply storage implementation. The hangar facility must fit two medium-size helicopters and it must provide shelter from the weather and suitable conditions for maintenance checks and refueling between flights. The helideck is located at the bow, from where the helicopters are pulled to hangar.

For the helicopter hangar, there is a boundary condition that there is no need for converting options, for example, fitting one large-size helicopter instead of two medium-size. This is due to that two helicopters make possible executing a large re-supply operation with various goods efficiently. In addition, if one of the helicopters is not operatable, the operation is not instantly foredoomed to failure.

The storage implementation for supply materials must be multifunctional as the material may vary from food, water or fuels to instruments and vehicles. The storage implementation must enable innovative ways for uploading and unloading both to and from the vessel as well as from the vessel to the helicopters and vice versa. It is notable that the uploading to the helicopters can be both via uploading the cargo into the helicopter or using a cargo hook.

Semi-Autonomous
The ship is capable of performing semi-autonomous operations, meaning that the ship can sail by herself, but the crew can still take control at any point. In this particular case, the ship will not be able to start its own engine for the purpose of safety, nor can the ship drop the anchor on its own. To make a ship able to sail by itself, the ship must gather data about its surroundings. Starting with the obvious, for a ship to know its position on the world, it needs to be connected to a system like the US GPS or the future European Galileo system. However, GPS cannot see obstacles in real time, so in order to avoid collisions with underwater obstacles like icebergs, the sonar system that is used for ocean research, will be expanded to send sound waves towards the front, back and sides of the ship. Moreover, a radar system will of course be used to scan the ship's surroundings above water. The sonar system and radar will have to be very precise, because the ship must be aware of both big and small obstacles

Furthermore, the ship's position needs to be known, so that the controlling computer knows what direction the ship is pointing at. An example where this is necessary is determining the ship's orientation towards the waves, so that the ship can be rotated accordingly.

All these functions must be controllable with a computer, which means that every navigation system, be it the generators or the rudder, must somehow be connected to the control computer using cables.

Energy Consumption, Generation and Heating Onboard
Although the propulsion system is set, being diesel electric, the rest of the ship must also be provided with energy. Especially the autonomous systems and the before mentioned research equipment will require large amounts of energy. Then there is the energy required for passenger/crew accommodation. The latter is in total the biggest energy consumer. Each passenger/crew is estimated to use the per person electricity use of Iceland, which is 5.777 kW (Orkustofnun, 2020). This number can include everything from heating to cooking and thus this is considered the worst-case scenario, since there is separate system for heating the ship and things like cooking can be done more energy efficiently in bulk.

The energy consumption by the vessel's onboard operative functions (research, air transportation etc.) increase the amount of electricity needed onboard. Laboratories consume from 300 to 1000 kWh/m² annually (FriendlyPower, n.d.). Based on this, we approximated that the laboratory facilities would need a 30 kW power source, as much of the laboratory equipment and processes need power continuously, such as refrigeration and ventilation. The helicopter hangar will need approximately 10 kW, mainly for lighting and ventilation. The power for starting the helicopters will be provided with s eparate ground power units that use diesel.

Four sources of sustainable energy were considered: wind energy, solar energy, and liquid hydrogen. Wind energy was discarded because any turbines added to the ship are a dangerous obstacle for the helicopters. Solar energy would only work during summer because the sun does not rise during arctic winter. In the end, liquid hydrogen has been selected as energy source. Hydrogen is made by electrolysis of water, which can be done with any energy source on land. It is then liquified by cooling the gas down to 20 K, which is the liquefaction temperature at atmospheric pressure (Rossini, 1970). Liquid hydrogen has an energy density of 8.5 MJ/L (US Department of Energy, 2001), and the total energy the hydrogen needs to provide for 64 days was calculated to be 3.4 TJ, the volume of liquid hydrogen required is 402 m^3.

Lastly, the hot air from the generators will be used to heat the ship by heating water, like is done in the RRS Sir David Attenborough. There will also be an electric heating system powered by hydrogen, for when the generators are turned off.

1.3 Design Parameters

Design parameters that affect the performance of vessels and can't be controlled by the design is environmental, economic and operational. The vessel operates in arctic or Antarctic conditions which is an uncertainty both due to icy conditions and the climate change. The ship needs to be designed for certain conditions for example to break up to 1,65 m thick ice and to operate in arctic conditions in general. The weather conditions change very likely from the conditions used in the design and for example the ice thickness varies during the year and by location. Difficulties from environmental parameters can appear in manoeuvring and control of the ship. Due to varying conditions the hull resistance also changes which can lead to speed loss and can't be easily estimated.

The vessel will be equipped with diesel-electric propulsion for which technology exists. The fuel price is an important parameter that shipping relies on. Changes in fuel price due to different matters can't be easily predicted. Different regulations and rules can for example affect the fuel price, but also other matters related to vessels and operating. New regulations are also hard to predict and the vessel could only be designed to meet the regulations and goals that are now in use (for example emissions).

The current pandemic situation is a good example on economic uncertainty. It has affected the industry in many ways both shipbuilding and operating ships. A situation like this changes many economic factors that couldn't be predicted in the design phase. Economic parameters also include operational costs like repair and maintenance, some of them can be scheduled but a vessel can also need repairs that necessary wasn't planned. An operational uncertainty are the long operating times in harsh conditions where the arrival time to next port can be unknown, which affects also loading and unloading of cargo.

1.4 Design Constraints

The ship is designed for operating in the Arctic area, thus constraints on ship's dimensions caused by the routes and ports of the Arctic are taken into examination. Also followed by constraints regarding to Polar class and ships operating in cold climate.

Constraints Set by Routes

From the current shipping routes in Arctic Ocean the following routes are considered: Northwest Passage (NWP), Northern Sea Route (NSR), and Arctic Bridge (AB). Routes are shown in picture below.

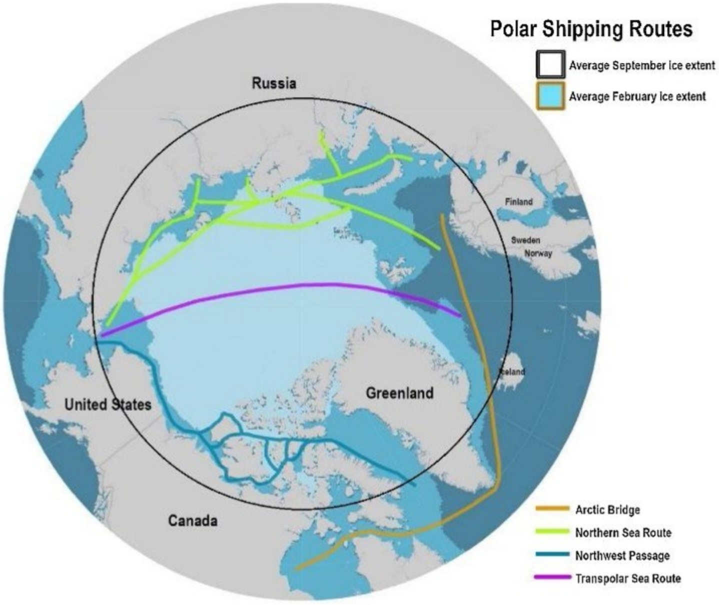

Figure 1. Arctic shipping routes (Rodriguez, 2010)

Northwest Passage includes seven different routes through the Canadian Arctic Archipelago. Two of the routes can be navigated with maximum draft of 6.4 m. Rest of the routes are suitable for drafts from 14m and more. Parts of the Northwest Passage which require draft of less than 6.4 m can be avoided while navigating through the Northwest Passage, thus constrain for draft set by the (NWP) can be considered as 14 m (Headland, 2020).

Northern Sea Route has multiple paths. Including straits with depth less than 10 m overall with depths varying between 8-250 m. However, shallowest areas can be avoided by taking different route. In result maximum draft for ships operating on NSR increases to 13 m (Arctic Council, 2009).

Arctic Bridge lays in relatively deep waters. Shallowest part of the Arctic bridge is the Hudson's bay (NOAA, 2020). Average depth in the bay is 125 m (W. Burt, 2016). Arctic Bridge route doesn't set any realistic constrains for draft of our vessel. In future ships can navigate through the Arctic Ocean using The Transpolar Sea Route (TSR). Currently, only heavy icebreakers are able to sail through TSR.

Vessel of our project is research and re-supply vessel, meaning it will also operate away from the typical shipping routes. Thus, examination of the surrounding waters is sensible. Depths of polar seas are presented in picture below.

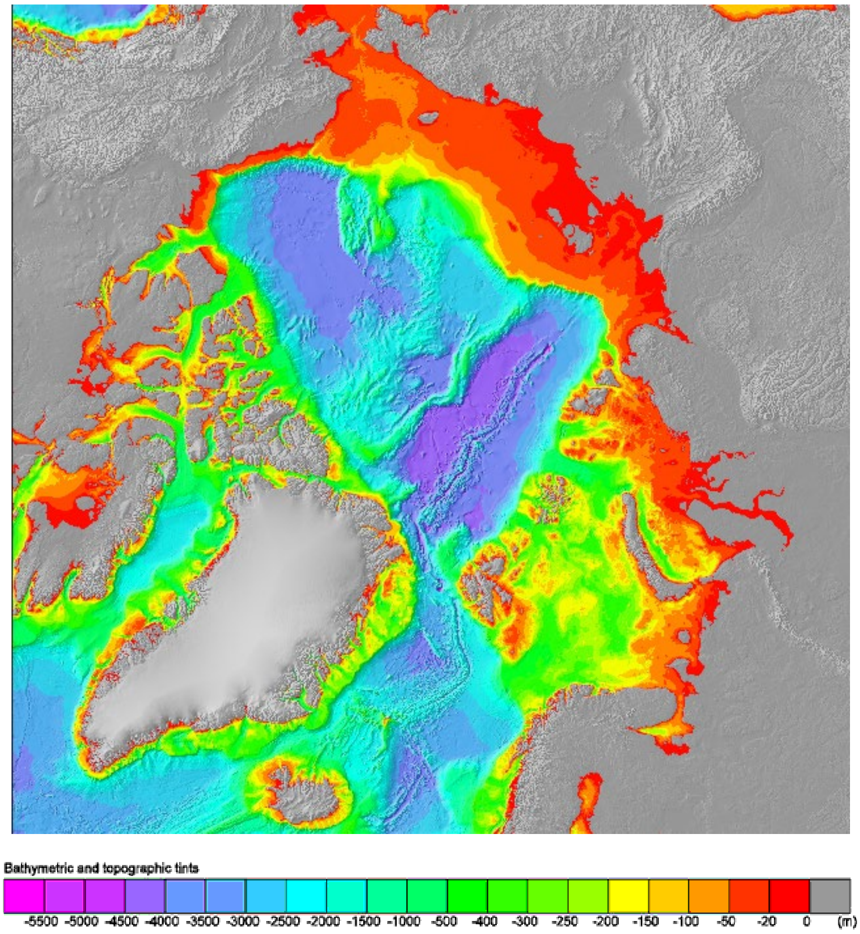

Figure 2 Bathymetric chart of Arctic area (NOAA, 2020)

As a result, from the pictures and constraints presented earlier, it can be concluded that operation area doesn’t cause much constraints regarding the dimensions of the ship. Only constrains are caused by the depths of the shipping routes. The constraints are affecting the maximum possible draft of the ship. Based on the depths, draft of the ship should be less than 13 m.

Constraints Set by Ports

Table 1 shows depths of ports in arctic waters. Many ports are less than 8 m deep, which is too shallow for our project ship. Fortunately, there are also ports where water depth is deep enough for our project ship. Especially in West coast of Greenland there are ports deeper than 8 m. Ports deeper than 8 m are 9.1 m or 10 m deep and so depths of ports limit the draft of our project ship to 9.1 m, which should be enough regarding refence ships. Max vessel length in most ports is up to 152 m and in some ports max length is more than 152 m, this limits our project ship to 152 m. Which means the depth of ports limit the main dimensions of the ship more than the depths of routes.

Table 1 Ports with cargo pier depth more than 8 m are marked with blue. (DP World, 2020)

Depths and lengths of some Arctic ports				
Country	Port	max depth [m]		max length [m]
		Gargo pier	Anchorage	
US	Nome	6.9		57.9
CA	Tuktoyaktuk	4.6		
CA	Churchill	10	21.3	>152
GL	North Star Bugt	7.6	16	>152
GL	Aasiaat	9.1	23.2	>152
GL	Qeqertarsuaq	7.6	13.7	<152
GL	Ilulissat	7.6	23.2	<152
GL	Qasigiannguit	7.6	23.2	<152
GL	Sisimiut	10	23.2	<152
GL	Maniitsoq	7.6	23.2	<152
GL	Faeringehavn	9.1	23.2	<152
GL	Paamiut	9.1	21.3	<152
GL	Kangilinnguit	10	23.2	<152
GL	Qaqortoq	7.6	23.2	<152
IS	Keflavik	7.6	23.2	
IS	Hafnarfjordur	9.1	12.2	>152
IS	Reykjavik	9.1	9.1	>152
IS	Djupivogur	3	13.7	
IS	Neskaupstadur	6.1	23.2	
IS	Seydisfjordur	7.6	23.2	
IS	Vopnafjordur	6.1	13.7	
IS	Raufarhofn	6.1	10	
IS	Akureyri	7.6	23.2	
IS	Skagastrond	4.6	13.7	
RU	Murmansk	7.6	21.3	>152
RU	Arkhangelsk	6.1	7.6	>152
RU	Dikson	6.1	7.6	<152
RU	Dudinka	7.6	9.1	
RU	Igarka	9.1	12.2	<152
RU	Tiksi	7.6	7.6	
RU	Pevek	6.1	12.2	>152

Other Design Constraints

Polar classes are described via ice descriptions. PC4 ships must be able to operate in thick first-year ice which may include old ice inclusions (IMO, 2015). Thick first-year-ice is 1.2-2 m thick (Headland, 2020). The Polar re-supply and research vessel must be capable to break 1.65 m thick ice sailing 3 knots. So PC4 is suitable ice class for The Polar re-supply and research vessel. Polar class sets requirements to strength of the hull, propeller properties and machinery. There are also rules and requirements to make ship capable to operate in cold. These rules apply for example ventilation, de-icing and life-saving appliances.

2 Reference Ship and Data

2.1 Ship Category

Our project ship is categorized as special purpose ship. Its main tasks as resupply and research vessel are resupplying Arctic research stations and do research in Arctic waters. To be able resupply research stations the vessel needs to have sufficient cargo space. Cranes mounted on deck enable loading and unloading supplies even outside of port facilities. The ship is also equipped with helicopter hangar, large enough to facility two medium size helicopters. Helicopter can be used to transport supplies when ship is unable to go close enough shore or ice field to unload supplies. Helicopter hangar can also be used to fix and maintain other than ship’s own helicopters.

To carry out its second main task, researching, the ship has science laboratories and offices spread across an area of 500 m². When needed helicopters are used to transport scientist to shore or ice fields to do research. In addition to laboratories, the ship has sensor system for underwater researching. The hull of the ship is instrumented with pressure gauges to collect ice load data. Ice load data can be then used to create models and methods to calculate ice loads. Laboratories and sensors enable study of such fields as biological oceanography, chemical oceanography, palaeoceanography, physical oceanography. Onboard science equipment requires great amount of electricity.

The ship has capability for semi-autonomous operations. Semi-autonomous operating requires hi-tech navigation systems and sensors to observe surroundings, but less crew is needed.

Resupply and research vessel enable precious research in Artic areas. Arctic research stations in harsh conditions are dependent on supply vessels having great ice breaking capability. And with so many scientists from different fields onboard there is great opportunity for diverse research.

2.2 General Characteristics

Since our ship is an icebreaking special purpose ship, we need to consider characteristics for icebreaking vessels and research vessels.

Some characteristics of ice-strengthened ships are; double hull with a gap filled with air or water ballast, special hull polymer paints that can withstand strength and has low frictions when in contact with ice, engine cooling arrangements so that inlet and water outlet doesn’t get blocked with ice, to help manoeuvring in different ice conditions powerful bow and stern thrusters, thicker steel at the bow and at water-line level and the rudder and propeller should be protected by the shape of the hull to prevent damage from ice moving (Coolantarctica, 2020).

The characteristics for research vessels vary with the research disciplines. It should be equipped with necessary equipment for research including helipads, helicopter hangar, laboratories, and spaces for personnel. Main purposes for research vessels and our vessel can be for example hydrographic survey, oceanographic research, polar research, or oil exploration.

The strength of the hull should especially be capable for navigation in ice-covered waters. For vessel, the resistance is greater in ice than in open water. For manoeuvrability in ice the features of hull shape that are important are length-to-breadth ratio, flare, mid-body and shapes of bow and stern. Conditions of ice like thickness, coverage and pressure also influences the manoeuvrability. The vessels hull structure should be capable for different impact forces from ice. The ice class PC4 we use should be able to operate year-round in thick first-year ice, which may include old ice inclusions (Canadian Coast Guard, 2012).

To reduce power for propulsion and increase the ship's manoeuvrability in ice some performance enhancing systems can be used. For instance, to reduce drag forces and to aid manoeuvrability low friction coatings and different air bubble systems or water jet/air injection systems could be possible (Canadian Coast Guard, 2012).

2.3 Requirements

There are several types of regulations that creates requirements for our ship type e.g. requirements based on operational area (arctic and Antarctic), regulations from classification society (DNV GL), the International Code for Ships Operating in Polar Waters (Polar Code) and SOLAS.

The Polar Code was adopted in 2014 and applies to ships operating in arctic and Antarctic waters, it includes both mandatory and recommendatory provisions for measures for ship safety and pollution prevention. Since the vessel is going to operate in low air temperature the materials used should be suitable for operation at polar service temperature and for ice strengthened ships the structure of the ship should be designed to resist both global and local structural loads from ice conditions. The polar code includes functional requirements for e.g. stability in intact conditions and in damaged conditions. The ship shall have sufficient stability intact conditions when subject to ice accretion. (IMO, 2015)

SOLAS specifies minimum standards for the construction, equipment and operation of ships, compatible with their safety (IMO, 1974). Also, a code of safety for special purpose ships exists. The code is for special purpose ships that are not less than 500 gross tonnage and carries more than 12 special personnel (persons needed for the operational duties of the ship and are carried in addition to those persons required for navigation, engineering and maintenance of the ships or those that provide services for persons onboard). The special personnel in our case are scientist for research. (MSC, 2008)

We choose DNV GL as classification society and they have classifications and requirements for both vessels for arctic and ice breaking service and for special purpose ships. For the vessels in arctic service the classification covers e.g. materials used in structures, strength for longitudinal and transverse hull girder, rudders and steering gears, propellers and propulsion machinery, and stability for subdivision, intact and damage (DNV GL, 2016). Since our ship is a special purpose ship and carries personnel that are neither crew members nor passengers the class sets requirements. The additional class notation adds additional level of safety in providing reference to design criteria, construction standards and other safety measures concerning special purpose ships. DNV GL also sets requirements for helicopter refuelling and hangar facilities e.g. how the helicopter fuel storage tanks shall be constructed, which materials are compatible and what safety equipment should be available. For the hangar e.g. structural restrictions are set (DNV GL, 2016).

Some technical requirements for ships operating in ice are that the propulsion plant and steering gear must be reliable and capable of responding fast to manoeuvring orders. It is also important for the safety that navigational and communications equipment are reliable. Ice and snow should be easily removable from the engine room and other necessary places where it can cause danger. And for visibility during night good searchlights should be available. For uncertainties with the condition's ships navigating in ice should carry fuel for manoeuvring and fresh water and other supplies if delays occur (Canadian Coast Guard, 2012).

2.4 Challenges

The challenges that affect our ship type are mostly related to the climate. The temperature, winds, different ice conditions and icing superstructure for example. Considering to the condition and regulations one challenge is to make the hull withstand changing ice and harsh conditions. A challenge is also to get the design of the vessel to fit everything needed for our purpose, research equipment and enough space for helicopters and cargo.

2.5 Reference Ships

Two ships have been chosen as a reference ships for our design project. The ships are British RRS Sir David Attenborough and Chinese MV Xue Long 2. Both ships are designed for Artic and Antarctic research and re-supply operations. The ships are chosen as references because they are designed for similar operations in the same operation area as the ship of the design project. Similar technical features like e.g. helicopter hangars, underwater research capability, moonpools and dynamic positioning can be found from the reference ships as from our design plan. Additionally, both ships are deployed into service in 2019, which ensures us that both selected references are up to date.

Table 2 Reference ships

	RRS Sir David Attenborough	MV Xue Long 2
Length overall [m]	128	122.5
Beam [m]	24	22.3
Draft [m]	7	8.3
Gross tonnage	15000	12769
Deadweight [t]	4475	4530
Machinery	Diesel powered, Bergen B33:45 engines (2x 9-cylinder and 2x 6-cylinder)	Diesel powered, Wärtsilä 32 engines (2x 16-cylinder and 2x 12-cylinder)
Power of machinery [kW]	2x 5400 + 2x 3600	2x 9280 + 2x 6960
Cargo volume [m³]	2100+660 of aviation fuel	Not published
Passengers	30 crew + 60 scientists	90
Year built	2019	2019

3 Hull Form and Hydrostatics

3.1 Main Dimensions

As discussed in Section 1.4, the constrains regarding our project vessel's main dimensions are set by the ports. From those comes the maximum draft of 9.1 m and maximum length of 152 m. As the main dimensions are constrained by the ports, our vessel's main dimensions are limited by the dimensions. We gave a couple of methods a try as we determined our ships main dimension:

Statistical Method

We tried the statistical method with the similar initial values as our reference ships have. The table from the course material, which had reference values for the ratio of deadweight tonnage and displacement tonnage (DWT/Δ), did not have a good reference vessel type regarding our project. Thus, we calculated the displacement in tonnes from the reference ships and divided the deadweight with that. This gave us a value for DWT/Δ, which was around 0.35. We compered this with the course material's reference table. The value landed close to RoPax vessels, but our value was a bit higher than the usual value of them. Thus, the value we calculated for the DWT/Δ was quite good represent of our vessel type, as it is somewhat close to the typical passenger vessels, but still is not one, as it has more complex mission.

In Figure 1, there is one example with the output of statistical method with the values of our reference ship. The results of this method were problematic no matter which reference values we used.

Table 3 Statistical method

Inputs	
Deadweight	4575
DWT/Δ	0.345544
V (Knots)	13
Density of water (t/m3)	1.025
Hull Section type	U-section

Ship's Main Characteristics	
Δ	13239.99
LPP	138.69
B	21.34
T	5.39
D	10.27
C_B	0.810
C_M	0.994
C_P	0.815
C_{WP}	0.878

The ships length was over 10 m longer than our reference ship, which alone would not be a problem, but the draft differed also a lot. The drafts of our reference ships are 7 m (RRS Sir David Attenborough) or 8.3 m (MV Xue Long 2). The statistical method, however, proposed that our draft should be only around 5.4 m. This would mean that our draft would be 23-35 % smaller than the reference ships'. Considering the ice breaking capability and the alike missions with the reference ships, we determined that this would be too big of a change in the main dimension, and thus decided not to use the statistical method to define the main dimensions.

Normand's Number

We used data of our reference ship RRS Sir David Attenborough to determine our vessel's main dimensions using Normand's Number. The data about the length, beam, draft, block coefficient, deadweight and displacement were available, but we used different approximations to determine the hull, machinery, outfitting and fuel weight for the calculation of the Normand's Number. The Normand's Number ended up being 2.45. Requiring at least a draft of 7 m, the length becomes 119 m, and the beam becomes 22 m.

Thus, the ship's main dimensions based on this method were:

Table 4 Normand's Number

Length	119 m
Beam	22 m
Draft	7 m
Displacement	12912 tonnes

Final Main Dimensions

The results of the Normand's Number were the starting point of defining further our hull form. The main dimensions got changed by a little during the hull forming process and the final values of our main dimensions are presented in Table 5:

Table 5 Main dimensions

Length between perpendiculars	117.1 m
Length overall	132.92 m
Beam	22 m
Draft	7 m
Displacement	11895.7 tons

3.2 Hull Form

The design process of the hull form for ice going vessels usually takes in consideration to minimize the ice resistance by optimal shapes of the beam and bow, to ensure good operational characteristics, enables the ship to go astern as much as required and minimizes the ice impact on the propellers (Riska, 2010). The design for ice-going vessels is primary based on the vessel's intended use, since our vessel is a research vessel (not a typical icebreaker) and is also going to operate in open water the hull is designed to have good manoeuvring (Quinton & Lau, 2005). While designing the hull for a polar class vessel the ice loads on different areas needs to be taken in consideration mainly when choosing the bow. An icebreaking bow (without a bulbous bow) enables the vessel to ride over the ice and exerts downward force to break the ice, compared to non-icebreaking bows which has a more crushing behaviour for the ice (Dolny, 2018). The hull form is typically optimized to clear the ice away from the propellers and other underwater appendages and to reduce the surface drag of the ice on the aft section (Dolny, 2018).

Sectional Area Curve

There are some typical characteristics related to the hull of ice-going ships. Hulls are designed to break, bend, and push the ice away by using its own weight. Form of the bow of ship has big effect on this capability. Usually, icebreakers are built with full bows. Full bow results in more displacement in the front of the ship which improves manoeuvring in the ice. Longitudinal centre of buoyancy (LCB) and the station of maximum beam is thus often shifted forward of the amidship (Quinton & Lau, 2005). Parallel mid-bodies on the ice breakers tend to be avoided because ice breaking capability of parallel mid-body is weak (Moton, 1991). These facts have effect on sectional area curves of ice breakers, which are often tilted to the forward of amidship.

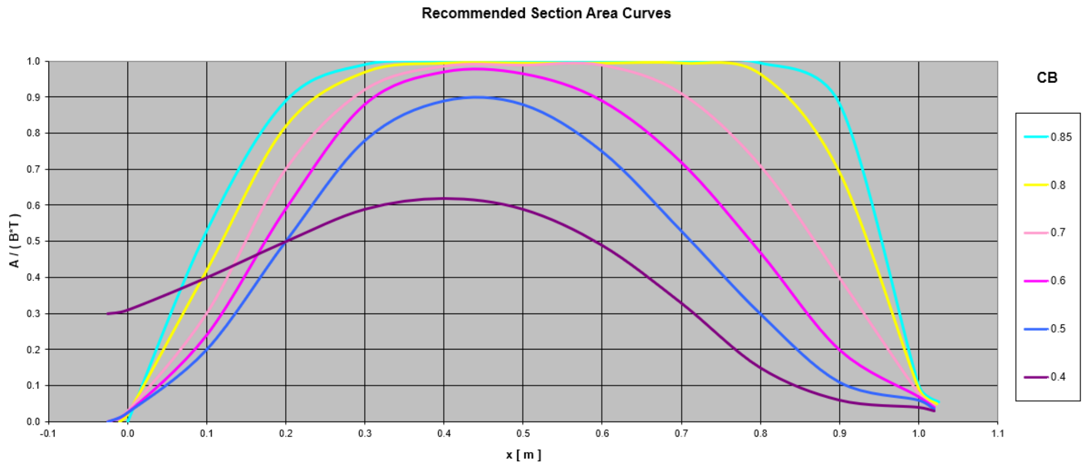

Figure 3 Recommended Section Area Curves

The sectional area curve gives the displaced volume of the vessel. While determining our vessels main dimensions we used the value for the block coefficient as 0.7 and looking at available data of icebreakers the block coefficient is on average around 0.62. Our value for the sectional area curve came to correspond the value earlier used. The curve matches the characteristics of a short mid-body described earlier and the form of the bow grows sharper than the stern. The centre of the area under the section area curve gives the LCB for the vessel, which in our case is backward of the amidship. Since our vessel is not designed as a typical icebreaker and to keep performance for open water the LCB does not need to be that fore as for an icebreaker.

Bow Design

The bow shape that has been selected for this ship is the spoon bow, seen in Figure 4.This bow shape is commonly used on icebreakers, including on both the RRS Sir David Attenborough and the MV Xuen Long 2. Furthermore, a spoon bow with a small stem angle (between 20-25 degrees) is considered to have very low ice resistance (Riska, 2010), (Quinton & Lau, 2005). The reason this stem angle must be small, is because a smaller stem angle increases the vertical component of the pushing force from the bow onto the ice. This in turn increases the downward bending load onto the ice. Thus, thicker ice can be broken with the same pushing force (Riska, 2010).

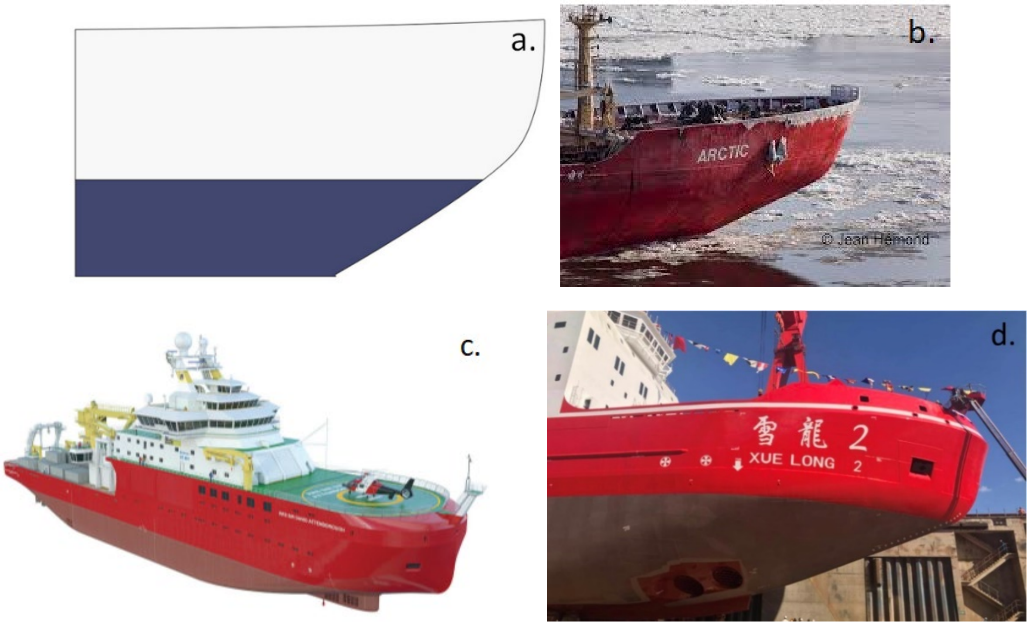

Figure 4 Ice breaking ships with spoon bows: a. schematic of a spoon bow, b. bow of the a Fednav Arctic ship (Hémond, 2014), c. Bow of the RRS Sir David Attenborough (Ingenia, 2018), d. Bow of the MV Xuen Long 2 (Aker Arctic, n.d.).

Furthermore, at the very bottom of the hull, from the bow to the shoulders, there will be a wedge that allows ice to flow beneath the bow and be pushed to the side, preventing ice from getting to the propellers (Czimmek, 1991). This design is illustrated in Figure 3. This adjustment was made at a late stage, so it is not shown in the line drawings at the end of this document.

Figure 5 Schematic of the wedge used to push ice away from the hull, adjusted from (Czimmek, 1991).

The bow should also prevent shoulder crushing, which is the piling up of ice that is in contact with the ship's shoulder. Shoulder crushing can create an increase in ice resistance; however, scale model tests are currently the only way shoulder crushing can be predicted and so shoulder crushing will not be considered in this ship's design (Riska, 2010).

Stern Design

Only little sources were found about stern design of icebreaking vessels that were not behind paywall. Viewing pictures of icebreaking vessels one can notice that they have long and gentle stern (Figure 4). Stern should have large enough clearances between tip of propeller blades and stern frames and bottom of the level ice sheet. Clearances must be large enough to avoid loads that can occur when ice floes are forced between the propeller and the stern frame and when propeller can hit large ice floes (Traficom, 2019). Number of propellers affects greatly to the stern design. Stern design must such that it protects rudders and propellers (Canadian Coast Guard, 2012).

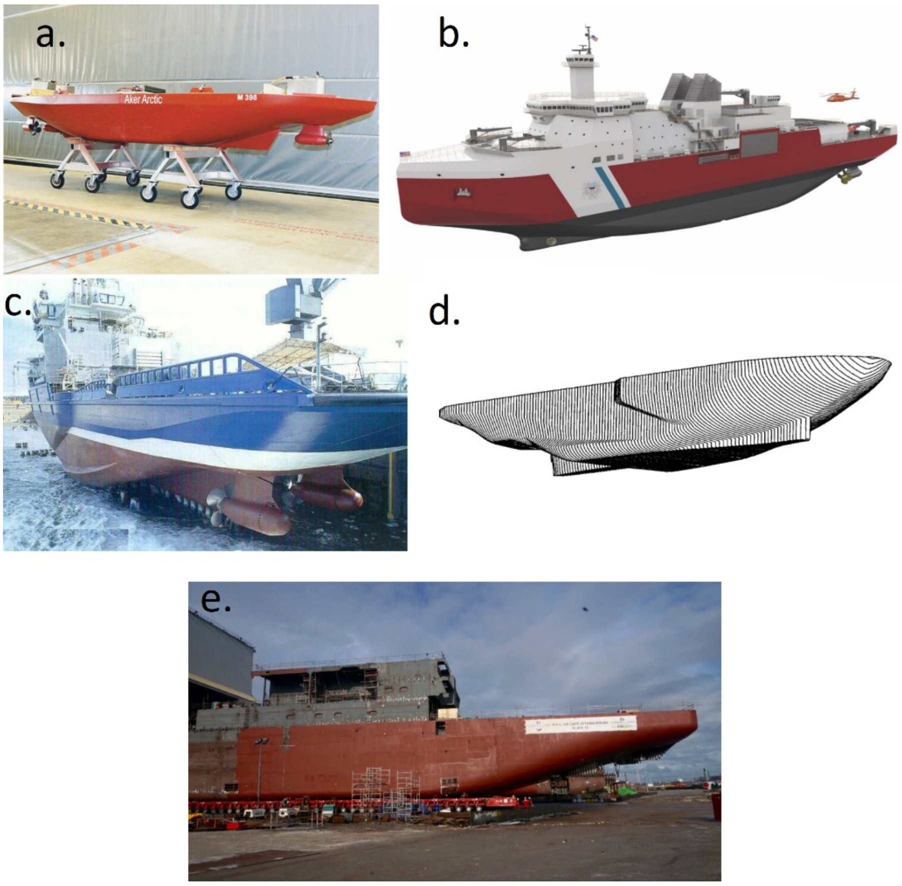

Figure 6. Sterns of icebreaking ships: a. hull model of icebreaker Polaris (Riska, 2010), b. planned U.S. Coast Guard Polar Security Cutter (Werner, 2019), c. stern of multipurpose icebreaker Botnica (Riska, 2010), d. hull shape of icebreakers Finnica and Nordica (Sodhi, 1995), e. stern of RSS David Attenborough (British Antarctic Survey, 2017).

Draft Sketch

The draft sketch was done with the provided *hull form* -excel file. The sketch was done by varying the non-dimensional values and keeping an eye on the Section Area Curves and on the values of the coefficients of fineness.

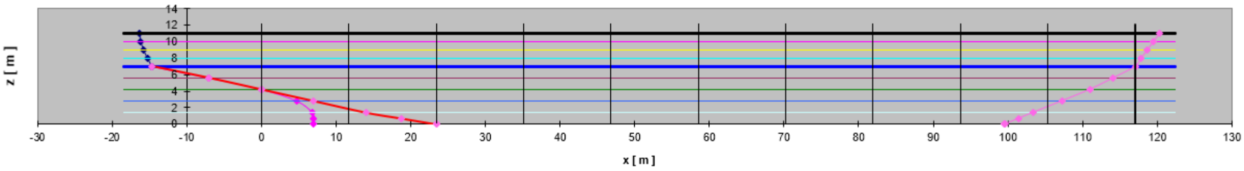

Figure 7 Profile sketch

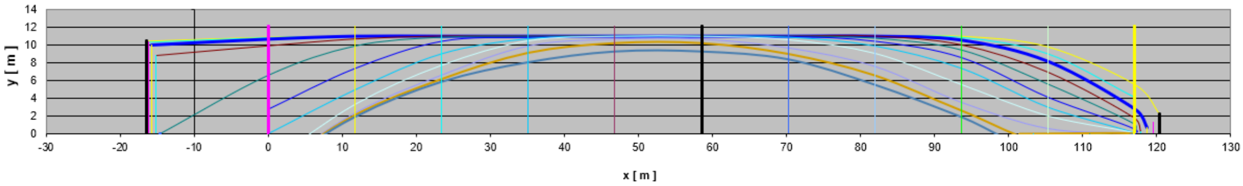

Figure 8 Waterline sketch

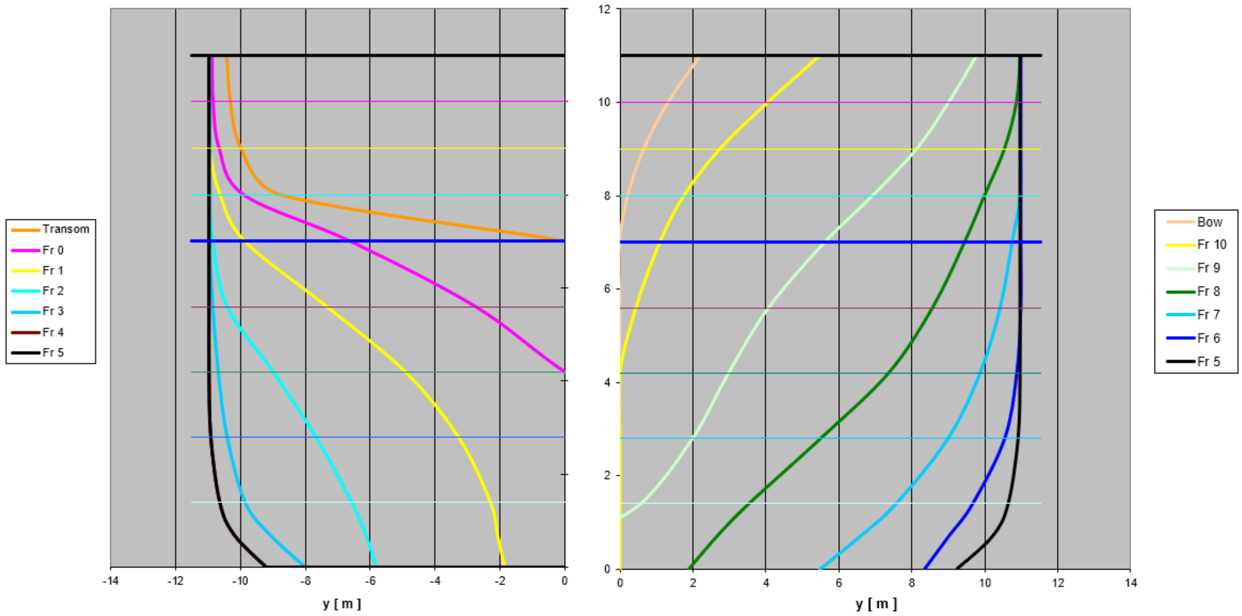

Figure 9 Frame Section sketches

3.3 Hydrostatics

Hull Model

The above presented draft sketch was the basis for further shaping the hull model. This was implemented by importing the draft sketch to Delftship and shaping the hull form based on them. The result of this process can be seen in Figure 10.

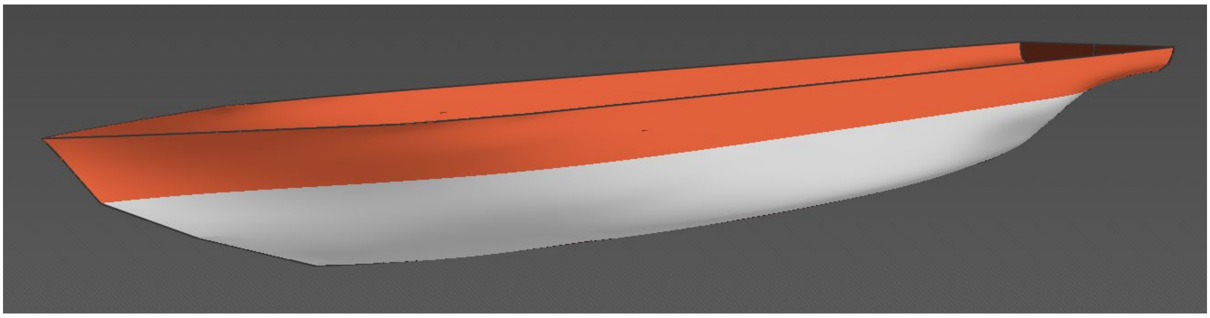

Figure 10 The hull model

After the model was ready, the waterlines and frame sections were determined to create the lines plan picture below.

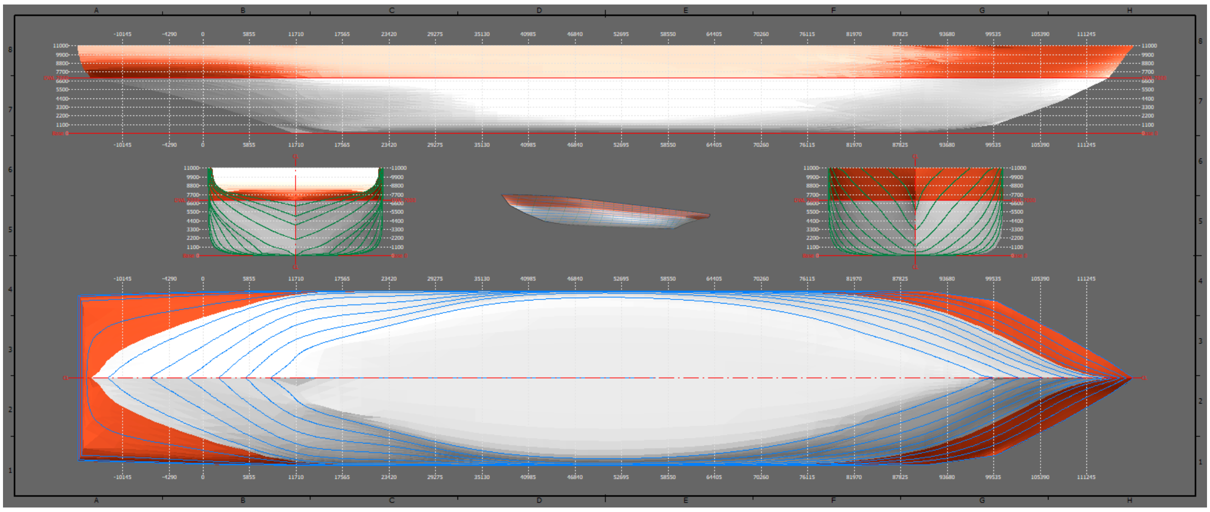

Figure 11 The Lines Plan

Main Dimensions and Coefficients of Fineness

The design's hydrostatic report in the Appendix 1: Design hydrostatics report. The main dimensions can be seen to match the dimensions determined earlier: length of perpendiculars being 117.10 m, beam of 22 m and draft being 7 m.

The total displacement volume of this design according to Delftship is 11605.5 m^3. The Hull Lines -excel that was used to create this model, approximated the displacement volume to be 12 163 m^3. Thus, there is a slight change. The block coefficient according to Delftship was 0.6436 and according to excel 0.678. The difference checks out as the main dimensions are the same, but the displacement volume is not.

These and the other coefficients of fineness from the different sources compared below in table 1:

Table 6 Coefficients of fineness

	Delftship	**Hull Lines -excel**
Block coefficient	0.6436	0.678
Prismatic coefficient	0.6803	0.691
Waterplane coefficient	0.8701	0.903
Midship area coefficient	0.9460	0.981

The Longitudinal Centre of Buoyancy

The longitudinal centre of buoyancy (LCB) according to the Delftship model was -6.094 %. This turned out to be worse than what the excel had predicted. Compared to empirical equations, the LCB should be in the range of -2 % to 0.15 % for block coefficient around 0.68 and in the range of -2.8 to -0.8 for block coefficient around 0.64. The excel predicted based on the draft sketch LCB to be -3.3 % which in this case would have been better.

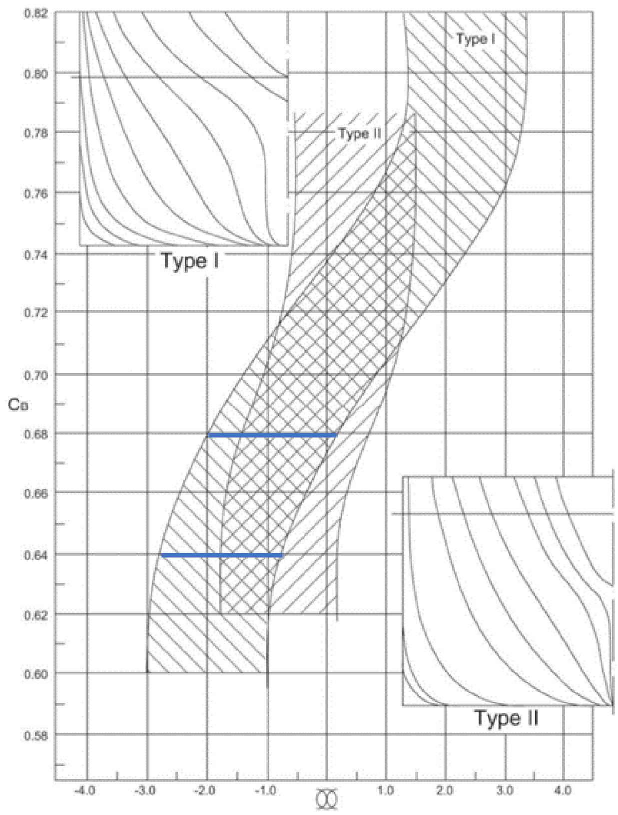

Figure 12 Empirical data about LCB

3.4 **Hull Volume** Estimation

Calculating Whole and Part Cubes

We estimated hull volume of our project ship by calculating whole and part cubes inside the hull using excel (Figure 13). Part cubes counted as half of the cubes. We determined volume of cubes using formula below.

$$x \times y \times z = frame\ length \times 1\,m \times distance\ between\ WPAs$$

Hull lines are from our hull line calculations and our estimation excel (Figure 13) checks if coordinates of corners of cube are inside the hull lines or not and then one can see if the whole cube is inside the hull lines or not.

		% step 2:	0.5 if corner touch whole square									
Y [m]	11	0	0	0	0.5	0.5	0.5	0.5	0	0	0	0
	10	0	0	0.5	0.5	0	0	0.5	0	0	0	0
	9	0	0	0.5	0	0	0	0.5	0.5	0	0	0
	8	0	0	0.5	0	0	0	0	0.5	0	0	0
	7	0	0.5	0.5	0	0	0	0	0.5	0.5	0	0
	6	0	0.5	0	0	0	0	0	0	0.5	0	0
	5	0	0.5	0	0	0	0	0	0	0.5	0	0
	4	0	0.5	0	0	0	0	0	0	0.5	0	0
	3	0.5	0.5	0	0	0	0	0	0	0.5	0.5	0
	2	0.5	0	0	0	0	0	0	0	0	0.5	0
	1	0.5	0	0	0	0	0	0	0	0	0.5	0
	0	0.5	0	0	0	0	0	0	0	0	0.5	0
		0	1	2	3	4	5	6	7	8	9	10
											X [frames]	

		% step 1:	1 if square corner inside of awp curve									
Y [m]	11	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	1	1	0	0	0	0	0
	9	0	0	0	1	1	1	0	0	0	0	0
	8	0	0	0	1	1	1	1	0	0	0	0
	7	0	0	0	1	1	1	1	0	0	0	0
	6	0	0	1	1	1	1	1	1	0	0	0
	5	0	0	1	1	1	1	1	1	0	0	0
	4	0	0	1	1	1	1	1	1	0	0	0
	3	0	0	1	1	1	1	1	1	0	0	0
	2	0	1	1	1	1	1	1	1	1	0	0
	1	0	1	1	1	1	1	1	1	1	0	0
	0	0	1	1	1	1	1	1	1	1	0	0
		0	1	2	3	4	5	6	7	8	9	10
	cubes:	43	% step 3:	calculating whole squares from coordinates manually							X [frames]	
	1/2 cubes	16										

Figure 13 Screenshot of excel sheet used to estimate hull volume. Blue cells mark coordinates of whole squares and green cells mark part squares on one specific WPA.

Estimation of the volume of the hull to upper deck is 21933.5 m^3, which is relatively good value when compared to 22700 m^3, value obtained from excel for our hull lines. Calculated volume is the volume of the hull between frames 0 and 10, meaning stern and the bow are not calculated.

Simpson's First Rule

The given excel for Simpson's first rule integration was used to calculate volume both with cross section areas on different frames and with waterplane areas on different waterlines. For the volume based on cross-sectional areas the ships length was divided into frames and calculated cross-sectional areas for each off them. The result for that became 21300 m^3 and for the second integration 21467.4 m^3. In the second integration the waterplane areas were calculated. There is a bit difference between the volumes which can be due to that the values used was approximated from the values we have used to calculate hull lines. Also, when integrating the volume with waterplane areas the area for stern and bow was not considered.

Table 7 Result from Simpson integration using cross-sectional areas.

Volume	21300	m3
Density of water	1,025	t/m3
Displacement	21832,87149	t
LCB from fr0	59,646	m

Table 8 Result from Simpson integration using waterplane areas.

Volume	21467,4	m3
KB	6,194	m

Volumes obtained from the given excel for Simpson's first rule are both smaller than the estimated volume, this might be due to actual volume of the hull inside the half cubes being smaller than volume of the half cubes.

The hull volume to upper deck has been calculated in the excel for our hull lines as 22700 m^3. And the difference between those can also be due to approximations and difference in waterlines and frames. From calculating the cross-sectional areas, a SAC curve was made and the LCB calculated. The SAC curve consists of the sectional areas for the whole length of the vessel. The LCB calculated is at 59,646 m which is more aft from our previous SAC lines. The SAC lines have difference in the x-coordinates. From the second integration we also get a value for the vertical location for centre of buoyancy from the keel (KB) as 6.194 m. Which seems a bit high since our draft is 7 m (maximum draft 11 m used in the integration) but the hull shape has a quite flat bottom and are not so deep at the aft, which could make the KB a bit high.

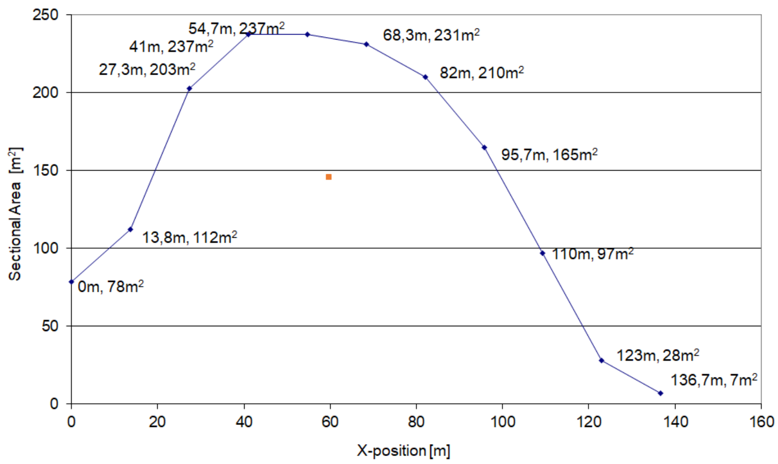

Figure 14 Sectional Area curve

The volume of the hull to upper deck was estimated to be 21933.5 m^3 by using whole and part cubes estimation. The Hull Lines -excel calculated that value to be around 22700 m^3. The Delftship does not calculate this value automatically, but by setting draft to almost at the height of the upper deck, the hydrostatic report can be used to obtain an estimated value. By doing this, we obtained that according to the Delftship, the whole hull volume would be around 21700 m^3. This estimate is valid when compared to the other two estimates.

4 General Arrangement (GA)

4.1 GA Requirements

Safety

Safety on the vessel is taken into account on many aspects. The personnel safety is considered by making the GA so that it is not labyrinthine. This way, in case of emergency, it is easier for the personnel to get to safety.

On decks 5 and 6, there is enough lifeboats for 110 % of the maximum personnel capacity of the vessel. The lifeboats are stationed so that they are easy to access from all places on board, i.e., close to the stairways and also so that they are accessible also from the outside areas of the decks.

There are also survival kits (both personal and group) suitable for the polar environment on the lifeboats as well as survival equipment on board in case the vessel gets stuck. The capacity of these equipment and kits is 110 % of the maximum number of persons on board.

The helicopter safety is taken care by arranging helicopter deck and hangar big enough so that the helicopter operations can be carried through safely.

Also, lot of other arrangements are also vital for the survivability of the crew. For example, the GA includes a hospital area so that minor infections can be handled accordingly and also needed help in case of personal injuries are available on board.

For safety according fire, detection and extinguishments systems are placed on the vessel. Since the vessel is operating in cold climate the fire-fighting systems need to be anti-freezing. It's also necessary that equipment with high fire risk is placed safely for example engine rooms and storage of liquids, and to use fire safe materials. The stairways are placed so that personnel and crew can escape to the lifeboats from each deck. For safety and escape reasons the breadth and length of stairs and corridors in different locations shall also meet the SOLAS regulations.

Water: Fresh, Grey and Black

The ship water treatment systems will make sure that the ship can continuously re-use freshwater, so that fresh water does not have to be replenished. This is because the ship should be able to stay on the sea for 64 days without going back to shore for water. Still some amount of fresh water will be lost in amongst the dry waste. However, if all water treatment systems fail in such a way that no new drinking water can be produced, there should be enough fresh water in the tank left for 14 days for normal service in order to fix the problem.

To calculate this required amount of fresh water, one must know how much freshwater people use. The amount of fresh water used by people in different countries varies, for example it is about 0.142 m^3 in the UK (Energy Saving Trust, 2013) and 0.150 m^3 in Finland (Helsinki Times, 2012) but sadly, there seems to be little clear data on how much water is used on ships. The number 0.3 m^3 per person per day seems to be pop up as well a lot, though often in the contexts of cruise ships. Given that the only two real sources use numbers at around 0.145 m^3 per person per day, a 0.16 m^3 of freshwater per person per day will be assumed, providing 15 extra litres of water per person per day as a safety factor. This leads to a total required amount 274 m^3 of water that needs to be added into the freshwater tank. 10 percent will be added to this to compensate for the potential water loss during treatment. Leading to a final total requires freshwater capacity of 300 m^3.

Now to determine how much of this 300 m^3 will go into the grey water tank and how much will go into the black water tank should the water treatment system fail. The average person in Germany uses 25-50 L of water every day just by flushing the toilet. Taking the highest number of 50 L, 110 L of the 160 L used per person per day would be left for showering, drinking, cooking and washing clothes. That means 69 % of the total is grey water and the remining 31 % is black water. That in turn means that the grey water and black water tanks need a capacity of 206 m^3 and 94 m^3 respectively.

Fuel: Hydrogen and Diesel

All power not required for seakeeping will be provided by liquid hydrogen. The total amount of hydrogen required is determined in chapter 6.5 to be 402 m^3.

On 62-day voyages fuel consumption for whole voyage is 1042 tons of fuel oil. Given a marine diesel density of 0.9 ton/ m^3 (Danish Environmental Protection Agency, 1998), the total required tank volume for diesel is 1158 m^3.

Table 9 Fuel oil consumption per voyage

	Open water	Light ice cond.	Heavy ice cond.	Sum.
Per voyage	70%	25%	5%	100%
Hours / voyage, h	1075.2	384	76.8	1536
Prop. Power, kW	2600	4388	21444	
Fuel cons., kg/h	442.26	746.40	3647.62	
Fuel/voyage, ton	475.5	286.6	280.1	1042

Ballast Water

At full capacity the ship should have a draft of 7 m, with a displaced volume of 11605 m^3 according to Delftship, which is equivalent to 11840 tonnes. Of this, the deadweight is 4475 tonnes. Even without the dead weight the ship should preferable still be at a draft of 7 m because no stability calculations have been performed yet. In order to achieve this, 4475 tonnes of seawater will have to be added, which means that total ballast water tank capacity must be 4564 m^3.

Frame Spacing

The frame spacing used in the GA is 800 mm as it in practise is between 500-900 mm. Since our vessel has an overall length over 120 m it will also have longitudinal frames with wider spacing (mixed framing system).

Height of the Bow

ILLC and Classification societies have regulations and guidelines for the minimum bow height for ships. Sufficiently high bow provides enough area for anchoring and mooring equipment and prevents water from splashing on the deck in rough sea conditions.

According to ILLC regulations (Mochammad, 2014), minimum bow height for ships below 250 m in length can be derived by following equation:

$$H_b = 56 \times L \times \left(1 - \frac{L}{500}\right) \times \frac{1.36}{C_b + 0.68} = 5587.18\,mm$$

, where $C_b = 0.688$ and L=139 m.

DNV GL (DNV GL, 2016) has it own requirements for the minimum bow hight derived with following equation:

$$H_b = \left[6075 \times \left(\frac{L_f}{100}\right) - 1875 \times \left(\frac{L_f}{100}\right)^2 + 200 \times \left(\frac{L_f}{100}\right)^3\right] \times \left[2.08 + 0.609 \times C_b - 1.603 \times C_{wf} - 0.0129 \times \left(\frac{L_f}{T}\right)\right] = 4637.96\ mm$$

, where freeboard length $L_f = 130.3\ m$, $T=7\ m$, $C_b = 0.688$ and water plane area coefficient forward of $\frac{L_f}{2}$ $C_{wf} = 0.85$.

Bow height of our ship is 7 m, which fulfils both requirements.

Double Bottom

Classification society requires double bottom from collision bulkhead to aft peak bulkhead. DNV GL has defined minimum height for the double bottom by following equation:

$$H_{db} = 1000 \times \frac{B}{20} = 1100\ mm\ , minimum\ allowed\ H_{db} = 760mm$$

, where $B=22\ m$. (DNV GL, 2016)

Height of double bottom of our vessel is 1200 mm which exceeds the value required by DNV GL.

Bulkheads

For ships with length between 125 m and 145 m DNV GL requires 6 transverse bulkheads if engine is aft, and 7 if engine is anywhere else. In our case engine is not at aft, thus required number of bulkheads is 7. All ships are required to have at least one collision bulkhead, one aft peak bulkhead and one bulkhead at each end of the engine room.

For ships with an electrical propulsion plant, like our ship, both the generator room and the engine room must be enclosed by watertight bulkheads. Space of four frames must be left between the engine and bulkheads to have space for maintaining and service. Aft peak bulkhead should form watertight compartment enclosing the stern tube and the rudder trunk.

Collision bulkhead is designed as a barrier for water in case of collisions. Location of collision bulkhead is defined by SOLAS and classification societies. For ships without bulbus bow and with length less than 200 m position of collision bulkhead should be

$$0.05 \times L_f \geq X_c \geq 0.08 \times L_f$$

, where X_c is the distance from forward perpendicular in meters.

In result, our collision bulkhead should be from 6.5 m to 10.4 m from the forward perpendicular. Our value is 8 m, which fits the required values.

Fire Zones

The fire zones will be divided by bulkheads, decks and doors. In practise the bulkheads for fire zones are constructed from steel and insulated to prevent spreading of smoke, heat and flame. According to SOLAS the main vertical zones have a maximum length of 48 m to meet the subdivision of watertight bulkheads (IMO, 2002), which means that at least three of our bulkheads (at frames 32, 85 and 105 in the GA) will be constructed to meet the regulations of fire zones and watertight. The maximum area of a main vertical zone is 1600 m^2 (IMO, 2002).

4.2 GA Definition

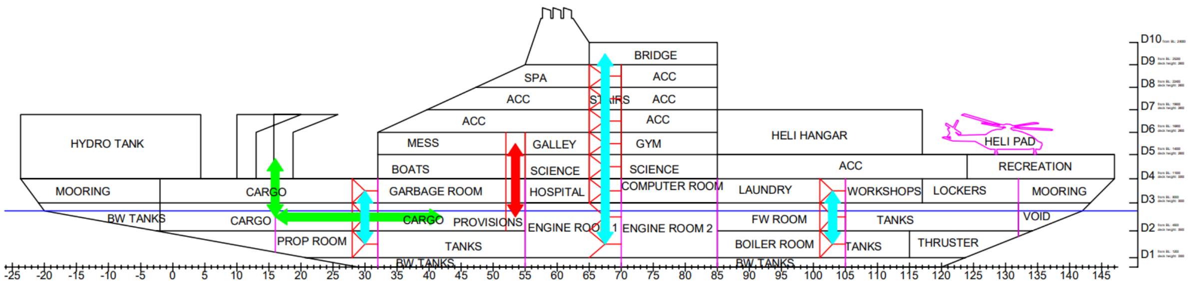

Figure 15 Sideview of Khione showing cargo flows (green), people flows (blue) through stairs and provision flow (red) from provision storages to galley.

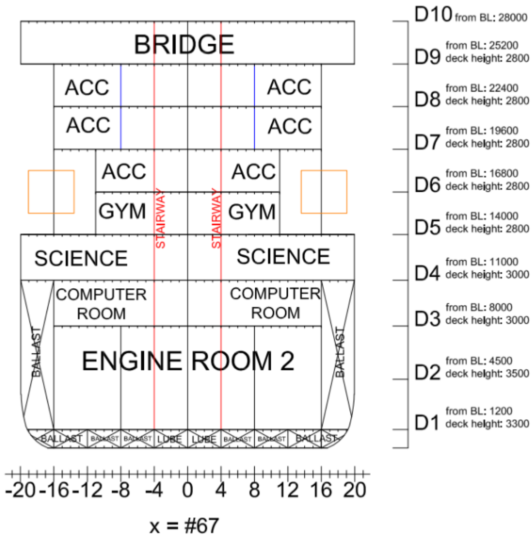

Figure 16 Midsection of Khione showing engine room.

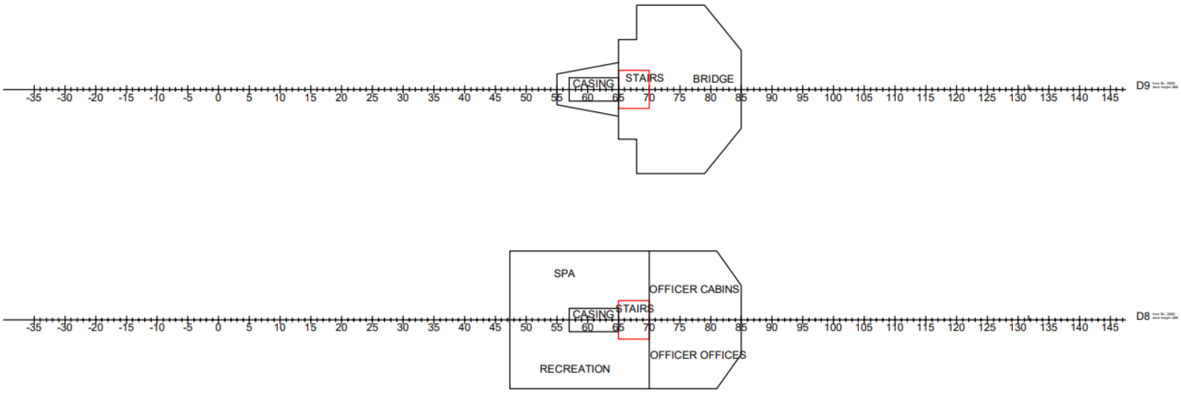

Figure 17 Decks 9 and 8.

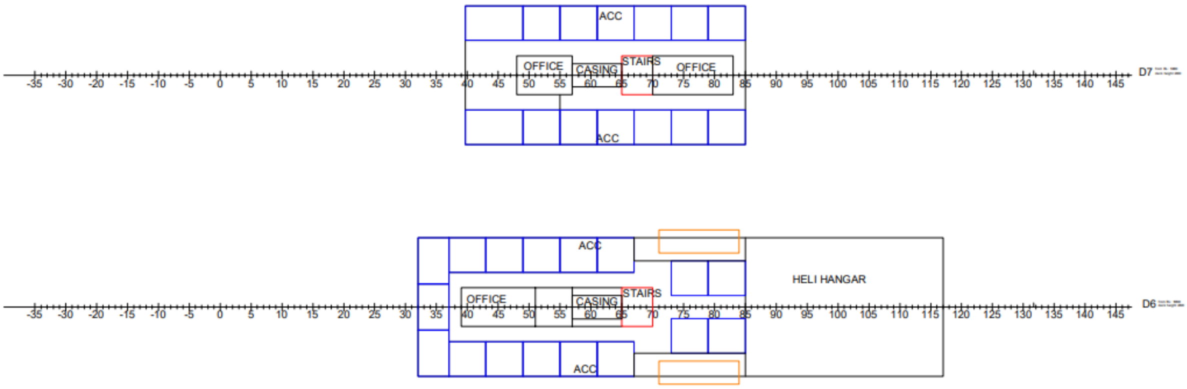

Figure 18 Decks 7 and 6.

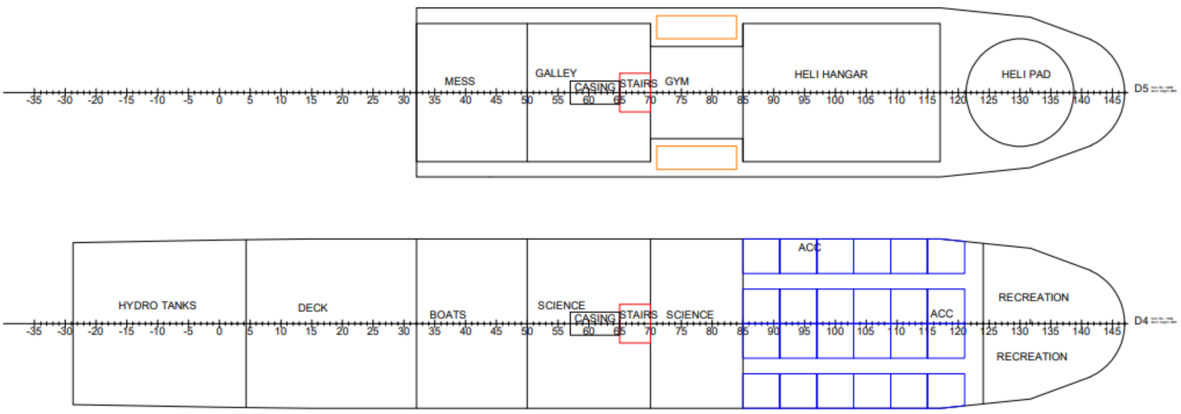

Figure 19 Decks 5 and 4.

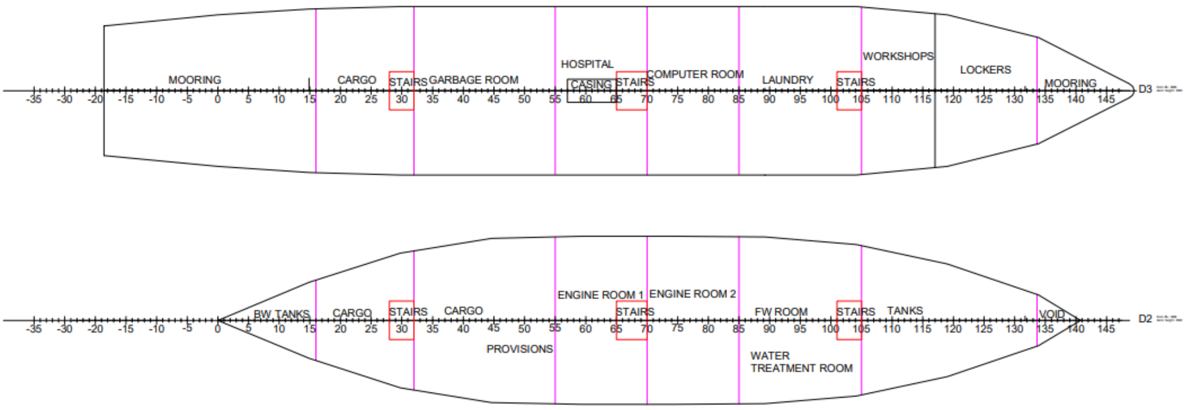

Figure 20 Dicks 3 and 2.

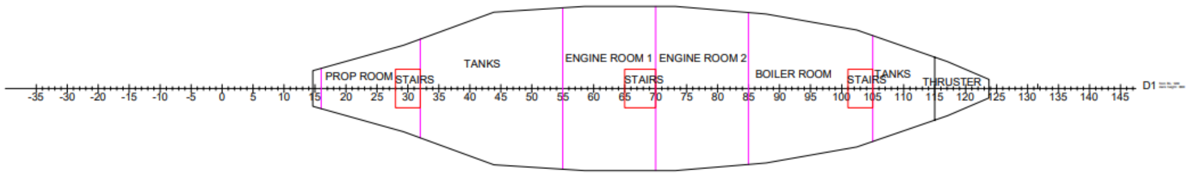

Figure 21 Deck 1.

5 Structure

5.1 Structural Requirements

Longitudinal Strength

DNV GL has its own regulations for ice class ships regarding the longitudinal strength. Required strength is assessed by combining ice loads and load of still water (DNV GL, 2016). Through equations, provided by DNV GL, combined stresses on the ship can be calculated. Calculated values should be compared to permissible bending and shear stresses at different locations along the ship. Also, local buckling strength must be verified. Equations for the combined stresses of blunt bow vessel are presented below.

Design vertical ice force $\mathbf{F_{IB}}$ at the bow, in MN

$$F_{IB} = minimun(F_{IB,1}; F_{IB,2})$$

, where

$F_{IB} = 0.534 \times {K_I}^{0.15} * sin^{0.2}(\gamma_{stem}) \times (\Delta_{kt} \times K_h)^{0.5} \times CF_L, in\ MN$

$F_{IB,2} = 1.20 \times CF_F, in\ MN$

$K_I = indendation\ parameter = \ K_f / K_h$

$K_f = (2 \times C \times B^{1-eb} / (1 + e_b))^{0.9} \times \tan{(\gamma_{stem})}^{-0.9\times(1+eb)}$

$CF_L = Longidutinal\ strength\ class\ factor$

$e_b = 0.4\ to\ 0.6\ for\ a\ spoon\ bow\ form$

γ_{stem} = Stem angle to be measured between the horizontal axis and the stem tangent at the upper ice waterline, in degrees

$C = 1/(2 \times (\frac{L_B}{B})^{eb}$

$L_B =$ Bow length used in the equation $C = 1/(2 \times (\frac{L_B}{B})^{eb}$

$\Delta_{kt} =$ Ship displacement, in ktonnes at UIWL, not to be taken less than 10 ktonnes

$A_{wp} = Ship\ water\ plane\ area, in\ m^2$

$CF_F = Flexural\ failure\ class\ factor$

Design vertical shear force along the hull girder, in MN

$$F_I = C_f \times F_{IB}$$

, where

$C_f = Longitudinal\ distribution\ factor\ to\ be\ taken\ as\ follows$:

a) Positive shear force
   $C_f = 0.0\ between\ the\ aft\ end\ of\ L_i and\ 0.6L_i\ from\ aft$

$$C_f = 1.0 \; between \; 0.9L_i and \; the \; forward \; end \; of \; 0.6L_i$$

b) Negative shear force

$$C_f = 0.0 \; at \; the \; aft \; end \; of \; L_i$$
$$C_f = -0.5 \; between \; 0.2L_i and \; 0.6L_i \; from \; aft$$
$$C_f = 0.0 \; between \; 0.8L_i \; from \; aft \; and \; the \; forward \; end \; of \; L_i$$

, where L_i is ship length in m

Design vertical ice bending moment along the hull girder, in MNm

$$M_I = 0.1 \times C_m \times L_i \times sin^{-0.2}(\gamma_{stem}) \times F_{IB}$$

, where

γ_{stem} *is as given*

F_{IB} *= design vertical ice force at bow, in MN*

For our ship M_I is 210.6 MNm.

C_m = Longitudinal distribution factor for design vertical ice bending moment to be taken as follows:

$$C_m = 1 \; between \; 0.5L_i \; and \; 0.7L_i \; from \; aft$$

$$C_m = 1 \; between \; 0.5L_i \; and \; 0.7L_i \; from \; aft$$

$$C_m = 0.3 \; at \; 0.95L_i \; from \; aft$$

$$C_m = 0.0 \; at \; the \; forward \; end \; of \; L_i$$

$$L_i = Ship \; lenght \; of \; upper \; ice \; waterline \; UIWL, in \; m$$

Longitudinal Strength Criteria

Table 10. Failure stresses

Failure mode	*Applied stress*	*Permissible stress when $R_{eH} / R_m \leq 0.7$*	*Permissible stress when $R_{eH} / R_m > 0.7$*
Tension	σ_a	$\eta \cdot R_{eH}$	$\eta \cdot 0.41 \, (R_m + R_{eH})$
Shear	τ_a	$\eta \cdot \tau_{eH}$	$\eta \cdot 0.41 \, (R_m + R_{eH}) \, / \, (3)^{0.5}$
Buckling	σ_a	σ_c for plating and for web plating of stiffeners σ_c / 1.1 for stiffeners	
	τ_a	τ_c	

, where

σ_a *= Applied vertical bending stress, in* N/mm^2

$\tau_a = Applied\ vertical\ shear\ stress, in\ N/mm^2$

$R_{eH} = Specified\ minimum\ yield\ stress\ of\ the\ material, in\ N/mm^2$

$R_m = Specified\ minimum\ yield\ stress\ of\ the\ material, in\ N/mm^2$

$\sigma_c = Critical\ buckling\ stress\ in\ compression, in\ N/mm^2$

$\tau_c = Critical\ buckling\ stress\ in\ shear, in\ N/mm^2$

$\eta = 0.8$

Hull Girder Ultimate Strength

DNV GL states that hull grider ultimate bending strength should be checked for hogging and sagging conditions. Hull grider ultimate bending capacity at any vertical hull transverse section must satisfy the following criteria:

$$M \leq \frac{M_U}{\gamma_R}$$

, where

$M =$ *Vertical bending moment based on still water hogging and sagging conditions and wave bending moment, in kNm*

$M_U =$ *Vertical hull girder ultimate bending capacity, in kNm*

$\gamma_R =$ *Partial safety factor for the vertical hull girder ultimate bending capacity*

Structural Continuity

Continuity means that the ship structures doesn’t have abrupt changes in their geometries. Discontinuities should be avoided because they gather stress concentrations and are most likely areas to fail. DNV GL has listed areas that should be paid special attention when considering the continuity of structures:

- in way of changes in the framing system
- at end connections of primary supporting members or stiffeners
- in way of the transition zones between midship area and fore part, aft part and machinery space
- in way of side and end bulkheads of superstructures

DNV GL also states that at the termination of a structural member, structural continuity shall be maintained by the fitting of effective supporting structure. Between the midship region and the end regions there shall be a gradual transition in plate thickness for bottom, shell and strength deck plating. Considering the longitudinal continuity DNV GL recuires to arrange longitudinal members in such way that continuity is kept. Precise description of arrangement of longitudinal members can be found in DNV GL Rules for Classfication, Part 5, Chapter 3 (DNV GL, 2016).

Ship Specific Challenges

Specific structural challenges for our vessel will mostly be on the main deck. We decided to use liquid hydrogen for all the other power onboard which means we have placed hydrogen tanks on the aft of the vessel, which makes additional weight placed there. The use of hydrogen also comes with safety requirements and will need space for all systems required for generating the power. Tanks take up space from the cranes also placed on the aft which makes the gap for cargo handling small. The cranes will be used for handling cargo, resupply and moving boats etc. and as the tanks needs space for systems required for the use.

Structural challenges are also the helicopter hangar which must be designed to fit the helicopters and equipment needed for the service of them. As the vessel is ice-going and has the PC4 requirements concerning them needs to be considered. Otherwise, the laboratories and inside areas doesn’t come with structural challenges and will be placed to fit the hull structures.

5.2 Steel General Arrangement

Preliminary Cross Section

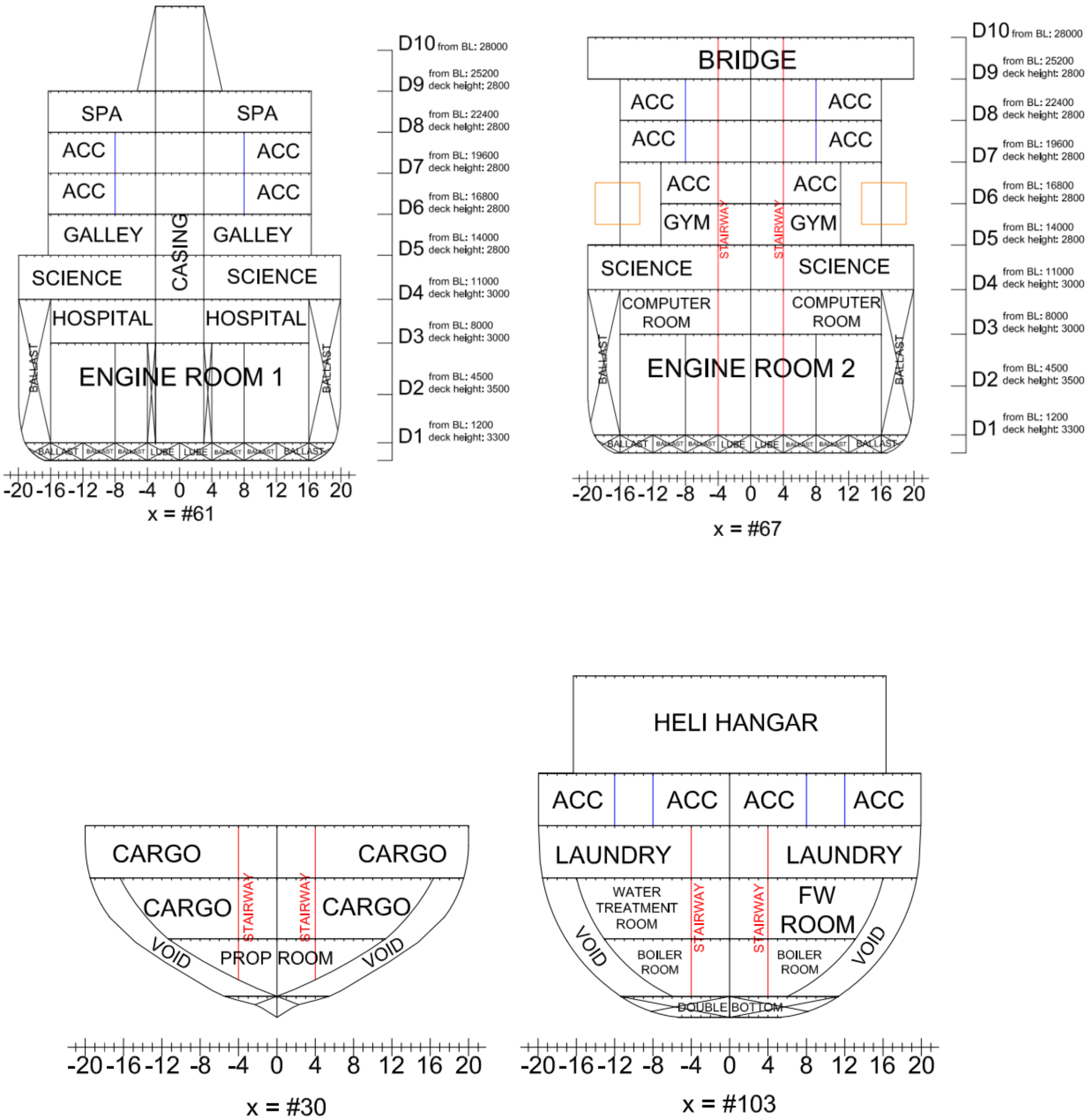

Figure 22 Cross sections on frames #61, #67, #30 and #103

We draw the preliminary cross sections drawings in four points: at transverse framing points #30, #61, #67, and #103. All longitudinal walls are drawn to align with the longitudinal spacing.

Framing System

Our project ship has longitudinal framing, because its overall length over 120 m. Longitudinal frames are fitted evenly on tank bottom with 550 mm spacing. Frame supports are spaced on every 500 mm along frames. In midships, where engine rooms are located, side girders are fitted on 4th, 8th, 12th and

16th longitudinals. Frame spacing influences to shell thickness t_{net} and it was iterated to have appropriate shell thickness.

Building Materials

The building materials for our vessel will follow the requirements from IACS Polar Ship Rules and DNV GL. Our vessel has the polar class 4 so the steels used shall be based on lower air temperatures than generally anticipated for worldwide operation (IACS, 2019). Cause the vessel operates in Arctic and Antarctic water the materials in exposed structures will be selected based on the design temperature and restrictions based on low temperatures shall be followed since the requirements for polar classes doesn't take the operating temperature in account. The operating temperature is defined as the lowest mean daily average air temperature of the operating area (IACS, 2018).

The mean temperature for January, February and early March is -37°C in the central Siberian Arctic and -34°C to -29°C in North America. When the lowest extreme temperatures in the winter are between -54°C and -46°C. (Britannica, n.d.) Based on the mean temperatures the vessel can be designed with the requirements for temperatures -36°C /-45°C as seen on **Error! Reference source**

Table 11 Application of Material Classes and Grades for Structures exposed at low temperatures (IACS, 2019).

Structural members	**Material class**
Shell plating within the bow and bow intermediate icebelt hull areas (B, B_{Ii})	II
All weather and sea exposed SECONDARY and PRIMARY, as defined in Table 1 of UR S6.1, structural members outside 0.4 L_{UI} amidships	I
Plating materials for stem and stern frames, rudder horn, rudder, propeller nozzle, shaft brackets, ice skeg, ice knife and other appendages subject to ice impact loads	II
All inboard framing members attached to the weather and sea-exposed plating, including any contiguous inboard member within 600 mm of the plating	I
Weather-exposed plating and attached framing in cargo holds of ships which by nature of their trade have their cargo hold hatches open during cold weather operations	I
All weather and sea exposed SPECIAL, as defined in Table 1 of UR S6.1, structural members within 0.2 L_{UI} from FP	II

not found..

Table 12 Application of Material Classes and Grades for Structures exposed at low temperatures (IACS, 2018).

Structural member category	Material class	
	Within 0.4L amidships	Outside 0.4L amidships
SECONDARY: Deck plating exposed to weather, in general Side plating above BWL Transverse bulkheads above BWL[5] Cargo tank boundary plating exposed to cold cargo [6]	I	I
PRIMARY: Strength deck plating [1] Continuous longitudinal members above strength deck, excluding longitudinal hatch coamings Longitudinal bulkhead above BWL[5] Top wing tank bulkhead above BWL[5]	II	I
SPECIAL: Sheer strake at strength deck [2] Stringer plate in strength deck [2] Deck strake at longitudinal bulkhead [3] Continuous longitudinal hatch coamings [4]	III	II

Table 13 Material grade requirements for Classes I, II and III at design temperature -36°C /-45°C (IACS, 2018), MS = Mild steel, HT = Hight-tensile steel.

Class I

Plate thickness, in mm	-36/-45⁰C MS	HT
t ≤ 10	D	DH
10 < t ≤ 15	D	DH
15 < t ≤ 20	D	DH
20 < t ≤ 25	D	DH
25 < t ≤ 30	E	EH
30 < t ≤ 35	E	EH
35 < t ≤ 45	E	EH
45 < t ≤ 50	∅	FH

Class II

Plate thickness, in mm	-36/-45⁰C MS	HT
t ≤ 10	D	DH
10 < t ≤ 20	E	EH
20 < t ≤ 30	E	EH
30 < t ≤ 40	∅	FH
40 < t ≤ 45	∅	FH
45 < t ≤ 50	∅	FH

Class III

Plate thickness, in mm	-36/-45⁰C MS	HT
t ≤ 10	E	EH
10 < t ≤ 20	E	EH
20 < t ≤ 25	E	FH
25 < t ≤ 30	∅	FH
30 < t ≤ 35	∅	FH
35 < t ≤ 40	∅	FH
40 < t ≤ 50	∅	∅

∅ = Not applicable

Based on the plate thickness needed in different structures (seen on Table 11 and Table 10) the vessel will be constructed with shipbuilding mild steel of grades D and E and/or high-tensile steel of grades DH, EH or FH. Shipbuilding steel plates are carbon and alloy steel plates used in marine and offshore structures. The steels of grade D and E requires good toughness in low temperatures and welding performance. High-tensile plates are used in high stress areas of ships and they offer the same strength as general strength steel but with a smaller thickness. (Octal Metals, n.d.) The structures for the fire zones are required to be insulated to A-60 class. For spaces with little or no fire risk (for example open deck space, sanitary space, tank, void) the class can be reduced to A-0. (IMO, 2002)

Shell Thickness

The outside shell of a ship is the part that is subjected directly to the elements. Considering this ship will sail through ice, the shell will of course be subjected to ice loads. Ice can crush the shell of a ship and so our vessel needs extra protection. The thickness of the outside shell can luckily be calculated using the regulations of the polar class, using equations below (I2.4.1 and I2.4.2 respectively (IACS, 2019)):

$$t_{shell} = t_{net} + t_s \text{ [mm]}$$

$$t_{net} = 500s\left(\left(AF \cdot PPF_p \cdot P_{avg}\right)/\sigma_y\right)^{0.5} \cdot (2 \cdot b/s - (b/s)^2)^{0.5}/\left(1 + s/(2 \cdot l)\right) \text{ [mm]}$$

In the second equation, the s is the spacing between the longitudinal frames, which can be set freely. In the case of the midship area, s is set as 0.55 m.

The symbol t_{net} is defined as the actual structural thickness required to support the loads. t_s is called the corrosion allowance, which is an extra layer of material that can be corroded away without affecting the structural integrity of the shell. The value of t_s is simply provided by a in the regulations, presented

Table 14 Corrosion/Abrasion additions for shell plate. (IACS, 2019)

Hull area	t_s [mm]					
	With effective protection			Without effective protection		
	PC1 - PC3	PC4 & PC5	PC6 & PC7	PC1 - PC3	PC4 & PC5	PC6 & PC7
Bow; Bow Intermediate Icebelt	3.5	2.5	2.0	7.0	5.0	4.0
Bow Intermediate Lower; Midbody & Stern Icebelt	2.5	2.0	2.0	5.0	4.0	3.0
Midbody & Stern Lower; Bottom	2.0	2.0	2.0	4.0	3.0	2.5

AF, the Hull Area Factor can also be simply found in a table as well, presented **Error! Reference source not found.**. This table is divided by Polar Class and the section of the ship. The number AF changes depending on whether you are designing for the Icebelt, the lower or the bottom section of the ship. Because this is PC4 (Polar Class 4), one can see that the bottom of the shell does not require any ice strengthening (This is what "**" signifies). Thus, the bottom thickness will simply be determined based on the stress calculations and common sense. The entire side shell will use the hull area factor for the Icebelt, which is 0.55. Since this is the highest factor, it will lead to the highest shell thickness and so it is a conservative assumption.

Table 15 Hull Area Factors (AF). (IACS, 2019)

Hull area		Area	Polar Class						
			PC1	PC2	PC3	PC4	PC5	PC6	PC7
Bow (B)	All	B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bow Intermediate (BI)	Icebelt	BI_i	0.90	0.85	0.85	0.80	0.80	1.00*	1.00*
	Lower	BI_l	0.70	0.65	0.65	0.60	0.55	0.55	0.50
	Bottom	BI_b	0.55	0.50	0.45	0.40	0.35	0.30	0.25
Midbody (M)	Icebelt	M_i	0.70	0.65	0.55	0.55	0.50	0.45	0.45
	Lower	M_l	0.50	0.45	0.40	0.35	0.30	0.25	0.25
	Bottom	M_b	0.30	0.30	0.25	**	**	**	**
Stern (S)	Icebelt	S_i	0.75	0.70	0.65	0.60	0.50	0.40	0.35
	Lower	S_l	0.45	0.40	0.35	0.30	0.25	0.25	0.25
	Bottom	S_b	0.35	0.30	0.30	0.25	0.15	**	**

Next, PPFP, which is called the Peak Pressure Factor, can be calculated using one of the equations in **Error! Reference source not found.**. Because this ship is longitudinally framed, the bottom right equation is used. For a given frame spacing, s, of 0.55 m, the Peak Pressure Factor becomes 1.54.

Table 16 Peak Pressure Factors. This is not entire table. (IACS, 2019)

Structural member		Peak Pressure Factor (PPF_i)
Plating	Transversely-framed	PPF_p = (1.8 - s) ≥ 1.2
	Longitudinally-framed	PPF_p = (2.2 - 1.2 · s) ≥ 1.5

Then comes the term P_{avg} and a term related to it, b_{NonBow}. P_{avg} is calculated using equation below (I2.3.4.i) (IACS, 2019). It depends on b_{NonBow} and w_{NonBow}, which are the defined as the height and width of the so called "Design Load Patch", respectively. b_{NonBow} in turn depends on w_{NonBow} and w_{NonBow} can be calculated using equation below.

$$P_{avg} = F/(b * w) \text{ [Mpa]}$$

$$b_{NoBow} = w_{NonBow}/3.6 \text{ [m]}$$

$$w_{NonBow} = F_{NonBow}/Q_{NonBow} \text{ [m]}$$

To solve these equations, the force F_{NonBow} and line load Q_{NonBow}, have to be found. These can be found using equations below respectively. DF is the displacement factor, which depends on the D_{UI}, which is the displacement of the ship that corresponds to the upper ice waterline in kilotonnes. For this ship, that number is 11.9 kilotonnes. Lastly, CF_C and CF_D are the crushing failure class factor and the load patch dimensions class factor respectively and these can be found in **Error! Reference source not found.**.

$$F_{NonBow} = 0.36 \cdot CF_C \cdot DF$$

$$Q_{NonBow} = 0.639 \cdot {F_{NonBow}}^{0.61} \cdot CF_D$$

$$DF = {D_{UI}}^{0.64}$$

That leaves only the yield stress of the steel, σ_y, which is 235 MPa for grade A, B, D and E (marineengineeringonline, n.d.). Finally, t_{net} is determined to be 21.6 mm. Adding the corrosion allowance t_s of 4 mm, leads to a tittle outer shell thickness of 25.6 mm.

Table 17 Class factors. (IACS, 2019)

Polar Class	Crushing failure Class Factor (CF_C)	Flexural failure Class Factor (CF_F)	Load patch dimensions Class Factor (CF_D)	Displacement Class Factor (CF_{DIS})	Longitudinal strength Class Factor (CF_L)
PC1	17.69	68.60	2.01	250	7.46
PC2	9.89	46.80	1.75	210	5.46
PC3	6.06	21.17	1.53	180	4.17
PC4	4.50	13.48	1.42	130	3.15
PC5	3.10	9.00	1.31	70	2.50
PC6	2.40	5.49	1.17	40	2.37
PC7	1.80	4.06	1.11	22	1.81

Section Modulus

Table 18 Moments for cross section calculations are obtained from geometries of structure elements.

Item [-]	Number of parts n [-]	Breadth b [m]	Depth d [m]	Height h_j [m]	Area $A=n*b*d$ [m^2]	1. Moment $S=A*h_j$ [m^3]	2nd Moment @ centroid $i=n*b*d^3/12$ [m^4]	2nd moment @BL $I_S=A*h_j^2$ [m^4]
Tank Bottom	1	18.359	0.012	0.006	0.220	0.001	2.64E-06	7.93E-06
Tank top	1	21.001	0.006	1.197	0.126	0.151	3.78E-07	1.81E-01
Deck 3	1	17.896	0.006	7.997	0.107	0.859	3.22E-07	6.87E+00
Deck 4	1	21.932	0.006	10.997	0.132	1.447	3.95E-07	1.59E+01
Outer shell	2	0.0266	11.680	6.7	0.621	4.163	7.06E+00	2.79E+01
Inner shell	2	0.009	9.800	6.1	0.176	1.076	1.41E+00	6.56E+00
Long. frames	24	0.002	0.150	0.075	0.007	0.001	1.35E-05	4.05E-05
Long. frames	28	0.002	0.150	1.125	0.008	0.009	1.58E-05	1.06E-02
Long. frames	24	0.002	0.150	7.925	0.007	0.057	1.35E-05	4.52E-01
Long. frames	30	0.002	0.150	10.925	0.009	0.098	1.69E-05	1.07E+00
Shell frames	2	0.15	0.002	1.751	0.001	0.001	2.00E-10	1.84E-03
Shell frames	2	0.15	0.002	2.301	0.001	0.001	2.00E-10	3.18E-03
Shell frames	2	0.15	0.002	2.851	0.001	0.002	2.00E-10	4.88E-03
Shell frames	2	0.15	0.002	3.401	0.001	0.002	2.00E-10	6.94E-03
Shell frames	2	0.15	0.002	3.951	0.001	0.002	2.00E-10	9.37E-03
Shell frames	2	0.15	0.002	4.501	0.001	0.003	2.00E-10	1.22E-02
Shell frames	2	0.15	0.002	5.051	0.001	0.003	2.00E-10	1.53E-02
Shell frames	2	0.15	0.002	5.601	0.001	0.003	2.00E-10	1.88E-02
Shell frames	2	0.15	0.002	6.151	0.001	0.004	2.00E-10	2.27E-02
Shell frames	2	0.15	0.002	6.701	0.001	0.004	2.00E-10	2.69E-02
Shell frames	2	0.15	0.002	7.251	0.001	0.004	2.00E-10	3.15E-02
Shell frames	2	0.15	0.002	7.801	0.001	0.005	2.00E-10	3.65E-02
Shell frames	2	0.15	0.002	8.351	0.001	0.005	2.00E-10	4.18E-02
Shell frames	2	0.15	0.002	8.901	0.001	0.005	2.00E-10	4.75E-02
Shell frames	2	0.15	0.002	9.451	0.001	0.006	2.00E-10	5.36E-02
Shell frames	2	0.15	0.002	10.001	0.001	0.006	2.00E-10	6.00E-02
Shell frames	2	0.15	0.002	10.551	0.001	0.006	2.00E-10	6.68E-02
Casing wall	2	0.009	9.800	6.1	0.176	1.076	1.41E+00	6.56E+00
Center girder	1	0.009	1.200	0.6	0.011	0.006	1.30E-03	3.89E-03
Side girder	8	0.009	1.200	0.6	0.086	0.052	1.04E-02	3.11E-02
Long. bulkhead	2	0.009	6.800	4.6	0.122	0.563	4.72E-01	2.59E+00
				Σ	1.821	9.623	10.371	68.605

Even though there are lot of longitudinal and shell frames they don't contribute so much to result as thick and long elements, such as tank bottom and inner and outer shell.

Table 19. Moment is Design vertical ice bending moment along the hull girder from page 27.

Load and response		
Moment	210595037	Nm
σ_{deck}	42.79	MPa
σ_{bottom}	39.56	MPa

Moment M_I for section modulus analysis was calculated using formula from page 27. M_I is 210.6 MNm. Stresses at deck and bottom are 43.79 MPa and 39.56 MPa.

Table 20 Values are solved with values from Table 16.

Total cross-section		
Ship Depth D	11.00	m
Neutral axis	5.28	m from BL
Elements, $i_{,tot}$	10.37	m^4
Elements, $I_{S,tot}$	68.60	m^4
I_{BL}	78.98	m^4
I	28.13	m^4
Z_{deck}	4.921029273	m^3
Z_{bottom}	5.323079424	m^3

Section modulus values for deck and bottom are 4.92 m^3 and 5.32 m^3. Neutral axis locates 5.28 m from base line.

Because our project ship is ice going vessel, it needs ice strengthening and its outer shell is relatively thick. Thick plating increases cross-sectional area of the structure and thus moment of inertia. Moment of inertia I is 28.13 m^4.

6 Power and machinery

6.1 Operating profile

Our vessel will not have a specific route that she will always follow. Her operating profile changes as the route she takes varies. Also, the profile will also vary regarding the re-supply and research operations during the voyage. A possible voyage (Figure 25) was defined to create the operating profile of our vessel. This voyage starts from Tuktoyaktuk, Canada to Reykjavik, Island via Aasiaat, Greenland. The voyage also includes a stop at the Canadian Arctic Archipelago close to Resolute Bay, where a re-supply operation is conducted with helicopters. The depth of the port of Resolute Bay is 4.9 – 6.1 m (Ports.com, n.d.), which is too low for our vessel.

Figure 23 The example voyage drawn on a map

The actual operating profile of this voyage is sketched in Figure 24. This profile was created by studying a possible ice conditions during the voyage: which parts of the voyage are possible ice covered and which are open sea. While drawing the profile, the travel range was calculated simultaneously with numerical integration to make the profile represent the actual voyage.

The first 200 nautical miles include the departure from Tuktoyaktuk and open sea voyage until the sea ice is met as the vessel approaches the Canadian Arctic Archipelago. This can be seen in the profile as a significant decrease in speed. The speed is not constant as the ice thickness and condition may vary in the archipelago. As the vessel reaches Resolute, it will stop for the duration of the re-supply operation. Simultaneously, research operations can be conducted, if possible and necessary. The range of a voyage between Tuktoyaktuk and Resolute is approximately 860 nautical miles. The vessel will continue its journey through the ice until it reaches the Baffin Bay, where the sea is no longer ice covered. After approximately 900 nautical miles, the vessel reaches Aasiaat. From there, the voyage will continue to Reykjavik, which it will reach after 1500 nautical miles.

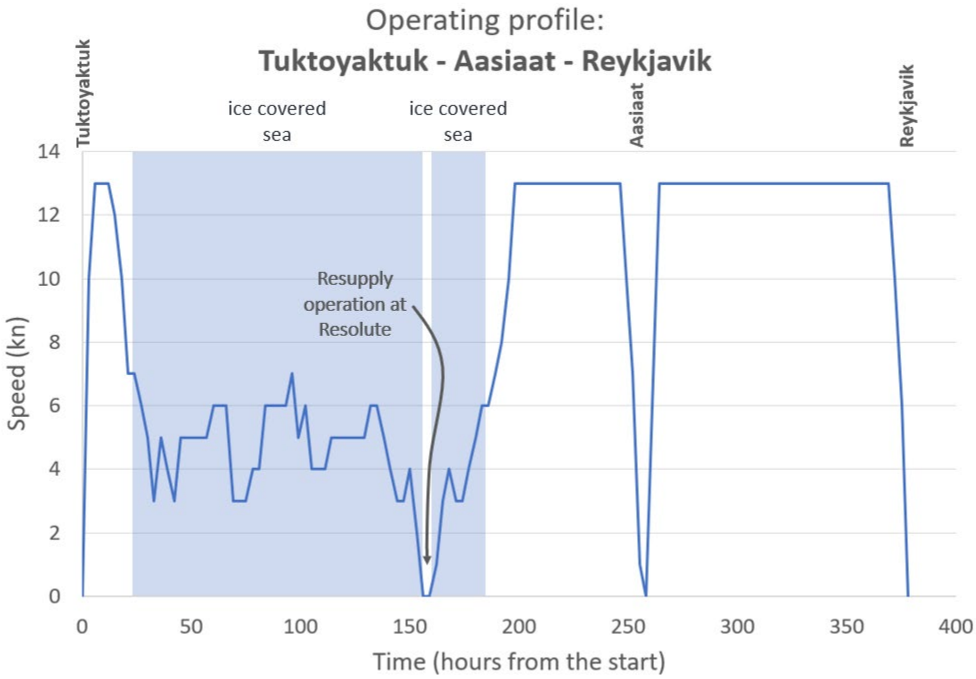

Figure 24 Example operating profile

6.2 Resistance and Propulsion Power

Air Resistance

The air resistance of a ship is usually quite low compared to the hydrodynamic and if applicable ice resistance on the ship, usually being about 2 % of the total resistance. However, the presence of a superstructure increases this resistance and during a headwind the resistance can increase even more. The superstructure of Khione has a frontal area of 262.5 m^2. An estimation of the drag can be given by the following equations (Garme, 2012):

$$C_{AA} = 0.001 \frac{A_{Frontal}}{S_{wetted}}$$

$$R_{AA} = \frac{1}{2}\rho(V + V_{wind})^2 \cdot S \cdot C_{AA}$$

In which $A_{Frontal}$ is the frontal area of the superstructure, S_{wetted} is the wetted area of the ship, C_{AA} is the aerodynamic resistance coefficient and R_{AA} is the aerodynamic resistance. Furthermore, ρ is the density of the air at sea level, being $1.225\ kg/m^3$, V is the speed of the ship and V_{wind} is the expected head wind speed. The latter two are $6.69\ m/s$ and $12\ m/s$ respectively, the wind speed being the average wind speed found on the Atlantic side of the artic ocean. The highest wind speed in the artic is about 50 m/s (Przybylak, 2003). Since the wetted area is cancelled in this system of equations, the aerodynamic resistance is calculated to be 56 N. With the maximum head wind speed of 50 m/s, the aerodynamic resistance becomes 517 N.

Ice Resistance

Ice resistance and then minimum power requirement for our project ship was calculated with Finnish-Swedish Ice Rules (Sjöfartsverket, 2017).

Table 21. Input values for ice resistance.

Input values		
L	117	m
L_{bow}	34.4	m
L_{par}	35.7	m
B	21.95	m
T	7	m
A_{wf}	520	m^2
α	31	deg.
$φ_1$	45	deg.
$φ_2$	44	deg.
D_P	5	m

Minimum engine output is calculated with formula:

$$P = K_e \frac{\left(R_{CH}/1000\right)^{3/2}}{D_P}\left[kW\right]$$

Where K_e is propulsion system coefficient and R_{CH} is resistance of the ship in ice:

$$R_{CH} = C_1 + C_2 + C_3 C_\mu \left(H_F + H_M\right)^2 \left(B + C_\psi H_F\right) + C_4 L_{PAR} H_F^{\ 2} + C_5 \left(\frac{LT}{B^2}\right)^3 \frac{A_{wf}}{L}$$

H_F and H_M are ice heights and C_1, C_2, C_3, C_4, C_5, C_μ and C_ψ are coefficients. For our project ship R_{CH} is 614.6 kN and P is 4388 kW, which is much smaller than 26600 kW and doesn't increase our need of power. 26600 kW propulsion power is requirement for our ship.

We also calculated ice resistance in required 1.65 m thick ice when sailing 3 knots. Calculations were made using formula for ice resistance by Lindqvist (Lindqvist, 1989):

Crushing component R_c for ice resistance is:

$$R_c = 0.5\sigma_B H_{ice}^{\ 2} \frac{\left(\tan\varphi + \dfrac{\mu_H \cos\varphi}{\cos\psi}\right)}{\left(1 - \dfrac{\mu_H \sin\varphi}{\cos\psi}\right)}$$

, where σ_b is flexural strength of ice and H_{ice} is thickness of ice. μ_H is friction coefficient between ship and ice. φ is the stem angle and α is the waterline entrance angle. ψ is then obtained $\psi = \tan^{-1}\left(\tan\phi / \sin\alpha\right)$.

Bending component R_b for ice resistance is:

$$R_b = 0.003\sigma_B B\left(H_{ice}\right)^{3/2}\left(\tan\psi + \frac{\mu_H \cos\varphi}{\sin\alpha\cos\psi}\right)\left(1+\frac{1}{\cos\psi}\right)$$

, where B is beam of the ship.

Submersion component R_s for ice resistance is:

$$R_s = \left(\rho_w - \rho_i\right) g H_{ice} B\left[\frac{T\left(B+T\right)}{B+2T} + \mu_H\left(0.7L - \frac{T}{\tan\varphi} - \frac{B}{4\tan\alpha} + T\cos\varphi\cos\psi\sqrt{\frac{1}{\sin^2\varphi}+\frac{1}{\tan^2\alpha}}\right)\right]$$

, where ρ_w and ρ_i are water and ice densities. L and T are length and draft of the ship.

Finally, ice resistance R_{ice} is obtained from formula:

$$R_{ice} = \left(R_c + R_b\right)\left(1+1.4\frac{v}{\sqrt{gH_{ice}}}\right) + R_s\left(1+9.4\frac{v}{\sqrt{gL}}\right)$$

R_{ice} gets value 1769.9 kN and when using power requirement from Finnish-Swedish Ice Rules P is 21444 kW, which is a bit lower than required propulsion power of 26600 kW. This leaves margin to survive harsher ice conditions that were required.

Open Water

Total resistance in open water was calculated using excel sheet given in this course. Input information for Principal particulars was collected from earlier progress of our project. For cruising speed 13 knots total resistance of the ship is 260 kN and effective power is 2600 kW.

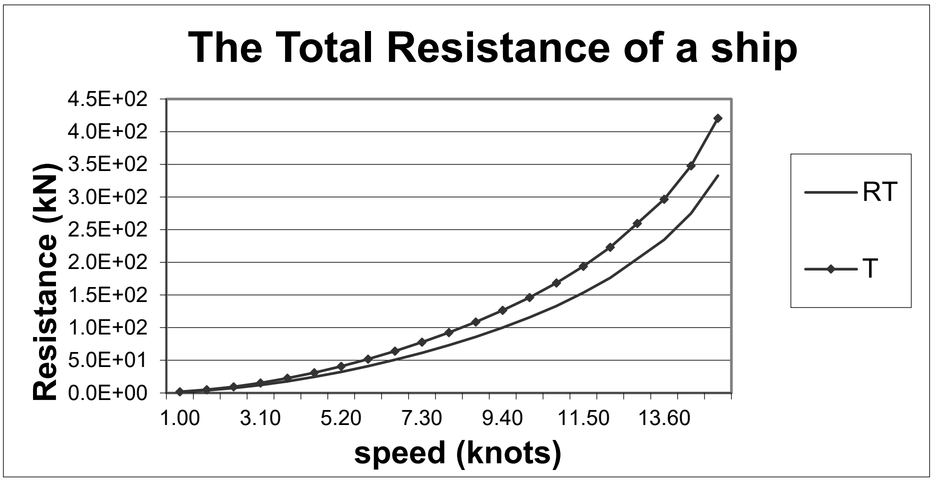

Figure 25 RT is the total resistance and T is the propeller thrust.

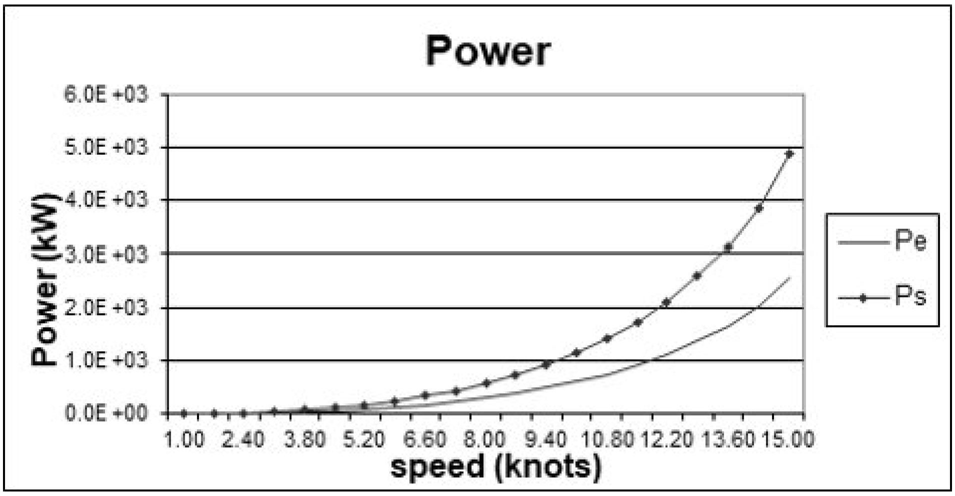

Figure 26 Pe is effective power and Ps is shaft power.

6.3 Total Power Demand

Total power demand of main engines is set by propulsion power as the hotel load of the ship is powered with auxiliary fuel, hydrogen. So minimum power demand of main engines is 21444 kW, but we use 26600 as power demand, because it was required.

6.4 Propulsor(s)

Propulsion systems that can be used are controllable pitch, fixed pitch propellers or podded/azimuthing propulsors. Our vessel is designed having propulsion with shafts so suitable propulsors are controllable pitch propellers, since they are especially suitable for vessels with routes with changing operating conditions and provides good performance and manoeuvrability (Wärtsilä, 2020). Advantages with controllable pitch propellers is the ability to change propellers pitch for changing direction or speed of ship rather than changing the speed for main engines (Marine Insight, 2019). The controllable pitch propeller enables better manoeuvrability than fixed pitch propellers even though they would be more cost-effective in manufacturing, installation, and operational costs.

Since the components of diesel-electric propulsion system can be located nearly anywhere the generators for the shafts can be fitted at the aft of the ship making the shafts shorter. There are several manufacturers for propellers. A suitable option is propellers from Wärtsilä since they have long experience of manufacturing propellers, has also specialization for more advanced applications and the propellers are compliant with all ice classes. Propellers with diameter of 5 m has been used in the resistance calculations.

6.5 Energy Sources

Ice-going vessels usually uses diesel-electric propulsion system, medium speed diesel and gearbox or low-speed diesel with direct shaft. The diesel-electric system is common in icebreakers since it's efficient at slow speeds and has excellent manoeuvring characteristics (Traficom, 2019). Generally, diesel-electric systems consist of diesel engines that drives electric generators to then produce electric power for the propellers and other use. Using a diesel-electric system the use of space is more efficient and flexible since the diesel generators, switchgear and propulsion motors can be located nearly anywhere (Aichele, 2007). Our vessel has two engine rooms with two engines each.

The vessel will be equipped with diesel-electric machinery which will use marine diesel oil as an energy source. Since the vessel will operate in arctic the fuel used must be reliable and easily available for the long operating times. Also, the environmental impact of the fuel is important. Marine diesel oil (MDO) is a blend of distillates (marine gasoil) and heavy fuel oil (HFO). Since the content of heavy fuel oil is low, the marine diesel oil has a maximum sulphur content of 3.5 %. It comes also in a low-sulphur variant (1 %) which can be used if the vessel crosses areas with stricter emission limits. In the Arctic polar code area ships mostly uses distillate marine fuels (marine gas oil and marine diesel oil) and 10 % uses HFO. MDO fuels are more expensive than HFO and therefore a big part of shipping still uses HFO. (Marquard & Bahls, 2015)

Figure 27 Example of Diesel-electric propulsion system (Ocean Time Marine, 2020)

Accommodation and Auxiliary Power

For other power than propulsion we have decided to use liquid hydrogen. The use of hydrogen is an innovation for our vessel and has been chosen since renewable energy sources like sun and wind would not have been effective and reliable enough. The tanks for liquid hydrogen are fitted at the aft on the vessel and will also need fuel cells and other systems for the power transmission.

According to the example operating profile, the ship will spend 16 days at sea with one stop in between at Asiaat. It will start in Tuktoyaktuk and end its journey in Reykjavik. A normal ship could probably refuel in both Tuktoyaktuk and Asiaat, however this ship uses hydrogen as its non-propulsive power source. One can hardly expect small settlements like Tuktoyaktuk and Asiaat to have the infrastructure to refuel hydrogen. So realistically, the ship can only potentially refuel its hydrogen once every two trips, which is when it is in Reykjavik. Thus, the ship is required to carry enough hydrogen for 32 days, a little over one month. However, since this is just an example operating profile, it is possible that the ship would also be taking longer trips. Therefore, it was decided that the ship will carry enough energy for 64 days at sea without refuelling hydrogen.

So, one must how much hydrogen the ship uses during this period. The power required was calculated resulting to 617 kW. Over the course of a 64-day period, the ship then uses 342 GJ of energy. This comes down to 402 m^3 of hydrogen, given hydrogen has power density of 8.5 MJ/L. But to turn this hydrogen into usable power, one needs hydrogen fuel cells. Hydrogen fuel cells have a specific power 0.5 kW/kg and have an efficiency of 80%. This means that to produce 617 kW, the ship needs 1544 kg of fuel cells.

6.6 Machinery Configuration

The main components of diesel-electric machinery are diesel generators, electric switchboards, electric propulsion motors and control room.

The diesel generators used will be 4-stroke engines by Wärtsilä, 2 x 12V31 and 2 x 14V31. Wärtsilä 31 is suitable for main propulsion, in hybrid installations, as auxiliary engine and as our case in diesel-electric configurations. These engines are chosen since Wärtsilä is a well-known company and the Wärtsilä 31 engines are designed to have good efficiency and emission performance, and to meet our needed power demand. The diesel version of the engine is separately optimised for heavy or light distillate fuels. (Wärtsilä, 2019)

The rated power for the 12V31 is 7320 kW and for 14V31 8540 kW which all together will provide 31720 kW.

Table 22 Engine dimensions (mm) and weights (tonnes).

Engine type	A*	A	B	C	F	Weight
12V31	7900	7840	3137	3500	1496	77.1
14V31	8540	8480	3137	3500	1496	84.6


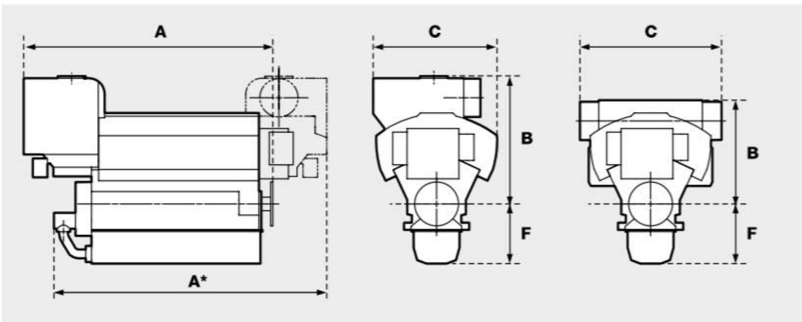

Figure 28 and 29 Wärtsilä 31 and definition of dimensions (Wärtsilä, 2019).

Since this ship is diesel-electric, the two propellers are not directly driven by the engine but by electric motors. The electricity generated by the engines is used to power these electric motors. An electric motor is a device that turns the generated electric energy into angular kinetic energy i.e., the rotation of the propeller shaft. The big advantage of electric motors over diesel motors is that motors can provide maximum torque at any speed, which is great for an icebreaker that must push its way through ice at a low speed (Wärtsilä, 2016). Each motor needs to be able to produce about 14 MW of power, which is quite significant. The selected motor is the INDAR IM Series Squirrel Cage Motor with 15 MW power output (Ingeteam, 2020). Each shaft will be powered by two of them, each having a footprint of about 2 by 2 m and a height of 3 m.

The switchboard of the system distributes the power from the generators. The main switchboard is usually located in the main engine room or machinery control room. In event of fire there's required installations which will shut down all ventilation and fuel oil systems (ETO, 2020).

Space requirements from the Polar Code according the machinery is to take the environmental conditions into account. Machinery shall be installed so that it's protected for example from ice accretion, snow accumulation and freezing and increased viscosity of liquids. DNV GL also sets requirements for the environmental conditions in the machinery space and general requirements for the construction. All spaces with machinery need ventilation under all conditions.

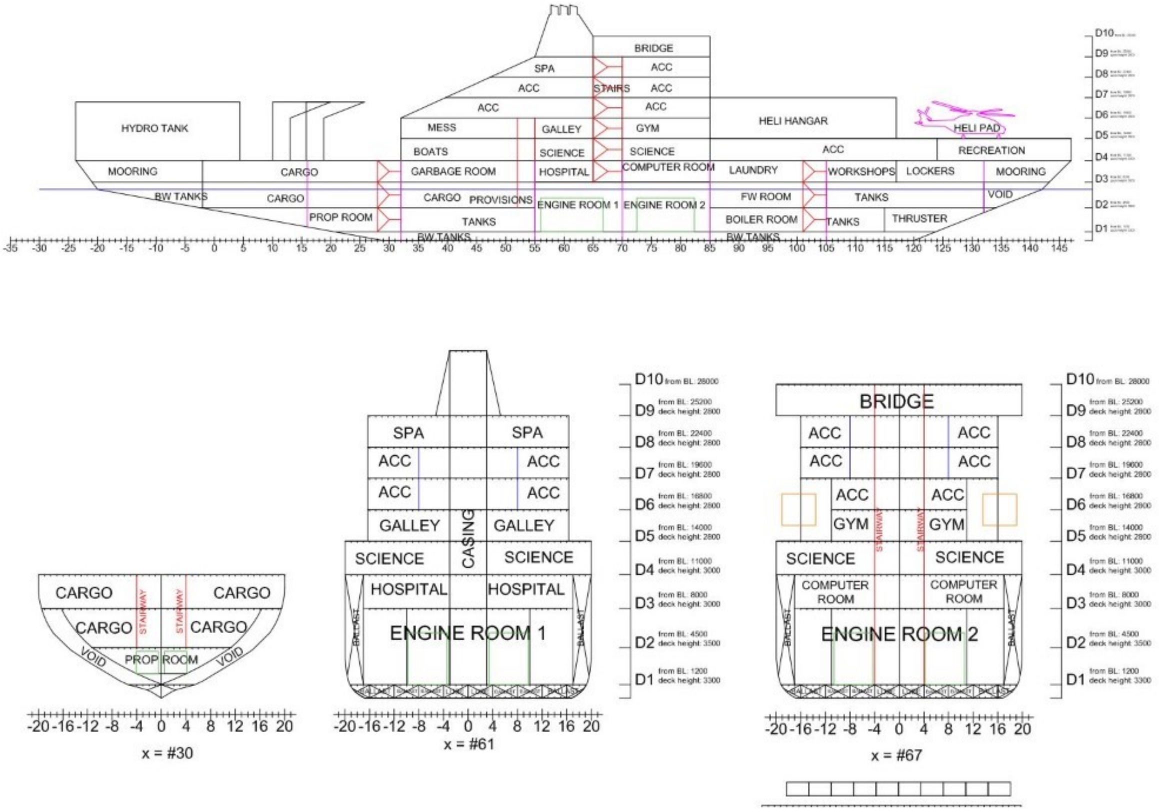

Figure 30 General Arrangement with fitted engines.

7 Outfitting

7.1 Main Equipment

For effective and safe operation, and for fulfilling our mission, ship must be properly equipped. Most crucial equipment for our ship is listed and categorized below.

Table 23 Required equipment.

Life saving	Lifeboats (enclosed type) Fast rescue boat Adequate thermal protection clothing for the crew Insulated immersion suits Searchlights Emergency signal equipment
Navigation equipment	Compasses Radar Autopilot GPS
Communication equipment	Lifeboat communication system and transmitters Ship communication system
Fire safety equipment	Fire extinguishers Fire pump Sprinkler system Firefighting outfits Fire hoses
Cargo handling	Cranes
Mooring and anchoring equipment	Mooring winches Anchor windlasses Chain stoppers Fairleads Anchors Chains Ropes
Research	Chainsaws Sensors Drills

7.2 Properties of main equipment

Anchoring and mooring

Required properties of anchoring and mooring system can be defined by equipment number provided by DNV GL. Formula for equipment number is presented in DNV GL Rules of Classification of Ships part 3 chapter 3 as below.

$$EN = \Delta^{2/3} + 2 \times B \times H + 0.1A$$

, where:

H = height from the summer load waterline to the top of the uppermost deckhouse, in m

Δ = Displacement in tonnes

B = Greatest breadth

A = area of profile view of the hull, in m^2

With our values of A = 1585 m^2, B = 22 m, H = 18.2 m, Δ = 12 900 t, equipment number EN results in 1509. Based on the equipment number DNV GL requires our vessel to have:

- 2x 4590 kg anchors
- 550 m chain
    - Diameter of the chain 52 mm – 68 mm (depending on material)
- 5 mooring lines
    - 190 m each
    - Minimum breaking strength 324 kN

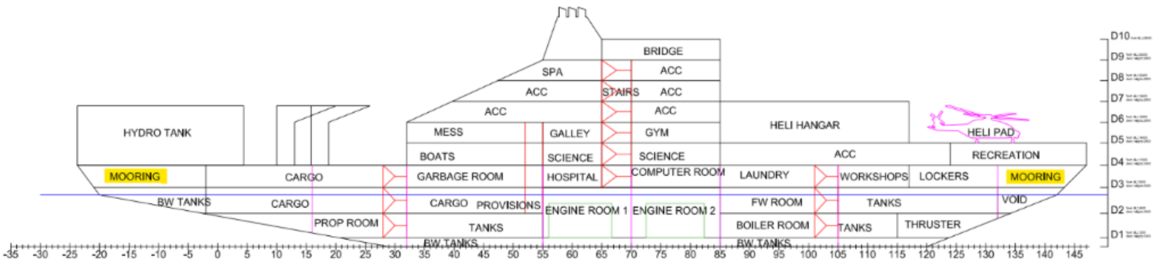

Figure 31 Location of mooring

Life-saving

Our ship is equipped with two lifeboats and one fast rescue boat, which is also used in research operations. SOLAS demands that lifeboats are at least 7.3 m long and have capacity of accommodating at least 125 % of the crew. In our case crew consists of 100 members, thus capacity must be 125 pax. Capacity of each lifeboat on board is 63, thus requirement is fulfilled. Lifeboats should have equipment like food, first aid, compass, signaling mirror and communication systems.

The type of totally enclosed lifeboats used on our ship are JYN-80.

Cargo Handling

Our cargo handling capability consists of two hydraulic TTS Cargo cranes on aft deck. Main crane is type CCL -crane and is capable of lifting 30 tonnes at 18 m. Auxiliary crane has smaller lifting capability but longer reach. Auxiliary crane is type GPC -crane with capability of 10 tonnes at 24 m. Main crane weights 47 tonnes and auxiliary crane 20 tonnes.

7.3 SFI Classification

This extensive section contains the SFI classification of the ship. It is mostly taken from (Wärtsilä, 2011), with changes where that is appropriate.

Main Group	Group	Sub groups	Code
Group 1 Ship General	11 Trials and tests	Trials general	111
		Machinery testing	112
		Inclining experiment	113
		Fuel- oil, lub. oil and hydraulic oil	114
		Dock testing and Trial trip	115
		Post Seatrial Inspection	116
	12 Guarantee	Guarantee	121
Group 2 Hull	20 Hull materials	Hull general	200
		Hull materials	201
		Sandblasting, Priming and Painting	202
		Testing of Tanks, Bulkheads etc	203
		All decks, flats, shell, bulkheads, etc. shall be hose tested as required by classification rules.	204
		X-ray and Ultrasonic testing of Hull parts	205
	21 Aft body	General from stern to bulkhead 3	210
		Shell plates	211
		Steering gear room	212
	22 Engine area	General, bulkhead 4 to 6	220
		Shell Plating	221
		Bottom, keel	222
		Inner bottom	223
		Deck platforms	224
	23 Midship/Cargo area	General, bulkhead 3-4 and 6-7	230
		Deck	231
		Bulkheads	232
	24 Forebody	General, bulkhead 7 to bow	240
		Shell plates	241
		Bow and stem section	242

	25 Superstructure and deckhouse	Superstructure and Deck house	250
		Superstructure	251
		Wheelhouse	252
	26 Hull outfitting	Hull marking	261
	27 Material protection external	Painting - General	270
		Superstructure, deckhouse	271
	28 Material protection internal	Ballast tanks, oily water tank, chain lockers, cofferdams, void spaces, roll reduction tank	281
		Fresh water tanks	282
		Fuel oil, lube oil, and hydraulic oil tanks	283
		Water ballast tanks	284
	29 Miscellaneous hull work	Miscellaneous internal areas, vent and air trunks, all other surfaces	290
Group 3 Equipment for cargo	31 Equipment for cargo	Cargo fittings on 2nd deck	311
Group 4 Ship Equipment	40 Manoeuvring machinery and equipment	Maneuvring control	401
		Rudder	402
		Steering gear	403
		Bow thrusters	404
	41 Navigation equipment	Radar system	411
		Sonar system	412
		GPS	413
		Gyro plants, Auto pilot, Compasses	414
		Echo sounder, Speed log	415
	42 Communication equipment	Radio plant	421
		Local area network (LAN)	422

		Calling, command and telephone systems	423
		Light and Signalling equipment	424
	43 Anchoring and mooring equipment	Anchor with chain and equipment	431
		Fixed mooring equipment	432
	44 Repair and cleaning equipment	Repair and maintenance equipment	441
		Washing system	442
		Incinerator	443
		Outfitting in store rooms	444
		Piping	445
Group 5 Equipment for crew and passengers	50 Lifesaving Equipment	General lifesaving equipment	500
		0 MOB boats	501
		503 Emergency marking	502
		Medicine and First Aid Equipment	503
		Loose firefighting equipment	504
	51 Insulation, panels, bulkhead, doors, side scuttles and windows	General	510
		Insulation, bulkheads and panelling	511
		Doors with coamings in accommodation	512
		External doors with coamings	513
		Side scuttles and windows	514
	52 Internal deck covering, ladders, steps, railing	Deck base covering, internal	521
		Deck top covering, internal	522
		Stairs, handrails in accommodation	523

		Floor plates, ladders and pl.forms in engine room	524
		Ladders, Platforms, Railings etc in tanks	525
	53 External decks	Deck covering	531
		Hand rails, Railings and Gates	532
		Ladders and Steps	533
	54 Furniture and Inventory	Crew Furniture	541
		Researcher furniture	542
		Communinal furniture	543
		Hospital supplies	544
	55 Galley, pantry, Provisions and laundry equipment	Galley and pantry equipment	541
		freezing and refrigeration system	542
		Laundry	543
		Garbage	544
	56 Transport equipment for crew	Gangway	561
		Ladder	562
	57 Ventilation, aircondition and heating systems	Ventilation and Aircond. systems for Accomodation	571
		Ventilation for the remaining parts of the vessel	572
		Ventilation for engine control room/ SW-board room	573
		Ventilation Engine room	574
		Ventilation of cargo area	575
	58 Sanitary system and equipment	Sanitary supply system	581
		Sanitary discharge system	582
		Sanitary equipment	583
		Drinking water system	584

Group 6 Machinery main components	61 Generator and motor	1 Generator	611
		2 Motor	612
		3 Switchboard	613
	62 Propellers, Transmission and foils	Propeller	621
		Propshaft	622
Group 7 Systems for machinery components	70 Fuel oil system	General fuel oil system	700
		Fuel oil transfer and drain system	701
		Fuel purification plant	702
		Fuel oil service system	703
	71 Lub oil system	Lub oil transfer and drain system	711
		Lube Oil Purification System	712
		Lub oil system for propulsion machinery	713
	72 Cooling system	General	720
		Sea water cooling system	721
		Fresh water cooling system	722
	74 Exhaust system	Exhaust gas system	741
		Exaust heat distribution system	742
	76 Distilled & make up water systems	Freshwater generators	761
		Fuel cell water recapture system	762
	79 Automation system for machinery and cargo systems	General	790
		Engine control room	791
		Common automatic equipment, engine alarm etc.	792

		Automation equipment for propulsion machinery and transmission, engine telegraph etc.	793
		Fuel cell control system	794
Group 8 Ship systems	80 Ballast, bilgde and drain systems, gutter pipes outside accomodation	General	800
		Ballast system	801
		Bilge system	803
		Scupper pipes outside accomodation	804
	81 Fire and lifeboat alarm systems, fire fighting systems	Fire fighting general	810
		Fire detection, fire and general alarm system	811
		Fire and washdown system	812
		Fire fighting system with gas	813
	82 Air and sounding system	Air and sounding systems in tanks	821
	83 Special common hydraulics oil systems	Special hydraulic oil systems	831
	85 Electrical systems, general part	Electrical system general	850
		Administrative net work	851
	86 Electrical supply system	General electrical supply system	860
		Shore Connection box	861
	87 Electrical common distribution	Main Ship service and Emergency switchboards	870
		Main Switchboard	871
		Emergency switchboard	872
		Distribution boards and panels	873

	88 Electrical cables and installation	Cableways general	880
		Cableways in accommodation	881
		Cableways on external decks	882
	89 Electrical distribution system	Electrical lighting systems for engine room etc	891
		Electrical lighting for superstructure/accommodation	892
		Electrical lighting system for weather decks	893
		Electrical motors, general	894

8 Weight and Stability

8.1 Weight

Deadweight

Deadweight, DWT, is calculated with following formula:

DWT = DWTc + DWTFO + DWTFW + DWTC&E + DWTPR.

In which: DWTc is the cargo deadweight; DWTFO is the fuel oil weight; DWTFW is the lube oil weight; DWTH is the hydrogen weight; DWTC&E represents the weight of crew and their effects and finally DWTPR is the weight of provisions.

Propulsion is powered with diesel engines and rest of the energy is produced with hydrogen. Fuel and lubrication oil capacities are calculated with engine loads due propulsion. FO and LO capacities are calculated for 32-day (768 h) voyages.

Table 24. Main engine consumption details

Engine details		
Engine output 14V31	8540	kW
Engine output 12V31	7320	kW
Engine output total	31720	kW
Fuel consumption	170.1	g/kWh
Lube oil consumption	0.45	g/kWh

Table 25. FO and LO consumptions per voyage.

Sea condition				
	open water	light ice	heavy ice	sum
per voyage	70%	25%	5%	100%
hours per voyage, h	537.6	192	38.4	768
prop. power, kW	2600	4388	20000	
fuel cons., kg / h	442.3	746.4	3402	
lube cons., kg / h	1.17	1.97	9	
fuel cons. per voyage, ton	237.8	143.3	130.6	**511.7**
lube cons. per voyage, ton	0.63	0.38	0.35	**1.35**

Minimum amount of fuel and lubrication oil required for 32-day voyages are rounded up to obtain DWTFO and DWETFW. DWTFO is 550 tonnes and DWTFW is 5 tonnes.

Hydrogen tank capacity is 402 m^3 and can contain 2.85 tons of liquid hydrogen. DWTH is 2.85 tons.

The vessel has 20 crew members and 80 scientists onboard (100 persons total). Weight of provisions, DWTPR, is calculated with formula:

$$DWTPR = 0.01t \times persons \times days$$

Weight of crew and their effects, DWTC&E, is calculated with formula:

$$DWTC\ \&\ E = 0.17t \cdot persons$$

For the vessel formula for DWTR gives 32 tonnes and formula for DWTC&E gives 17 tonnes.

The vessel has 960 m^2 of cargo space in two floors equaling 3074 m^3. The cargo of the vessel is manly supply for arctic research centers. Supply is usually food and spare parts. Cargo space can't be filled 100 % full, but more like 80 % full. Average density of supplies is assumed to be 1000 kg/m^3. Cargo deadweight, DWTc, of the vessel is then 2460 tonnes.

Table 26. Deadweight calculation

	DWTFO	DWTFW	DWTH	DWTC&E	DWTPR	DWTc	**DWT**
tons	550	5	2.85	17	32	2460	**3066.85**

Lightship Weight

The lightship weight estimation was conducted with the given excel sheet. The initial values including the main dimensions and coefficients of fineness were obtained from the latest iteration of our hull model design from Delftship. The vessel's main characteristics and the final lightship weight estimation and the vessel's estimated vertical center of gravity can be seen in Figure 1 below:

Table 27 Ship's main characteristics

Ship's main characteristics	
L(m)	132.92
B(m)	22
T(m)	7
D(m)	11
CB	0.6436
LCB(m) @AP (m)	50.751
Lightship weight	
9450.87	
KG_{Light}	
6.394	

The structural weight of our vessel was estimated based on the modified Lloyd's equipment number E. E is defined as following in the lecture notes.

$$E = L(B+T) + 0.85\,L(D-T) + 0.85\sum_i h_i + 0.75\sum_j h_j$$

The h_i is a profile area of a superstructure element and the h_j is a profile area of a deckhouse element. The size of the vessel's superstructure and deckhouse was estimated using the general arrangement we have drawn on AutoCAD. This gave us E of the rough value of 5990. Finally, the structural weight was estimated with the following formula from the lecture notes:

$$W_S = K\,E^{1.36}[1 + 0.5\,(C_B - 0.7)]$$

Here, the factor K varies with the ship type. The data provided in the lecture notes stated that a research vessel's typically have K of value 0.045. However, this data implemented that the value of E in these cases would vary between 1350 and 1500. This did not correspond our value of E at all. Thus, we decided to use the value of 0.038 for K, typical for passenger ships, as it corresponds to our value of E better. The data claimed that typical E for this value of K was between 5000 and 15000.

These values lead to our structural weight estimation to be 5068.44 tonnes.

The machinery weight includes propulsion machinery (prime mover, reduction gear, shafting and propeller). Since we are using diesel-electric machinery we calculated the estimated weight for the total machinery with the equation from lecture notes.

$$W_M = 0{,}72 * (MCR)^{0{,}78}$$

As MCR we used the total produced power from the diesel engines, 31720 kW. Resulting to a machinery weight of 2335.46 tonnes. The Wärtsilä diesel engines has given weights on 77.1 tonnes (12V31) and 84.6 tonnes (14V31) which means exact weight of the diesel engines are 323.4 tonnes. Since the estimated machinery weight calculates the total machinery, the remaining 2012 tonnes is for the other machinery needed. The other machinery includes four electric generators, two shafts and two propellers.

The outfitting weight is estimated with the following formula from the lecture notes:

$$W_O = C_O\, L\, B$$

where the factor C_O is the outfitting weight coefficient. In order to retrieve the value for this factor, there is Figure 33. Our vessel's length between perpendiculars is 117.1 m. Since there is no ship type represented in the figure, that corresponds ours, we decided to calculate our vessels value L/B and use one of the coefficients for passenger vessels. In our case, $L/B = 132.92/22 \approx 6.04$. Thus, as seen in Figure 33, we used the value of 0.7 as our C_O.

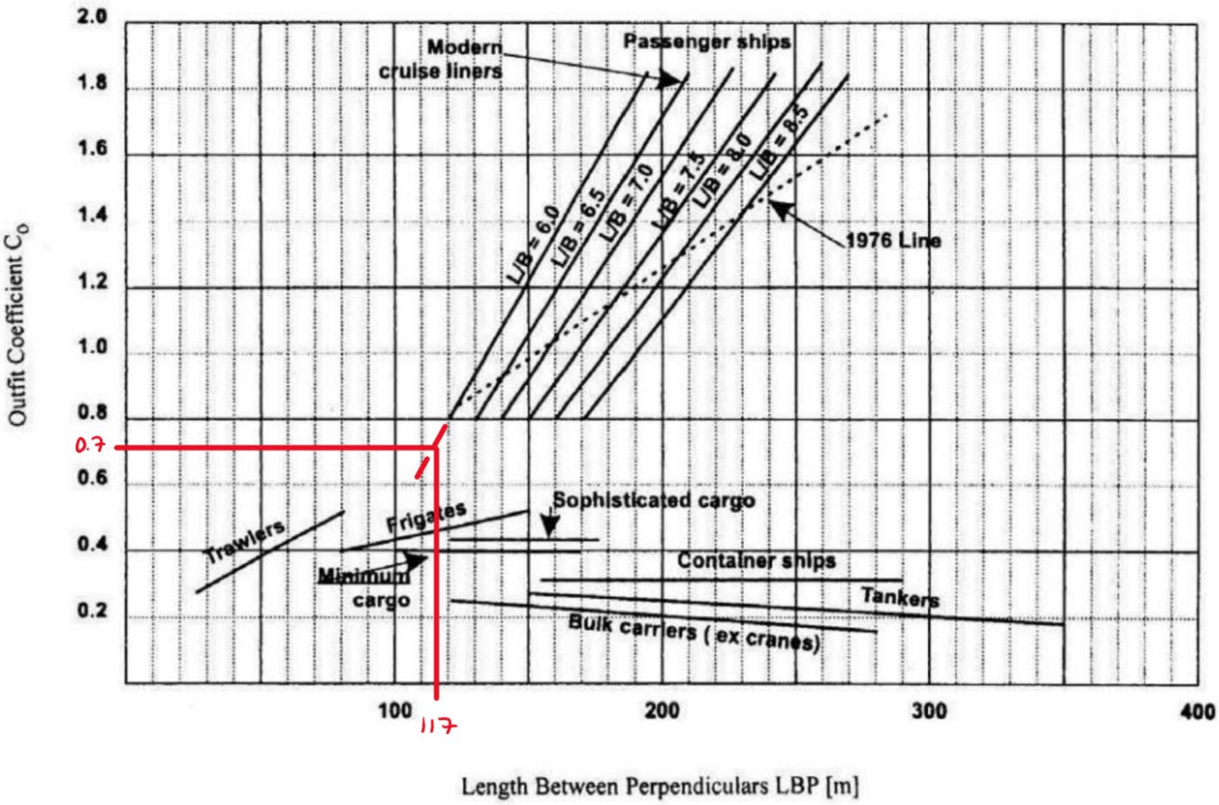

Figure 32 Outfit coefficients.

Thus, our outfitting weight ended up being 2046.968 tonnes.

Further, our final lightship weight estimation was made by summing the structural, machinery and outfitting weight together:

$$W_{LS} = W_S + W_M + W_O$$

As earlier seen in Table 27, this value ended up being 9450.87 tonnes. Deadweight is difference between displacement and lightship weight, resulting that displacement is sum of deadweight and lightship weight. Displacement of the vessel is 12517.72 tonnes according to the calculations. The displacement of our hull form according to Delftship is 11895.7 tonnes. Between the calculated value and the Delftship calculation, there is a difference of 622.02 tonnes. This is clearly a problem as the calculations go over the weight that this hull form can carry. Thus, more iterations and more precise calculations are needed as adding the weight reserve increases this difference further.

Weight Reserve

Ship of our project is highly unconventional and specialized. In concept design phase, weight assessments are rough, and done by statistical methods, and by direct calculations. In case of highly specialized ship, like a ship in question, statistical methods can be problematic due to lack of applicable data. As known, using statistical method with lack of data can cause uncertainty in weight calculations. Highest uncertainty of statistical method is related to the structural weight due to the ice strengthening. Ice strengthening narrows down the possible data used for statistical method, leading to increased uncertainty.

Uncertainty in weight calculations is dealt by adding reserve to weight and to vertical centre of gravity of ship. Weight reserve is expressed as percentage of ships total lightweight and reserve in vertical centre of gravity is expressed in meters. At the time of delivery of a ship, target values are 0 % and 0.1 m, respectively. Values are considered again at every new iteration of the design process. In the conceptual stage, values are at their extreme. Values depends on deadweight/displacement -ratio of the ship. At current conceptual design stage of our project, with deadweight/displacement -ratio of roughly 0.3, weight reserve of 15 % and vertical centre of gravity reserve of 1 m should be applied.

8.2 Intact Stability

Centre of gravity can be defined as the point from where the total weight force of the ship acts vertically downwards. It has as an effect on vessels righting lever (GZ) and the ability to return the vessel in upright position.

The centre of gravity can be estimated from the centres of gravities for the superstructure, machinery and outfitting and weights on the different parts, as following equation.

$$KG_{light} = \frac{W_S * KG_S + W_M * KG_M + W_0 * KG_0}{W_{light}}$$

From our estimated weights it results in a centre of gravity at 6.394 m. The transverse metacentric height (GM) is given as 10.5 m in our hydrostatics report on our Delftship model which means the centre of gravity is placed below that and the vessel should be stable.

9 Building costs

As the data available regarding the cost coefficients of different ship systems and spaces was limited, we first estimated the total building costs based on the estimated hull structure cost and comparing that to a possible cost distribution. As the building cost of our reference ship RRS David Attenborough was also available, we also calculated another estimate of total building cost based on it.

9.1 Hull structure costs

The cost of the hull structure can be estimated with the following equation:

$$C_{ST} = K_{STEEL} \times W_S + K_{MAN} \times MHS$$

where K_{STEEL} is the cost of steel per ton, W_S is the structural weight, K_{MAN} is the man hour cost and MHS is the required number of man hours (Papanikolaou, 2014). The cost of steel per ton is at the moment roughly 575 € per tonnes (MEPS, 2020). Our structural weight was in the previous week estimated to be roughly 5000 tonnes. Cost of man hour is estimated to be 45 €/h. The required working hours can be estimated with the following formula:

$$MHS = a \times (W_S)^b$$

where a in our case can be estimated to be 243 and b to be 0.85 (Papanikolaou, 2014, p. 445). Thus, the required working hours in our case is roughly 342 000 hours. Further, the hull structure cost can be estimated to be approximately 18.3 million €.

9.2 Distribution of Cost

As the data regarding costs of other systems of the vessel was limited, we used the obtained estimate for hull structure cost to approximate the total building cost based on a possible cost distribution. In Table 23, the cost distribution of a platform supply vessel (PSV) is represented (Shetelig, 2013).

Table 28 Distribution of costs for PSVs.

Technological group	Portion of total cost
Hull	20 – 30 %
Machinery and Propulsion	25 %
Cargo containment and handling	20 – 25 %
Ship common systems / Ship assembly and systems integration (for outfitting yard)	20 %
Hotel and accommodation	5 %
+ Financial costs	+ Financial costs

As the cargo containment and handling is a relevant part of our vessel's mission, not to forget that we also have to build a fully functional helicopter hangar onboard, this part of the total cost was approximated to be 25 %. Also, the hotel and accommodation cost are estimated to take a bigger slice of the total cost, 10 %, since they must be more lavish compared to a usual PSV. Financial costs were approximated to take a 5 % part of the total costs. Thus, 15 % of the total cost is the share of hull structure cost. Therefore, based on this method, our total building cost is roughly 122 million €.

9.3 Comparison with Reference Ship and Final Total Building Cost Estimation

The RRS Sir David Attenborough took £200 million to build (Anon., 2019). Based on current market conditions, that equals to roughly 225 million euros. Given this, our previous estimate was not realistic.

The total building cost can be approximated with the following formulas from lecture notes:

$$P = C_1(DWT)^B$$

where B is typically 0.7 - 0.8, or

$$P = C_2(W_E)^{0.87}$$

The value of coefficients C_i can be approximated as the deadweight and lightship weigh, W_E, are known. In RRS Sir David Attenborough's case, the deadweight is 4475 tonnes, and the displacement of the vessel is 12790 tonnes. This leads to the lightship weight of 8315 tonnes. Thus, if the exponent B is varied from 0.7 to 0.8, the first formula gives that the coefficient C_1 is from approximately 270 000 to 626 000, and the second gives the C_2 of rough value 87500, as the total building cost P is 225 million €.

Based on previous week, our vessel's deadweight is 3066.85 tonnes, and the lightship weight is roughly 8538.65 based on displacement. Thus, the first formula, varying C_1 from 270 000 to 626 000, gives us the total building cost of 166.2 to 172.7 million €. The second formula gives the total building cost of 230.3 million €. To conclude the total building cost analysis, the mean value of these approximates are used. That was calculated to be roughly 190 million €.

The final cost distribution of our vessel based on the SFI system, can be seen in Figure 34. The distribution was based on the approximated roughly 190 million € of total building costs and the earlier calculated roughly 18.3 million € of hull structure costs. The hull can be seen to take 10 % slice of the total costs. The mission of our vessel is quite versatile, which explains why different equipment for both the crew and for the ship herself along with different ship systems, take bigger slice than what was shown in Table 23. The hydrogen implementation also increases the costs regarding the main components of machinery and the systems for it.

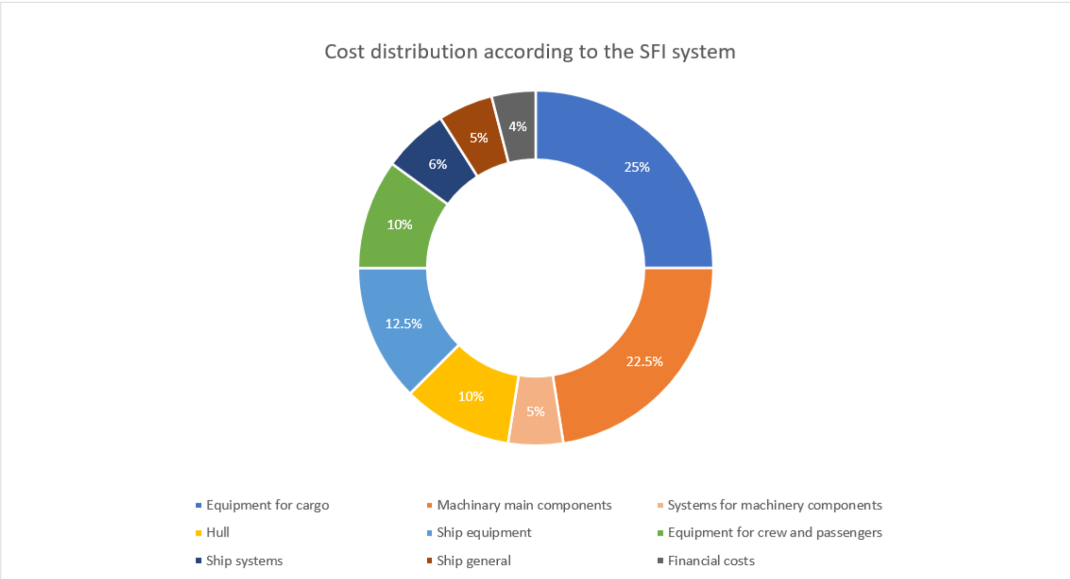

Figure 33 Cost distribution of Khione.

In Table 29, the cost estimate for each group is presented.

Table 29 Cost distribution.

	M €	%
Equipment for cargo	47.5	25%
Machinery main components	42.75	22.5%
Systems for machinery components	9.5	5%
Hull	19	10%
Ship equipment	23.75	12.5%
Equipment for crew and passengers	19	10%
Ship systems	11.4	6%
Ship general	9.5	5%
Financial costs	7.6	4%
Total building cost	190	

10 Evaluation

10.1 Economic Assessment

Vessel of our design project is made for research and resupply operations in remote Arctic areas. Because of our partly non-commercial mission, incoming annual cashflow is limited. Operation of the vessel is widely supported by the government. However, resupply operations are conducted during 10 months of each year bringing cashflow for the vessel. Cargo capacity of our vessel is 2460 tonnes. Since big part of the resupply is done to small and isolated communities and research centres, rate of transporter cargo each year is not great. It is estimated that on average it takes a month for the vessel to deliver the full capacity of cargo. Resulting that yearly 2460 tonnes x 10 = 24600 tonnes of cargo is transported. Freight rates for the transported cargo is significantly higher than typical because of the challenging transport routes and locations. It is estimated that on average freight rate would be 1500 € per tonne.

Net present value (NPV) -analysis has been performed to the ship. Lifetime of the ship is designed to be 30 years and initial investment 190 million €. Annual costs consist of maintenance, salaries, and fuel. Estimations for yearly maintenance and fuel costs are based on Swedish Viking ice breakers, which are normally used in offshore operations of Northern Sea. For severe winters fuel cost of those ice breakers has been 4.3 million € and maintenance costs 3.95 million € (Lindborg & Andersson, 2020). Annual cost for our vessel is roughly estimated to be 15 million € based on previously presented values. High number of crew members (100 pax) adds significant annual cost in form of salaries. Interest rate is 10%. Performed net present value -analysis is presented in table below.

As mentioned in beginning, vessel is designed for research and resupply operations which are not only driven by commercial success. NPV -analysis shows that governmental support is indeed required for ship to operate. During its lifetime, our vessel is not able to turn NPV to positive. After 30 years of operation, net present value of the ship is –28.6 million €.

Net present value at the end of the lifetime of the ship could be improved by several ways. In production lowering the building costs by increasing the efficiency could be done. Efficiency can be improved by lowering required work hours for example by using prefabricated modules, and by precise design and planning work. As mentioned, great piece of annual costs comes from salaries of our crew. Reduction of the people on deck would lead in significant savings. However, interest rate has a crucial role on development of NPV of the ship. Now interest rate is assumed to be 10 %. Even small reductions in interest rate would have significant effect on the NPV of the vessel. For example, with reduction of 1.5 %, from 10 % to 8.5 %, our NPV value at the end of the lifetime of the ship would change from –28.6 million € to -2 million €, which could be already considered as a breaking even.

Table 30 Net present value analysis

			Year	NPV, annual cash flow	NPV
Initial investment	190,000,000	EUR	0	-190,000,000 €	-190,000,000 €
Transport capacity	24,600	ton/year	1	19,909,091 €	-170,090,909 €
Freight rate	1,500.00	EUR/ton	2	18,099,174 €	-151,991,736 €
Annual revenues	36,900,000	EUR	6	12,361,979 €	-139,629,756 €
Annual costs	15,000,000	EUR	7	11,238,163 €	-128,391,594 €
Annual cash flow	21,900,000	EUR	8	10,216,512 €	-118,175,082 €
Interest rate	10.0 %		9	9,287,738 €	-108,887,344 €
			10	8,443,398 €	-100,443,946 €
			11	7,675,816 €	-92,768,130 €
			12	6,978,015 €	-85,790,115 €
			13	6,343,650 €	-79,446,465 €
			14	5,766,954 €	-73,679,510 €
			15	5,242,686 €	-68,436,825 €
			16	4,766,078 €	-63,670,747 €
			17	4,332,798 €	-59,337,948 €
			18	3,938,907 €	-55,399,041 €
			19	3,580,825 €	-51,818,216 €
			20	3,255,295 €	-48,562,920 €
			21	2,959,360 €	-45,603,561 €
			22	2,690,327 €	-42,913,234 €
			23	2,445,752 €	-40,467,482 €
			24	2,223,411 €	-38,244,072 €
			25	2,021,282 €	-36,222,789 €
			26	1,837,529 €	-34,385,260 €
			27	1,670,481 €	-32,714,779 €
			28	1,518,619 €	-31,196,159 €
			29	1,380,563 €	-29,815,596 €
			30	1,255,057 €	-28,560,539 €

10.2 SWOT

Our mission was to design a safe, reliable, and efficient research and re-supply vessel for use in Arctic and Antarctic areas. The operation of the vessel will focus on research and to provide supply to small communities and research centers. Since the vessel operates in extreme conditions and for long periods and the arriving time to next port can be uncertain the vessel needs to have enough capacity for storage, tanks etc. for long periods.

The opportunities of Khione are to bring new services to the arctic and Antarctic areas where the amount of service is limited. And of course, contribute the state with new research and broaden information of the operating areas. Because of the operating area the vessel needs to be designed with ice as a big aspect, the design and size of the vessel is still flexible for other operational areas as well.

Khione will use new technologies including hydrogen as an auxiliary energy source. The use of hydrogen will bring both positive and negative aspects. Since it's a new energy source in shipping it will bring weaknesses and threats because it is not so researched and the safety and security with the use needs to be considered. Another technology is the vessel being semi-autonomous which will bring the amount of crew down but it's also a new technology and needs a lot of implementing. The use of these technologies will bring new experience and visibility in terms of opportunities for their future use.

Since it's a research and resupply vessel it will mostly be funded by the government. The amount of supply is small and will not bring that much cashflow, thus a large amount of economic support and investments are needed for fulfilling the operation and research work. There are several requirements and regulations according the design and operation of the vessel which must be met and new regulations are probably coming during the vessels life-time, and we also want that the vessel is safe and reliable for the arctic areas.

Table 31 SWOT analysis.

Strengths New technologies • Hydrogen • Semi-autonomous Flexibility	Weaknesses New technologies • Hydrogen • Semi-autonomous Long operation times Large economic governmental support needed
Opportunities Services to arctic and Antarctic New research	Threats Safety and security regarding new technology used New regulations

11 Discussion

Designing a ship from the very beginning is always demanding process. This applied also to our project. Special purpose of the ship and new innovations caused some further challenges to already demanding project but they also made it more rewarding in terms of learning. Design process began with the initial requirements related to ice breaking and research capabilities and with keeping the semiautonomous operations in mind. Process pushed forward using the ship design circle. Finally, the whole conceptual design phase was executed following the structure of the design circle.

Aim of the design was to create modern, ecologic, and effective ice breaking research and resupply vessel for the most demanding seas of the world. New innovations were performed in the fields of autonomous operations and energy, which indeed caused some challenges during the design. Initially, hydrogen was even considered to be the energy provider for the propulsion system but with current technology, we had to reduce the idea. Hydrogen is currently designed to be used as energy source for auxiliary purposes. Autonomous operations were given big attention in design of the ship, which can be seen in great amount of computing space and sensors on board.

All the innovations and decisions in the design of the ship are made keeping the mission of the vessel in mind. Autonomous operations and top-level research facilities and scientific equipment will guarantee the best possible environment for the researchers to do their job. Resupply capabilities are taken care by large cargo handling and storing capacity.

As mentioned, just the conceptual phase is done, and many iterations are needed for our design to be complete. However, experience achieved from work done until now is absolutely crucial for the next stages of the design, and for future designs.

11.1 Learning process

Anniina Isokorpi

Before this course, my understanding and knowledge regarding maritime technology and ship industry in general contained basically only the experiences I had gained from travelling on a cruise ship from Helsinki to Stockholm. Thus, even though this course did not go too deep into any of the topics – but rather created the base for the big picture – this course gave me a lot, as I started basically from zero. This course gave me a general insight of ship building and naval architecture, what are the basic building blocks of the design process, how everything is connected to each other and, through practical experience, how this leads to that iterative process is a must. At the beginning, I wasn't sure whether a course this big and vague was good as the first course of the subject, as I would like to know something about the subject before I do something big with it. But now, as the course is almost complete, I see how this course was actually very good as it is easier to gain more specialised knowledge as the basis for the info is now built.

Sanna Granqvist

During this course I have learnt and got basic knowledge from the field. Since the earlier experience I had was from doing the bachelors thesis and summer work the course gave me a lot of new information and strengthened what I had learnt. The construction of the course made a good learning process and I now feel that I have a good basic understanding of shipbuilding and what is done during the design phases. The knowledge I have got from this course designing our ship and working as a team will for sure be helpful for other courses and future work.

Stephan van Reen

When starting out with the course, I had some experience with the theory behind naval architecture and had designed a boat before. What this project taught me was how designing a real ship looks like in a company setting with a team. I realised that I expect more details to be known than I can realistically expect to know at early design stages and that this is perfectly normal. I always thought that once I have a job, I am expected to know everything, but this course taught me that it is okay to not know something and in turn gave me more confidence. Furthermore, having no experience with icebreakers, never having seen one in real life before, it was hard to imagine how we would create an icebreaker out of nowhere. But by utilising the knowledge of more experienced people and reference ships, it was still possible to design an icebreaker regardless. No other course has made me really feel like I was standing on the shoulders of giants.

Oskar Veltheim

Before this course I have been working two summers and one winter at shipyards, so I had some basic knowledge of ships. I have also been active in LRK and learned also something there. At some point the course handled similar things I worked with at shipyard, which was nice. This first round of design circle has taught me a lot. Every theme of this week has taught something. One important thing, that going through all themes during this course, has taught is, that I know better, which direction I am going with rest of my studies and what I want to learn more about. I had heard a lot about this course before from my friends, especially how demanding this can be. Course has been motivating, because I have a great interest for the field of marine technology. I am also happy with my group, which is also motived group of fine people. As a group we have a good selection of special knowledge.

Juhan Voutilainen

Until this course my knowledge of naval architecture was relatively little. I spent summer before this course working in ship design company where I got some of the basic knowledge about naval architecture before the course. However, this course gave the context to those loose bits of information and a lot more. This course and this project included much work, but it also gave a good picture of the whole complex shipbuilding process, and all the aspects related to it. I cannot say that the course gave me much practical skills for future work, more the foundations for it, but at least now I know what I do not know.

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Appendices

Appendix 1: Design hydrostatics report

DELFTSHIP MARITIME SOFTWARE

Design hydrostatics report

Designer			
Created by			
Comment			
Filename		Straightfromexcel.fbm	
Design length	117.10 (m)	Midship location	58.550 (m)
Length over all	132.92 (m)	Relative water density	1.0250
Design beam	22.000 (m)	Mean shell thickness	0.0000 (m)
Maximum beam	22.000 (m)	Appendage coefficient	1.0000
Design draft	7.000 (m)		

Volume properties		Waterplane properties	
Moulded volume	11605.5 (m^3)	Length on waterline	127.98 (m)
Total displaced volume	11605.5 (m^3)	Beam on waterline	21.962 (m)
Displacement	11895.7 (tonnes)	Entrance angle	8.030 (Degr.)
Block coefficient	0.6436	Waterplane area	2241.7 (m^2)
Prismatic coefficient	0.6803	Waterplane coefficient	0.8701
Vert. prismatic coefficient	0.7396	Waterplane center of floatation	47.350 (m)
Wetted surface area	3076.1 (m^2)	Transverse moment of inertia	76093 (m^4)
Longitudinal center of buoyancy	50.751 (m)	Longitudinal moment of inertia	2121929 (m^4)
Longitudinal center of buoyancy	-6.094 %		
Vertical center of buoyancy	3.942 (m)		

Midship properties		Initial stability	
Midship section area	145.7 (m^2)	Transverse metacentric height	10.499 (m)
Midship coefficient	0.9460	Longitudinal metacentric height	186.78 (m)

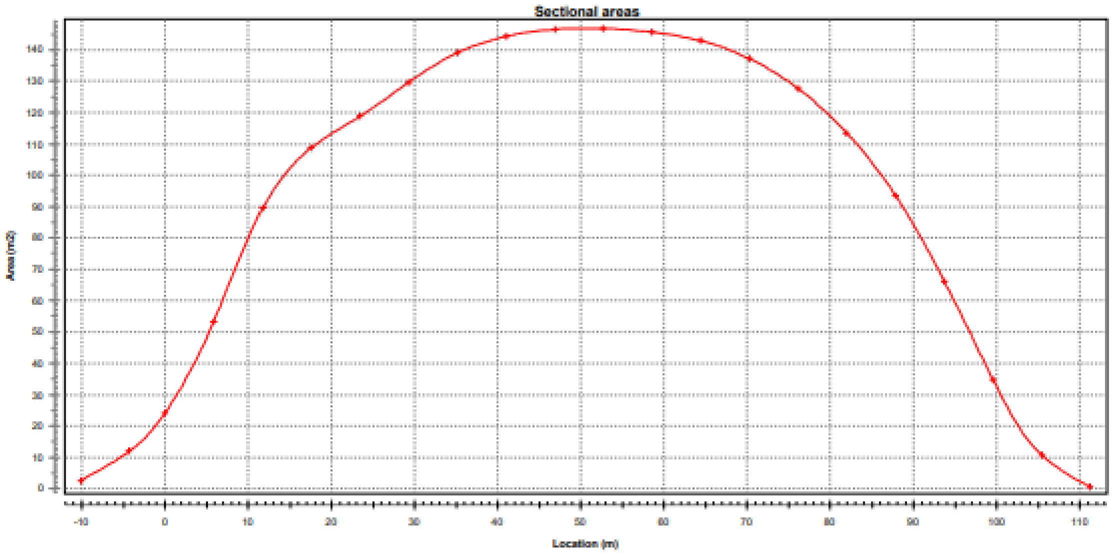
Lateral plane	
Lateral area	734.8 (m^2)
Longitudinal center of effort	52.732 (m)
Vertical center of effort	3.754 (m)

The following layer properties are calculated for both sides of the ship

Location	Area (m^2)	Thickness (m)	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)
Layer 2	4417.6	0.000	0.0	47.729	0.000 (CL)	4.429

Sectional areas

Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)	Location (m)	Area (m^2)
-10.145	2.6	17.565	108.8	46.840	146.6	76.115	127.7	105.390	10.8
-4.290	12.0	23.420	118.8	52.695	146.8	81.970	113.5	111.245	0.6
0.000	24.2	29.275	129.7	58.550	145.7	87.825	93.5		
5.855	53.1	35.130	139.1	64.405	142.9	93.680	66.1		
11.710	89.6	40.985	144.4	70.260	137.2	99.535	34.9		



NOTE 1: Draft (and all other vertical heights) is measured from base Z=0.000
NOTE 2: All calculated coefficients based on project length, draft and beam.